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Use of Performance Assessment in Assessing Compliance With the Containment Requirements in 40 CFR Part 191

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ABSTRACT

This report summarizes the role of performance assessment in assessing compliance with the containment requirements in 40 CFR Part 191, the Environmental Protection Agency's Standard for the disposal of spent nuclear fuel, high-level and transuranic radioactive wastes. In 1986, Hunter et al. prepared a similar report (NUREG/CR-4510, SAND86-0121) which provided an overview of the approach to assess compliance with this standard. The present report builds on its predecessor in that it incorporates advances in performance assessment subsequent to Hunter et al.'s report. The main purpose of this report is to serve as a mechanism for transferring to the Nuclear Regulatory Commission (NRC) and its contractors the performance assessment methodologies (PAMs) developed by Sandia National Laboratories (SNL) for high-level radioactive waste repositories. The report starts with a discussion of the requirements in 40 CFR Part 191 and focuses on the containment requirements (Section 191.13). It follows with a discussion of the role of performance assessment and its use in regulatory compliance. The report concludes with a discussion of sources of uncertainty, treatment of uncertainties, and the construction of the complementary cumulative distribution function of summed normalized total releases to the accessible environment for one or more scenarios. Examples are presented of the demonstration of performance assessment methodologies for high-level waste disposal at two hypothetical sites. Consistent with the technology transfer objective, numerous references are made throughout this report to publications related to the SNL PAMs. As such, this is not a stand-alone report and the reader is encouraged to consult those references.

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1.0 INTRODUCTION

In 1982, the United States Congress passed the Nuclear Waste Policy Act (NWPA), which among its several provisions and requirements, called for the Environmental Protection Agency (EPA) to promulgate generally applicable environmental standards for the management, storage, and disposal of spent nuclear fuel, high-level, and transuranic radioactive wastes. In addition, the NWPA prescribed that the EPA standards be implemented by the U.S. Nuclear Regulatory Commission (NRC) as part of the repository licensing process. For the purpose of this report, we shall refer collectively to spent nuclear fuel, high-level, and transuranic wastes as high-level waste (HLW). The EPA promulgated its standard governing the management, storage, and disposal of high-level wastes in the form of 40 CFR Part 191 in September 1985 [EPA, 1985].[1]

The EPA Standard (for simplicity, hereinafter referred to as the Standard) places limits on the radiation exposures to members of the public prior to waste disposal and establishes containment requirements that limit release of radioactivity to the accessible environment for 10,000 years following closure of the repository. Additional requirements, related to the disposal of HLW, include a set of six qualitative assurance requirements, the individual protection requirements, and the ground-water protection requirements. The focus of this report is on assessing compliance with the EPA containment requirements (40 CFR Part 191.13). The NRC promulgated a "Final Rule," 10 CFR Part 60, that prescribes rules governing the licensing of geologic repositories [NRC, 1983]. Regulation 10 CFR Part 60 incorporates the Standard as the overall performance requirements for an HLW repository. The requirements in 10 CFR Part 60.112 set an overall system performance objective that amounts to meeting the EPA's containment requirements, while certain other sections set forth subsystem performance objectives.

In 1976, the NRC contracted to Sandia National Laboratories (SNL) to develop performance assessment methodologies (PAMs) that will permit the NRC to assess compliance with the containment requirements in the Standard. To date, SNL has developed two such methodologies: one applicable to repository in bedded salt [Cranwell et al., 1987] and another applicable to basalt [Bonano et al., 1989a]. A third PAM, which is applicable to tuff formations, is presently under development.

All three PAMs share the same basic structure which consists of four main components. These are:

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[1] 40 CFR Part 191 was vacated by the U.S. Court of Appeals for the First Circuit and remanded to the EPA for further consideration. This report was prepared under the assumption that this regulation, or at least Section 191.13 (the containment requirements), will be repromulgated with few or no changes.

1. Methods for selecting and screening scenarios,
2. Models and computer codes for simulating the processes in the scenarios and estimating the consequences of scenarios,
3. Probabilistic and statistical techniques for estimating risk and performing uncertainty and sensitivity analyses, and
4. Procedures for utilizing the PAM.

The purpose of this report is to summarize and discuss the PAM and its application in assessing compliance with 40 CFR Part 191.13. This report contains five other chapters. In Chapter 2 the Standard is summarized. Performance assessment is discussed in Chapter 3. In Chapter 4, different types of uncertainty that should be considered in a performance assessment are addressed. Also, a specific method of incorporating results of multiple deterministic calculations (i.e., Monte Carlo simulations) is presented. Two examples of the application of the PAMs are provided in Chapter 5. Some concluding remarks are provided in Chapter 6.

It should be noted here that this report is not a stand-alone report. Many references are made to publications related to the PAMs. It is expected that the reader will examine the publications referenced in this report to gain a more in-depth knowledge of the SNL PAMs and their application in assessing compliance with the containment requirements in the Standard.

2.0 DISCUSSION OF EPA STANDARD, 40 CFR PART 191

This chapter presents a relatively brief discussion of the Standard. A more extensive discussion on this regulation appears in Davis et al. [1990].

The Standard contains two subparts: Subpart A and Subpart B; in addition, Appendix A and Appendix B are supplements to Subpart B.

Subpart A applies to radiation doses received by members of the public as a result of activities related to the management and storage of HLW. Specifically, it prescribes limits during the preclosure phase (i.e., during the operational phase of the repository and prior to permanent closure) on the combined annual dose equivalent to any member of the public in the general environment.

Subpart B applies to the disposal of HLW; i.e., it sets requirements for the long-term performance of an HLW repository following closure of the repository. In Subpart B limits are placed on (1) the likelihood that cumulative releases of radioactivity to the accessible environment will exceed certain numerical values (containment requirements), (2) the radiation doses received by members of the public as a result of such disposal (individual protection requirements), and (3) radionuclide concentrations in special source(s) of ground water in the vicinity of a disposal system (ground-water protection requirements). In addition, Subpart B contains a set of qualitative requirements that are termed "assurance requirements." The requirements in Subpart B are briefly described below.

2.1 40 CFR Part 191.13: Containment Requirements

The containment requirements specify, in a probabilistic manner, the quantitative limits on the cumulative releases of radioactivity to the accessible environment for 10,000 years following closure of the repository. Compliance with the containment requirements consists of providing a reasonable expectation, based upon performance assessment,[2] that the projected releases of specific radionuclides will be within the prescribed limits. A discussion of the phrase "reasonable expectation" is found in 40 CFR Part 191 [EPA, 1985]. Furthermore, a performance assessment must consider all significant processes and events that may affect the disposal system. The Standard states that the cumulative releases shall:

> " (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); 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)."

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[2] The term "performance assessment" is defined in Chapter 3.

2.2 40 CFR Part 191.14: Assurance Requirements

The six assurance requirements in 40 CFR Part 191.14 are designed to provide confidence for long-term compliance with the containment requirements. The requirements (or provisions) pertain to (1) active institutional controls, (2) monitoring of disposal systems, (3) passive institutional controls, (4) multiple-barrier concept, (5) resource potential at the disposal site, and (6) retrievability for a reasonable time after disposal.

Technically speaking, the assurance requirements do not apply to facilities regulated by the NRC. However, 10 CFR Part 60 contains substantially similar provisions so that, in effect, these requirements have to be met by all proposed HLW disposal facilities.

2.3 40 CFR Part 191.15: Individual Protection Requirements

According to these requirements, disposal systems must be designed such that the annual dose equivalent from the disposal system to individuals (i.e., any member of the public in the accessible environment) is less than a prescribed limit. Specifically, it is required that for 1,000 years[3] after disposal, undisturbed performance of the system shall not cause the dose to exceed 25 millirems to the whole body or 75 millirems to any critical organ.

These requirements are different from the containment requirements in three ways: (1) the period of regulation is 1,000 years instead of 10,000 years; (2) annual dose equivalent rather than the probability of a certain cumulative release of radioactivity is the basis for the requirements; and (3) only undisturbed performance needs to be addressed. However, the PAMs have also been designed to allow the assessment of compliance with the individual protection requirements [e.g., see Bonano et al., 1985, 1989 a,b; Cranwell et al., 1987; and Davis et al., 1990]

The Standard uses the term "undisturbed performance" in both 40 CFR Part 191.15 and 191.16 (see Section 2.4). This term is defined by EPA in the following manner:

> "Undisturbed performance means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events."

It is not clear at this time whether the reference to the consideration of uncertainties in this definition includes uncertainties in the future states of the system (i.e.,

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[3] This was the length of the regulatory period for both the individual protection requirements and the ground-water protection requirements prior to the Standard being vacated. The length of this regulatory period may be changed by EPA as part of its current consideration of the Standard.

scenarios). Whether or not scenarios need to be considered depends largely on the definition of undisturbed performance used by the NRC in 10 CFR Part 60. If NRC equates "undisturbed performance" to "anticipated processes and events," then a licensee must consider the uncertainty in the future states of the system when demonstrating compliance with the individual protection requirements. However, it is clear that the licensee needs to consider uncertainties in modeling and uncertainties in data and parameters when attempting to demonstrate compliance with these requirements. Therefore, a probabilistic approach, such as that implemented in the SNL PAMs, seems appropriate for assessing compliance with the individual protection requirements.

2.4 40 CFR Part 191.16: Ground-water Protection Requirements

These requirements are imposed with the intent to protect special sources of ground water in the vicinity of an HLW repository. The repository system must be designed to provide a reasonable expectation that, for 1,000 years following closure of the repository, undisturbed performance of the system shall not result in the release of specific radionuclides to exceed concentration limits prescribed in 40 CFR Part 191.16(a). In case the concentrations existing in a special source of ground water prior to repository construction already exceed those limits, then the increase in radionuclide concentration due to undisturbed performance of the disposal system must be less than the limits established in 40 CFR Part 191.16(a). Demonstration of compliance with these requirements is expected to be similar to that for the individual protection requirements.

2.5 Appendix A and Appendix B of 40 CFR Part 191

Appendix A and Appendix B in the Standard provide (1) the release limits for the containment requirements and (2) guidance on the steps recommended to demonstrate compliance with these requirements, respectively. Given the importance of the information contained in these two appendices with respect to the containment requirements--the subject of this report--the appendices are briefly discussed below.

2.5.1 Appendix A

The specific release limits for different radionuclides that must be met to satisfy the containment requirements are listed in Table 1 of Appendix A. This table has been reproduced here as Table 2.1 for the convenience of the reader. The limit for a given radionuclide (or type of radionuclide) is the maximum allowable release, if no other radionuclides are released. This appendix also contains six lengthy notes on the application of this table. In particular, it dictates the method by which the limiting values of release are to be determined when more than one radionuclide is predicted to be released to the accessible environment in 10,000 years.

2.5.2 Appendix B

The long-term performance of the disposal system will need to be evaluated to determine compliance with the requirements in Subpart B of 40 CFR Part 191.

Table 2.1

Release Limits for Containment Requirements (Cumulative Releases to the Accessible Environment for 10,000 Years After Disposal)

Radionuclide	Release Limit per 1,000 MTHM (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-266	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

Appendix B provides guidance for implementation of Subpart B. Although the EPA does not consider Appendix B to be an integral part of 40 CFR Part 191, it has provided this guidance to communicate the Agency's assumption regarding the implementation of Subpart B. The topics addressed in Appendix B are:

1. Consideration of Total Disposal System
2. Scope of Performance Assessments
3. Compliance with 40 CFR Part 191.13
4. Compliance with 40 CFR Part 191.15 and 191.16
5. Institutional Controls

6. Consideration of Inadvertent Human Intrusion into Geological Repositories

7. Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories

The SNL PAMs focus on topics (2) and (3) above.

3.0 PERFORMANCE ASSESSMENT

The EPA [1985] defines "performance assessment" as follows:

> "... an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable."

The SNL PAMs provide a systematic approach that, when followed, ensures that all the aspects comprising a performance assessment are effected in a logical sequence consistent with this definition.

3.1 Role of Performance Assessment

The containment requirements explicitly state that performance assessments be utilized to estimate the cumulative release of radionuclides and to provide a reasonable expectation that the likelihood of exceeding specific release quantities is less than applicable limits specified in 40 CFR Part 191.13. The NRC in 10 CFR Part 60 requires the license application to consist of general information and a Safety Analysis Report (SAR). Among the required contents of the SAR is a description and assessment of the HLW repository site. This assessment must include, among other analyses, "an evaluation of the performance of the proposed geologic repository for the period after permanent closure, assuming anticipated processes and events, . . . and a similar evaluation which assumes the occurrence of unanticipated processes and events." (10 CFR Part 60.21(c)(1)(ii)(C)). Each regulation, therefore, clearly assigns a key role to performance assessment as a tool that will assist in ascertaining the system's compliance with 40 CFR Part 191.13 and 10 CFR Part 60.112.

Implicit in the definition of performance assessment is all the analyses to be performed in support of a HLW repository license application. These analyses, in general, are expected to require the use of conceptual and mathematical models and associated computer codes to predict the long-term behavior of the disposal system.

The stated role of performance assessment translates into providing reliable quantitative predictions of future disposal-system behavior under different sets of plausible conditions. The term "conditions" encompasses realistic ranges of initial and boundary conditions, anticipated processes and events, and unanticipated processes and events that may affect the disposal system. These conditions may vary in time and space. The measure of system performance with respect to the containment requirements is the integrated releases of radioactivity to the accessible environment over 10,000 years following closure. A significant aspect of performance assessment is the consideration of the important sources of uncertainty and the propagation of these uncertainties, to the extent practicable, to the results of the analysis.

3.2 Steps in a Performance Assessment Analysis

A performance assessment analysis consists of five basic steps [Bonano et al., 1985, 1989a,b; Cranwell et al., 1987; Davis et al., 1990]. These are:

1. System Description,
2. Scenario Development and Screening,
3. Consequence Analysis,
4. Uncertainty Analysis, and
5. Sensitivity Analysis.

Each of these steps is briefly summarized below. The reader is directed to the references provided for more detailed discussions of each of these steps.

3.2.1 System Description

System description means the characteristics of the waste, engineered facility, and the host geologic formation. The characteristics of the waste include, among other things, the total metric tons of heavy metal from which the waste was generated, the initial radionuclide inventory, the decay chains, and the half-lives of the radionuclides. The characteristics of the facility refer to the size of the repository, thermal loading due to heat dissipated by the waste, emplacement of shafts and drifts, properties of engineered barriers, etc. The description of the host formation comprises the geology, hydrology, and geochemistry of the formations as well as other factors such as initial and boundary conditions.

In developing PAMs for NRC, SNL was chartered with examining the "far field," i.e., the portion of the host formation bounded by the disturbed zone and the accessible environment. Therefore, the SNL PAMs do not contain detailed models of the repository itself or the host formation in the immediate vicinity of the repository--the "near field" or disturbed zone. It was the NRC's intention to have contractors other than SNL develop models and computer codes appropriate for these portions of the disposal system that would fit into the SNL PAMs. In developing these PAMs, SNL emphasized the undisturbed characteristics of the host formation [e.g., see Guzoswki and Cranwell, 1983].

3.2.2 Scenario Selection and Screening

Because both NRC [1983] and EPA [1985] require that physically plausible events and processes that could affect the disposal system be considered in a performance assessment, SNL developed a methodology that provides a general road map for the development of scenarios [Cranwell et al., 1990]. The term "scenario" has been defined as a combination of events and processes representing a possible realization of the future state of the disposal system [Bonano and Cranwell, 1988; Cranwell et al., 1990].

It should be noted that neither 10 CFR Part 60 nor 40 CFR Part 191 explicitly uses the term "scenario." Nevertheless, "scenario" is a well-accepted term [e.g., see Bingham and Barr, 1979; DOE, 1988; Andersson and Eng, 1989; Hodgkinson and Summerling, 1989; Stephens and Goodwin, 1989] within the nuclear waste management technical community.

The SNL scenario methodology [Cranwell et al., 1990] provides a systematic approach for treating uncertainties associated with postulating the possible future state(s) that the disposal system could attain during the regulatory period (i.e., 10,000 years). It has been adopted, and customized as needed, in several national waste management programs [e.g., see Hodgkinson and Summerling, 1989; Andersson and Eng, 1989; Stephens and Goodwin, 1989]. This methodology has its critics as well [e.g., Thompson, 1988] because of the need to rely heavily on expert judgments. However, to date, the proposed alternative is the "environmental simulation" approach [Hodgkinson and Summerling, 1989], which relies equally on expert judgments. Procedures for the formal elicitation and use of expert judgments in the performance assessment of HLW repositories, including selection and screening of scenarios, have been outlined by Bonano et al. [1990].

The SNL scenario development and screening methodology consists of six main steps:

1. Identify events and processes.
2. Classify events and processes.
3. Screen events and processes.
4. Formulate scenarios.
5. Screen scenarios.
6. Arrive at final set of scenarios.

Details on what comprises each of these steps are provided by Cranwell et al. [1990].

Initial identification of events and processes must be done carefully to increase the likelihood that the list is exhaustive and potentially significant events and processes have not been inadvertently neglected. This refers to addressing "completeness" [Bonano and Cranwell, 1988].

The need to screen out events and processes arises because the initial list tends to be generic [e.g., see Cranwell et al., 1990]--although it does not have to be--and it needs to be shortened on a site-specific basis. For example, it is not expected that tsunamis will be important at the proposed Yucca Mountain repository site; hence, it seems unreasonable to retain tsunamis in a performance assessment for a repository at this site. There is no unique manner to screen out events and processes.

SNL has opted to use criteria based on physical reasonableness, likelihood of occurrence, and potential consequence. These criteria have been adopted by other national waste management programs [e.g., see NEA, 1989]. The critical issue associated with using these criteria is that there is a tendency to apply one criterion independent of the others; i.e., eliminate an event and/or process based on a relatively low likelihood of occurrence without considering its potential consequence. Much discussion on the proper approach to deal with these criteria has taken place within the technical community.

Typically, even after screening out events and processes, the number of scenarios that can be generated from the surviving events and processes is likely to be impractically large. It is recognized that the final set of scenarios to be analyzed should be reduced to a manageable but meaningful set from a regulatory point of view. Different approaches have been used to accomplish this. For example, in Sweden [Andersson and Eng, 1989] a base-case scenario called the "process system" has been used to include as many events and processes as possible; thus, leaving few events and processes from which to formulate alternative scenarios. The formulation of alternative scenarios is then conditioned using various factors so that the number of these scenarios is not very large.

SNL's approach to screen out scenarios is based on the same three general criteria discussed above for the screening of events and processes: physical reasonableness, likelihood of occurrence, and potential consequence. In addition, SNL has also advocated examining potential consequences as a means to identify scenarios that result in very similar consequences so that these scenarios can be combined to further reduce their number.

It should be noted that a basis has been provided in 40 CFR Part 191 to screen out those categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. When events and processes are screened out on this basis, it implies that scenarios that would have been generated from these events and processes would have had a likelihood of occurrence less than that of any of the individual events and processes. This means that a screening of the scenarios on the basis of the likelihood of occurrence of their constituent events and processes would be warranted. However, it is prudent to exercise care when screening a large number of scenarios, each with a very small likelihood of occurrence because it is possible that the cumulative likelihood of occurrence for these scenarios may not be insignificant insofar as the containment requirements are concerned. It is very important that the impact of screening such a group of scenarios on the complementary cumulative distribution function (ccdf) of total releases of radioactivity to the accessible environment called for in 40 CFR Part 191.13[4] be assessed in a preliminary performance assessment. If the cumulative likelihood of

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[4] The construction of the ccdf is discussed in Section 4.2. The reader is referred to that section for more details on the impact of scenario probabilities on the ccdf.

occurrence of this group of scenarios is not insignificant, then the only justification for eliminating these scenarios must be on the basis of low consequences.

3.2.3 Consequence Analysis

Scenario screening should eliminate many scenarios such that only a select number--those with a significant likelihood of occurrence and potentially significant consequences, based on preliminary analyses--remain for further consideration. The next step in the SNL PAMs is detailed consequence analyses for each of the surviving scenarios. At the overall repository-system level, the performance measure of interest is the integrated release of radioactivity to the accessible environment in 10,000 years following closure of the repository.

In a deep geologic HLW disposal system, many processes are expected to occur on a continuous basis. These include, but are not limited to, ground-water flow, heat transfer, rock-mass deformation, waste-container corrosion, and radionuclide decay. Other processes may be initiated upon the occurrence of certain events. Most notably, radionuclide transport will start following breach of containment (i.e., waste package failure). For each of the selected scenarios, the consequence analysis will typically consist of developing and implementing a conceptual model, a mathematical model (i.e., equations that mathematically describe the conceptual model), and one or more computer codes designed to implement the solution, either analytically or numerically, of the equations in the mathematical model. Appropriate data sets for the input parameters in the model will need to be defined in order to exercise the model and the associated code(s), and perform the consequence analysis.

Figure 1 presents the SNL PAMs schematically; the general structure of the methodology is generic irrespective of the host geologic formation. The consequence modeling component of the methodology can accommodate, in principle, capabilities to simulate the source term, ground-water flow, radionuclide transport in the geosphere, radionuclide transport in the biosphere, and dosimetry and health effects. These capabilities allow the assessment of compliance not only with the containment requirements in the Standard, but also the individual protection requirements and the ground-water protection requirements as well as the subsystem requirements in 10 CFR Part 60: waste-package lifetime, release rate from the engineered barrier system, and pre-waste emplacement ground-water travel time. SNL was charged with developing the aspects of the methodology that pertain only to the "far-field," i.e., the portion of the disposal system comprising the region between the edge of the so-called disturbed zone and the accessible environment. For this reason, the SNL PAMs do not include sophisticated models and associated codes for the source term or near field. Fairly simple source-term models are included in several of the transport codes developed, e.g., NEFTRAN [Longsine, et al., 1987].

The consequence modeling component of the methodologies is modular in nature. This provides several advantages. First, it allows ready modification of specific aspects of the methodologies without having to dismantle the entire methodology. As a matter of fact, since 1983 when the focus of SNL's HLW performance assessment

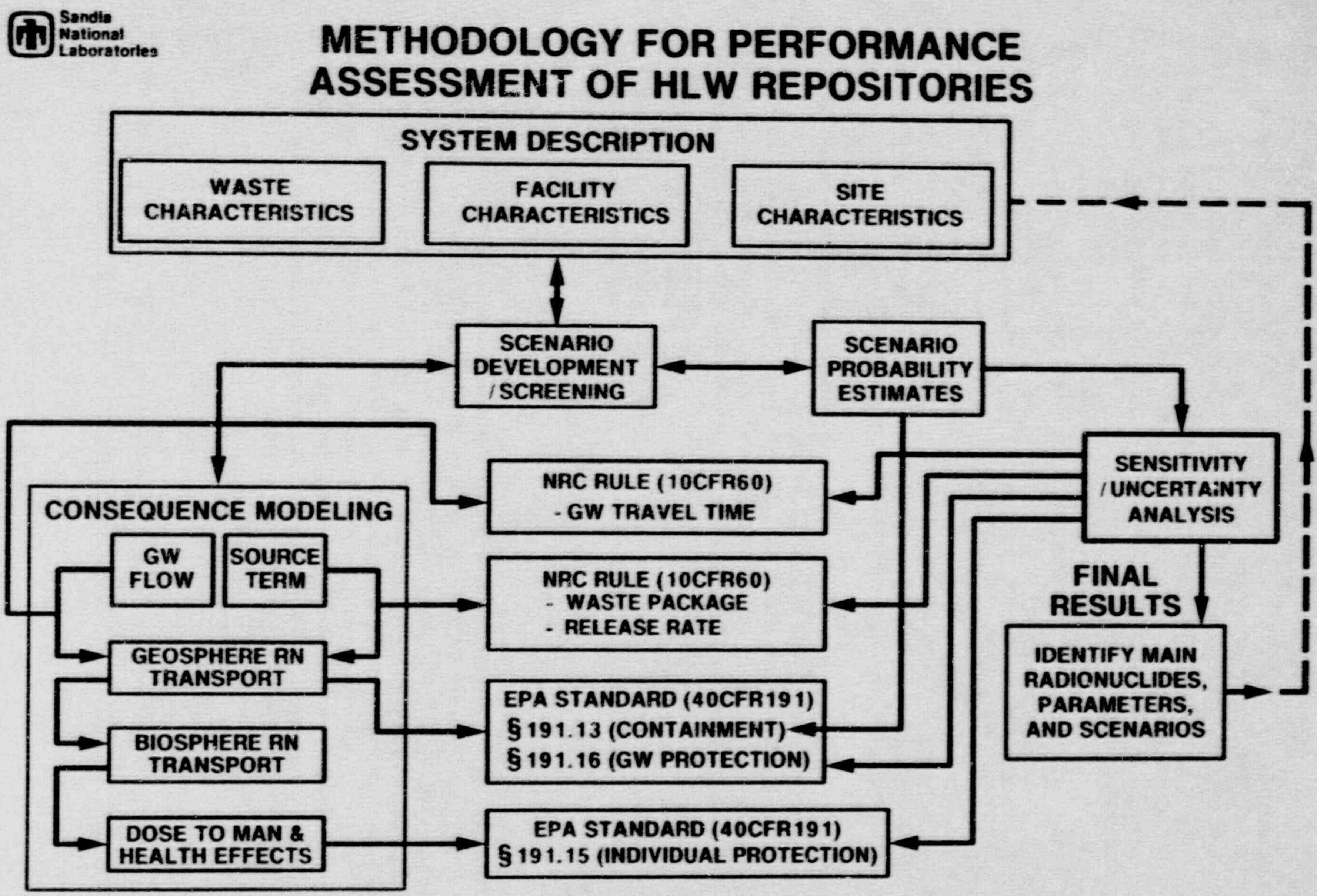

Figure 1. Flowchart for SNL Performance Assessment Methodology.

program for the NRC changed to modifying the original methodology (developed for bedded salt) to render it applicable to other geologic media, the major emphasis has been on replacing the computer codes for ground-water flow and radionuclide transport only [Bonano et al., 1989b]. Second, the modular structure provides the capability for using one or more of the codes for specific isolated analyses outside the integrated methodology. Third, it allows screening of scenarios based on intermediate results and allows assessing compliance with multiple regulatory requirements (e.g., subsystem requirements).

The flow of information in the consequence modeling component of the methodology is as follows. The output from the source term (discharge rate as a function of time) serves as inlet condition for the transport code. Independent of the source-term simulation, the ground-water flow, which provides a velocity field for the transport analysis, is predicted. The output of the geosphere transport simulation, either as integrated discharge or as discharge rate, can be used as input to the biosphere transport calculation. The output from the latter as radionuclide concentration provides the input for the estimation of dosimetry and health effects.

The set-up of the consequence modeling component just outlined is convenient, although it may not be correct in a strict mathematical sense. Transport equations are usually elliptic or parabolic partial differential equations (pde's). When the system is conceptually divided into several domains (e.g., source term, geosphere, and biosphere), the coupling of these pde's for two domains requires continuity of the potential (e.g, concentration) and the associated flux (e.g., contaminant flux) across the interface between domains. However, in practice, one can predict neither the potential nor the flux a priori; therefore, when simulating a system with two or more domains in series, it is customary to assume that only continuity of the potential needs to be satisfied.

3.2.4 Uncertainty Analysis

Because of the large temporal and spatial scales over which the performance of an HLW disposal system must be assessed, the impact of uncertainties on the results of an analysis to predict the system's behavior must be examined. Bonano and Cranwell [1988] discuss the different sources of uncertainties that must be considered in a performance assessment. Recently, Davis et al.[5] expanded the discussion of Bonano and Cranwell to include recent advances in uncertainty analysis and summarize work conducted by SNL for the NRC under Task 2 of FIN A1165, Technical Assistance for Performance Assessment. There are three major sources of uncertainty that must be considered in a performance assessment [Bonano and Cranwell, 1988]. These are (1) uncertainty in the future state of the disposal system, (2) model uncertainty, and

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[5] Davis, P. A., E. J. Bonano, K. K. Wahi, and L. L. Price, Uncertainties Associated with Performance Assessment of High-Level Radioactive Waste Repositories: A Summary Report, SAND88-2703, NUREG/CR-5211, Sandia National Laboratories, Albuquerque, NM, to be published.

(3) data and parameter uncertainty. To date, SNL has implemented approaches for considering uncertainties in the future state of the disposal system and the propagation of uncertainty in parameters through the suite of codes in the PAMs. Efforts to develop methods for considering model uncertainty in performance assessment have only recently begun.

SNL developed a scenario selection and screening methodology [Cranwell et al., 1990] which was briefly discussed in Section 3.2.2. Implementation of this methodology results in a set of scenarios representing possible realizations of the future state of the disposal system. As explained in Section 3.2.3 and discussed further in Chapter 4, each of these scenarios is simulated using the suite of models and associated computer codes in the PAMs.

The approach currently implemented in the PAMs for the propagation of parameter uncertainty to the results of the consequence analysis is Monte Carlo simulation. Uncertainty in the input parameters is described with a probability distribution function, Latin hypercube sampling is used to generate multiple vectors of input parameter values, and a consequence analysis calculation is performed for each of the vectors. This procedure results in multiple values of the performance measure of interest. These values are then used to express the uncertainty in results. In recent years other approaches have been proposed for considering the uncertainty in parameters. Although SNL has not incorporated these approaches into the PAMs, the approaches have been examined. Zimmerman et al. [1990] present available approaches and techniques, and discuss their applications, advantages, and disadvantages.

3.2.5 Sensitivity Analysis

Although neither 40 CFR Part 191 nor 10 CFR Part 60 requires that sensitivity analysis be part of a performance assessment, SNL has included the capabilities of carrying out a sensitivity analysis in the PAMs. This capability was included because of SNL's belief that performance assessment should be an iterative process providing feedback during site characterization. This feedback should identify the most important contributors to the uncertainty in the prediction of the performance measure of interest (in this report, total integrated discharge in 10,000 years to the accessible environment).

The approach in the PAMs uses the results of the Monte Carlo simulation as the basis for a regression analysis. The regression analysis estimates the values of the coefficients in a regression expression. The relative importance of the uncertain parameters can then be established by examining the magnitude of these coefficients. Examples of the application of this approach in the demonstration of the bedded salt and basalt PAMs are given by Cranwell et al. [1987] and Bonano et al. [1989a], respectively.

Other approaches and/or techniques for sensitivity analysis have been published in the literature; Zimmerman et al. [1990] discusses these in details.

It should be noted that the approach used by SNL as well as others discussed by Zimmerman et al. [1990] only allow examination of the relative importance of uncertain parameters. As pointed out by Carrera and Samper [1989], uncertainty in parameters is far less important than uncertainty in assumptions regarding the conceptual model of the disposal system; SNL's experience seems to support this assertion. Therefore, a major drawback of the available approaches for sensitivity analysis, including that used by SNL, is their inability to address the importance of uncertainty in assumptions in conceptual models. It is clear that the need exists to develop sensitivity analysis techniques that will permit the elucidation of the relative importance of assumptions in conceptual models.

3.3 Use of PAMs in Regulatory Process

Cranwell et al., [1987] and Bonano et al. [1989a] have demonstrated that the PAMs can be used to assess compliance with the regulatory requirements in both 40 CFR Part 191 and 10 CFR Part 60 pertaining to the postclosure phase of HLW disposal. Several aspects of the PAMs, mainly those in the consequence modeling component, have been used to assist in the development of the containment requirements in the Standard as well as to examine the impact that the requirements in 10 CFR Part 60 could have on the requirements in the Standard. In addition, some of the models and associated computer codes in the PAMs have been used to assist in the development of technical rationale for technical position papers prepared by NRC.

In Chapter 4 the use of the PAMs in the regulatory process is discussed in more detail with emphasis on the construction of the ccdf of total releases of radioactivity to the accessible environment in 10,000 years.

4.0 USE OF PERFORMANCE ASSESSMENTS IN REGULATORY COMPLIANCE

In its definition of performance assessment, cited in the introduction to Chapter 3, the EPA explicitly states that uncertainties must be considered when estimating the cumulative releases of radioactivity to the accessible environment. Therefore, an important aspect of a performance assessment is the implementation of procedures to account for these uncertainties and, to the extent practicable, reduce their impact on the results of the assessment. This does not necessarily mean that all potential sources must be quantified, and hence, factored in the construction of the ccdf of releases to the accessible environment. As a matter of fact, there are some sources of uncertainty that are not quantifiable and, as a result, cannot be built into the ccdf. Nonetheless, this does not mean that they can be ignored in a performance assessment.

4.1 Sources of Uncertainty

Bonano and Cranwell [1988] point out that the major sources of uncertainty in a performance assessment are (1) uncertainty in the future state of the disposal system, (2) uncertainty in the development and application of models, and (3) uncertainty in the data and parameters. Below issues associated with each of these sources of uncertainty are briefly discussed. The reader is reminded that, in addition to the paper by Bonano and Cranwell [1988], Davis et al. (see footnote number 5) also present an extended discussion on these issues.

4.1.1 Uncertainty in Future State of the Disposal System

In reality, there is only one future state that the disposal system can attain during the regulatory period, i.e, 10,000 years. However, the inability to predict this state with any degree of confidence introduces uncertainty in the assessment of the long-term behavior of the disposal system. The most widely used approach to address this uncertainty is the formulation of scenarios representing, in principle, multiple possible realizations of the future state of the system. Care must be exercised when formulating scenarios to avoid problems such as (1) possible lack of completeness in identifying the processes and events that comprise a scenario, (2) possible lack of precision in the estimated probability of the occurrence of processes and events, and (3) difficulty in setting and applying screening criteria [Bonano and Cranwell, 1988]. Another potential difficulty is that associated with the neglect of the temporal correlation of the events and processes and their time of onset.

There is no unequivocal way of ascertaining that these potential difficulties have been adequately addressed. However, a systematic approach such as that described by Cranwell et al. [1990] for developing and screening scenarios provides an appropriate road map for minimizing the impact of the pitfalls that can be encountered when formulating scenarios. The scenario methodology developed by SNL was described earlier in Section 3.2.2 and shall not be repeated here. It is clear that this methodology relies on expert judgments and Bonano et al. [1990] provide some insights regarding the formal elicitation and use of these judgments.

Formalization of the expert judgments increases the likelihood that (1) the issue of completeness is adequately addressed; (2) the screening criteria for events and processes as well as scenarios are meaningfully developed and applied; and (3) all available information is used to estimate the probability of occurrence of events and processes as well as scenarios.

The consideration of the time-dependent correlation of events and processes is one that is gaining some popularity. In principle, the SNL scenario methodology is able to accommodate this correlation. Cranwell et al. [1990] demonstrate the mathematical procedure for incorporating this correlation in the analysis when assessing compliance with the containment requirements in the Standard. It should be noted that implementation of that procedure in practice relies on the availability of models that adequately simulate the attendant events and processes and, more importantly, their couplings. The "environmental simulation" approach [see e.g., Hodgkinson and Summerling, 1989] seeks to develop such models. Many believe that as the state of the art advances in developing these models, the scenario approach and the environmental simulation approach will become one and the same.[6]

One of the most difficult tasks is the estimation of probability of occurrence for events and processes and the subsequent combination of these probabilities to arrive at the probability of a scenario. Hunter and Mann [1989] present a literature review of available techniques for determining the probability of events and processes. Recently, Apostolakis et al.[7] suggested approaches for estimating these probabilities and presented some examples for faulting, climate change, and human intrusion. These authors demonstrated the manner in which historical data, modeling results, and expert judgments can be used to update prior probabilities using Bayesian theory. However, it is clear that limited information and the need to forecast so far into the future will make the estimation of probabilities a formidable task. It is also obvious that much work remains to be done in order to be able to make such estimates with an acceptable degree of confidence.

4.1.2 Uncertainty in Models

Development and application of models is an integral part of performance assessment. Because models are by definition simplifications of a real system, there is inherent uncertainty associated with their use in any analysis. Although the terminology may vary some, most investigators in the waste-management community

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[6] Campbell, J. E., Private Communication to E. J. Bonano, Sandia National Laboratories, Albuquerque, NM.

[7] Apostolakis, G. E., R. L. Bras, L. L. Price, J. Valdes, and K. K. Wahi, Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories: Volume II - Suggested Approaches, SAND86-0196,NUREG/CR-3964, Vol. 2, Sandia National Laboratories, Albuquerque, NM, to be published.

accept that a model consists of three essential components: a conceptual model, a mathematical model, and the associated computer code. Uncertainty in models arises from uncertainties in the formulation of a conceptual model of the system (or subsystem) for a given scenario, in the construction of the mathematical model that represents the conceptual model, and in the implementation of the solution of the mathematical model, typically in a computer code. Of all available approaches for reducing model uncertainty, model validation is the most important approach.

Conceptual Model Uncertainty. A conceptual model describes all the assumptions about the real system. These assumptions include, but are not necessarily limited to, the processes taking place, the parameters that describe these processes, the initial and boundary conditions, and the scale of the spatial and temporal domains. The uncertainty in the conceptual models arises from two sources. First, the development of the conceptual model involves simplifications to permit the representation of the system with a tractable mathematical model that, in turn, can be solved using available analytical and/or numerical techniques. This is required because a performance assessment must yield quantitative results. Second, poor characterization of the real system may cause misinterpretation of the system's behavior. At present, there is no procedure that can lead to the quantification of the uncertainty in conceptual models. It is recognized that expert judgment will play a major role in the development of conceptual models [Bonano and Cranwell, 1988; Bonano et al. 1990, Davis et al. (see footnote number 5)]. A methodology that forces experts, in a formal manner, to examine all available information (both soft and hard information), articulate all assumptions, and develop alternative conceptualizations consistent with the given information may provide a tool for considering uncertainty in conceptual model.

Mathematical Model Uncertainty. Uncertainty in mathematical models arises from the solution of the equations (algebraic, differential, integral, and/or a combination of these) using analytical, semianalytical, or numerical techniques. For the most part, the mathematical models needed in performance assessment are too complicated to only allow numerical solutions typically implemented in a computer code. Uncertainty in numerical solutions arise from incompatibility of the numerical discretization with the actual equations, and instability and poor convergence of the solution method. Even in the case of relatively simple models that allow an analytical solution, uncertainty arises from the evaluation of some function (e.g., trigonometric functions, Bessel functions, exponential, etc.) by approximating an infinite series with a finite number of terms in the series. This approximation introduces errors due to poor convergence after a certain number of terms and/or machine round-off if the solution is implemented in a computer code. Quantifying the uncertainty in mathematical models is not possible at the present time.

Testing the compatibility (or consistency, as used by some numerical analysts) of the numerical algorithm with the actual equations in the mathematical model is often taken for granted. However, caution must be exercised to ensure that the numerical equations are compatible with the true model equations [Carnahan et al., 1969]. These authors present examples of compatibility tests for finite-difference methods used to solve pde's. The tests basicly examine the behavior of the truncation error as the time and space increments approach zero. They show that in some cases the truncation error approached zero and the original pde was recovered, while in other cases, this error became a constant non-zero value and a pde different from the original one was obtained. Zienkiewicz [1977] discusses tests for examining the compatibility of numerical solutions of pde's using the finite-element method, with the original pde's.

Carnahan et al. [1969] also discuss conditions for testing the convergence of the numerical solution of pde's using finite differences. Simply, the tests consist of defining the "numerical error" as the difference between the "true" solution and the numerical solution. However, in practice one does not know the true solution; otherwise, why obtain a numerical solution? If one assumes that the "true" solution exists and that this solution has enough partial derivatives, then this solution can be expanded using a Taylor series. The finite-difference equation is then subtracted from the Taylor series expansion for the "true" solution to obtain an equation for the numerical error. The convergence test consists of examining the behavior of the numerical error as the size of the time and space increments approach zero. If the numerical error approaches zero as well, then the numerical solution is said to be convergent. It should be noted that since numerical solutions are typically implemented in a computer code, the value of the numerical error, in practice, never becomes exactly zero because of computer round-off error.

Related to the convergence of a numerical solution is the "stability" of that solution. Carnahan et al. [1969] state that, if a compatibility criterion has been satisfied for a linear pde, stability is a necessary and sufficient condition for convergence. Stability refers to the existence of an upper bound such that any piece of information in the numerical solution will not exceed this bound as the time increment approaches zero [Carnahan et al., 1969]. This information can be brought into the solution through the initial conditions, boundary conditions, or error in the implementation of the numerical method. Carnahan et al. present a brief treatment of the stability of finite-difference methods, and the reader is referred to their book for details.

It should be noted that most of the explicit tests in the literature for compatibility, convergence, and stability of numerical solutions are demonstrated using fairly simple pde's. Whether or not these tests can be applied to more complex pde's or systems of pde's, such as those typically solved in simulating the behavior of HLW disposal sites, is not known. One approach to gain confidence in the quality of the numerical solutions for mathematical models used in the analysis of HLW disposal is code verification.

Computer Code Uncertainty. Uncertainty in computer codes comes from possible coding errors, computational limitations, and user errors. Like the uncertainty in mathematical models, uncertainty in computer codes cannot be quantified. Strict quality assurance procedures and benchmarking are two mechanisms for reducing the uncertainty in computer codes.

Model Validation. Model validation is the most important way of reducing model uncertainty (conceptual model, mathematical model, and computer code). In principle, this involves the comparison of the model predictions to observations in the real system. However, because of the spatial and temporal scales in a HLW disposal system, validation, in the strictest sense of the word, cannot be accomplished. In practice, one must rely on a synthesis of laboratory experiments, controlled field experiments, and natural analogs to gain confidence in the predictive ability of the models [Bonano and Cranwell, 1988; Davis et al., (see footnote number 5)]. Davis and Goodrich[8] have submitted that one can never unequivocally assert that a given model is "valid," but rather, that the model is "not invalid." Hence, model validation seeks to disqualify models that are not consistent with available information rather than to ascertain the validity of models.

4.1.3 Uncertainty in Data and Parameters

The term "data" refers to directly measured quantities whereas the term "parameter" denotes a quantity derived from data. Uncertainty in data results from limited accuracy and precision in making measurements. The limited accuracy and precision can be the result of instrument errors as well as human errors. Uncertainty in parameters, which incorporates data uncertainty, can be caused by the use of incomplete and/or biased data as well as misinterpretation of data. Davis et al. (see footnote number 5) also introduce the term "coefficient" to denote proportionality constants in models; e.g., the hydraulic conductivity in ground-water flow models is an example of a coefficient. Here, the definition of parameter also includes coefficients. Uncertainty in model parameters arises primarily from the use of a model to infer the numerical value of these parameters from data. This uncertainty is a combination of uncertainty in the data and the uncertainty in the model used to analyze the data and estimate the value of the model parameter(s).

Of all the major sources of uncertainty, the treatment of uncertainty in data and parameters has received the most attention. Perhaps this is a reflection of the fact that this type of uncertainty can be quantified and its effect propagated to the results of a performance assessment. Zimmerman et al. [1990] have reviewed the techniques available to propagate uncertainty in data and parameters through a suite of models. They discussed advantages and disadvantages of these techniques and their recommended uses.

By and large, most methods for propagating the uncertainty in data and parameters through a suite of models require that the uncertainty be quantified in the form of a pdf. These pdf's should be derived, to the extent possible, from existing data. However, because of paucity of data, the pdf's are typically derived using heuristic arguments. In some cases it has been demonstrated that the uncertainty in hydraulic conductivity can be described with a lognormal pdf. Therefore, it is customary to assume that a lognormal pdf can be used when insufficient evidence exists.

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[8] Davis, P. A., and M. T. Goodrich, Guidelines to NRC for Judging the Validity of Models for Performance Assessment of HLW Repositories, SAND90-0575, NUREG/CR-5537, Sandia National Laboratories, Albuquerque, NM, to be published.

There are two main ways of reducing the uncertainty in data and parameters. One way is to simply obtain more measurements to infer values of the parameters. The other way seeks to obtain other types of information that could be used to learn more about the parameter. Examples of other types of useful information include (1) "soft data", (2) cross-correlation between two parameters, and (3) autocorrelation for a single parameter [Davis et al.,see footnote number 5.

4.2 Generation of CCDF with Monte Carlo Simulation

The guidance for implementation of Subpart B of the Standard is provided in Appendix B of the regulation. In particular, a brief discussion on compliance with Section 191.13 states the EPA's assumption that "....whenever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with 191.13 into a 'complementary cumulative distribution function' that indicates the probability of exceeding various levels of cumulative release" [EPA, 1985]. The standard does not advocate any particular method or approach to construct this ccdf. A mathematical definition of ccdf and a method for its generation, for the case when Monte Carlo simulations have been used in the performance assessment analyses, are presented next. The material in the remainder of this section is derived largely from the report by Hunter et al. [1986], including many of the illustrations.

For a given value x of a random variable X, the cumulative distribution function (cdf) of X at x is the function that estimates the probability of X being less than or equal to x; the notation $P(X \leq x)$ is used here to indicate this probability. As shown in Figure 2, the cdf is an accumulation of probabilities of values of X less than or equal to x [Hoel et al., 1971; Hunter et al., 1986]. When a finite number of simulations are carried out (as in Monte Carlo simulation) the curve in Figure 2 becomes a series of discrete steps instead of being continuous. In any event, a ccdf is simply the complementary function of a cdf; that is, $P(X>x) = 1 - P(X \leq x)$ (see Figure 3).

Suppose that as a result of scenario development and screening, K scenarios have been retained for further analysis that includes both consequence modeling and uncertainty analysis. Based on the repository design and available data, ranges and distributions are assigned to the uncertain parameters required as input for the models resulting in a pdf for each of these parameters. The pdf's are sampled statistically (e.g., using Latin Hypercube sampling, simple random sampling, or importance sampling) to generate sets of different values of the uncertain input parameters that are often referred to as "input vectors." Multiple input vectors would be necessary for each scenario when using Monte Carlo simulation.

Assume that m sets of input vectors are obtained by sampling and that, for each scenario, m simulations are performed. The same set of m input vectors should be used for all scenarios. This would provide assurance that any variation in results among the scenarios is due to scenario differences and not due to sampling. Of course, the m sets of results for a given scenario are expected to be different for each input vector.

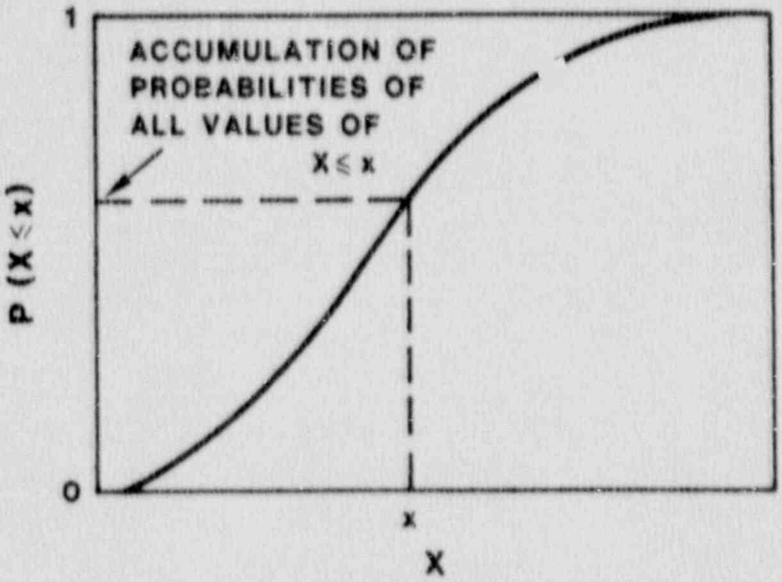

Figure 2. Example of Cumulative Distribution Function.

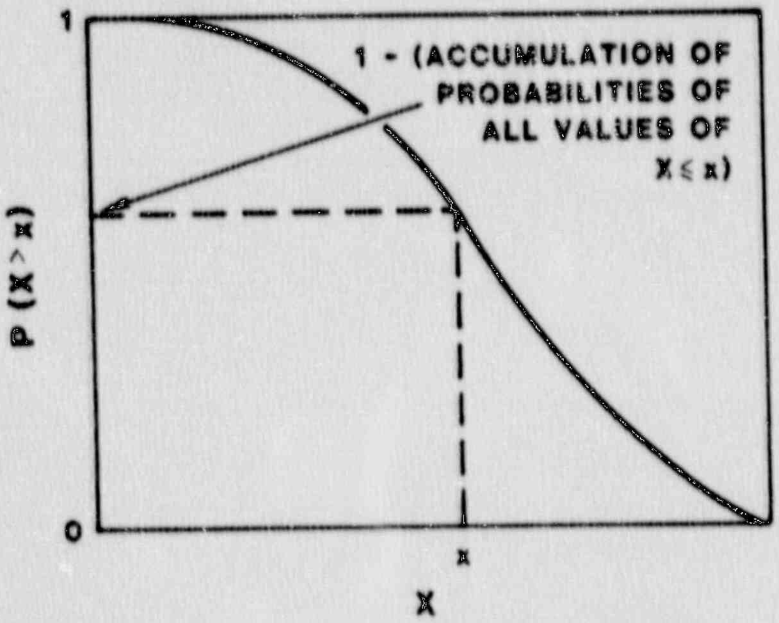

Figure 3. Example of Complementary Cumulative Distribution Function.

4.2.1 Construction of CCDF for a Single Scenario

The reader should not interpret the discussion that follows as advocating that a single scenario is necessarily sufficient to demonstrate compliance with the containment requirements in the Standard. Rather, the material is presented here for two reasons. First, once one understands the construction of the ccdf for a single scenario, it is a straightforward extension to construct the ccdf for multiple scenarios, as shown in Section 4.2.2. Second, and perhaps more importantly, a ccdf for a single scenario may be an useful tool for examining the sensitivity of the results of the performance assessment to given processes and assumptions in the models. Bonano et al. [1989a] provide an example of the use of the ccdf based on a single scenario to examine the effect of matrix diffusion on total releases.

Let us say that the base-case scenario (i.e., no disruptive events) for a disposal system can be represented by a sequence of three models: source-term model (Model A), a near-field flow and transport model (Model B), and a far-field flow and transport model (Model C). Output of Model A becomes a part of the input to Model B, the output of Model B becomes a part of the input to Model C, and the output of Model C is the cumulative releases of radioactivity to the accessible environment. This is illustrated in Figure 4. This modeling approach does not insure the conservation of fluxes and potentials across the interface between models (see discussion in Section 3.2.3). However, it is convenient and it is believed to be a reasonable approximation when estimating cumulative releases.

If there are p input parameters for Model A, q additional parameters for Model B, and r additional parameters for Model C, then the sampling of m input vectors may be represented by the diagram in Figure 5; note that $(p + q + r) = s$. Assume that there are N different, and potentially significant, radionuclides that can be released. The cumulative releases $Q_1, Q_2, \ldots, Q_N$ for the j^{th} input vector ($j = 1,2,\ldots,m$) are divided by the appropriate release limits from Table 1 in Appendix A of the Standard (also included in this report as Table 2.1), RL ($\ell = 1,2,\ldots N$), and summed as follows:

$$R_j = \frac{Q_1^j}{RL_1} + \frac{Q_2^j}{RL_2} + \ldots\ldots + \frac{Q_N^j}{RL_N} \qquad (1)$$

where R_j is a normalized release sum for the j^{th} input vector. There are m such terms for the m input vectors; namely, $R_1, R_2, \ldots, R_m$.

A ccdf can be generated using the m values of R_j as follows. Arrange the R_j's in a descending order of magnitude; that is, $R_{max}, \ldots, R_{min}$. Plot these values on a graph of P (probability of Rel being greater than R) versus Rel (EPA release sums). The first point would have the coordinates $[R_{max}, 1/m]$, the next point would be the second highest value of R_j along the abscissa and $2/m$ along the ordinate, and so on. The last data point on this step-like curve (with m steps) would be $[R_{min}, 1]$. Now the two-step limiting function of the EPA standard can be superimposed on the ccdf as shown in Figure 6.

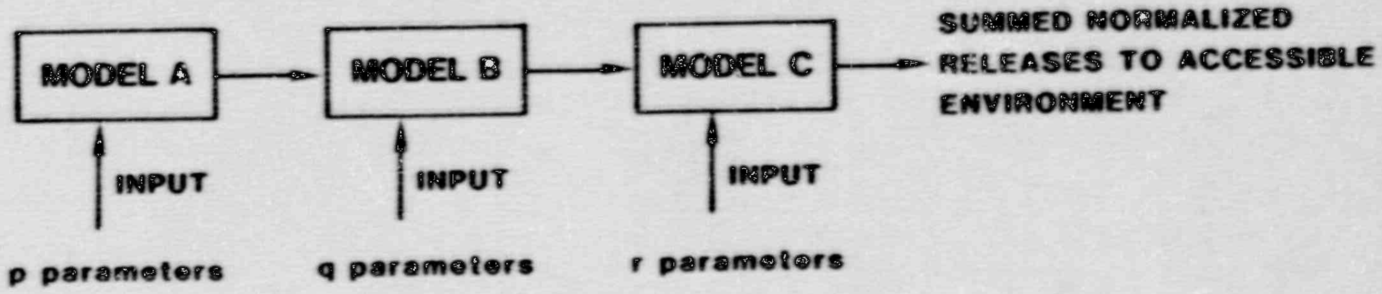

Figure 4. Example of Sequence of Models used in a Consequence Analysis.

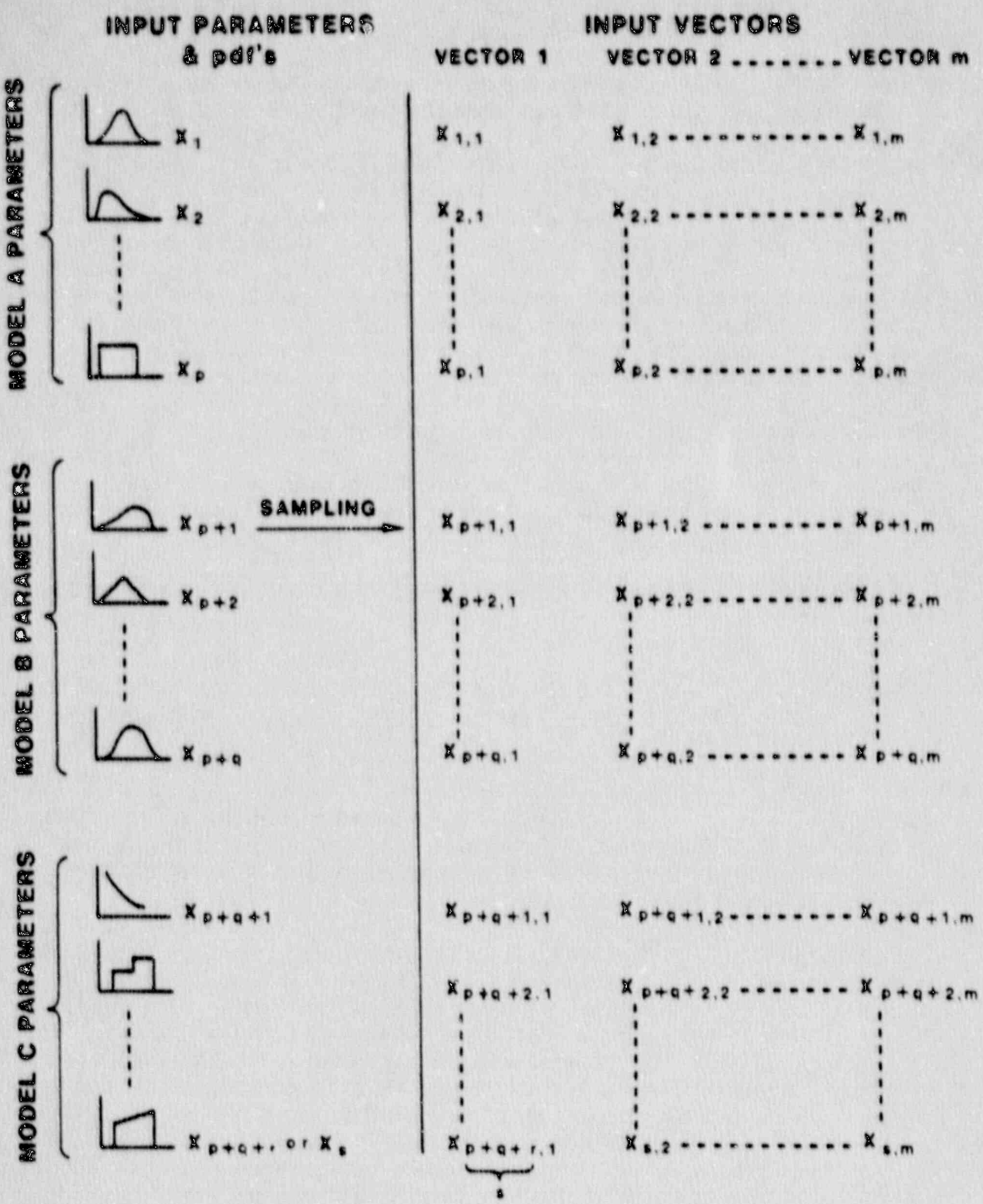

Figure 5. Example of Statistical Sampling Approach used in Monte Carlo Simulation.

4.2.2 Construction of CCDF for Multiple Scenarios

All of the discussion in Section 4.2.1 applies to the case of multiple scenarios, except for the last part that deals with the generation of the ccdf.

Let us say that a total of K scenarios are analyzed (a base-case scenario and K - 1 disruptive scenarios). Typically [see Cranwell et al., 1987; Bonano et al., 1989a], scenarios other than the base-case scenario have been treated as perturbations to the former. The simulation of these additional scenarios usually requires parameters in addition to those in the base-case scenario. These additional parameters are combined with those for the base-case scenario and this total number of parameters is statistically sampled to generate m input vectors. It should be noted that, in this case, the total number of input vectors, m, is larger than the number of input vectors needed for the base-case scenario only (also denoted by m in Section 4.2.1).

A total of m simulations are performed for each scenario resulting in m x K values of the total releases of radioactivity to the accessible environment. The estimates of releases for a given simulation are summed according to Equation (1), resulting in m x K terms of summed normalized releases. These releases and the associated scenario probabilities are used to generate a ccdf as described below.

The probability of exceeding R needed to construct the ccdf can be represented mathematically as

$$P\,(\mathrm{Rel} > R) = \sum_{i=1}^{K} P\,(\mathrm{Rel} > R|S_i)\; P(S_i) \tag{2}$$

where $P(\mathrm{Rel} > R)$ is the probability that the summed normalized release will be greater than R; $P(\mathrm{Rel} > R|S_i)$ the conditional probability that the summed normalized release will be greater than R, given scenario S_i; and $P(S_i)$ the probability of scenario S_i occurring over 10,000 years.

The quantity $P(\mathrm{Rel} > R|S_i)$ represents the probability of the summed normalized release exceeding R for a single scenario, S_i. One way to visualize the ccdf for the multiple-scenarios case is to think of the probability of exceeding R as weighted by the probability of occurrence of individual scenarios at various values of R. Alternatively, it is the ccdf of total releases of radioactivity to the accessible environment regardless of scenario. The probabilities of the scenarios should sum to one. A ccdf constructed using the latter concept contains m x K discrete steps. The height of each step (the incremental probability) is $P(S_i)/m$, where $P(S_i)$ is the probability of the scenario producing the particular summed normalized release on the abscissa corresponding to the step in the curve. This assumes that values of R are not repeated. In theory, it is possible that values of R are repeated. In this case, the height of the step in the ccdf corresponding to a repeated value of R is the sum of the probability for each of the simulations resulting in the given value of R.

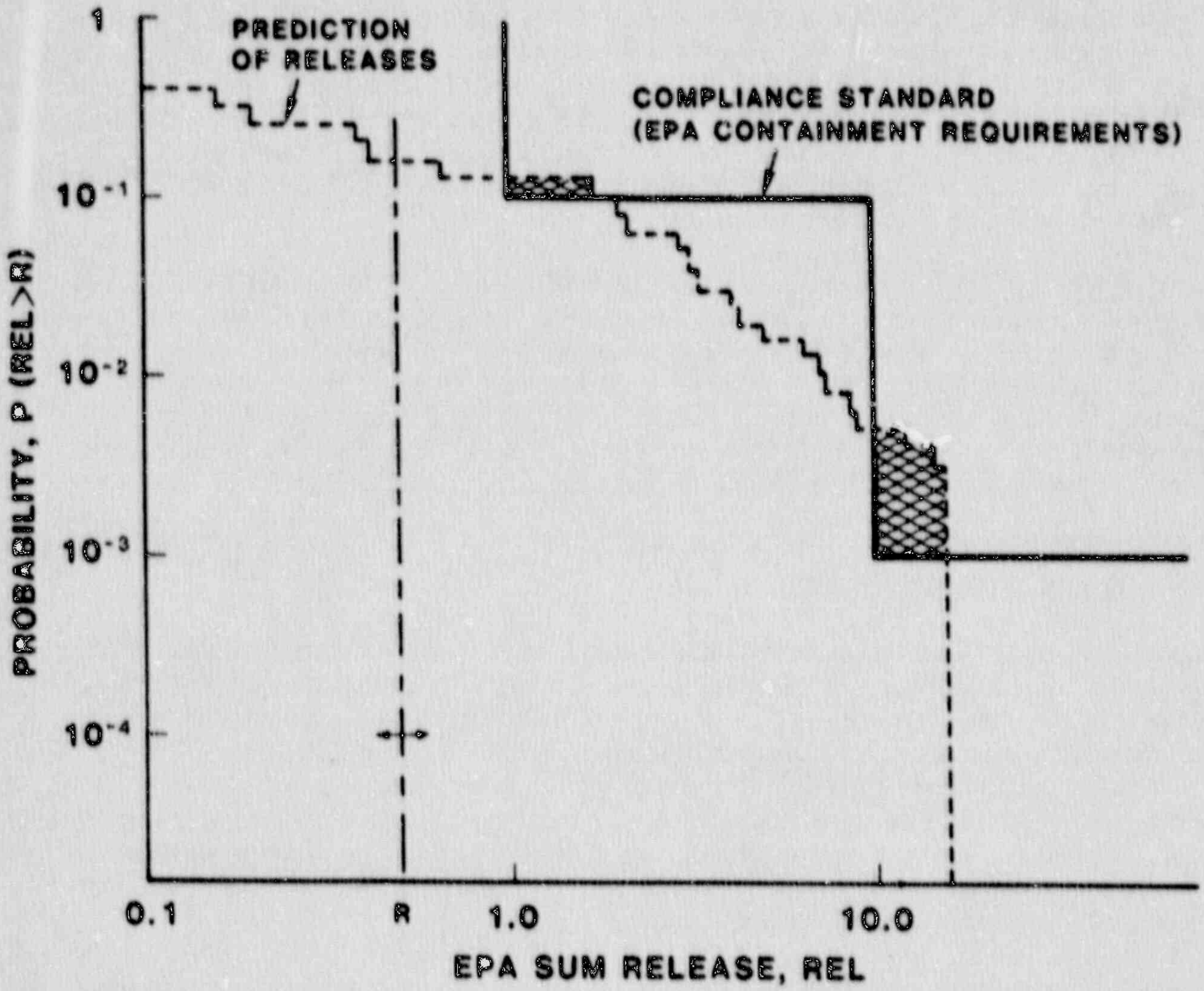

Figure 6. Example of Comparison Between Ccdf for Total Releases to Accessible Environment in 10,000 years and the Standard.

5.0 EXAMPLES OF PERFORMANCE ASSESSMENT

Application of the techniques, steps, and procedures presented in earlier chapters is illustrated with two examples. Both examples are based on demonstrations of SNL's PAM for HLW disposal at two different hypothetical sites [Cranwell et al. 1987; Bonano et al., 1989a]. In these two examples, the application of the SNL scenario development methodology considered "undetected features" of the disposal site along with events and processes in the generation of scenarios. Since then, much debate regarding the appropriateness of including undetected features in scenario development has taken place. NRC has opted to handle undetected features using the provisions in 10 CFR Part 60.122(a)(2). In a recent, revised publication of the SNL scenario-development methodology [Cranwell et al., 1990], consideration of undetected features has been eliminated.

In 1987, the US Congress amended the NWPA of 1982 by making the Yucca Mountain site in the State of Nevada the only proposed site for an HLW repository. Currently, SNL is completing a modification of the PAM to render it applicable to unsaturated, fractured rock formations such as those found at the Yucca Mountain site. Demonstration of this latter version of the PAM has not been accomplished. Nonetheless, the SNL PAM is sufficiently generic in structure that its application can be demonstrated with examples that do not necessarily apply to the Yucca Mountain site.

5.1 Hypothetical Bedded Salt Site

This example is based entirely on the work reported by Cranwell et al. [1987] concerning the analysis of a HLW repository in a hypothetical bedded-salt formation. A large number of repository-breaching events and several radionuclide-transport mechanisms were examined, and scenarios postulated. A representative set of twelve scenarios was selected for site analysis by implementing the scenario-development methodology [Cranwell et al., 1990]. The methodology considered physical reasonableness of the scenario, probability of scenario occurrence, different types of consequences (including cumulative releases to the accessible environment), and health risk to individuals or a population.

Three-dimensional hydrologic analyses of the site indicated that a two-dimensional representation of the flow system was adequate. The SWIFT computer code [Reeves and Cranwell, 1981] was used to establish the regional flow characteristics such as hydraulic heads and velocity field. The results of the analyses with SWIFT provided the boundary conditions for a local-scale flow model as well as justification to use a network flow and transport model with one-dimensional segments. A total of thirty-three input parameters were considered uncertain; twenty-seven of these were common to all scenarios, and up to six additional parameters were scenario specific. Ranges and distributions (lognormal, normal, uniform, etc.) were assigned to distribution coefficients (K_d's) for twelve elements, solubility limits for nine elements, hydraulic conductivity and porosity for upper and lower aquifers, dispersivity, and duration of waste-form leaching. Input vectors were generated using LHS [McKay et al., 1979]. A sample size of 35 was used for consequence and uncertainty modeling, and a sample size of 105 was used to perform sensitivity analyses for three of the twelve scenarios.

The consequence modeling included, but was not restricted to, predictions of integrated discharges (or cumulative releases) to the accessible environment over 10,000 years. Biosphere transport and health effects calculations were also performed; however, these are not considered necessary for assessing compliance with the containment requirements. Modeling related to cumulative release predictions included primarily flow and transport calculations. However, transient thermal response, structural response, and waste/host-rock interaction calculations were also performed to quantify the time-dependent source at the engineered boundary and to obtain other scenario-specific data.

A ccdf was generated based on the calculated consequences from each of the twelve scenarios analyzed. The procedure described in Section 4.2.2 was used to generate the ccdf. Specifically, for each simulation, the cumulative releases for the 26 isotopes included in the analysis were divided by the appropriate release limits and summed according to Equation (1). A total of 420 sums of normalized releases corresponding to the product of number of input vectors and the number of scenarios was obtained. These sums were arranged according to decreasing magnitude, and plotted by pairing with a cumulative probability value in accordance with Equation (2). The resulting ccdf is shown in Figure 7. Note that very low values of the EPA sum ($<10^{-6}$) and of cumulative relative frequency, P(Rel > R), have been omitted from the log-log plot. The EPA limits are shown in dashed lines.

5.2 Hypothetical Basalt Site

This example is based on a study that demonstrates SNL's PAM for HLW disposal in basalt formations. Only the highlights of the study will be presented here, and the reader is referred to the report by Bonano et al. [1989a] for complete details. The methodology used is an extension of the methodology applicable to bedded salt [Cranwell et al., 1987], which was the subject of the previous example. The differences between the two methodologies relate primarily to the difference between the properties of the geologic media. These differences dictated that many of the consequence models and associated computer codes also be different from those utilized in the previous methodology. Because the basic structure and many of the techniques of the bedded salt PAM were retained in the basalt PAM, the analysis performed by Bonano et al. [1989a] focused on demonstrating the modeling capabilities in the latter and not on all aspects of the PAM.

A reference site, in which basalt sequences are present, was selected in the Columbia Intermontane Province in the northwestern United States. Flow and transport through fractured media were considered in addition to porous media flow and transport. A total of 318 credible scenarios were postulated [Hunter, 1983], of which the following seven were selected for analysis:

1. Thermohydrological effects due to heat released by the waste;

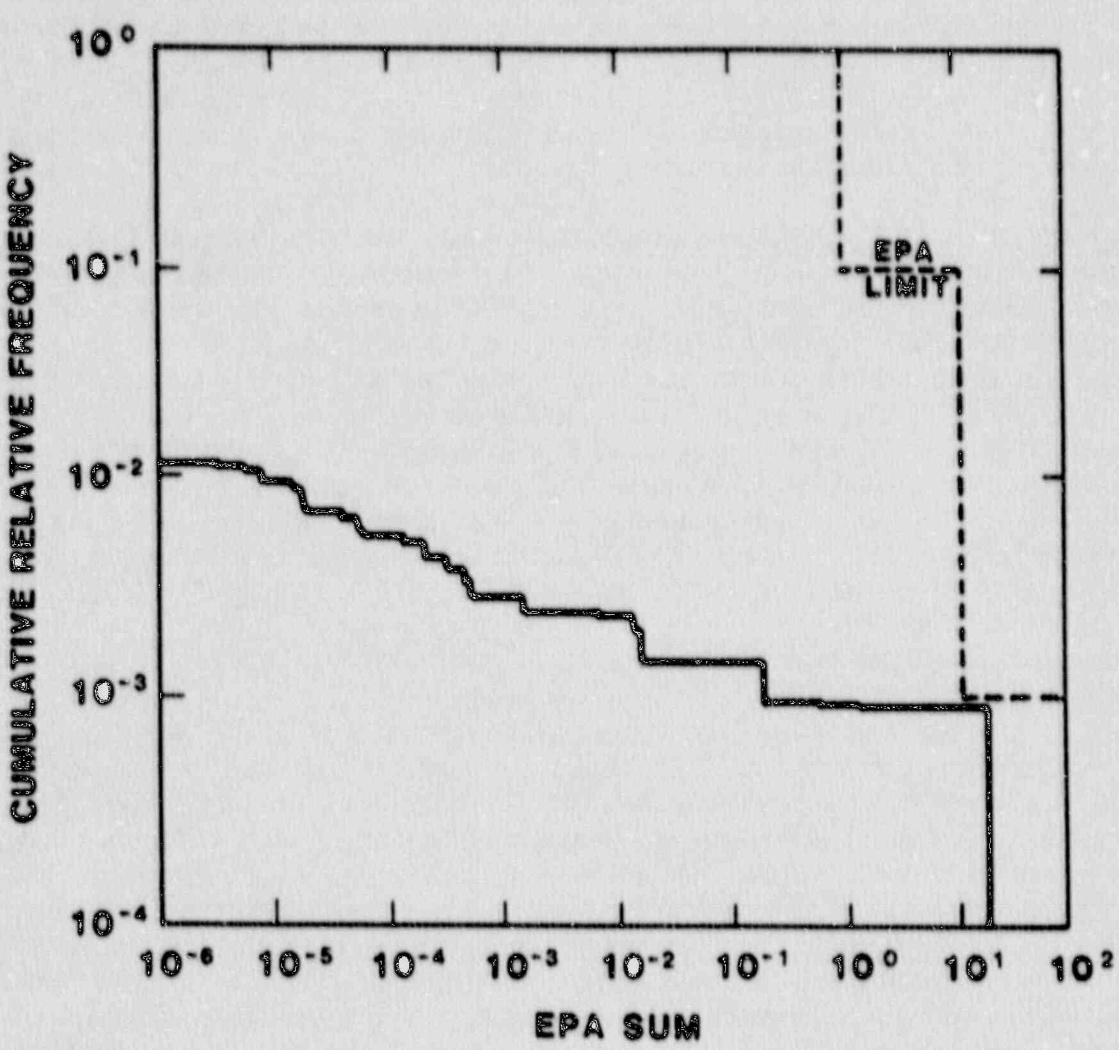

Figure 7. Composite Ccdf for Twelve Scenarios for Hypothetical Repository in Bedded-Salt [from Cranwell et al., 1987].

2. Mechanical-loading effects due to the advance and retreat of a glacier;
3. Pre-waste emplacement ground-water flow;
4. Pumping of ground water for irrigation;
5. Change in the river channel;
6. Drilling of a borehole through the repository; and
7. Creation of a new fault intersecting the repository.

Scenario screening, by way of preliminary analysis, was performed on the first two scenarios. This was done to determine whether it was necessary to consider the unique effects associated with the first two scenarios in the other five scenarios. It was established that, in the context of releases in 10,000 years, alterations to the flow field due to heat released from the waste would not be significant. As a result, heat transfer was ignored in the other scenarios. Likewise, the stress-strain response of the rock mass due to a variable external load (simulating a moving glacier) indicated permeability changes that were relatively insignificant. Therefore, surface mechanical-loading effects were not included in the remaining five scenarios.

The scenario describing the undisturbed ground-water flow conditions (the third scenario in the list above) was labelled the "base-case scenario" and served as a basis for comparison with the other four scenarios retained for consequence analysis. The uncertainty analysis was restricted to the base-case only. A regional ground-water flow model was constructed that incorporated major hydrogeologic features of the site. In addition to providing a framework for the other scenarios, the regional-scale analysis provided head boundary conditions for the local (repository vicinity) model that used a more refined layering than the regional model. The results of flow modeling at the local scale allowed the construction of a network for the radionuclide-transport simulation. The source term was solubility limited. For the base-case, ranges and distributions (pdf's) were assigned to 57 input parameters including hydrologic, geochemical, source, and transport parameters. Uncertainty analysis was performed by generating 70 samples (input vectors) of the 57 uncertain parameters. The samples were obtained using LHS [Iman and Shortencarrier, 1984]. For each sample, a regional flow model, a local flow model, and a radionuclide-transport model simulations were performed. Only one of these samples (input vector #44) was used in analyzing the consequences associated with the other four scenarios.

The ground-water travel time (GWTT) from the edge of the repository to the accessible environment was estimated using a particle tracking technique. A cdf of the GWTT estimates was constructed to demonstrate the capability of assessing compliance with the GWTT criterion in 10 CFR Part 60. Integrated releases at the accessible environment for each of the 30 isotopes in the initial inventory were estimated using 70 simulations of transport.

Two separate, single-scenario ccdf's were constructed; one for the "low matrix diffusion" base-case and the other for the "high matrix diffusion" base-case.[9] The total discharge for each isotope from each simulation was divided by the corresponding release limit and a normalized sum obtained over all isotopes. The 70 normalized sums were arranged from largest to smallest and the probability of exceeding each sum was estimated from the sample probability. Each successive sum essentially increased the probability by 1/70. A plot of the ccdf corresponding to the low matrix diffusion base-case is shown in Figure 8, with the Standard superimposed. A similar plot for the high matrix diffusion base-case is shown in Figure 9. The procedure outlined in Section 4.1.2 was used to construct the ccdf that appears in both figures.

Comparing the ccdf's in Figures 8 and 9, one can observed the change brought by matrix diffusion. Increasing matrix diffusion reduces the likelihood of violating the Standard. The apparent violation of the Standard shown in Figure 9 was due to relatively high releases of I129 and C14.

It should be noted that the apparent violations of the Standard shown in Figures 8 and 9 do not provide a sufficiently strong basis for disqualifying a proposed disposal site. Rather, it underscores the need for sensitivity analyses to examine the importance of the direct cause of the violation. Single-scenario ccdf's, such as those used by Bonano et al. [1989a], become useful in conducting these sensitivity analyses.

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[9] The single-scenario ccdf's were constructed for the purpose of examining the sensitivity of assessing compliance with the Standard to matrix diffusion in fractured rock. As stated earlier (Section 4.1.2), it may not be necessarily sufficient to use a single-scenario ccdf to demonstrate compliance with the containment requirements.

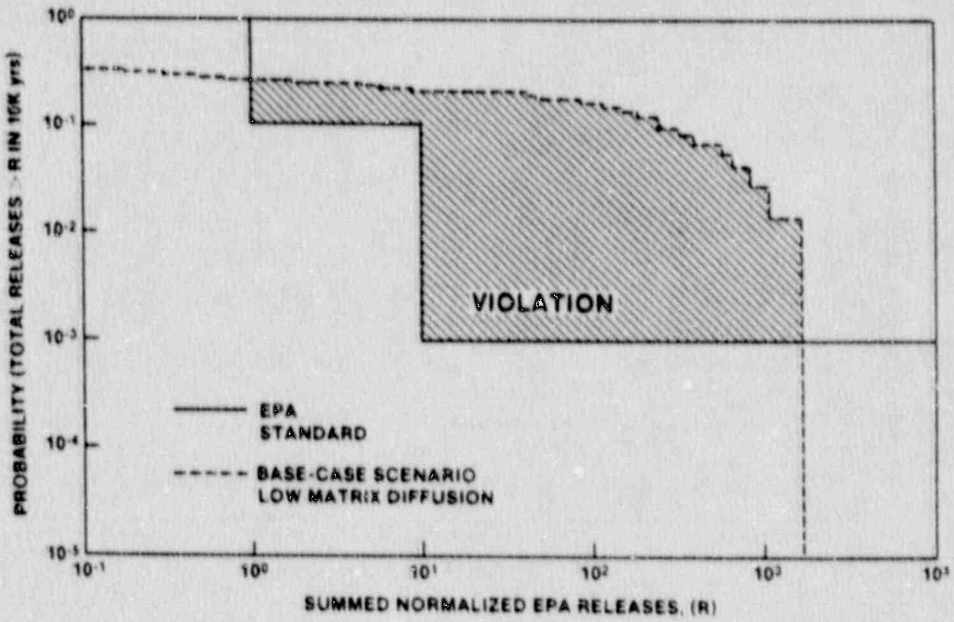

Figure 8. Comparison of Ccdf for Total Radionuclide Releases in 10,000 Years for the Base-Case Scenario With Low Matrix Diffusion to the EPA Standard [from Bonano et al., 1989a].

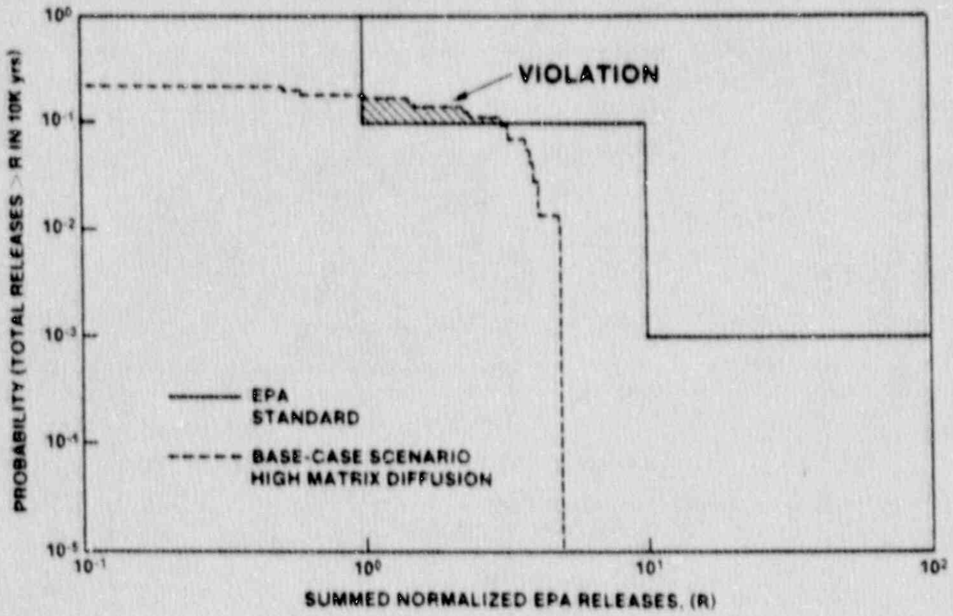

Figure 9. Comparison of Ccdf for Total Radionuclide Releases in 10,000 Years for the Base-Case Scenario With High Matrix Diffusion to the EPA Standard [from Bonano et al., 1989a].

6.0 SUMMARY AND CONCLUSIONS

The role of performance assessment in demonstrating or assessing compliance with the containment requirements in the Standard has been described and discussed in practical terms. The SNL PAMs, their capabilities, limitations, and applicability to the assessment of compliance with this regulation were discussed. Where appropriate, references to the literature, with particular emphasis to recent SNL publications on performance assessment, have been made to enable the reader to study the SNL PAMs in further detail.

Essential steps involved in a performance assessment are scenario development and screening, consequence analysis, and compilation of all the results in a form that permits a direct comparison with regulatory standards. Inherent in these analyses is the need to assign meaningful probability values to events that have the potential to affect system performance; some refer to this as the uncertainty in the future states of the repository system. Different types of uncertainty that will be encountered and potential methods of treating these uncertainties in the context of performance assessment have been described briefly.

Generation of ccdf's from the results of the various consequence and uncertainty analyses has been discussed. Use of such functions appears to be acceptable to the regulatory agencies in assessing compliance with quantitative requirements such as the EPA's containment requirements. Methods have been shown for constructing a ccdf for single or multiple scenarios in a given performance assessment.

Two examples have been provided that demonstrate applications of the steps and techniques presented in this report. One example considers a hypothetical bedded-salt site for a high-level radioactive waste repository. The other example considers a site in hypothetical basalt formations. Both examples conclude with the construction of ccdf's from the results of their respective performance analyses.

In descending order of difficulty and importance, the areas that deserve the most attention to improve the confidence that should be put on the results of a performance assessment are:

1. Development of an adequate set of representative scenarios and estimation of the probability of occurrence for each of the scenarios;
2. Development of confidence in the conceptual model, mathematical models, and computer codes used in the analysis; and
3. Reduction of uncertainty in data and parameters.

While the procedure exists, and has been demonstrated, for constructing a ccdf from the results of a performance assessment, much work is still needed in the above areas, particularly in the first two, to increase the likelihood that a sufficiently robust ccdf can be obtained to use as the basis for regulatory decisions. It is clear that the emphasis should not be in the development of techniques for propagating uncertainties in data and parameters because this aspect of uncertainty analysis seems manageable at this time.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report summarizes the role of performance assessment in assessing compliance with the containment requirements in 40 CFR Part 191, the Environmental Protection Agency's Standard for the disposal of spent nuclear fuel, high-level and transuranic radioactive wastes. In 1986, Hunter et al. prepared a similar report (NUREG/CR-4510, SAND86-0121) which provided an overview of the approach to assess compliance with this standard. The present report builds on its predecessor in that it incorporates advances in performance assessment subsequent to Hunter et al.'s report. The main purpose of this report is to serve as a mechanism for transferring to the Nuclear Regulatory Commission (NRC) and its contractors the performance assessment methodologies (PAMs) developed by Sandia National Laboratories (SNL) for high-level radioactive waste repositories. The report starts with a discussion of the requirements in 40 CFR Part 191 and focuses on the containment requirements (Section 191.13). It follows with a discussion of the role of performance assessment and its use in regulatory compliance. The report concludes with a discussion of sources of uncertainty, treatment of uncertainties, and the construction of the complementary cumulative distribution function of summed normalized total releases to the accessible environment for one or more scenarios. Examples are presented of the demonstration of performance assessment methodologies for high-level waste disposal at two hypothetical sites. Consistent with the technology transfer objective, numerous references are made throughout this report to publications related to the SNL PAMs. As such, this is not a stand-alone report and the reader is encouraged to consult those references.

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