Performance Assessment of Radioactive Waste Repositories

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The current plans for permanent disposal of radioactive waste call for its emplacement in deep underground repositories mined from geologically stable rock formations. The U.S. Nuclear Regulatory Commission and U.S. Environmental Protection Agency have established regulations setting repository performance standards for periods of up to 10,000 years after disposal. Compliance with these regulations will be based on a performance assessment that includes (i) identification and evaluation of the likelihood of all significant processes and events that could affect a repository, (ii) examination of the effects of these processes and events on the performance of a repository, and (iii) estimation of the releases of radionuclides, including the associated uncertainties, caused by these processes and events. These estimates are incorporated into a probability distribution function showing the likelihood of exceeding radionuclide release limits specified by regulations.

MANY HUMAN ACTIVITIES PRODUCE LONG-TERM ADVERSE effects on the environment. For example, disposal of hazardous wastes on or in the land may result in the release of toxic chemicals into ground water or surface water for hundreds or even thousands of years. Large-scale construction projects such as dams or canals or other major human undertakings such as massive strip mining can also have long-term environmental effects. The disposal of radioactive wastes from nuclear reactors also has potential long-term effects. Radioactive waste disposal is, however, subject to regulations that set standards for disposal system performance that apply for periods of up to 10,000 years after repository closure. This stringent requirement has its origins in the public perception that nuclear energy presents a high level of risk to present and future generations (*1*).

The U.S. Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. Department of Energy (DOE) have developed rules governing radioactive waste disposal. The EPA has set environmental standards (*2*) for management and disposal of spent nuclear fuel, high-level, and transuranic radioactive wastes. These environmental standards include containment requirements [(*2*), 191.13], individual protection requirements [(*2*), 191.15], and ground-water protection requirements [(*2*), 191.16]. The primary standard for disposal is the containment requirement limiting releases of radionuclides to the environment for 10,000 years after disposal. This requirement sets low limits for high-probability releases and higher limits for low-probability releases [(*2*), table 1, appendix A]. It has long been the most controversial of the EPA disposal requirements and presents the greatest technical challenge for demonstrating compliance.

The NRC has also established procedural and technical requirements that incorporate the EPA standard by reference (*3*). As part of these requirements, performance objectives were developed to support an assessment of compliance with the EPA containment requirement (*4*). These performance objectives consist of (i) a minimum waste package lifetime, (ii) a maximum radionuclide release rate from the underground engineered facility, and (iii) a minimum ground-water travel time to the environment. DOE has developed siting criteria and guidelines that also incorporate the EPA standard (*5*).

In this article we discuss a methodology that can be used to assess the performance of a geologic radioactive waste repository and to evaluate compliance with the EPA containment requirement (*6, 7*). Although the methodology was developed simultaneously with and specifically for the containment requirement, it has applicability to the other EPA disposal requirements and the NRC performance objectives.

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Performance Assessment

Performance assessment, in the context of radioactive waste disposal, is the process of quantitatively evaluating the ability of a disposal system to contain and isolate radioactive waste. This quantitative evaluation will be used to support the development of a radioactive waste repository and to determine compliance with applicable regulations. The EPA and NRC require the use of a performance assessment to evaluate compliance with the EPA containment requirement (*2, 3*).

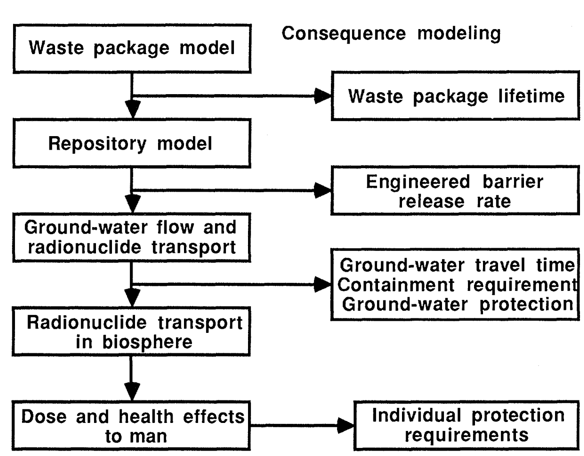


Fig. 1. Illustration of consequence modeling sequence showing points of compliance assessment with EPA and NRC regulations.

Performance assessments of geologic radioactive waste repositories have specific requirements. The 10,000-year regulatory period specified by the EPA will, for example, require identification of the physical processes and events that could cause release of radioactive wastes to the environment. Furthermore, the EPA containment requirement is probabilistic, thus requiring an estimate of the likelihood of each process and event. These important processes and events and their likelihood of occurrence are incorporated in scenarios that represent potential future histories of the disposal system.

The possible effects of these scenarios on the disposal system must also be examined. As it is not possible to experimentally observe the disposal system for 10,000 years, computer models will be used to predict these effects. Because of the uncertainties associated with these predictions, uncertainty analysis will be part of the performance assessment.

To assess compliance with the containment requirement, the EPA requires that the results of a performance assessment be assembled into a single distribution function displaying the likelihood of exceeding specified limits of radionuclide releases to the environment caused by all significant processes and events (*2*). The EPA assumes that a disposal system is in compliance if this single distribution function meets specific limit requirements for radionuclide release [(*2*), 191.13(a)].

Thus, the methodology for performance assessment of a geologic radioactive waste repository consists of the following: (i) procedures for scenario development, (ii) models for use in estimating consequences from these scenarios, and (iii) procedures for combining these estimates into an overall compliance assessment with regulatory standards (*6*).

Scenario Development

Several investigators have published lists of processes and events that could disrupt a geologic repository (*8–11*). These lists are usually grouped into natural phenomena (climate change, earthquakes, and undetected faults), human activities (exploratory drilling and mining), and repository-related phenomena (failure of materials sealing the access shafts and cracking of the rocks surrounding the repository). Comprehensive lists provide a useful starting point for scenario development. For a real site, however, scenario development might logically focus on processes or events that could degrade the characteristics that make the site desirable. For example, the most attractive feature of salt as a disposal medium is its extremely low permeability to fluid flow. For a repository in bedded salt, it is expected (*12*) that radioactive wastes would remain dry or that any movement of fluid around the wastes would be extremely slow. Scenarios that could increase salt permeability near the repository or effectively short-circuit this barrier should get considerable attention (*10*). Such scenarios could occur if heat from the radioactive waste caused the salt to crack or if there were high-permeability interbeds near the repository.

If the proposed site in Nevada (*13*) is used, the repository would be located in welded tuff above the water table. Although the tuff is fractured, water infiltration rates are low so very little water is expected to reach the wastes (*13*). Therefore, an important scenario would focus on the possibility that future increases in rainfall could increase water infiltration rates. Another possible scenario would consider that fluctuations in the water table caused by tectonic processes could cause flooding of the repository (*14*). If either of these scenarios should occur, fractures could provide migration pathways that would permit radionuclides to reach the environment.

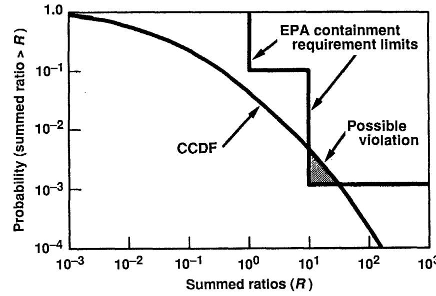


Fig. 2. Comparison of a CCDF for radionuclide release to the accessible environment with the release limits set by the EPA containment requirement. The summed ratios (R) are dimensionless units as defined in the text.

Once scenarios have been identified, it is necessary to estimate their probabilities of occurrence. Ideally, these probability estimates would be based on observed frequencies. For example, the probability of an exploratory drill hole penetrating the repository can be estimated on the basis of historical drilling activities near the site or in similar areas. In some cases, it may be possible to use a probability model if assumptions can be made concerning the randomness of the event in space or time. For example, if the assumption is made that faults occur randomly within a region and that faults have a preferred orientation, then a Poisson probability model can be used in conjunction with geometric probability theory (*15*) to form an estimate of the probability that faulting will disrupt a repository (*16*).

Another quantitative method for estimating scenario probabilities involves the use of mathematical models to represent the physical process of interest. For example, the possibility of thermal cracking around the repository can be studied by using thermal-mechanical models to predict the stress fields that would develop near the repository as a result of heat from the radioactive wastes. When data are sparse or nonexistent, it will be necessary to rely on expert judgment to estimate probabilities.

Consequence Analysis

After a realistic set of scenarios has been developed, the consequences of each one are evaluated. In risk analysis, consequences are often expressed in terms of number of health effects. The EPA has established limits on radionuclide releases to the environment (*17*). These limits [(*2*), table 1, appendix A] are intended to ensure that the risks to future generations from radioactive waste disposal are no greater than those that would have existed if the uranium ore used to create the wastes had never been mined. Thus, for purposes of the EPA containment requirement, consequence analysis refers primarily to predicting radionuclide releases to the environment for the selected scenarios. The models used to predict these releases generally include waste package models, repository models, and groundwater flow and radionuclide transport models.

Waste package model. The waste package consists of the radioactive waste, the waste canister, and any packing or absorbing materials immediately surrounding the canister. Waste package models analyze the degradation of the waste package and the release of radionuclides from the waste package into the underground facility. The simplest waste package model would assume complete failure of the waste canister at a given time followed by leaching of radionuclides from the waste. A more comprehensive model would account for effects on the waste package of heat and radiation from waste decay as well as repository stresses and fluids. Such a model would also account for waste form leachability and radionuclide solubilities. Output of the waste package model will consist of the time-dependent release rates of radionuclides from the waste package into the underground facility (*18*).

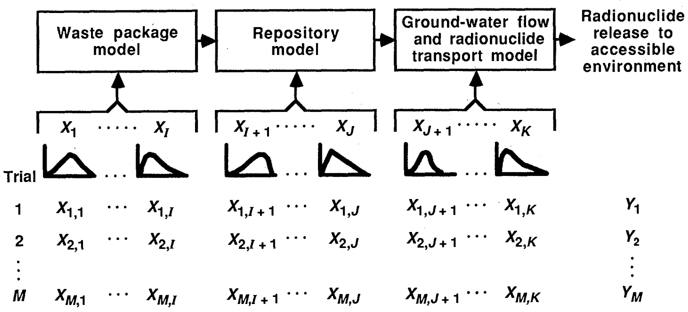


Fig. 3. Illustration of the use of statistical sampling to treat data uncertainties in consequence modeling. The first I variables are used in the waste package model. Variables $I + 1$ through J are used in the repository model, and variables $J + 1$ through K are used in the ground-water flow and radionuclide transport model.

Repository model. The repository model deals primarily with the underground facility, which includes the underground structure, backfill materials, and any openings that remain after backfilling. This model uses radionuclide release rates from the waste package model, accounts for migration of radionuclides through the underground facility, and predicts the rate of escape of radionuclides into circulating ground water. The simplest repository model would accumulate radionuclide release rates from all failed waste packages and equate the result to the release rate from the underground facility. A comprehensive repository model would simulate fluid movement and radionuclide transport through the underground facility by accounting for the hydraulic and sorption properties of the backfill, the geometry of the mined area, thermal and other driving forces, and radionuclide solubilities.

Ground-water flow and radionuclide transport. Information from the repository model is used in the ground-water flow and radionuclide transport model to simulate movement of dissolved radionuclides from the repository to the environment. The simplest flow and transport models are one dimensional, assume a known fluid velocity, and use simple analytic solutions for radionuclide transport (*19*). A more realistic model uses a network system to model ground-water flow and an efficient numerical scheme to determine radionuclide transport (*20*). In application, the flow network is designed to identify the significant radionuclide migration pathways. The most complex flow and transport models currently available are implemented in fully three-dimensional computer codes capable of analyzing fluid flow, heat, brine transport, and radionuclide transport (*21*).

The output of these transport models is usually expressed as concentrations in ground water or time-dependent environmental discharge rates. The time-dependent discharge rates can be integrated to give the cumulative releases of radionuclides needed for comparison with the EPA containment requirement. The concentrations can be used to assess compliance with the ground-water protection requirement [(*2*), 191.16], which limits radionuclide concentrations in ground water for 1000 years after disposal.

Other modeling requirements. The EPA standard also includes an individual protection requirement [(*2*), 191.15] limiting the annual dose to any member of the public for 1000 years after permanent disposal. Two additional modeling components, radionuclide transport in the biosphere and dosimetry and health effects, are needed to assess compliance with this requirement. Discharge rates generated by the ground-water flow and radionuclide transport model are used in a biosphere transport model to simulate movement of radionuclides through the surface environment and to estimate their concentrations in the atmosphere, surface waters, soil, and sediments (*22*). These concentrations are then used to predict curie intake through ingestion, inhalation, and external exposure. Intake of radionuclides through the various pathways are converted to dose levels to body organs (*23*).

Regulatory Compliance Assessment

The main points in the consequences modeling sequence at which compliance with the EPA and NRC regulations and performance objectives would be assessed are illustrated in Fig. 1. The EPA containment requirement specifies that cumulative releases of individual radionuclides to the accessible environment from all significant processes and events for 10,000 years after disposal shall (i) have a likelihood of less than one chance in 10 of exceeding specified quantities [(*2*), table 1, appendix A] and (ii) have a likelihood of less than one chance in 1000 of exceeding ten times these quantities. When several radionuclides are projected to be released, the limiting values are determined as follows:

$$R = \frac{Q_{\mathrm{A}}}{RL_{\mathrm{A}}} + \frac{Q_{\mathrm{B}}}{RL_{\mathrm{B}}} + \ldots + \frac{Q_{\mathrm{N}}}{RL_{\mathrm{N}}} \leq 1 \text{ (or 10)}$$

where $Q_{\mathrm{A}}, Q_{\mathrm{B}}, \ldots, Q_{\mathrm{N}}$ are projected releases of radionuclide A, B, . . . , N, respectively, and $RL_{\mathrm{A}}, RL_{\mathrm{B}}, \ldots, RL_{\mathrm{N}}$ are the applicable release limits [(*2*), table 1, appendix A].

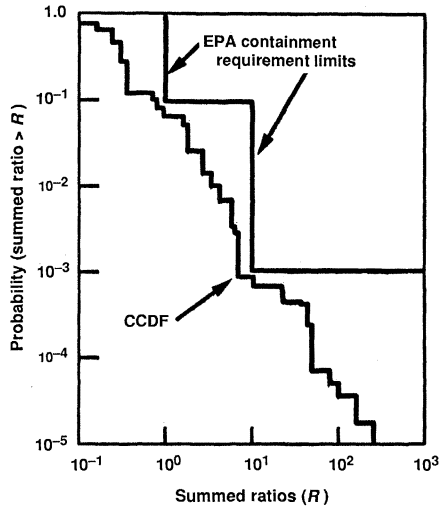
When the results of a performance assessment are displayed in the format of these summed ratios (R), the EPA containment requirement takes the form of a step function. If this step function is imposed on a graph of the Complementary Cumulative Distribution Function (CCDF) of summed ratios for all radionuclides projected to be released from all significant processes and events, then compliance with the EPA containment requirement can be evaluated as illustrated in Fig. 2. The EPA assumes that a CCDF that falls below the step function in Fig. 2 indicates that the disposal system has satisfied the containment requirement, whereas any portion of a curve that falls outside the step function may signify noncompliance with the requirement. Figure 2 illustrates a possible violation of the EPA containment requirement.

The need to develop a CCDF implies a need to present the effects of data uncertainties on predicted radionuclide discharge. The sequence of models shown in Fig. 3 is appropriate for scenarios involving release of radionuclides to ground water. Each model has its own input data requirements. For example, data requirements for the waste package model will include data on canister corrosion and waste form leaching. The repository model will require geochemical data from within the repository and hydraulic properties of the backfill material.

Input data for the flow and transport model will include hydraulic properties of aquifers and any disruptive features through which flow occurs as well as geochemical data for these areas. Uncertainties in these data will be represented by probability distributions (Fig. 3). In instances of ample data availability, these distributions may represent measurement error. For spatially variable properties such as permeability or porosity, the distribution may represent a spatial average. In many instances where data are sparse, expert judgment may be needed to develop these distributions.

To generate a CCDF, the variable distribution will be sampled either randomly or by using a stratified sampling method such as Latin hypercube sampling (*24*), and repeated trials will be performed. If M trials are required, then M input vectors will be formed where each vector consists of one sampled value from each of the input variables. For each input vector, one output value (Y) is calculated that represents cumulative radionuclide discharge to the environment. The resulting M values of radionuclide discharge can then be used to produce the desired CCDF.

Fig. 4. Comparison of a CCDF generated by multiple simulations with the EPA containment requirement.



This type of analysis must be performed for each scenario. Different scenarios may require sequences of models different from that shown in Fig. 3. Also, different or additional variables will be required for different scenarios.

In a performance assessment in which multiple simulations are used to account for parameter uncertainty, the CCDF in Fig. 2 would be a step function, as shown in Fig. 4. The number of steps and the step heights would depend on the number of scenarios being analyzed, their probabilities, and the number of simulations. In the case where a possible violation of the EPA containment requirement is indicated, the methodology discussed here readily allows identification of the scenarios and repository system properties causing the violation.

Summary

The EPA containment requirement is both controversial and technically challenging because of the long regulatory periods over which compliance predictions must be made and the need to incorporate uncertainties in these predictions into a single probability distribution. The methodology presented in this article can be used to demonstrate compliance or noncompliance with this standard as well as with other EPA and NRC regulations and performance objectives. A key feature of this methodology is its ability to incorporate data uncertainties in addition to uncertainties in future processes and events.

Two problem areas not treated in this article are model uncertainty and the data requirements of performance prediction models. Model uncertainty can arise from questions concerning the conceptualization of a disposal system, the ability of mathematical algorithms to accurately represent the conceptual model, and implementation of the mathematical model into a computer code. Conceptual model uncertainty can be dealt with by using scenarios representing alternate conceptualizations of the disposal system. Mathematical model and computer code uncertainties are addressed through a strong software quality assurance program (*25*) that includes comparison with real data where possible, peer review, and comparison with other models. Verification and validation efforts are under way to build confidence in mathematical models and computer codes used in performance assessment activities (*26, 27*).

Data requirements of performance prediction models are massive, and only limited site-specific data will be available in the early stages of site characterization. This does not imply, however, that performance assessment must await completion of detailed site characterization. In the absence of site-specific data, generic data (data from other similar areas) combined with expert judgment can provide the information needed to predict repository system performance. Although the uncertainties in these predictions will be very large, sensitivity analyses to determine important contributors to these uncertainties will provide valuable guidance for site characterization activities. Thus, the use of performance assessment throughout site characterization can help ensure that data collection is properly focused to reduce uncertainties in the predicted performance of the disposal system.

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