NUREG/CR-4510
SAND86-0121

Assessing Compliance With the EPA High-Level Waste Standard: An Overview

Prepared by R. L. Hunter, R. M. Cranwell, M. S. Y. Chu

Sandia National Laboratories

**Prepared for
U.S. Nuclear Regulatory
Commission**

Reprinted March 1987

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, Post Office Box 37082, Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-4510
SAND86-0121

Assessing Compliance With the EPA High-Level Waste Standard: An Overview

Manuscript Completed: October 1986
Date Published: October 1986

Prepared by
R. L. Hunter, R. M. Cranwell, M. S. Y. Chu

Sandia National Laboratories
Albuquerque, NM 87185

Prepared for
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN A1165

ABSTRACT

The US Environmental Protection Agency has set a standard for the performance of geologic repositories for the disposal of high-level radioactive waste. The standard is divided into several sections, including a section on containment requirements. The containment requirement is probabilistic, in that it allows certain small amounts of radioactive waste to be released at high probabilities and larger amounts to be released at lower probabilities. The US Nuclear Regulatory Commission is responsible for implementing the standard. Implementation of the standard will probably involve development and screening of scenarios, assignment of probabilities to the scenarios, determination of consequences of the scenarios, and analysis of uncertainties.

Scenario development consists of first, identifying events and processes that could initiate waste releases or affect waste transport, and second, combining the events and processes in physically reasonable ways. Scenarios can be screened on the basis of low probabilities or consequences. Consequences of scenarios are estimated using a series of models that simulate the movement of radionuclides out of the waste package and underground facility and the transport of the radionuclides by ground water or other means to the accessible environment. Sensitivity and uncertainty analysis examines the sources and effects of uncertainties on the calculations. This document uses a simple example to illustrate techniques for the implementation of the standard.

CONTENTS

CONTENTS (concluded)

FIGURES

TABLES

ACKNOWLEDGMENTS

This work was carried out under the sponsorship of the US Nuclear Regulatory Commission Division of Waste Management, Repository Projects Branch. The authors appreciate the continuing support and technical direction of Dr. Atef Elzeftawy, the program manager, and the review comments of John Trapp, Dr. Dan Fehringer, Dr. Malcolm Knapp, and Seth Coplan of the NRC staff.

EXECUTIVE SUMMARY

There are almost 100 operating commercial nuclear power plants in the US, which have generated large volumes of spent fuel and high-level radioactive waste (HLW) since the late 1950s. A recent projection of spent fuel to be accumulated through the year 2030 is 140,000 metric tons of heavy metal (MTHM) (US Department of Energy, 1984). These wastes are intensely radioactive and will remain so for thousands of years, necessitating a safe and permanent method of isolating the wastes from the biosphere, so that they will not threaten public health and safety now or in the future. In 1982, Congress passed the Nuclear Waste Policy Act (the Act), which requires all HLW to be permanently isolated in deep geologic repositories. The Act sets a schedule for repository development, provides a means of financing development, and assigns responsibilities for standard setting, licensing, and construction and operation to appropriate government agencies. The Act established a process for the selection of sites for HLW repositories and assigns to the US Department of Energy (DOE) the responsibility for locating, constructing, operating, closing, and decommissioning repositories. Waste disposal will be governed by the environmental standard of the US Environmental Protection Agency (EPA) as implemented by the US Nuclear Regulatory Commission (NRC).

The EPA has set a standard (the Standard, 40CFR191) that requires any repository to protect the public from significant radiation doses for at least 10,000 yr after closure by releasing less than a predetermined amount of each radionuclide to the biosphere (EPA, 1985). The NRC is responsible for assuring that any DOE repository will meet the Standard, that is, NRC is responsible for implementing the EPA Standard. The NRC has set a regulation (the Rule, 10CFR60) that requires the Standard to be met and, in addition, sets specific numerical requirements for the performance of some repository elements (NRC, 1983). In its license application to the NRC for the construction of a repository, the DOE must demonstrate that the repository will comply with the Standard and the Rule. The NRC will independently evaluate the DOE's license application by performing a licensing assessment.

The Standard is divided into two subparts. Subpart A sets environmental standards for management and storage of spent nuclear fuel and high-level and transuranic radioactive wastes (all will be called HLW in this report), and Subpart B sets standards for the disposal of the same. "Management" includes any activity conducted to prepare HLW for storage or disposal and any activity associated with emplacement of waste in a disposal system, exclusive of transportation. "Storage" is the retention of HLW with the intent and capability of ready retrieval for subsequent use, processing, or disposal. "Disposal" is the permanent isolation of HLW with no intent of recovery, when the repository is backfilled and sealed. The containment requirement is probabilistic, in that it allows certain small amounts of radioactive waste to be released at high probabilities and larger amounts to be released at lower probabilities. Assessing compliance with the containment requirements of Subpart B is the main focus of this report.

This document is an overview of techniques that may be used to determine whether a repository will meet the Standard. It is intended to demonstrate that the techniques needed to carry out and evaluate a performance assessment now exist, although it does not comprehensively describe the details of each technique. After describing a typical procedure for carrying out a performance assessment, it demonstrates the procedure with a simple but realistic example. The typical procedure and the example are not intended to offer guidance on required techniques for performance assessment; rather they demonstrate existing techniques judged by the authors to be acceptable. Because the NRC regulation requires additional demonstrations of acceptability, demonstrating compliance with the Standard does not necessarily guarantee the licensability of a site. This report also comments on some of the important judgments that must be made in preparing a performance assessment.

A performance assessment can be divided into four parts:

- Scenario development and screening
- Consequence assessment
- Sensitivity and uncertainty analysis
- Regulatory-compliance assessment.

Scenario development and screening comprehensively examines possible future occurrences or existing but unrecognized conditions that might affect a repository, assigns probabilities to them, and determines which possibilities merit detailed consideration. Consequence assessment estimates the releases that might arise from the scenarios of interest. Sensitivity and uncertainty analyses identify important processes and parameters, illuminate the sources and extent of uncertainty in the consequence assessment, and enable the regulator to evaluate the amount of confidence that can be placed in the results. Finally, regulatory-compliance assessment combines the results of scenario analysis, consequence assessment, and sensitivity and uncertainty analysis to determine whether the repository is in compliance with requirements of the EPA standard.

Scenario Development and Screening

The future of a repository site holds many possibilities, some of which would degrade the expected performance of a repository. Waste-management analysts usually use "scenarios" to study these possible futures. As used in waste management, a "scenario" is a physically possible sequence of events and processes that could lead to release and transport of radionuclides from a repository to the accessible environment. Scenarios are site specific, but a general and systematic procedure can be used to identify the scenarios of interest at any given site. This procedure consists of first, identifying the events and processes that could initiate release or affect radionuclide transport and, second, combining the events and processes in physically reasonable ways to form scenarios.

Scenarios are the basis for consequence modeling. Although the Standard does not use the term "scenario," Sections 191.12 (q) (the definition of performance assessment) and 191.13 (a) (the containment requirement) clearly require their development and analysis during performance assessment. The number of scenarios and the explanation of the scenario-development techniques used must inspire confidence that all processes and events that significantly affect the disposal system have been considered. A large number of scenarios can easily be developed for the kinds of sites currently being investigated by DOE. In general, it is desirable to develop and document as many physically reasonable scenarios as possible. Conservative preliminary estimates of scenario probabilities and consequences can be used to screen scenarios before full-scale consequence modeling. The regulator and the public, not just the applicant, must see the breadth of scenarios initially considered and the basis for screening in order to develop confidence that consequences have been determined for all important scenarios.

Determining the probabilities of scenarios and of the geologic events and processes that make up scenarios is essential because the Standard is probabilistic. Although much work has been done in the development of techniques for determining such probabilities, only a small part of that work has been applied in waste management. Under the sponsorship of the NRC Repository Projects Branch, Sandia National Laboratories Division of Waste Management has undertaken a major review of probabilistic techniques in eight fields of geology (Hunter and Mann, 1986). These fields are hydrology, climatology, volcanology, tectonism and seismicity, resource exploration, mining engineering, thermomechanical effects, and geochemistry.

Section 191.13 (b) of the Standard states that, because proof cannot be obtained that the assigned probabilities are correct, complete assurance that the probabilistic requirements will be met is not required. Rather, the performance assessment must give the regulator a reasonable expectation that compliance will be achieved. Appendix B of the Standard suggests that in determining the probabilities, a variety of methods may be used, including numerical models, analytical theories, and prevalent expert judgment. Techniques are available for the determination of the probability of the various geologic events and processes of interest (Hunter and Mann, 1986; Cranwell and others, 1982a). Events and processes for which data or theory are inadequate to numerically determine a probability will require the use of expert judgment. Techniques such as decision analysis will be useful when expert judgment is required.

Consequence Assessment

After scenarios have been selected, a sequence of models is used to estimate the consequences of each scenario. Typically, the first suite of models examines the release of radionuclides from the waste packages, using data describing waste-package characteristics and the underground facility. After the radionuclides exit from the waste packages, a second analysis describes the movement of radionuclides out of the underground facility. After that, transport of radionuclides by ground water to the accessible environment is analyzed. Several physical phenomena are considered by the consequence assessment. They include the flow of ground water, the movement of radionuclides by ground water, radioactive decay and the production of new radionuclides, and retardation of radionuclides by the host rock. In addition, because the decay heat generated by HLW and the dissolved waste itself can affect the rock and ground-water system, models describing waste/host rock interactions are necessary. These models include geochemical, hydrological, and thermomechanical phenomena.

Sensitivity and Uncertainty Analysis

Because experimental data cannot be collected over a period of 10,000 yr, decisions about the acceptability of a facility must be based largely on its predicted behavior, as derived from computer models that represent the salient features and simulate the processes affecting its performance. The quantity of prime interest to regulatory agencies is the predicted cumulative release of radioactive waste to the accessible environment over 10,000 yr. This calculated release is not unique, as the calculation has uncertainties associated with it. Because regulatory decisions will be based on model predictions, it is important to investigate the sources of uncertainty that affect these predictions.

Uncertainty in the analysis of geologic waste disposal has three primary components: scenario uncertainty, data or parameter uncertainty, and model uncertainty. Two major types of uncertainty arise from the consideration of scenarios: uncertainty associated with their "completeness," and uncertainty associated with their screening. Model uncertainty can arise from several sources, including problems associated with determination of appropriate parameters for use in model construction, mathematical formulation of models, and numerical techniques used in the models. Uncertainties also arise from a lack of understanding of the processes being modeled, a limited capability to mathematically represent these processes, or insufficient data describing the system or the processes acting on it. Data or parameter uncertainty is caused by (1) random and/or systematic measurement errors in the data used to make parameter estimates for a model, (2) incomplete data on parameters known to vary spatially or temporally, (3) heterogeneities within the hydrogeologic system that have not been detected during data collection, and (4) misuse or misinterpretation of data.

"Sensitivity analysis" generally refers to a means of quantitatively estimating the amount of variation in model output due to specified variation in model input parameters. It is a means of identifying important parameters. An uncertainty analysis uses the results of a sensitivity analysis to help quantify the uncertainty in model output induced by uncertainty in model input parameters.

Regulatory-Compliance Assessment

Section 191.13 of the Standard requires that cumulative releases of individual radionuclides to the accessible environment from all significant processes and events that may affect the disposal system for 10,000 yr after disposal shall (1) have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1, Appendix A of the Standard; and (2) have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1, Appendix A. For projected releases of several radionuclides, there is the additional requirement that

$$\frac{Q_A}{RL_A} + \frac{Q_B}{RL_B} + \ldots + \frac{Q_N}{RL_N} \leq 1 \text{ (or 10)} \tag{1}$$

where Q_i is the projected release of radionuclide i, and RL_i is the release limit of radionuclide i. This sum will be referred to here as the "EPA sum" or "summed normalized releases."

The Standard also states that, whenever practicable, assessing compliance with Section 191.13 will be accomplished by assembling all results of a performance assessment into a "complementary cumulative distribution function" (CCDF). In the context of the containment requirements of Section 191.13, a CCDF indicates the probability of exceeding particular values of the EPA sum. Stated differently, for a given value of the EPA sum, say R, a CCDF accumulates all of the probabilities of EPA sums greater than R. A graph of the CCDF can therefore be obtained by plotting EPA sums vs. accumulated probabilities (Figure E-1).

The graph illustrated in Figure E-1 can be used as the basis for assessing compliance with the containment requirements of Section 191.13. A step function added to Figure E-1 illustrates the containment requirements of 191.13 (a) and 191.13 (b) (Figure E-2). A CCDF that falls below the envelope in Figure E-2 indicates that the disposal system has satisfied the containment requirements of Section 191.13, whereas any portion of a curve that falls outside the envelope may signify noncompliance with the requirement.

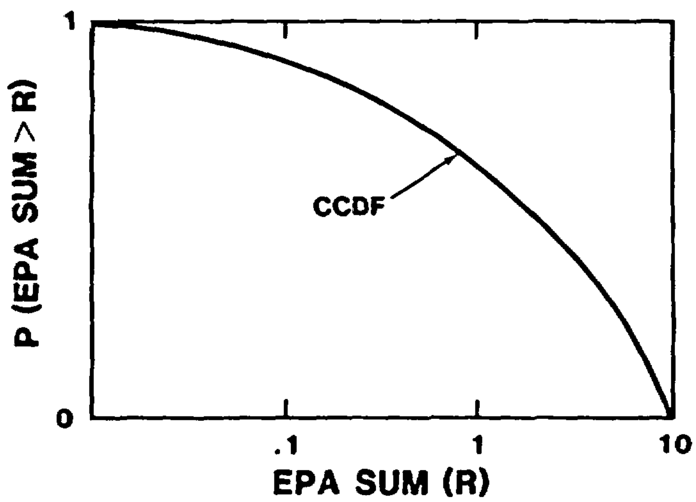

Figure E-1. CCDF of EPA sums as accumulated probabilities.

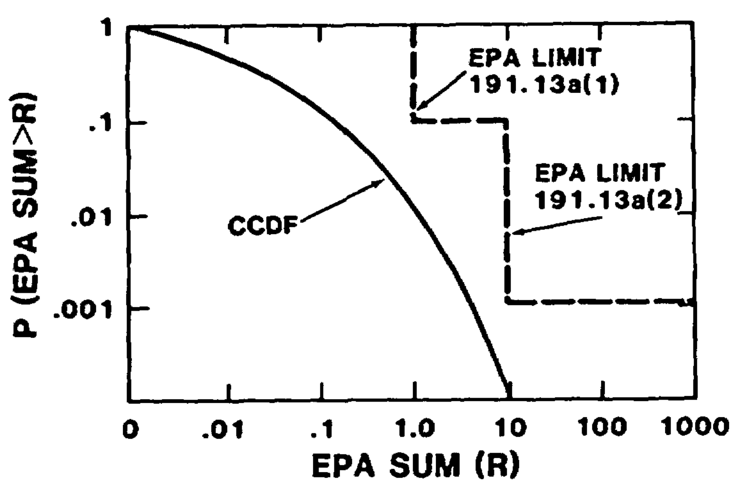

Figure E-2. Graph of probability vs. allowable release under the EPA containment requirement.

1. INTRODUCTION

There are almost 100 operating commercial nuclear power plants in the US, which have generated large volumes of spent fuel and high-level radioactive waste (HLW) since the late 1950s. A recent projection of spent fuel to be accumulated through the year 2030 is 140,000 metric tons of heavy metal (MTHM) (US Department of Energy, 1984). These wastes are intensely radioactive and will remain so for thousands of years, necessitating a safe and permanent method of isolating the wastes from the biosphere, so that they will not threaten public health and safety now or in the future. In 1982, Congress passed the Nuclear Waste Policy Act (the Act), which requires all HLW to be permanently isolated in deep geologic repositories. The Act sets a schedule for repository development, provides a means of financing development, and assigns responsibilities for standard setting, licensing, and construction and operation to appropriate government agencies. The Act established a process for the selection of sites for HLW repositories and assigns to the US Department of Energy (DOE) the responsibility for locating, constructing, operating, closing, and decommissioning the repository. Waste disposal will be governed by the environmental standard of the US Environmental Protection Agency (EPA) as implemented by the US Nuclear Regulatory Commission (NRC).

The EPA has set a standard (the Standard, 40CFR191) that requires any repository to protect the public from significant radiation doses for at least 10,000 yr by releasing less than a predetermined amount of each radionuclide to the biosphere (EPA, 1985). The NRC is responsible for assuring that any DOE repository will meet the Standard, that is, NRC is responsible for implementing the EPA Standard. The NRC has set a regulation (the Rule, 10CFR60) that requires that the Standard be met and, in addition, sets specific numerical requirements for the performance of some repository elements (NRC, 1983). In its license application to the NRC for the construction of a repository, the DOE must demonstrate that the repository will comply with the Standard and the Rule. The NRC will independently evaluate the DOE's license application by performing a licensing assessment.

Purpose

This document is an overview of the techniques that the NRC may use in performing a licensing assessment to determine whether a repository will meet the Standard. It is intended to demonstrate, simply but convincingly, that the techniques needed to carry out and evaluate a performance assessment now exist. Chapter 2 describes a typical procedure for carrying out a performance assessment. Chapter 3 demonstrates the procedure with a simple example. The example is simple enough to follow without an extensive background in performance assessment or recourse to the references, but complex enough to be a realistic demonstration of the techniques. The typical procedure and the example are not intended to offer guidance on required techniques for performance assessment; rather they demonstrate existing techniques judged to be acceptable by the authors. Because the NRC regulation requires additional demonstrations of acceptability, demonstrating compliance with the Standard does not necessarily guarantee the licensability of a site. This report also comments on some of the important judgments that the analyst must make in using these or alternative techniques.

EPA Standard: Content and Intent

The Standard itself is brief, less than five pages long in the Federal Register; the EPA's accompanying introduction and explanation are close to 20 pages long. Documentation of a performance assessment is likely to be hundreds or even thousands of pages in length. This report briefly outlines each section of Subpart B of the Standard per se, in order to provide a common basis for understanding the techniques for evaluating a performance assessment, which are the primary focus of this paper.

The Standard is divided into two subparts. Subpart A sets environmental standards for management and storage of spent nuclear fuel and high-level and transuranic radioactive wastes (all will be called HLW in this report), and Subpart B sets standards for the disposal of the same. "Management" includes any activity conducted to prepare HLW for storage or disposal and any activity associated with emplacement of waste in a disposal system, exclusive of transportation. "Storage" is the retention of HLW with the intent and capability of ready retrieval for subsequent use, processing, or disposal. "Disposal" is the permanent isolation of HLW with no intent of recovery, when the repository is backfilled and sealed. Assessing compliance with the containment requirement of Subpart B is the main focus of this report. Sections 191.01 through 191.05 are in Subpart A. Sections 191.11 through 191.18 are in Subpart B.

Subpart B

191.11 Applicability. Subpart B applies to releases of radioactive materials into the accessible environment, radiation doses to members of the public, and radioactive contamination of certain sources of ground water as a result of disposal of HLW, but not to disposal into the oceans or to disposal that took place before September 19, 1985.

191.12 Definitions. The important terms of Subpart B are defined in Section 191.12. In addition to those defined above, several are of particular interest here. "Disposal system" means any combination of engineered and natural barriers that isolate HLW after disposal. "Barrier" means anything that prevents or substantially delays movement of water or radionuclides toward the accessible environment. "Accessible environment" means the atmosphere, land surfaces, surface water, oceans, and all of the lithosphere that is beyond the controlled area. "Performance assessment" means an analysis that identifies processes and events that might affect the disposal system; examines the effects of these processes and events on the performance of the disposal system; estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events; and incorporates these estimates into an overall probability distribution of cumulative release to the extent practicable.

191.13 Containment Requirements. The containment requirements are the heart of the Standard and the focus of this report. In essence, this section states that disposal systems shall be designed to provide a reasonable expectation that the cumulative releases of HLW to the accessible environment for 10,000 yr from all significant processes and events shall have

- less than one chance in 10 of exceeding the quantities calculated according to Table 1, and

- less than one chance in 1000 of exceeding ten times those quantities.

This section states explicitly that performance assessments need not provide complete assurance that these requirements will be met. It states that because there will be substantial uncertainties in projecting disposal-system performance, proof of the future performance cannot be had in the ordinary sense of the word. Instead, the Standard requires a reasonable expectation, on the basis of the record before the implementing agency, that compliance will be achieved.

Sections 191.14 through 191.18. The assurance requirements set forth in Section 191.14 will be incorporated into the NRC regulation, but will not be discussed here. Section 191.15 protects individuals in the population from large releases during the first 1000 yr after disposal by limiting the annual dose that any member of the public may receive. Section 191.16 provides specific protection to certain community supplies of ground water near the repository. Although Sections 191.15 and 191.16 may well affect repository location or design in important ways, they are not within the major concern of this report, i.e., the containment requirements. Section 191.17 allows the EPA Administrator to change Subpart B under certain circumstances. Section 191.18 made Subpart B effective on September 19, 1985.

Appendix A

Appendix A consists of Table 1 and instructions for its use (see p. 20).

Appendix B

Appendix B offers guidance for implementing Subpart B. Although the NRC and DOE are not required to follow the guidance in Appendix B, the task of implementing the Standard becomes more clear, and in some cases, easier, if the guidance is followed. The typical procedure and the example that make up the bulk of this report assume that the guidance will be followed.

The EPA believes that DOE and NRC must determine compliance with the containment requirements by evaluating long-term predictions of the performance of disposal systems and by predicting the likelihood of events and processes that may disturb those systems. The EPA believes that various techniques for making the predictions are appropriate, including complex computational models, analytical theories, and prevalent expert judgment. Because of the uncertainties that are likely to exist, sole reliance on the numerical calculations may not be appropriate; Appendix B states explicitly that supplementary qualitative judgments may be used.

Table 1. Release limits for containment requirements (cumulative releases to the accessible environment for 10,000 yr after disposal) (after EPA, 1985, Table 1)

Radionuclide	Release Limit per 1000 MTHM or other unit of waste (curies)
Americium-241 or -243	100
Carbon-14	100
Cesium-135 or -137	1000
Iodine-129	100
Neptunium-237	100
Plutonium-238, -239, -240, or -242	100
Radium-226	100
Strontium-90	1000
Technetium-99	10000
Thorium-230 or -232	10
Tin-126	1000
Uranium-233, -234, -235, -236, or -238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1000

The EPA assumes that credit will be taken for all barriers that contribute to isolation, even if their performance is uncertain.

The EPA assumes that categories of events or processes estimated to have less than one chance in 10,000 of occurring over 10,000 yr need not be considered in performance assessments. Not all releases from more likely events need be evaluated in detail: some may be omitted from the performance assessment if there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed.

The EPA assumes that, whenever practicable, DOE or NRC will summarize the results of the performance assessment into a complementary cumulative distribution function (CCDF) indicating the probability of exceeding various levels of cumulative release. The effects of the uncertainties will be incorporated into a single CCDF for each disposal system. If this CCDF meets the requirements of Section 191.13, the disposal system complies with that Section.

The EPA assumes that the possibility of human intrusion into the repository cannot be eliminated, but that it is not productive to consider conceivable intrusions that no reasonable siting or design precautions could alleviate. The EPA suggests that no more than 30 boreholes per km^2 per 10,000 yr for repositories in or near sedimentary rock or 3 boreholes per km^2 per 10,000 yr for repositories in other rocks be assumed to occur. Limits on releases that occur as a result of these intrusions are also suggested.

2. A TYPICAL PROCEDURE FOR DEMONSTRATING AND ASSESSING COMPLIANCE WITH THE STANDARD

The Standard requires a performance assessment that culminates to the extent practicable in the preparation of a CCDF. This chapter describes a procedure considered acceptable by the authors for carrying out a performance assessment that will lead to a CCDF. It also comments on some of the important judgments the analyst will make in preparing a performance assessment. It is likely that other acceptable procedures could be devised, but the results of each would be evaluated in the same manner.

A performance assessment can be divided into four parts:

- Scenario development and screening
- Consequence assessment
- Sensitivity and uncertainty analysis
- Regulatory-compliance assessment.

Scenario development and screening comprehensively examines possible future occurrences that might affect a repository, assigns probabilities to them, and determines which occurrences merit detailed consideration. Consequence assessment calculates the releases that might arise from the scenarios of interest. Sensitivity and uncertainty analyses identify important processes and parameters and illuminate the sources and extent of uncertainty in the consequence assessment and enable the regulator to evaluate the amount of confidence that can be placed in the results. Finally, regulatory-compliance assessment combines the results of scenario analysis, consequence assessment, and sensitivity/uncertainty analysis to determine whether the repository is in compliance with requirements of the EPA standard.

Scenario Development and Screening

The future of a repository site holds many possibilities, some of which would degrade the expected performance of a repository. Waste-management analysts usually use "scenarios" to study these possible futures. As used in waste management, a "scenario" is a physically possible sequence of events and processes that could lead to release and transport of radionuclides from a repository to the accessible environment (e.g., Bingham and Barr, 1979; Ortiz and Cranwell, 1982; Hunter and others, 1982; Hunter, 1983). Scenarios are site specific, but a general and systematic procedure can be used to identify the scenarios of interest at any given site. This procedure consists of first, identifying the events and processes that could initiate release or affect radionuclide transport, and second, combining the events and processes in physically reasonable ways to form scenarios.

Scenarios are the basis for consequence modeling. Although the Standard does not use the term "scenario," Sections 191.12 (q) (the definition of performance assessment) and 191.13 (a) (the containment requirement) clearly require their development and analysis during performance assessment. The number of scenarios and the explanation of the development techniques used must inspire confidence that all processes and events that could significantly affect the disposal system have been considered. A large number of scenarios can easily be developed for the kinds of sites currently being investigated by DOE (e.g., Bingham and Barr, 1979; Hunter and others, 1982; Hunter, 1983). In general, it is preferable to develop and document as many physically reasonable scenarios as possible and then to screen most of them out than to begin and end with a small number of scenarios that are considered by the investigator to be the "most important." The regulator, not just the applicant, must see the breadth of scenarios initially considered and the basis for screening in order to develop confidence that consequences have been determined for all important scenarios. For example, a screening technique that describes a large number of very narrowly defined scenarios, each of which is highly improbable, in order to eliminate a significant release phenomenon would probably be unacceptable.

The first step in scenario development is to prepare a checklist of potential release and transport events and processes that could occur at a site. In preparing this site-specific checklist, the investigator can be guided by some of the reasonably comprehensive, site-independent checklists that have been developed previously (e.g., Table 2). Some events and processes can be screened out a priori; for example, dissolution of the host rock is unimportant at hard-rock sites, and volcanism is unimportant at Gulf Coast sites. The second step is to combine the remaining events and processes into scenarios that could occur at the site. This procedure is described below.

Development

Methods for the development of waste-release scenarios have been documented (Bingham and Barr, 1979; Cranwell and others, 1982a; Hunter, 1983). Scenarios are commonly constructed in the form of diagrams (Figure 1) that have been called "event trees," "logic diagrams," or "combinations of release and transport phenomena," hereinafter called "trees." (These combinations of release and transport phenomena are not fault trees. They are physically reasonable chains of events and processess that might affect release.) The first entry in a tree is a brief description of an event or process that might begin a sequence of phenomena leading to the release of radionuclides from the repository. This initial event or process can be called a "release phenomenon." Beside it are written brief descriptions of other phenomena, called "transport phenomena," that could conceivably be second steps, third steps, and so forth, in sequences leading to radionuclide release; Figure 1 shows two tiers of such steps. The process of adding steps continues until each sequence has reached a final step in which radionuclides enter the accessible environment. In Figure 1, the final step is labeled "Release to biosphere." If the tree has been formed carefully, it contains all the scenarios that might credibly arise from the release phenomenon. Each path through the tree, from the release phenomenon along a set of lines to the last step, is a scenario.

Table 2. Phenomena potentially relevant to release scenarios (after International Atomic Energy Agency, 1981)

<u>Natural Processes and Events</u>	
Climate change	Uplift/Subsidence
Hydrology change	Orogenic
Sea level change	Epeirogenic
Denudation	Isostatic
Stream erosion	
Glacial erosion	Undetected features
Flooding	Faults, shear zones
Sedimentation	Breccia pipes
Diagenesis	Lava tubes
Diapirism	Intrusive dykes
Faulting/Seismicity	Gas or brine pockets
Geochemical changes	
	Fluid interactions
Magmatic activity	Groundwater flow
Intrusive	Dissolution
Extrusive	Brine Pockets
<u>Human Activities</u>	
Undetected past intrusion	Climate control
Undiscovered boreholes	
Mine shafts	Large scale alterations of hydrology
Improper design	
Shaft seal failure	Improper operation
Exploration borehole seal failure	Improper waste emplacement
Transport agent introduction	Inadvertent future intrusion
Irrigation	Exploratory drilling
Reservoirs	Resource mining (mineral, water, hydrocarbon, geothermal, salt, etc.)
Intentional artificial groundwater recharge or withdrawal	
Chemical liquid waste disposal	
<u>Waste and Repository Effects</u>	
Thermal effects	Mechanical effects
Differential elastic response	Canister movement
Non-elastic response	Local fracturing
Fluid pressure, density, viscosity changes	
Fluid migration	Radiological effects
	Material property changes
Chemical effects	Radiolysis
Corrosion	Decay product gas generation
Waste package--rock interactions	
Gas generation	
Geochemical alterations	

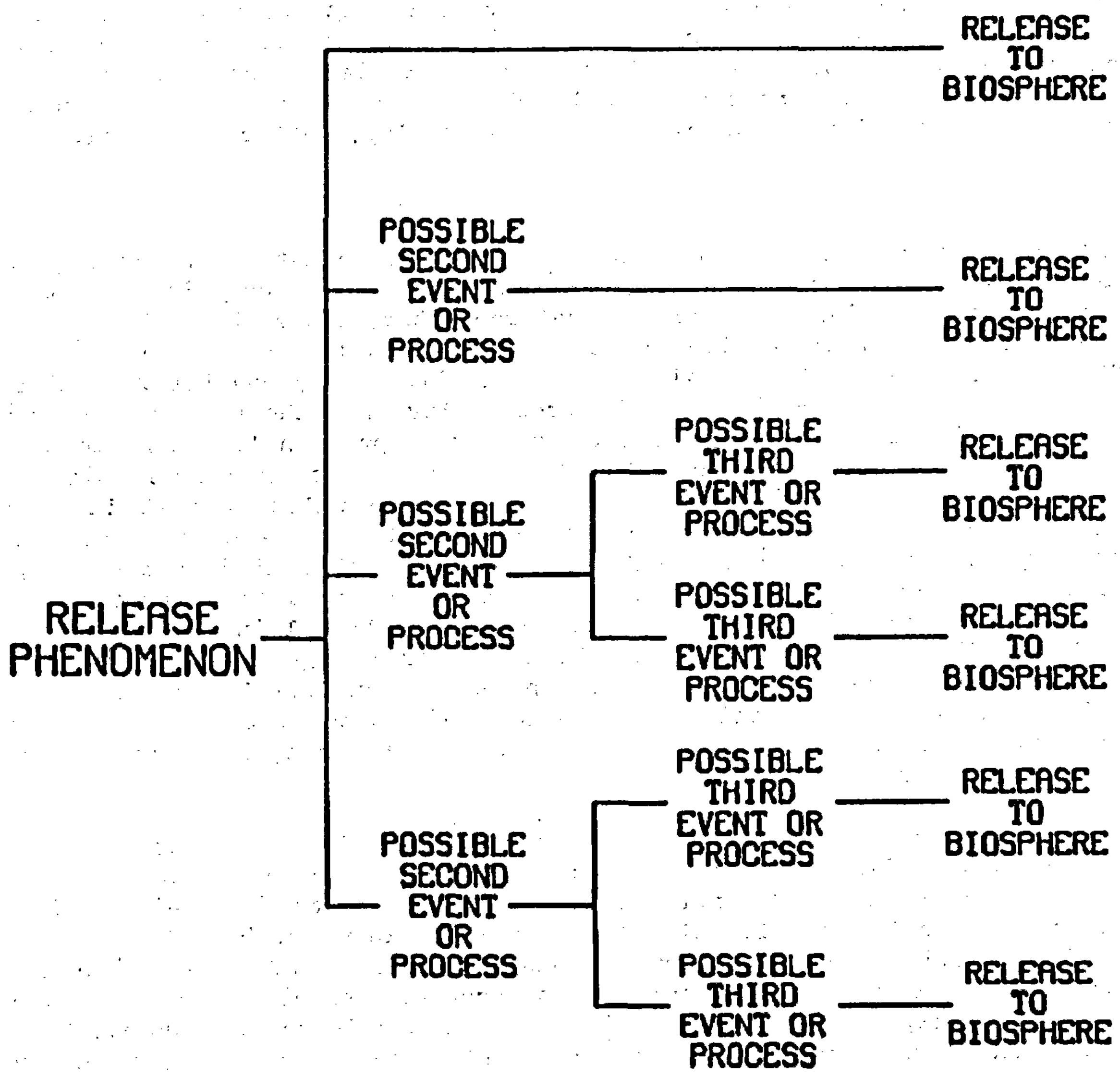

Figure 1. Generalized event tree (after Hunter, 1983).

Pairs of scenarios within a tree developed in this fashion may or may not be mutually exclusive (i.e., cannot both occur). In some cases, a branch in a tree will give rise to two scenarios that are obviously mutually exclusive, but usually the relationship between two scenarios is unknown at the time of scenario development. Whether two scenarios are mutually exclusive may be considered in developing the set that will be modeled; the modeler may wish to incorporate two or more closely related scenarios into one. The final set of scenarios for modeling can be more easily developed after screening.

Screening

It is neither practical nor necessary to model in detail the consequences of all scenarios that can be developed, because not all scenarios are equally likely or consequential. In fact, actual repository sites should be carefully chosen such that no disruptive events are expected to take place during the 10,000-yr lifetime of the repository (DOE, 1983). The probability of disruptive events should be small, and the probability that the site will continue more-or-less in its present-day condition should approach 1. Scenario probabilities offer a means of screening the scenarios to determine which ones should be modeled. Some disruptive events are so unlikely that it is not worthwhile to model their consequences, even if the consequences are likely to be severe. Appendix B of the Standard suggests that it is unnecessary to model the consequences of any scenario containing an event or process estimated to have a probability of occurrence of less than 1 in 10,000 in 10,000 yr. Other disruptive events might have a fairly high probability, say 1 chance in 10 or 100 of occurring within 10,000 yr, and their consequences must be evaluated. For still other events, the probability and its bounds are simply unknown. Such events must be retained for consequence modeling, at least during initial investigations.

A preliminary estimate of consequences can also be used to screen scenarios before full-scale consequence modeling. Appendix B suggests that scenarios may be omitted from performance assessments if their inclusion probably would not significantly change the remaining probability distribution of cumulative releases. Thus, depending on the number of scenarios, a simple but conservative estimate of consequences showing that a scenario causes, say, only a 0.1% increase in cumulative release may justifiably be used to omit that scenario from further consideration. An increase of, say, 1% is probably large enough to prevent omitting the scenario on the basis of low consequence alone.

Probability Assignment

As discussed in Chapter 1, the Standard is probabilistic. Whether a release of a certain size is allowable is determined by its probability. For this reason, the probability of occurrence of each individual process or event that might cause a significant release must be determined or estimated. Commonly, the probability that is determined is the conditional probability of an event or process given that other preceding events or processes in a scenario have already occurred. For the third branch from the top in Figure 1, the probability of "possible second event or process" is conditional upon the "release phenomenon" having occurred, the probability of "possible third event or process" is conditional upon the second event having occurred, and the probability of "release to biosphere" is conditional upon the third event having occurred. The probability of the scenario is determinined by multiplying the probabilities of all the events and processes in it, that is, by multiplying the probabilities of the first, second, third, and final events or processes. If an event or process has a conditional probability of occurrence of less than one chance in 10,000 in 10,000 yr, then any scenario containing it can probably be omitted from further consideration (EPA, 1985, Appendix B), because the probability of the scenario as a whole will be at most that of the event. In order to develop a CCDF as required by the Standard, the sum of the probabilities of the scenarios must be normalized so that it is less than or equal to one. Techniques for determining probabilities of geologic processes and events are described in more detail below.

Determining Probabilities

Determining the probabilities of scenarios, and therefore of geologic events and processes that make up scenarios, is essential to the generation of a CCDF. Section 191.13 (b) of the Standard states that because proof that the assigned probabilities are correct cannot be obtained, complete assurance that the probabilistic requirements will be met is not required. Rather, the performance assessment must give the regulator a reasonable expectation that compliance will be achieved. Appendix B of the Standard suggests that in determining the probabilities, a variety of quantitative and qualitative methods may be used, including numerical models, analytical theories, and prevalent expert judgment. Techniques are available for the determination of the probability of various geologic events and processes of interest to performance assessments (Hunter and Mann, 1986; Beckman and Johnson, 1980; Cranwell and others, 1982a; Donath and Cranwell, 1981). Events and processes for which data or theory are inadequate to numerically determine a probability will require the use of expert judgment.

The theory of probability imposes certain constraints on the probabilities assigned to scenarios. One such constraint is that the sum of probabilities assigned to the final set of scenarios remaining after the screening process must be less than or equal to 1. If the sum exceeds 1, it is necessary to reexamine the probabilities (Heising and others, 1983). This constraint tends to restrain the natural tendency to assign overly conservative probabilities to scenarios, particularly to those having a high probability of occurring.

The techniques used to generate scenario probabilities generally fall into one of the following three categories:

- the use of probability models,
- the use of deterministic models to predict event occurrences, or
- expert opinion.

Probability models can be used if data exist on the frequency of occurrence of the event and if assumptions can be made as to the randomness of its occurrence, either in space or time. Predictive deterministic models can be used to estimate event probabilities by generating a distribution of potential occurrence times, provided data exist to simulate the event. Finally, when data are sparse or nonexistent, expert opinion can be used to make some estimate about the event probability. Probabilities determined using expert opinion may be more variable than those derived from numerical techniques; sensitivity analysis may indicate whether such increased variability is important.

Although much work has been done in the development of techniques for determining such probabilities, only a small part of that work has been applied in waste management. Under the sponsorship of the NRC Repository Projects Branch, Sandia National Laboratories Division of Waste Management has undertaken a major review of probabilistic techniques in eight fields of geology (Hunter and Mann, 1986). These fields are hydrology, climatology, volcanology, tectonism and seismicity, resource exploration, mining engineering, thermomechanical effects, and geochemistry. For the most part, the techniques described below do not result in the calculation of a probability. Instead, they allow the calculation of some factor related to probability, like frequency of occurrence, which in turn allows the assignment of a probability that can be used in accordance with Appendix B of the Standard, using one of the three basic procedures described in the previous paragraph.

Resource Exploration. The probability of human intrusion as a result of resource exploration will likely be assigned using expert judgment supported by estimates of the potential of the crust at a repository site to contain resources; the assigned probabilities may be limited by the guidance contained in Appendix B of the Standard. Harbaugh (1986) used probability trees in analyzing the interdependent relationships between human and geological factors as they affect estimates of the probability of intersection of HLW repository sites by exploratory boreholes in the future. The trees reveal that human factors cannot be ignored. Techniques do exist for qualitatively estimating the potential for endowment of portions of the crust with mineral resources. Harbaugh (1966) recommended the use of a combination of these techniques in spite of their associated uncertainty, which arises from their difficulty in application and lack of adequate data. The assigned probability of human intrusion should be determined by an area's mineral-resource potential and by the explicit guidance about the frequency and severity of human intrusion that should be assumed in a performance assessment in Appendix B of the Standard, where appropriate.

Mining Engineering. Einstein and Baecher (1986) stated that there is basic understanding of mechanisms of tunnel performance and of uncertainty in geotechnical engineering and that a number of engineering methods for predicting tunnel performance exist. Practical methods to determine geotechnical uncertainties, to propagate them through engineering analyses, and to probabilistically assess risks associated with particular designs also exist. Adaptable design approaches, in which tunnel design is modified to accommodate encountered conditions, are in widespread use and could be developed for waste-repository applications.

Einstein and Baecher (1986) recommended the use of existing validated performance-assessment methods for tunneling aspects of waste repositories and further research and development on improved methods of assessing and combining subjective probabilities, validation of methods for relating site-characterization activities to the confidence of performance assessments, and the extension of existing cost and scheduling models into large-scale integrated performance assessment techniques.

Thermomechanical Effects. Thermomechanical effects on underground structures have not been considered probabilistically in the past. Wahi (1986) indicated that, given the state of the art, these probabilities will likely be assigned based on expert judgment for repository performance assessments. Rock as a materical cannot be characterized with great certainty. Heterogeneities, local anomalies, joints, and fractures all introduce uncertainties into models of thermomechanical response in a rock system. State-of-the-art thermomechanical models include non-linear behavior, discrete discontinuities, and coupled effects; however, such models have not been adequately validated and are expensive to use. At this time, therefore, bounding analyses are preferable to Monte Carlo approaches. The data base on site-specific rock properties and their dependence on temperature is just starting to emerge. Proper site characterization is essential no matter what technique is chosen to assign probabilities. For example, identification of major structural discontinuities such as faults, brecciated zones, brine pockets, and so on, would help in making appropriate design adjustments and performing relevant scenario analyses. A careful repository design and a reasonable factor of safety can provide a significant reduction of uncertainties in the expected thermomechanical response of the repository system.

Hydrology. Existing numerical methods in hydrology can be used to calculate, for example, a probabilistic distribution of travel times or of parameter-value distributions in space or time. Numerical methods are available for use in estimating the probabilities of hydrologic processes applicable to nuclear-waste management. Methods and procedures in ground-water hydrology for probabilistic predictions (Gutjahr, 1986) fall into three major categories: deterministic porous-media models, where the probabilistic component enters primarily through parameter variations; stochastic porous-media models, where the probabilistic component enters through the medium itself as well as through parameter variations; and fractured-media models, where both stochastic and deterministic features may appear.

Gutjahr (1986) compared and contrasted these methods and discussed the availability of data, the incorporation of data, the role of site-specific vs. generic data, and the estimation procedures used by the models. Gutjahr indicated that some areas of weakness require both long- and short-term study but recommended specific procedures that may be implemented by the waste management community.

Climatology. The existing numerical methods of predicting climatic changes must be used in conjunction with expert judgment in order to assign probabilities to possible changes. Bartlein and Webb (1986) found that the prediction of climatic variations over 10^3 to 10^6 years is still in its infancy. Prediction methods are under development, but no study so far has combined all of the individual models to estimate future climates at the spatial resolution required for the siting of repositories. Bartlein and Webb described the major components of the climate system that must be considered in modeling its long-term variations and models of the "slow" and "fast" processes of the climate system that can be used for climatic prediction. Bartlein and Webb suggested that combining existing numerical techniques may provide a usable method, but they cautioned that such a combination has not been tested or validated.

Tectonism and Seismicity. Callender (1986) found that many techniques can be used to support a probabilistic assessment of tectonic activity at a repository site but that none of the techniques provide a high degree of certainty about the probabilities, thus requiring the use of some expert judgment. Earthquake prediction is dependent on the availability of long- and short-term precursors, a well-established historical seismic record, and detailed monitoring networks for precursors of all kinds. In both seismic and aseismic areas, prediction of the magnitude of future events is largely based on the qualitative perception of the possible extent of rupture; few quantitative data exist.

A number of high-quality data bases are readily available for the qualitative evaluation of tectonic and seismic phenomena. Four kinds of geologic data are most useful for predicting potential tectonic activity near a waste repository: surface ruptures along fault zones; stratigraphic sequences related to tectonic activity; landforms related to surface rupture and regional uplift or subsidence; and relationships between seismicity and tectonic features.

Volcanology. Either analytic techniques or expert judgment may be appropriately used in assigning probabilities of volcanic activity, depending on the regional setting. McBirney (1986) found that methods of assessing the probability of volcanic disruption of a nuclear-waste repository differ widely, both in rationale and in reliability, depending on the geologic setting of the site. Quantitative estimates of probabilities are possible only in regions where Cenozoic volcanism has occurred within the same structural province as the proposed site and where detailed geological and geophysical studies have established patterns for the structural and magmatic evolution of the region. A very stable region, such as the eastern United States, can be considered a very unlikely site for volcanic activity, but calculations of a probability for an igneous event at a given site in such a region are less realistic than expert opinion.

Because volcanism tends to be strongly episodic, events cannot be taken as random, and because the nature and magnitude of eruptions are governed by factors such as the previous history of the system and the length of time between eruptions, events cannot be assumed to be independent of one another. It is necessary, therefore, to have enough data on the nature and age of previous activity to define patterns of frequency and trends of distribution in space and time. Provided these limitations are taken into account, the methods used to estimate volcanic hazards near recently active volcanic centers can be adapted to analyses of broader regions with infrequent prehistoric activity.

Consequence Assessment

After scenarios have been selected, a sequence of models is used to estimate the consequences of each scenario. Typically, the first suite of models examines the release of radionuclides from the waste packages, using data describing waste-package characteristics and the underground facility. After the radionuclides exit from the waste packages, a second analysis describes the movement of radionuclides out of the underground facility. After that, transport of radionuclides by ground water to the accessible environment is analyzed. Several physical phenomena are considered by the consequence assessment. They include the flow of ground water, the movement of radionuclides by ground water, radioactive decay and the production of new radionuclides, and retardation of radionuclides by the host rock. In addition, because the decay heat generated by HLW and the dissolved waste itself can affect the rock and ground-water system, models describing waste/host rock interactions are necessary. These models include geochemical, hydrological, and thermomechanical phenomena. Because techniques for consequence assessment are well developed and have often been documented in the waste-management literature (e.g., Cranwell and others, 1982b; Chu and others, 1983; Pepping and others, 1983), each of the modeling areas is described only briefly below.

Source Models

Source models analyze the release of radionuclides from waste packages and the underground facility. They usually involve the modeling of leaching of radionuclides from the waste form and their migration from the waste packages through the repository and finally out of the underground facility. At least one source model accounts for time-dependent canister failure rate and time- and temperature-dependent leach rate (Chu and Axness, 1984). A waste-package performance assessment code developed by DOE, WAPPA (INTERA, 1983), includes five distinct, coupled degradation-process models that are driven internally by waste decay heat and externally by repository stresses and fluids. The output of this code quantifies the heat and radionuclide fluxes to the repository. The source model of Chu and Axness uses the concept of a mixing cell to calculate the fluxes of radionuclides leaving the engineered facility. Codes that describe the detailed transport of radionuclides within the underground facility appear to be lacking at this time.

Ground-water Flow and Transport Models

Many ground-water flow codes exist. They range from simple, one dimensional analytical solutions to complex, three-dimensional numerical codes. Contaminant-transport codes usually are dispersive-advective models that include sorption and decay and production of radionuclides. SWIFT (Dillon and others, 1978; Reeves and Cranwell, 1981) is a three-dimensional, fully transient code to solve coupled equations for transport in geologic media. NWFT/DVM (Campbell and others, 1980) is a simple, efficient code used to calculate transport. This code uses a known flow field and simplifies the velocity field as a net-work of one-dimensional segments through which radionuclides are transported. During transport through fractured rock, diffusion into the rock matrix can be a significant retardation mechanism and therefore is usually included in the modeling. The output of these transport models is usually expressed as time-dependent discharge rates or concentrations in an aquifer. These time-dependent discharge rates can then be integrated over time to give the cumulative releases of radionuclides required by the Standard.

Sensitivity and Uncertainty Analysis

Because experimental data cannot be collected over a period of 10,000 yr, decisions about the acceptability of a facility must be based solely on its predicted behavior, as derived from computer models that simulate the salient features and processes affecting its performance. The quantity of prime interest to regulatory agencies is the predicted cumulative release of radioactive waste to the accessible environment over 10,000 yr. This calculated release is not unique, as the calculation has uncertainties associated with it. Because regulatory decisions will be based on model predictions, it is important to investigate the sources of uncertainty that affect these predictions.

Sources of Uncertainty

Uncertainty in the analysis of geologic waste disposal has three primary components: scenario uncertainty, data or parameter uncertainty, and model uncertainty (Cranwell and Helton, 1981).

Scenario Uncertainty. Two major types of uncertainty arise from the consideration of scenarios: uncertainty associated with their "completeness," and uncertainty associated with their screening.

First, the question of completeness asks whether all possible scenarios have been considered. A systematic method of compiling scenarios, such as that described above, can provide confidence about completeness. It is not possible, however, to prove completeness in the sense of unequivocally establishing that all possible scenarios have been compiled. Through care in scenario development and appropriate independent review, assurance can be sought that a collection of scenarios is acceptably complete.

Next, there is uncertainty associated with the screening of scenarios. The scenario-generation technique should yield more scenarios than can be incorporated into the final performance assessment, so a suitable subcollection of these scenarios must be selected. Assuming that the scenario-development process disallows physically unreasonable scenarios, two criteria can be used to screen scenarios for inclusion in the final site analysis: consequence and probability. Scenarios with very low consequences can be omitted because of their small potential to affect risk and to cause uncertainty in the analysis of risk. Similarly, scenarios with very low probabilities can also be omitted. Conservatism in the assignment of probabilities and the preliminary calculation of consequences can reduce the likelihood of screening out important scenarios.

Model Uncertainty. Model uncertainty can arise from several sources, including problems associated with determination of appropriate parameters for use in model construction, mathematical formulation of models, and numerical techniques used in the models. Uncertainties also arise from a lack of understanding of the processes being modeled, a limited capability to mathematically represent these processes, or insufficient data describing the system or the processes acting on it.

Another source of model uncertainty is the use of existing models that may not be suitable for processes taking place in geologic media. For example, the convective/diffusion equation may not accurately describe dispersion in geologic media.

Finally, model uncertainty can arise from the implementation of a mathematical model as a computer code, including coding errors and computational limitations. Because computers have finite word lengths, truncation errors in calculated values occur. In addition, algorithms used by computers to perform certain calculations (such as the square root function) have built-in limitations in accuracy. A subtle error is the use of data outside the ranges of validity of previously written algorithms.

The uncertainty associated with the incompleteness of a mathematical description of reality can be addressed by comparing model predictions with experimental data or with the predictions of models previously compared with experimental data. This is called "model validation." The model uncertainty associated with coding errors, solution techniques, and computational limitations can best be addressed through code verification programs, benchmarking efforts, and well established software Quality Assurance programs.

Parameter Uncertainty. Data or parameter uncertainty is caused by (1) random and/or systematic measurement errors in the data used to make parameter estimates for a model, (2) incomplete data on parameters known to vary spatially or temporally, (3) heterogeneities within the hydrogeologic system that have not been detected during data collection, and (4) misuse or misinterpretation of data.

There are several possible sources of measurement error. First, the measuring technique may be incorrect or misapplied. For example, laboratory tests to determine distribution coefficients might be conceptually incorrect or conceptually correct but misapplied. Second, measurement error could have a physical source due to the treatment of the material to be studied. For example, a specimen may be taken at depth, removed to a laboratory, and then tested. The specimen may be damaged by the release of ambient at-depth stresses. A new stress and thermal state are then applied and measurements are taken, resulting in measured properties that differ from those in existence in the field. Finally, measurement error could have a statistical source. For example, commonly used estimators for the autocovariance of spatial variability may be statistically biased.

Data often display significant scatter across a site due to spatial variation of rock properties. These properties would vary in space even if it were possible to measure them without error. Uncertainty is introduced by replacing such spatial variability by lumped parameters (i.e., averages) or by distributed but deterministic parameters (e.g., trend surfaces). Adequately characterizing spatial variation may be difficult. Better characterization by increased sampling (e.g., more drill holes) may compromise the integrity of the site. Various techniques are available for spatial interpretation and extrapolation of data, notably, kriging (e.g., Doctor, 1980).

Uncertainty can also arise from misinterpreting data. For example, even for similar rock and ground-water conditions, measured distribution coefficients may vary over several orders of magnitude. An overly simplistic interpretation of distribution coefficients and a resultant misinterpretation of field data may explain this variation. More detailed models for the causes of radionuclide partitioning may more meaningfully interpret and use the field data. Approaches to the treatment and reduction of parameter uncertainty are discussed in the next section.

Approaches to Parameter Uncertainty Analysis

Several procedures exist for handling parameter uncertainty in the modeling of geologic waste disposal processes. The more common of these are analytical approaches, Monte Carlo techniques, and differential analysis. Iman and Helton (1985) compared Monte Carlo techniques and differential analysis with several different models.

Analytical Approaches. In the analytical approach, a simple closed-form expression relates model input to model output (e.g., $Y = aX$). The distribution of model output (Y) is derived directly from the distribution of model input (X) using the functional relationship between model input and output. However, such simple relationships are seldom encountered in waste management modeling issues.

Monte Carlo Techniques. Most extant computer models accept only a single input value for each parameter (referred to as "deterministic" models). In order to accommodate the acknowledged variation in parameter values, model input parameters are treated as random variables with a distribution of values. Specific values for model input are then selected using a statistical sampling procedure. The sampled values are used to generate a distribution of output values. This procedure is commonly called "Monte Carlo simulation." Monte Carlo techniques provide a simple and direct method of propagating model input-parameter uncertainty to model output.

Two advantages of Monte Carlo techniques are that direct estimates of model output distribution and variance are obtained without the need for fitting a response surface and that no software modifications are required, except possibly a Monte Carlo driver to generate random samples. Disadvantages are that repeated runs of the model are required and that computer costs are potentially high.

Differential Analysis. In a differential analysis approach, the model is replaced by, say, a second order Taylor series expansion. The mean and variance of model output is approximated using first- and second-order series terms. The partial derivatives of the Taylor series are evaluated either directly or using methods such as the "adjoint technique" (Harper, 1983).

Differential analysis approaches are efficient in the required number of computer runs and can handle a large number of model input parameters. These approaches also have disadvantages. An indirect estimate of model output distribution is obtained using Monte Carlo simulations with Taylor series expansion about a "base case" point. Further, the results can depend strongly on the choice of the "base case" point. The approach can require major modifications to code, e.g., in nonlinear systems. Implementing a differential analysis can be very time-consuming and prone to error.

Stochastic Modeling and Geostatistical Approaches to Parameter Uncertainty. An area of recent development in ground-water modeling is the growth of stochastic models and geostatistical approaches such as kriging and statistical inverse problems. These approaches to addressing parameter uncertainty primarily involve accounting for the effects of spatial variability or heterogeneity in the modeling of ground-water flow.

Stochastic models treat varying parameters as spatially random fields and then solve the appropriate stochastic equations for the mean quantities and the variance of their fluctuations. This approach has been followed in the area of transport modeling of dissolved species in ground water (Bakr and others, 1978; Gelhar and others, 1979; Gutjhar and others, 1978).

Kriging is a statistical technique that can be used to determine a surface from spatially distributed data (e.g., Matheron, 1969, 1970; Delhomme, 1976; Delfiner, 1976; Journel and Huijbregts, 1979). Kriging considers the observational record as coming from the realization of a random function of some sort and seeks to construct linear estimators that have the properties of unbiasedness and minimum variance; i.e., estimators that will have a satisfactory average behavior when applied to many realizations of the random function.

Kriging has several advantages over alternative approaches such as least squares, polynomial interpolation, and distance weighting of the data. It reconstitutes the measured values as estimates at the data points whereas the least squares method does not, because it is meant for regression rather than interpolation. Kriging will not produce the contortions that result from trying to force a polynomial to fit the data and makes a minimum of assumptions for the structure of the field.

Kriging is frequently thought of as a subset of a broader, more general, statistical parameter-estimation technique called "geostatistics." The geostatistical approach referred to is a modification of nonlinear regression techniques combined with kriging and is associated with the inverse-problem solution proposed by Clifton and Neuman (1982). This approach addresses some of the weaknesses of conventional approaches to parameter estimation. These weaknesses include the non-use of measured data, overparameterization, physically implausible solutions, excessive computational effort, and overdependence on assumptions about the spatial distribution of the property of interest.

Sensitivity Analysis

"Sensitivity analysis" generally refers to a means of quantitatively estimating the amount of variation in model output due to specified variation in model input parameters. It is a means of identifying important parameters. An uncertainty analysis uses the results of a sensitivity analysis to help quantify the uncertainty in model output induced by uncertainty in model input parameters.

For non-stochastic models, two major approaches exist for performing sensitivity analyses. The first involves the use of statistical sampling of input parameter values, commonly followed by stepwise regression analysis of output values as a function of input parameter values to identify key parameters (Iman and others, 1978). Statistical methods such as this typically fit a polynomial to describe the relationship between input and output parameters. The second approach, sometimes referred to as the differential or deterministic approach, uses the explicit relationship between input and output as described in the computer code. Key parameters are then identified using either a direct method or the adjoint method (Harper, 1983). This approach is generally more difficult than statistical methods in that it requires knowledge of the mathematical relationship used in the code. With adjoint implementation, this approach may result in savings in computer costs compared with statistical methods, for which multiple runs are required. Both approaches are suitable means for performing sensitivity analyses; neither technique is universally superior to the other.

Regulatory-Compliance Assessment

The Standard requires that cumulative releases to the accessible environment for 10,000 yrs after disposal shall have a likelihood of less than one chance in 10 of exceeding the quantities listed in Table 1 and a likelihood of less than one chance in 1000 of exceeding ten times the quantities listed in Table 1. The release limits listed in Table 1 apply only if that particular radionuclide is released and no other.

For projected releases of several radionuclides, there is the additional requirement that

$$\frac{Q_A}{RL_A} + \frac{Q_B}{RL_B} + \ldots + \frac{Q_N}{RL_N} \leq 1 \text{ (or 10)} \quad (1)$$

where Q_i is the projected release of radionuclide i, and RL_i is the release limit of radionuclide i. This sum will be referred to here as the "EPA sum" or "summed normalized releases." Its calculation is described in detail in Appendix A of the Standard.

Comparison with the Standard requires the calculation of a probability vs. consequence curve, with emphasis on cumulative releases of radionuclides of a magnitude equal to or ten times the releases specified in Table 1. Such curves are generally in the form of complementary cumulative distribution functions (CCDFs).

A CCDF is, as its name implies, the complement of a "cumulative distribution function" (CDF). For a given value of x of a random variable X, the CDF of X at x is the function that gives the probability that X is less than or equal to x, written $P(X \leq x)$ (see, e.g., Hoel and others, 1971). That is, the CDF accumulates probabilities of all values of X less than or equal to x (Figure 2). Thus, the CCDF of X is one minus the accumulation of probabilities of all values of X less than or equal to x, written $P(X > x)$ (Figure 3).

In a Monte Carlo simulation using "deterministic" models, the following approach can be used to generate a CCDF. (If a stochastic model is used, such as the one-dimensional transport model discussed in the section on uncertainty, other techniques would be used to generate a CCDF.)

Let us assume that for a given repository system, K scenarios have been identified as being important. These scenarios are analyzed by choosing appropriate ranges and distributions for model input parameters and then statistically sampling from these ranges to obtain sets of input values (referred to as "input vectors") for each scenario. Assume that m sets of input vectors are generated and analyzed for each scenario. The same set of m input vectors is used for all scenarios. This is done to insure that any observed variation in results is due to scenario differences and not to sampling differences. For a given scenario, this procedure is illustrated in Figures 4 through 6 for a sequence of three models, where, for example, Model A might be a waste-package model, Model B a near-field (engineered facility) transport model, and Model C a far-field (engineered facility to accessible environment) model. Output from Model A would be releases from the waste package; output from Model B would be releases from the engineered facility; and output from Model C would be cumulative releases of radionuclides to the accessible environment.

For each of the m input vectors analyzed for the given scenario, the resulting cumulative releases are normalized by dividing by the appropriate release limits listed in Table 1 and then summing according to Eq. 1. Thus, each input vector $\bar{X}_k$, $k = 1, 2, \ldots, m$, has associated with it a sum, R_k, of normalized releases given by

$$R_k = \frac{Q^k_{A_k}}{RL_{A_k}} + \frac{Q^k_{B_k}}{RL_{B_k}} + \ldots + \frac{Q^k_{N_k}}{RL_{N_k}}$$

where

$Q^k_{i_k}$ = projected release of radionuclide i_k, and

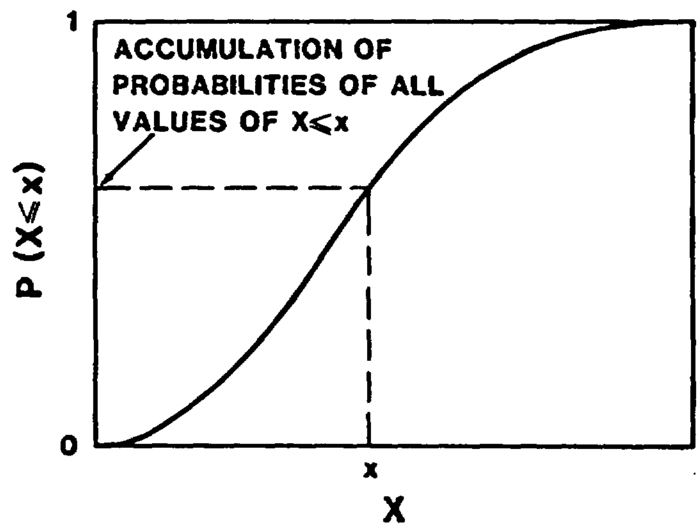

Figure 2. Graph of CDF.

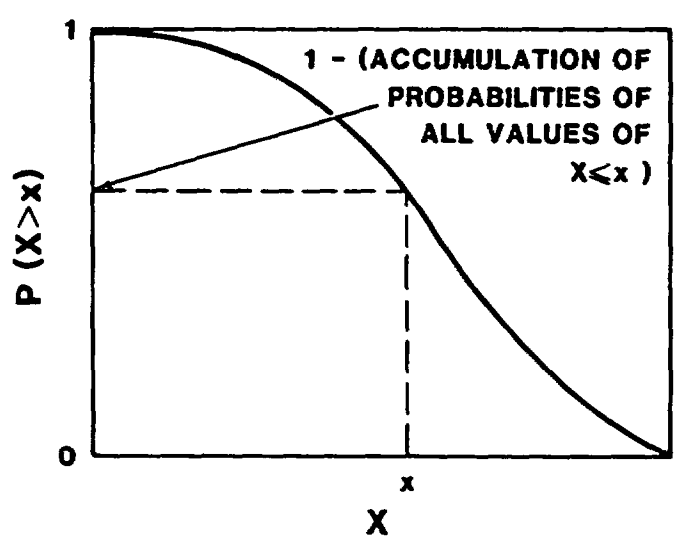

Figure 3. Graph of CCDF.

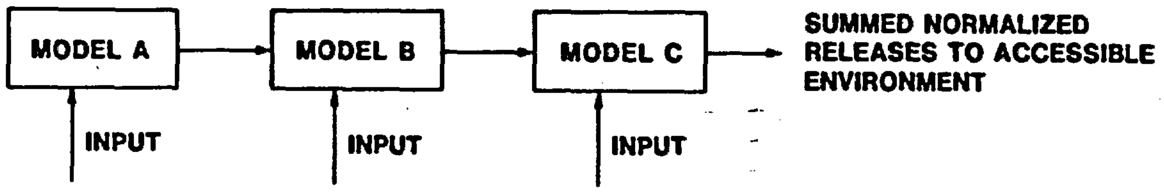

Figure 4. System of three models.

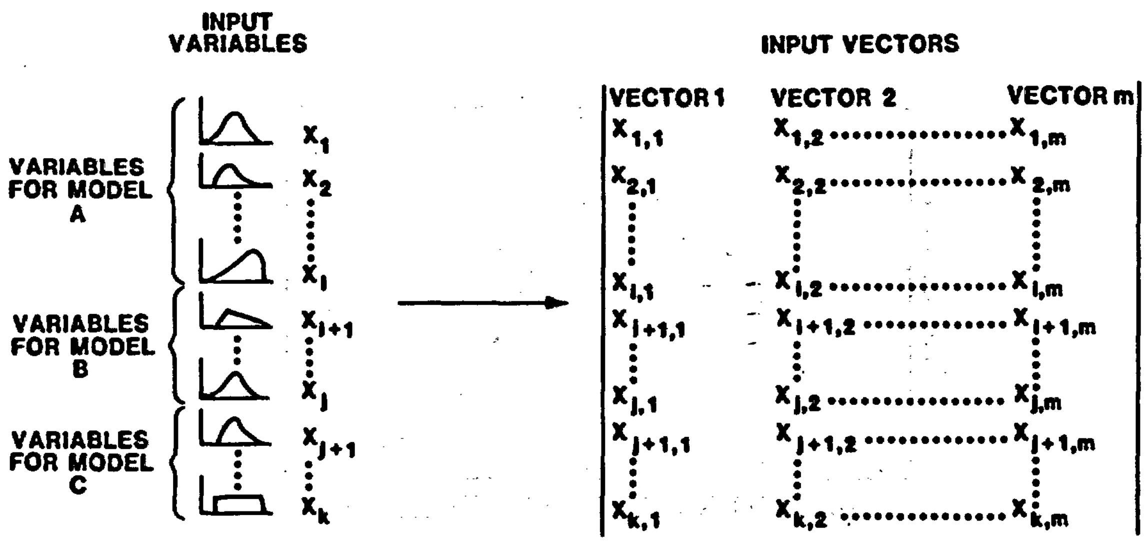

Figure 5. Generation of input vectors.

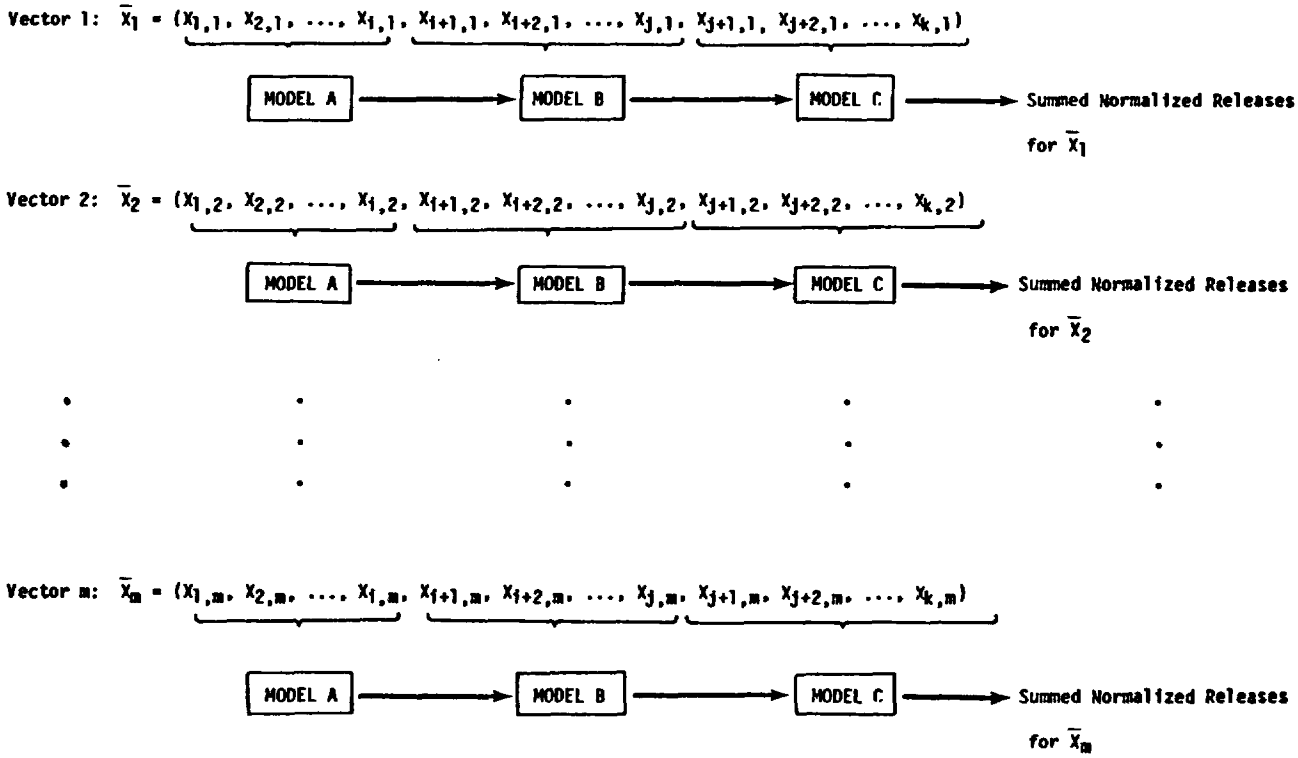

Figure 6a. Generation of output values for a three-model system.

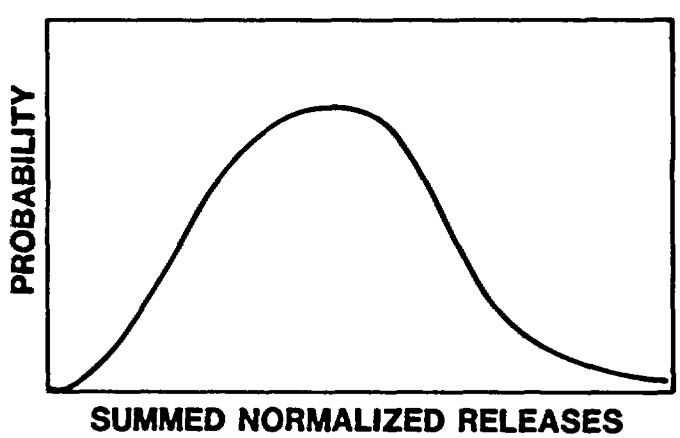

Figure 6b. Distribution of summed normalized releases for a given scenario.

RL_{i_k} = release limit of radionuclide i_k.

Consequently, each scenario has associated with it m of the summed normalized releases, R_k, k = 1, 2, ..., m.

The procedure illustrated above is carried out for each of the K scenarios being analyzed, yielding mK summed normalized releases to the accessible environment. These releases, and the associated scenario probabilities, are used to generate a CCDF in the following manner.

A CCDF can be generated using the relationship (Cranwell and others, 1982b)

$$P(Rel > R) = \sum_{j=1}^{K} P(Rel > R|S_j)\, P(S_j) \qquad (2)$$

where

$P(Rel>R)$ = probability of summed normalized release > R,

$P(Rel>R|S_j)$ = probability of summed normalized release > R, for Scenario S_j, and

$P(S_j)$ = probability of Scenario S_j occurring over 10,000 yr.

The quantity $P(Rel>R|S_j)$ can be estimated by observing the frequency of input vectors for Scenario S_j producing a summed normalized release greater than R. That is,

$$P(Rel>R|S_j) \approx \frac{\#\text{ of vectors producing releases} > R \text{ for Scenario } S_j}{\text{total }\#\text{ of input vectors (m)}}$$

This relationship holds if input vectors for each scenario are sampled with equal probability (such as is the case with Latin hypercube sampling).

As described on p. 20, the probabilities of the scenarios S_j, j = 1, 2, ..., K satisfy the relationship

$$\sum_{j=1}^{K} P(S_j) \leq 1$$

A CCDF generated in this manner is actually a step function (empirical function) consisting of mK steps. The height of each step is $1/m \bullet P(S_j)$, where $P(S_j)$ is the probability of the scenario producing the particular summed normalized release on the horizontal axis corresponding to the step in the curve (Figure 7).

To summarize, a CCDF can be constructed in the following way:

1. Choose probabilities for each of the scenarios.
2. Choose appropriate ranges and distributions for model input parameters to analyze scenarios.
3. Statistically sample from these ranges to obtain m input vectors.
4. Generate m cumulative releases of radionuclides to accessible environment.
5. Normalize and add to obtain m summed normalized releases for each of the K scenarios.
6. Plot the mK summed normalized releases vs. the complementary cumulative values of the scenario probabilities using Equation 2.

To account for uncertainty in scenario probabilities or frequency, multiple CCDF's similar to those in Figure 8 could be generated by assigning ranges and distributions to scenario frequencies and statistically sampling from these ranges to obtain specific values of scenario probabilities. A CCDF would be generated for each set of scenario probabilities obtained. Figure 8 shows three empirical CCDF's for three different sets of scenario probabilities. The three empirical CCDF's could be collapsed into one CCDF representing the mean (or median) of the three separate curves.

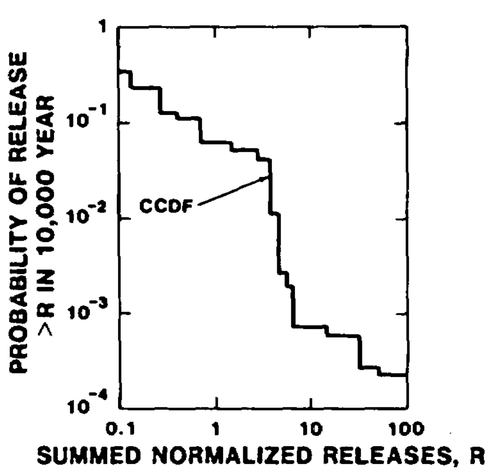

Figure 7. Empirical CCDF.

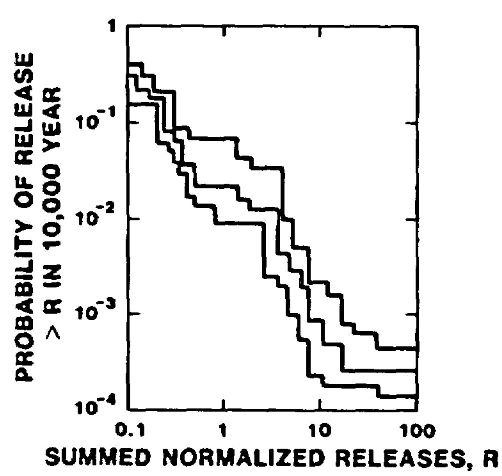

Figure 8. Family of empirical CCDF curves showing effects of uncertainty in scenario probability.

3. EXAMPLE

This section contains a simple example (the Example) illustrating the principles of performance assessment described above. It is intended to show that the techniques necessary to implement the Standard for a real site now exist. As mentioned above, scenario development, probability assignment, and consequence analysis must be site specific in order to have any meaning. Because much NRC-sponsored work has dealt with a hypothetical repository in the basalts of the Columbia Plateau, the Example is placed in that setting for convenience. Although the repository is hypothetical, the site is real: real data have been used to the extent possible, although this discussion has been greatly simplified for illustration, and for that reason some distortion is inevitable. The Example is not intended to reflect in any way upon the Basalt Waste Isolation Project or any real repository being planned by that organization.

It is assumed throughout the Example that the techniques described in Chapter 2 have been used to assign probabilities. Some of the probabilities in the Example have, in fact, been chosen arbitrarily in order to keep the Example simple. Some of the probabilities in the Example have two or three significant figures, solely to make the subsequent calculations easier to follow. The significant figures do not imply anything about the precision obtainable or necessary in a real analysis.

Scenario Development, Screening, and Probabilities

A reasonably comprehensive scenario-development excercise gave rise to 318 long-term, far-field scenarios for the release of radioactive waste from a hypothetical repository in basalt of the Columbia Plateau (Hunter, 1983). Relative probabilities were assigned to the scenarios. A limited number of those scenarios are used in the Example, but the probabilities used here do not in every case correspond to those assigned by Hunter. Since that time, other work, both published and unpublished, has made it possible to screen some of the scenarios from further investigation. Many other scenarios have been omitted for the sake of simplicity.

Hunter (1983) screened the IAEA list (Table 2) and determined that nine release phenomena were important to a basalt repository. For simplicity in the Example, only five of these phenomena are considered to be capable of initiating the release of waste. These five represent a broad spectrum of probabilities and potential consequences. They are the normal flow of ground water through the repository to the Columbia River; climatic change that alters the flow of ground water; failure of shaft seals that increases the flow of ground water through the repository; drilling; and faulting through the repository. (Other release points than the Columbia River were considered by Hunter.) Only the event trees arising from two of these release phenomena will be described in detail here: one tree is very simple and the other is complex. The remaining three initiating events would be treated similarly in a performance assessment. Important combinations of the initial scenarios are also discussed below.

Normal Flow of Ground Water

Figure 9 shows scenarios that might begin with the flow of water that normally exists in a host rock whether a repository is built there or not. The tree assumes that water is carried to an aquifer that eventually discharges into the Columbia River. The release phenomenon, "Normal flow of water continues through pores and fractures," is assigned a probability of ~1, because there is no reason to believe that the presence of a repository will stop the flow of ground water. The normal flow might continue more-or-less unaltered after the emplacement of a repository, that is, the gross direction of flow might continue unchanged except for slight changes induced by thermal gradients. On the other hand, heat from the waste might alter the hydraulic gradient so profoundly that thermally induced recirculation of fluids (somewhat like a convective cell) may occur in the vicinity of the repository. Unpublished thermohydrologic modeling by the Waste Management Systems Division of Sandia National Laboratories suggests that such thermally induced recirculation is unlikely to occur. For this reason, this event (labeled 2 in Figure 9) is assigned here a low probability of 10^{-6} and the other transport event (labeled 4) is assigned a probability of ~1 (Table 3). Thus the upper branch of the tree, with a probability of 10^{-6}, is screened out, and the lower branch, with an assigned probability of ~1, is retained.

Climatic Change

The Columbia Plateau was repeatedly and profoundly affected by continental and alpine glaciation during Pleistocene time. Climatic change, catastrophic flooding, and changes in the erosional regime on the Plateau as a result of glaciation to the north have all been documented. Hunter (1983) developed a complex event tree with 162 scenarios arising from glaciation of the Columbia Plateau. Only the small portion of that tree, beginning with the entry of an ice sheet into the Columbia River drainage, is considered here (Figure 10). Even this portion illustrates the complexity of event trees that can easily arise during a comprehensive scenario development. Hunter considered the probabilities of events 55, "Continental ice sheets readvance," and 61, "Ice sheet enters Columbia River drainage," to be ~1 during the next 10,000 yr. Two of the following events, "Outwash plain effects occur," and "Missoula floods occur," illustrate the possibility that in developing the initial trees, scenarios may not be mutually exclusive. In fact, both these events would be certain to occur if event 61 occurred, so both are assigned conditional probabilities of ~1. (If neither scenario were screened out, they would be combined in some manner in the development of the final set of scenarios.) Hunter assigned event 65, "Fracture network is altered by loading and unloading," a probability of ~1 in the absence of data. Preliminary mechanical modeling (Wahi and Hunter, 1985) of fracture alteration by glacial loading suggests that scenarios including this event will have very small consequences; all scenarios in this branch are screened out for the purposes of this example. Hunter assigned event 66, "Permafrost affects repository," a probability of 0.1. Because permafrost would be likely to stop or greatly retard the flow of ground water at some point along the flow path to the

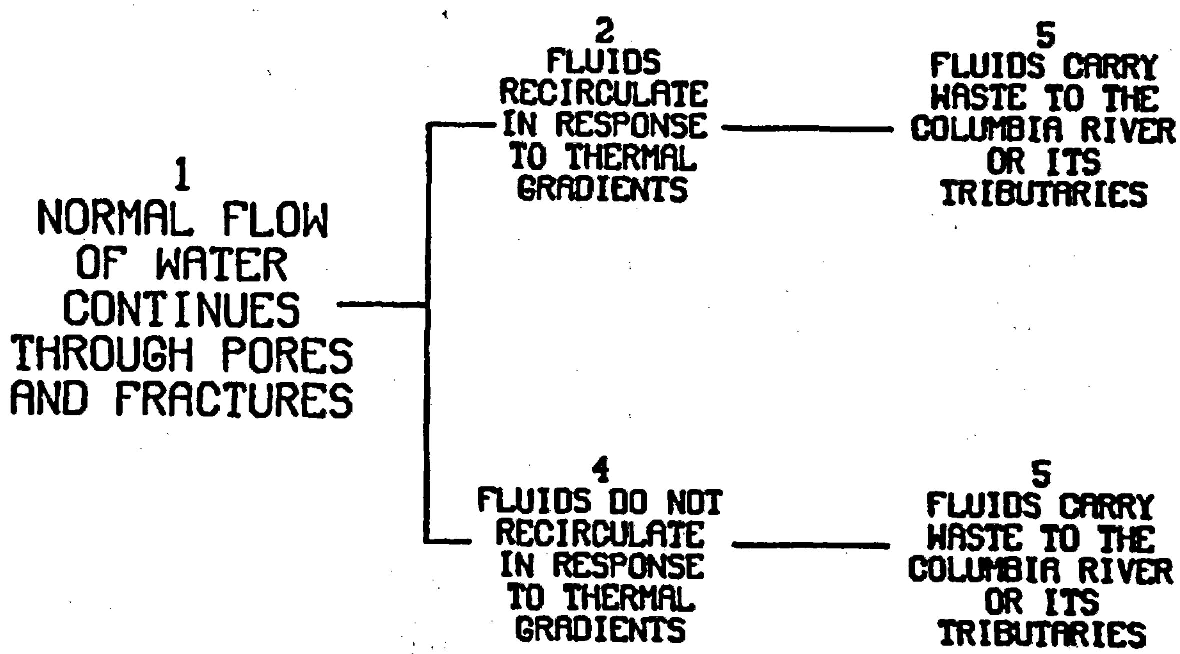

Figure 9. Event tree showing scenarios arising from normal ground-water flow and leading to releases to the Columbia River (Hunter, 1983, Figure 3).

Table 3. Relative probabilities of the scenarios arising from normal ground-water flow and illustrated in Figure 9. (Scenarios are numbered from top to bottom.)

Scenario	Probability in 10,000 yr
1	10^{-6}
2	~1

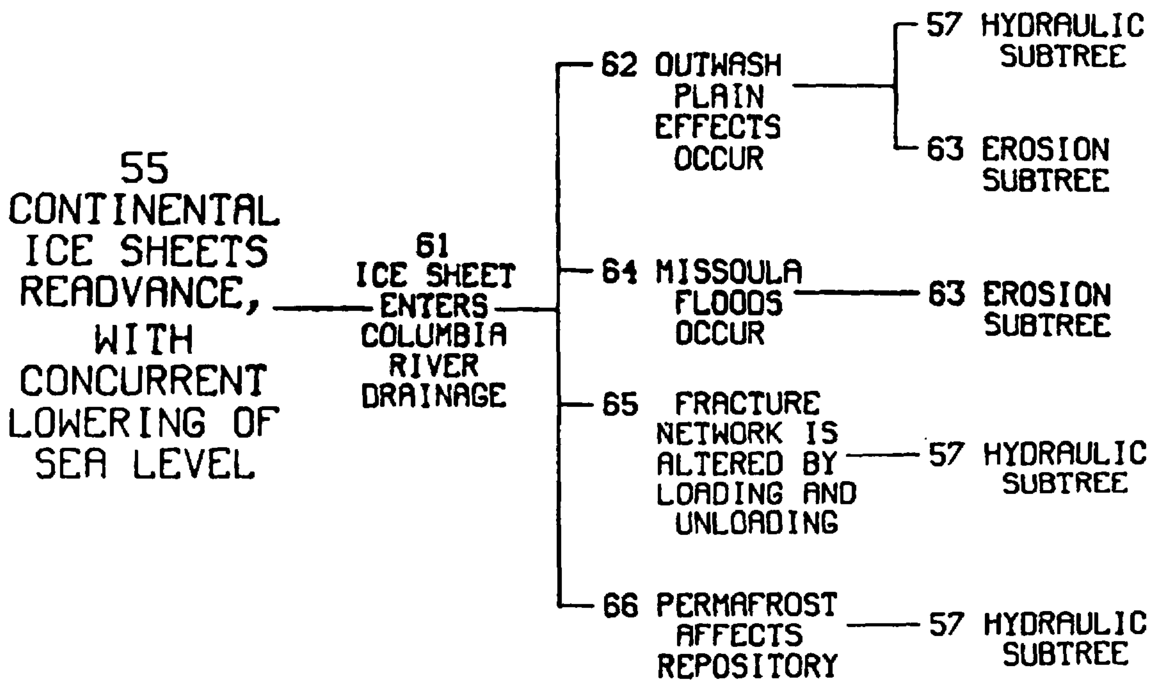

Figure 10. Event tree showing scenarios arising from renewed continental glaciation that entails an ice sheet entering the Columbia River drainage basin (after Hunter, 1983, Figure 8). "Erosion subtree" means that this tree incorporates the subtree shown in Figure 11. "Hydraulic subtree" means that this tree incorporates the subtree shown in Figure 12. Each of the five branches of this tree thus contain several scenarios. The scenario numbers in Table 4 contain two digits, the first referring to a branch in this tree, and the second refering to a branch in the subtree, numbered in each case from top to bottom.

accessible environment, this branch and all its scenarios are also screened out on the basis of low consequence.

Three branches in Figure 10 lead to complex subtrees (Figures 11 and 12). Table 4 presents the probabilities of all the scenarios in the tree, including those in the subtrees. Table 4 shows that many of the scenarios in the first three branches have probabilities of 0.1 or ~1. In a performance assessment, fairly complex investigations might be required to screen them out, or they might all have to be retained. For the purposes of this Example, one scenario, glaciation and climatic change that profoundly alter the ground-water flow regime, will be retained and assigned a probability of 0.1.

Human Intrusion

Drilling is of interest for two reasons: the repository may be directly compromised, or water withdrawals from boreholes may alter ground-water flow. Hunter (1983) arbitrarily assigned a probability of 0.1 to the penetration of the repository by a borehole within 10,000 yr. Hunter developed a tree beginning with drilling and leading to releases to the Columbia River that contained 20 scenarios. In this exercise, a higher probability is assigned based on Appendix B of the Standard. The Standard states that no more than 3 boreholes per km^2 of repository per 10,000 yr should be assumed. Essentially, this recommends the assumption of penetration by boreholes, a probability of ~1. This provides an example of two release phenomena (normal flow and human intrusion) that are not mutually exclusive and that will be combined during the development of the final set of scenarios. Claiborne and Gera (1974) estimated that, if drilling penetrates a repository, the probability of disturbing a canister is 0.01 and of missing a canister is ~1. If a canister is disturbed, releases to the surface occur.

In the Columbia Plateau, pumpage of ground water for irrigation has altered the configuration of the water table substantially in some areas (e.g., Garrett, 1968; Luzier and Burt, 1974), although such changes may or may not change flow at the repository. For this reason, the alteration of flow by pumpage is assigned a moderate probability, 0.001. Several scenarios in this tree can be screened out on the basis of low probability.

Seal Failure

Shafts and boreholes drilled in connection with repository construction will be carefully sealed. The exploration boreholes mentioned above cannot be assumed to be so well sealed; indeed, such holes may not be sealed at all. It is therefore possible, even likely, that seal failure will occur and ground water will flow through the borehole into the repository. Hunter's tree (1983) contained three scenarios that began with seal failure and led to releases to the Columbia River. If holes are drilled, it seems that seal failure over 10,000 yr has a high probability, approaching 1. One seal-failure scenario is that seal failure directs water into the repository, ground-water flow continues out of the repository along more-or-less the same paths that it would follow under the normal-flow scenario, and that the increased volume of fluids carries waste to the Columbia River. This scenario is assigned a probability of 0.05 for this Example.

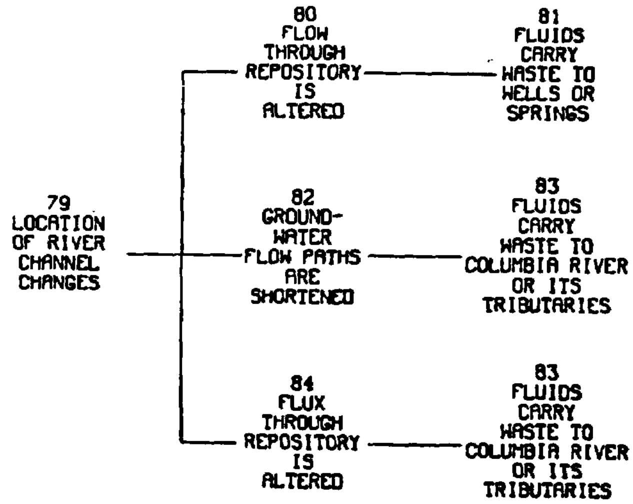

Figure 11. Erosion subtree (after Hunter, 1983, Figure 20).

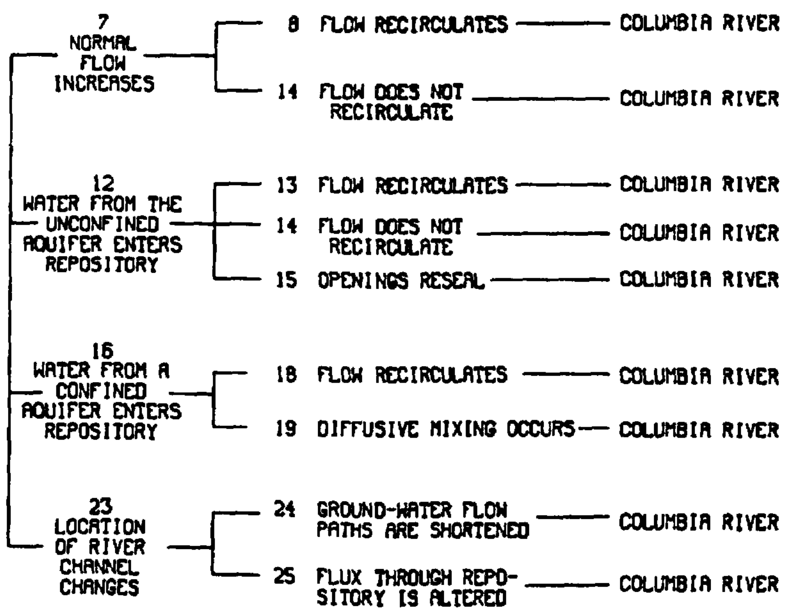

Figure 12. **Hydraulic subtree (Hunter, 1983, Figure 22). "Flow recirculates" means "Fluids recirculate in response to thermal gradients." "Flow does not recirculate" means "Fluids do not recirculate in response to thermal gradients." "Openings reseal" means "Flow channels close and reopen later."**

Table 4. Relative probabilities of the scenarios arising from renewed continental glaciation and illustrated in Figure 10 (after Hunter, 1983, Table 8). (Scenarios are numbered from top to bottom.)

Scenario		Probability in 10,000 yr
First branch, hydraulic subtree	1-1	10^{-7}
	1-2	~1
	1-3	10^{-7}
	1-4	~1
	1-5	.01
	1-6	10^{-7}
	1-7	~1
	1-8	.01
	1-9	.01
Second branch, erosion subtree	2-1	.1
	2-2	.1
	2-3	.1
Third branch, erosion subtree	3-1	.1
	3-2	.1
	3-3	.1
Fourth branch, hydraulic subtree	4-1	10^{-7}
	4-2	~1
	4-3	10^{-7}
	4-4	~1
	4-5	.01
	4-6	10^{-7}
	4-7	~1
	4-8	.01
	4-9	.01
Fifth branch, hydraulic subtree	5-1	10^{-8}
	5-2	.1
	5-3	10^{-8}
	5-4	.1
	5-5	.001
	5-6	10^{-8}
	5-7	.1
	5-8	.001
	5-9	.001

New Fault

The final release phenomenon considered here is the occurrence of a new fault that intersects the repository. Hunter assigned the occurrence of such a new fault a probability of 10^{-4} within 10,000 yr in the Columbia Plateau. The event tree arising from a new fault contained 13 scenarios. Ten can be screened out on the basis of low probability. Three have probabilities just barely above the screening cut-off. For this example, one scenario is retained and assigned a probability of 0.0001. In this scenario, a new fault intersects the repository and allows water from a confined aquifer to enter the repository along the fault. Fluids leave along the new fault and eventually enter the Columbia River.

Final Set of Scenarios for Modeling

The scenarios developed and screened above are not necessarily appropriate as the final set of scenarios to be modeled and included in the performance assessment. Some of the scenarios are obviously mutually exclusive and can be modeled independently, but there may be important combinations of scenarios whose effects are synergistic. Other combinations may be physically possible, but so improbable that they are not of concern. For this reason, simultaneous or sequential occurrences of scenarios must be examined to determine whether such occurrences are probable enough to be considered in the final performance assessment. Because this type of examination has not often been described in the waste-management literature, this part of the scenario analysis is described in detail below.

Normal Flow with Thermal Effects. Normal flow with thermal effects has been assigned a probability of ~1. (If there is a nonzero probability that any other event or process will occur, the probability of this scenario is not in fact 1. Because the probability is unknown but high, the preliminary assignment of ~1 is the usual procedure.) For this reason, the effect of combining this scenario with each of the other scenarios must be examined.

Only one other preliminary scenario, drilling through the repository without hitting a canister, has an assigned probability of ~1. Thus in the final set of scenarios, the so-called normal flow or expected performance of the repository actually is not ground-water flow with thermal perturbations, but instead is ground-water flow with thermal perturbations and human intrusion. At this point a new scenario comes into existance and the two preliminary scenarios are dropped. In practice, the two aspects of this new scenario would probably be modeled separately, and their consequences combined.

The remaining four combinations of normal flow and another scenario are physically impossible and need not be considered. The effects of climatic change on the ground-water flow regime could be profound. The scenarios beginning with glaciation have been assigned a probability of 0.1. Note that 0.1 is the probability that glaciation changes the ground-water flow regime. The normal-flow scenario does not involve any unlikely change in flow; therefore it is impossible for both scenarios to occur simultaneously. They must both be retained for independent modeling.

The same argument rules out the existance of scenarios that combine normal flow with shaft-seal failure that changes the normal flow profoundly enough to be considered a scenario on its own; normal flow with pumpage that changes the ground-water flow boundary conditions; and normal flow with faulting that changes the ground-water flow. Either normal flow <u>or</u> changed flow may occur, but they may not <u>both</u> occur simultaneously. In fact, climatic change, shaft seal failure, pumpage, and faulting would probably all change the flow regime in different ways. Each must be retained for independent modeling.

<u>Climatic Change.</u> The scenario for climatic change that profoundly alters the ground-water flow regime has been assigned a probability of 0.1. This is not so high that it must necessarily be combined with any other scenario, nor so low that the simultaneous occurrence of this and some other moderate-probability scenario can be ignored. The probability that climatic change and shaft-seal failure will both alter ground-water flow during the next 10,000 yr is 0.1 x 0.05 or 0.005. This combination of scenarios should be incorporated into the final set in addition to (not instead of) the two initial scenarios.

The occurrence of both climatic change and pumpage that profoundly alter ground-water flow is 0.1 x 0.001 or 0.0001. This is equal to the cutoff probability of 0.0001 in 10,000 yr. The new scenario should be retained for modeling.

The occurrence of both climatic change and faulting has a probability of only 0.1 x 0.0001 or 0.00001. This is below the cutoff of 0.0001 and need not be considered.

<u>Shaft-seal Failure.</u> The combination of shaft-seal failure with normal flow and with climatic change has been considered above. The combination of shaft-seal failure with pumpage has a probability of 0.05 x 0.001 or 0.00005. The combination of shaft-seal failure and faulting is even lower, 0.05 x 0.0001 or 5 x 10^{-6}. The probabilities of these scenarios are below the cutoff, and they need not be considered.

<u>Pumpage.</u> Two scenarios involving pumpage--pumpage that alters ground-water flow boundary conditions and the combination of pumpage with climatic change--are retained because of their probabilities. The combination of pumpage and shaft-seal failure is screened out, as discussed above. The combination of pumpage and faulting has a probability of 0.001 x 0.0001 or 10^{-7} and is screened out.

<u>Faulting.</u> The probability that faulting will alter ground-water flow is 0.0001, just above the cutoff. This scenario is retained, but no combinations of faulting with other scenarios are retained, as discussed above.

<u>Scenarios to be Retained for Modeling.</u> Seven scenarios thus make up the final set to be modeled (Table 5). In a performance assessment, all these scenarios would be retained for modeling; however, for simplicity in this Example, and so that the reader can more easily follow the discussion below, scenarios 6 and 7 will be omitted at this point.

Table 5. Probabilities of the scenarios used in the Example

Scenario	Probability in 10^4 Yrs
1. Normal Flow (with thermal effects and drilling)	~1
2. Climatic change that alters ground-water flow	0.1
3. Shaft seal failure that alters ground-water flow	0.05
4. Pumpage that alters ground-water flow boundary conditions	0.001
5. Faulting that alters ground-water flow	0.0001
6. Climatic change plus shaft-seal failure	0.005
7. Climatic change plus pumpage	0.0001

Normalizing the Probabilities

The probabilities in Table 5 do not reflect the fact that the scenarios in the final set are mutually exclusive; thus the sum of these probabilities is larger than 1. As discussed above, probability theory requires that the probability estimates for all scenarios be normalized so that their sum is less than or equal to 1 (Heising and others, 1983). The sum of the assigned probabilities of the five scenarios to be used in the remainder of the Example is 1.1511. This sum is normalized to 1 before the CCDF is developed. Each probability P is normalized by multiplying it by the inverse of the sum, that is

$$\text{assigned P} \times \frac{1}{\Sigma \text{ assigned P}} = \text{normalized P.}$$

The normalized probabilities of the five scenarios considered here are given in Table 8 (p. 39). These normalized probabilities are used in developing the CCDF. (The normalized probabilities of the five scenarios sum to 1.000957 because of roundoff error.)

Consequence Assessment

The Example repository contains 50,000 MTHM of spent fuel. The corresponding release limits are therefore adjusted for 50,000 MTHM (Table 6).

The derivation of the EPA sum values for the normal-flow scenario is described in more detail below. For illustration, it is assumed that five

Table 6. Adjusted release limits for the Example repository

Radionuclide	Adjusted Release Limit (curies)
Americium-241 or -243	5000
Carbon-14	5000
Cesium-135 or -137	50,000
Iodine-129	5000
Neptunium-237	5000
Plutonium-238, -239, -240, or -242	5000
Radium-226	5000
Strontium-90	50,000
Technetium-99	500,000
Thorium-230 or -232	500
Tin-126	50,000
Uranium-233, -234, -235, -236, or -238	5000
Any other alpha-emitting radionuclide with a half-life greater than 20 years	5000
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	50,000

Table 7. Cumulative releases over 10,000 yr for radionuclides in the normal-flow scenario of the Example

Radionuclide	Cumulative releases over 10,000 yr (in Curies)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
C-14	350	400	500	700	800
Tc-99	5000	5000	10,000	10,000	15,000
U-234	0	100	150	200	250
U-236	0	100	200	250	300
U-238	75	85	125	125	150
Pu-240	25	15	75	75	100

vectors (sampled inputs) are generated as illustrated in Figure 5. For each set of sampled input data, source-term, ground-water flow, and radionuclide-transport models are used to calculate the time-dependent discharges of radionuclides. These time-dependent discharges are integrated over 10,000 yr to give the cumulative release over 10,000 yr for each radionuclide.

For simplicity, only six radionuclides are assumed to be released to the accessible environment in the normal-flow scenario of the Example; their cumulative releases are listed in Table 7. The EPA sum for each sampled calculation for this scenario is calculated according to Eq. 1:

$$\text{Sample \#1:}\quad \text{EPA Sum} = \frac{350}{5000} + \frac{5000}{500{,}000} + \frac{75}{5000} + \frac{25}{5000} = 0.1$$

$$\text{Sample \#2:}\quad \text{EPA Sum} = \frac{400}{5000} + \frac{5000}{500{,}000} + \frac{100}{5000} + \frac{100}{5000} + \frac{85}{5000} + \frac{15}{5000} = 0.15$$

$$\text{Sample \#3:}\quad \text{EPA Sum} = \frac{500}{5000} + \frac{10{,}000}{500{,}000} + \frac{150}{5000} + \frac{200}{5000} + \frac{125}{5000} + \frac{75}{5000} = 0.23$$

$$\text{Sample \#4:}\quad \text{EPA Sum} = \frac{700}{5000} + \frac{10{,}000}{500{,}000} + \frac{200}{5000} + \frac{250}{5000} + \frac{125}{5000} + \frac{75}{5000} = 0.29$$

$$\text{Sample \#5:}\quad \text{EPA Sum} = \frac{800}{5000} + \frac{15{,}000}{500{,}000} + \frac{250}{5000} + \frac{300}{5000} + \frac{150}{5000} + \frac{100}{5000} = 0.35$$

These EPA sums are the five values that appear in Table 8 for the normal-flow scenario. Similar analyses are carried out for the other scenarios, producing the results displayed in Table 8.

The next step calculates the probability of releases that lead to a consequence greater than a given EPA Sum (Eq. 2). For example, the probability of having releases greater than an EPA sum of 158.40 is equal to 1/5 (0.000087), where 1/5 is the fraction of samples in the faulting scenario that result in an EPA sum greater than 158.40 and 0.000087 is the probability of the faulting scenario. The calculation of the probability of releases greater than each EPA sum value is detailed in Table 9.

In the construction of a CCDF, the EPA sums and the probabilities from Table 9 are plotted on the x and y axes respectively. The final CCDF is shown in Figure 13. The area that is outside the EPA containment requirement envelope indicates possible violation of the EPA standard. This area includes the following three EPA sums and their probabilities:

EPA Sum	Probability
23.00	0.000435
15.85	0.009035
7.25	0.009209

Table 8. Probabilities, normalized probabilities, and EPA sums for the scenarios used in the Example

Scenario	Probability in 10^4 Yr	Normalized Probability in 10^4 Yrs	EPA Sum
1. Normal Flow (with thermal effects and drilling)	~1	0.87	0.1[illegible] 0.15 0.23 0.29 0.35
2. Climatic change that alters ground-water flow	0.1	0.087	0.75 0.83 0.99 1.58 7.25
3. Shaft seal failure that alters ground-water flow	0.05	0.043	0.003 1.87 2.95 3.75 23.00
4. Pumpage that alters ground-water flow boundary conditions	0.001	0.00087	0.20 1.75 15.85 42.00 49.20
5. Faulting that alters ground-water flow	0.0001	0.000087	37.00 79.20 105.60 158.40 252.30

Table 9. Values of EPA sum and probabilities used in Figure 13

EPA sum	Probability of releases greater than the EPA sum
252.30	0
158.40	1/5 (0.000087) = 0.0000174
105.60	1/5 (0.000087) + 0.0000174 = 0.0000348
79.20	1/5 (0.000087) + 0.0000348 = 0.0000522
49.20	1/5 (0.000087) + 0.0000522 = 0.0000696
42.00	1/5 (0.00087) + 0.0000696 = 0.0002436
37.00	1/5 (0.00087) + 0.0002436 = 0.0004176
23.00	1/5 (0.000087) + 0.0004176 = 0.000435
15.85	1/5 (0.043) + 0.000435 = 0.009035
7.25	1/5 (0.00087) + 0.009035 = 0.009209
3.75	1/5 (0.087) + 0.009209 = 0.026609
2.95	1/5 (0.043) + 0.026609 = 0.035209
1.87	1/5 (0.043) + 0.035209 = 0.043809
1.75	1/5 (0.043) + 0.043809 = 0.052409
1.58	1/5 (0.00087) + 0.052409 = 0.052583
0.99	1/5 (0.087) + 0.052583 = 0.069983
0.83	1/5 (0.087) + 0.069983 = 0.087383
0.75	1/5 (0.087) + 0.087383 = 0.104783
0.35	1/5 (0.087) + 0.104783 = 0.122183
0.29	1/5 (0.87) + 0.122183 = 0.296183
0.23	1/5 (0.87) + 0.296183 = 0.470183
0.20	1/5 (0.87) + 0.470183 = 0.644183
0.15	1/5 (0.00087) + 0.644183 = 0.644357
0.10	1/5 (0.87) + 0.644357 = 0.818357
0.003	1/5 (0.87) + 0.818357 = 0.992357
0.0	1/5 (0.043) + 0.992357 = 1.000957

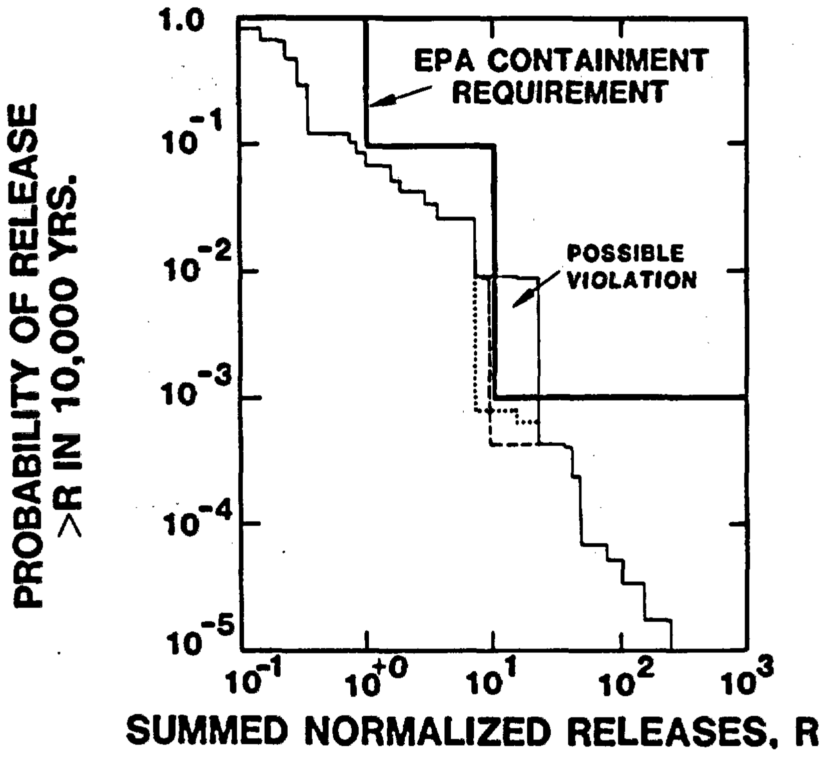

Figure 13. CCDF for the Example plotted with EPA containment requirement.

One possible factor contributing to the violation is the probability of the seal-failure scenario. If the probability of this scenario were 0.001, for example, instead of 0.043, the probability of exceeding an EPA sum of 15.85 would become 1/5 (0.001) + 0.000435 = 0.000635. The probability of exceeding an EPA sum of 7.25 would be 1/5 (0.00087) + 0.000635 = 0.000809. These changes would bring the CCDF curve inside the EPA containment requirement envelope, as shown by the dotted line in Figure 13.

Another factor contributing to the violation is the EPA sum values of 23.00 and 15.85. If these two values were 9.5 and 8.2, for example, the CCDF curve would be inside the EPA envelope if the scenario probabilities were to remain the same, as shown by the dashed line in Figure 13. Thus, this procedure for generating a CCDF allows the regulator to examine the effect of each chosen parameter value on the position of the curve relative to the EPA containment requirement.

4. CONCLUSIONS

The analyst must make several important judgments while developing and screening scenarios for a performance assessment. First, the initial checklist of events and processes must be comprehensive enough to ensure that all important events and processes are considered. Second, the initial screening must remove only those events and processes that offer <u>prima facie</u> evidence of irrelevance. Third, the initial suite of scenarios must be broad and complex enough to inspire confidence that it fairly represents all conceivably important scenarios. Finally, probabilities and consequences of those scenarios that are screened out from the performance assessment must be sufficiently well described and conservative to offer reasonable assurance that the scenarios' contributions would be insignificant if they were retained.

The technique used in assigning probabilities to events, processes, and scenarios must be the best available; for example, if technically defensible numerical and analytical techniques exist, they should be used in preference to expert judgment. Data employed in determining the probabilities must be adequate in quality and quantity and must be appropriately used; for example, their temporal and spatial distribution must be compatible with the techniques.

In assessing consequences, the analyst must first decide whether the parameters of the scenarios are adequately represented by the equations in the code and whether the physical repository system is adequately represented by the models. Codes must have been adequately verified, and the models, validated. Data must be of high quality, numerous enough to reflect any spatial or temporal variations, and used appropriately in the codes and models.

The quality of an uncertainty analysis is particularly important in any performance assessment. The various techniques for uncertainty analysis have advantages and disadvantages, depending on the modeling approach used. The qualitative uncertainties present in scenario analysis are best addressed by using systematic techniques for development and screening. Although sensitivity analysis is <u>not</u> equivalent to uncertainty analysis, it is an essential precursor to a full understanding of overall system uncertainty.

A CCDF generated in the way indicated above allows for flexibility in assessing the impact that each component of a performance assessment has on the CCDF. For example, if any portion of the empirical CCDF lies above the envelope representing compliance with the EPA Standard, exactly which of the scenarios, model parameters, isotopes, and scenario probabilities are causing the noncompliance can be determined. If unrealistic parameters resulted in the noncompliance, that portion of the analysis can be redone without carrying out additional analyses on the remaining portions of the overall performance assessment.

5. REFERENCES

Bakr, A. A., L. W. Gelhar, A. L. Gutjhar, and J. R. MacMillan, 1978, "Stochastic Analysis of Spatial Variability in Subsurface Flows 1. Comparison of One- and Three-Dimensional Flows," Water Resources Research, vol. 14, p. 263-271.

Bartlein, P. J., and Thompson Webb III, 1986 (in preparation), "Climatology," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 6-1--6-43.

Beckman, R. J., and M. E. Johnson, 1980, A Probabilistic Model for Estimating the Effects of Volcanism on a Nuclear Waste Repository, LA-UR80-2166, Los Alamos Scientific Laboratory, Los Alamos, NM.

Bingham, F. W., and G. E. Barr, 1979, Scenarios for Long-Term Release of Radionuclides from a Nuclear-Waste Repository in the Los Medanos Region of New Mexico, SAND78-1730, Sandia Laboratories, Albuquerque, NM.

Callender, J. F., 1986 (in preparation), "Tectonics and Seismicity," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 7-1--7-54.

Campbell, J. E., D. E. Longsine, and M. Reeves, 1980, Risk Methodology for Geologic Disposal of Radioactive Waste: The Distributed Velocity Method of Solving the Convective-Dispersion Equation, SAND80-0717, NUREG/CR-1376, Sandia National Laboratories, Albuquerque, NM.

Chu, M. S., and C. L. Axness, 1984, "A Comparison Study of Different Source Models for High-Level Waste," Waste Management '84, vol. 1, p. 401.

Chu, M. S. Y., N. R. Ortiz, K. K. Wahi, R. E. Pepping, and J. E. Campbell, 1983, An Assessment of the Proposed Rule (10CFR60) for Disposal of High-Level Radioactive Waste in Geologic Repositories, NUREG/CR-3111, SAND82-2969, Sandia National Laboratories, Albuquerque, NM.

Claiborne, H. C., and F. Gera, 1974, Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico, ORNL-TM-4639, Oak Ridge National Laboratory, Oak Ridge, TN.

Clifton, P. M., and S. P. Neuman, 1982, "Effects of Kriging and Inverse Modeling on Conditional Simulation of the Avra Valley Aquifer in Southern Arizona," Water Resources Research, vol. 18, p. 1215-1234.

Cranwell, R. M., and J. C. Helton, 1981, "Uncertainty Analysis for Geologic Disposal of Radioactive Waste," in D. C. Kocher, ed., Proceedings of the Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High-Level Radioactive Waste, Gatlinburg, TN, March 9-13, 1981.

Cranwell, R. M., R. V. Guzowski, J. E. Campbell, and N. R. Ortiz, 1982a, Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure, SAND80-1429, NUREG/CR-1667, Sandia National Laboratories, Albuquerque, NM.

Cranwell, R. M., J. E. Campbell, J. C. Helton, R. L. Iman, D. E. Longsine, N. R. Ortiz, G. E. Runkle, and M. J. Shortencarier, 1982b, Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report, SAND81-2573, NUREG/CR-2452, Sandia National Laboratories, Albuquerque, NM.

Delfiner, P., 1976, "Linear Estimation of Non-Stationary Spatial Phenomena," in M. Guarascio and others, Advanced Geostatistics in the Mining Industry, NATO Advanced Study Institute Series, D. Reidel Publishing Co., Boston.

Delhomme, J. P., 1976, "Applications de la Theorie des Variables Regionalisees dans les Sciences de l'Eau," Doctoral Thesis, Centre d'Informatique Geologique, ENSMP, Paris.

Dillon, R. T., R. B. Lantz, and S. B. Pahwa, 1978, Risk Methodology for Geologic Disposal of Radioactive Waste: The Sandia Waste Isolation Flow and Transport (SWIFT) Model, SAND78-1267, NUREG/CR-0424, Sandia Laboratories, Albuquerque, NM.

Doctor, P. G., 1980, "The Use of Geostatistics in High Level Radioactive Waste Repository Site Characterization," Radioactive Waste Management, vol. 1, p. 193-210.

Donath, F. A., and R. M. Cranwell, 1981, "Probabilistic Treatment of Faulting in Geologic Media," Mechanical Behavior of Crustal Rocks, Geophysical Monograph 24, Amer. Geophys. Union, p. 231-241.

Einstein, H. H., and G. B. Baecher, 1986 (in preparation), "Tunneling and Mining Engineering," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 4-1--4-72.

Garrett, A. A., 1968, Ground-water Withdrawal in the Odessa Area, Adams, Grant, and Lincoln Counties, Washington, Washington State Dept. of Water Resources in cooperation with the US Geological Survey, Water-Supply Bull. No. 31, 84 p.

Gelhar, L. W., A. L. Gutjhar, and R. L. Naff, 1979, "Stochastic Analysis of Macro-Dispersion in a Stratified Aquifer," Water Resources Research, vol. 15, p. 1387-1397.

Gutjahr, A. L., 1986 (in preparation), "Hydrology," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 5-1--5-50.

Gutjhar, A. L., L. W. Gelhar, A. A. Bakr, and J. R. MacMillan, 1978, "Stochastic Analysis of Spatial Variability in Subsurface Flows 2. Evaluation and Application," Water Resources Research, vol. 14, p. 953-959.

Harbaugh, J. W., 1986 (in preparation), "Resource Exploration," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 2-1--2-39.

Harper, W. V., 1983, Sensitivity/Uncertainty Analysis Techniques for Non-Stochastic Computer Codes, ONWI-444, Battelle Memorial Institute, Columbus, OH.

Hoel, P. G., S. C. Port, and C. J. Stone, 1971, Introduction to Probability Theory, Houghton Mifflin Co., Boston, 258 p.

Hunter, R. L., 1983, Preliminary Scenarios for the Release of Radioactive Waste from a Hypothetical Repository in Basalt of the Columbia Plateau, SAND83-1342, NUREG/CR-3353, Sandia National Laboratories, Albuquerque, NM.

Hunter, R. L., and C. John Mann, eds., 1986 (in preparation), Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 1, Nuclear Regulatory Commission, Washington, DC.

Hunter, R. L., G. E. Barr, and F. W. Bingham, 1982, Preliminary Scenarios for Consequence Assessments of Radioactive-Waste Repositories at the Nevada Test Site, SAND82-0426, Sandia National Laboratories, Albuquerque, NM.

Iman, R. L., and J. C. Helton, 1985, A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models, SAND84-1461, NUREG/CR-3904, Sandia National Laboratories, Albuquerque, NM.

Iman, R. L., J. C. Helton, and J. E. Campbell, 1978, Risk Methodology for Geologic Disposal of Radioactive Waste: Sensitivity Analysis Techniques, SAND78-0912, NUREG/CR-0397, Sandia National Laboratories, Albuquerque, NM.

INTERA Environmental Consultants, 1983, WAPPA: A Waste Package Performance Assessment Code, ONWI-452, Battelle Project Management Division, Columbus, OH.

International Atomic Energy Agency, 1981, Safety Assessment for the Underground Disposal of Radioactive Wastes, Safety Series No. 56, Int. Atomic Energy Agency, Vienna, Austria.

Journel, A. G., and C. J. Huijbregts, 1979, Mining Geostatistics, Academic Press, New York, 600 p.

Heising, C. D., H. J. Lipschitz, and M. S. Brown, 1983, Uncertainty Analysis in Risk Studies of High-Level Waste Repositories, submitted to Sandia National Laboratories, Albuquerque, NM.

Luzier, J. E., and R. J. Burt, 1974, Hydrology of Basalt Aquifers and Depletion of Ground Water in East-central Washington, Washington State Dept. of Ecology in cooperation with the US Geological Survey, Water-Supply Bull. No. 33, 53. p.

Matheron, G., 1969, "Le Krigeage Universal," Cah. Centre Morphol. Math., 1, Fontainebleau.

Matheron, G., 1970, "The Theory of Regionalized Variables and its Applications," Cah. Centre Morphol. Math., 5, Fontainebleau.

McBirney, A. R., 1986, "Volcanology," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, p. 8-1--8-24.

Ortiz, N. R., and R. M. Cranwell, 1982, Risk Assessment Methodology for High Level Waste: Assessing Compliance with the EPA Draft Standard Including Uncertainties, SAND82-0596, Sandia National Laboratories, Albuquerque, NM.

Pepping, R. E., M. S. Y. Chu, and M. D. Siegel, 1983, Technical Assistance for Regulatory Development: Review and Evaluation of the Draft EPA Standard 40CFR191 for Disposal of High-Level Waste. Volume 2: A Simplified Analysis of a Hypothetical Repository in a Basalt Formation, NUREG/CR-3235, SAND82-1557, Sandia National Laboratories, Albuquerque, NM.

Reeves, M., and R. M. Cranwell, 1981, User's Manual for the Sandia Waste-Isolation Flow and Transport Model (SWIFT), Release 4.81, SAND81-2516, Sandia National Laboratories, Albuquerque, NM.

US Department of Energy, 1983, Draft Revised General Guidelines for Recommendation of Sites for Nuclear Waste Repositories, May 27, 1983.

US Department of Energy, 1984, Mission Plan for the Civilian Radioactive Waste Management Program, Volume 1, Overview and Current Program Plans, DOE/RW-0005 DRAFT, Washington DC.

US Environmental Protection Agency, 1985, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste, Final Rule," 40CFR191, Federal Register, v. 50, p. 38066-38089.

US Nuclear Regulatory Commission, 1983, "10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories, Technical Criteria, Final Rule," Federal Register, vol. 48, p. 28194-28229.

Wahi, K. K., 1986 (in preparation), "Thermomechanical Effects," in R. L. Hunter and C. John Mann, eds., Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories, NUREG/CR-3964, SAND86-0196, Vol. 2, Nuclear Regulatory Commission, Washington, DC, Ch. 3.

Wahi, K. K., and R. L. Hunter, 1985, "Mechanical Effects Associated with Surface Loading of Dry Rock Due to Glaciation," Proceedings, International Topical Meeting on High Level Nuclear Waste Disposal, Pasco, Washington, September 1985.

NRC FORM 335
(2-84)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-4510
SAND86-0121

2. TITLE AND SUBTITLE
Assessing Compliance with the EPA High-Level Waste Standard: An Overview

3. LEAVE BLANK

4. DATE REPORT COMPLETED
MONTH: October YEAR: 1986

5. AUTHOR(S)
R. L. Hunter, R. M. Cranwell, and M. S. Y. Chu

6. DATE REPORT ISSUED
MONTH: October YEAR: 1986

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Sandia National Laboratories
Albuquerque, NM 87185

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
FIN A-1165

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Waste Management
Office of Nuclear Material Safety & Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

11a. TYPE OF REPORT
Technical

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

The US Environmental Protection Agency has set a standard for the performance of geologic repositories for the disposal of high-level radioactive waste. The standard is divided into several sections, including a section on containment requirements. The containment requirement is probabilistic, in that it allows certain small amounts of radioactive waste to be released at high probabilities and larger amounts to be released at lower probabilities. The US Nuclear Regulatory Commission is responsible for implementing the standard. Implementation of the standard will probably involve development and screening of scenarios, assignment of probabilities to the scenarios, determination of consequences of the scenarios, and analysis of uncertainties. Scenario development consists of first, identifying events and processes that could initiate waste releases or affect waste transport, and second, combining the events and processes in physically reasonable ways. Scenarios can be screened on the basis of low probabilities or consequences. Consequences of scenarios are calculated using a series of models that describe the movement of radionuclides out of the waste package and underground facility and the transport of the radionuclides by ground water or other means to the accessible environment. Sensitivity and uncertainty analysis examines the sources and effects of uncertainties on the calculations. This document uses a simple example to illustrate techniques for the implementation of the standard.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
EPA, High-Level Waste

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page) Unclassified
(This report) Unclassified

17. NUMBER OF PAGES

18. PRICE

*U.S. GOVERNMENT PRINTING OFFICE:1987-181-682:60033

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

SPECIAL FOURTH-CLASS RATE
POSTAGE & FEES PAID
USNRC
WASH. D.C.
PERMIT No. G-67