REVIEW AND CRITIQUE OF THE NRC/CNWRA SCENARIO METHODOLOGY USED IN IPA PHASE 2

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ABSTRACT

A review and critique have been conducted of scenario analysis methods and the current implementation of consequence analysis modules in the Iterative Performance Assessment (IPA) being conducted by the U.S. Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA). The purpose of this review is to identify key topics associated with the methods used to analyze disruptive events in order to recommend improvements for future IPA work. Specific applications that are reviewed include:

- NRC/CNWRA IPA Phases 1 and 2
- Sandia National Laboratories (SNL) Total-System Performance Assessment (TSPA)
- SNL Waste Isolation Pilot Plant (WIPP)
- Electric Power Research Institute (EPRI) Phases 1 and 2
- Atomic Energy of Canada Limited (AECL)
- Swedish Nuclear Power Inspectorate (SKI) and Swedish Nuclear Waste Management Company (SKB)
- United Kingdom/Department of Environment/Her Majesty's Inspectorate of Pollution (UK/DOE/HMIP)

Key topics associated with the current IPA Phase 2 implementation of disruptive events are also identified. Specific disruptive events that are reviewed include:

- climate change
- volcanism
- human intrusion
- seismo/tectonics

Based on this review, recommendations for future IPA work are presented.

CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

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NOMENCLATURE

ADL	Arthur D. Little, Inc.
AECL	Atomic Energy of Canada Limited
ASCE	American Society of Civil Engineers
CC	Climate Change
CEC	Commission of European Communities
CCDF	Complementary Cumulative Distribution Function
CM	Consequence module
CNWRA	Center for Nuclear Waste Regulatory Analyses
DoE	Department of the Environment (United Kingdom)
DOE	U.S. Department of Energy
EBS	Engineered Barrier System
EP	Event and/or Process
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESM	Environmental Simulation Method
FEP	Feature, Event and/or Process
GS	Geologic Setting
HI	Human Intrusion
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
IPA	Iterative Performance Assessment
LHS	Latin Hypercube Sampling
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
PA	Performance Assessment
PDF	Probability Distribution Function
RN	Random Number
SNL	Sandia National Laboratories
SKB	Swedish Nuclear Fuel and Waste Management Company
SKI	Swedish Nuclear Power Inspectorate
SOTEC	SOurce TErm Code
ST	Seismo/Tectonics
TSPA	Total-System Performance Assessment (the act)
TPA	Total Performance Assessment (the code)
UK/HMIP	United Kingdom, Her Majesty's Inspectorate of Pollution
US	United States
VE	Volcanic Event
WIPP	Waste Isolation Pilot Plant

1 INTRODUCTION

1.1 BACKGROUND

Postclosure performance assessment (PA), as a scientific evaluation process, will provide the quantitative basis for judging the ability of the proposed repository at Yucca Mountain to comply with the U.S. Nuclear Regulatory Commission (NRC) performance objectives and the U.S. Environmental Protection Agency (EPA) standards. As part of the NRC Iterative Performance Assessment (IPA) exercises, a general model of total-system performance is being developed for eventual use in postclosure PA compliance determination methods. This total-system model, which uses a probabilistic methodology, is designed to simulate long-term repository performance taking into account a wide spectrum of: (i) physical and chemical processes; (ii) phenomenological interactions; and (iii) future system states, as well as their associated uncertainties.

A key aspect of modeling total-system performance is the consideration of future system states that constitute disruptions of the repository. These system states are associated with the natural geologic evolution of the site and potential future human activities. Disruptive scenarios are used in the probabilistic PA methodology to account for the effects of future system states. At present, four types of disruptive processes are considered in the NRC Total-System Performance Assessment (TSPA):

- climatology — changes in the precipitation (and infiltration) at the site and attendant effects on radionuclide fluxes from the repository and water travel times to the accessible environment
- volcanism — magmatic intrusions and extrusions through the geologic setting (GS) and their effects on waste package failure and radionuclide releases
- drilling — deleterious effects of drilling into a waste package causing radionuclide releases and creating preferential pathways through the unsaturated zone
- seismicity — mechanical failure of the waste package induced by repetitive seismic motions

These four disruptive processes were selected on the basis of their perceived importance at Yucca Mountain. Initial mathematical representations of these four types of processes were formulated, coded, and implemented in the IPA Phase 2 version of the total-system code (Nuclear Regulatory Commission, 1993; Sagar and Janetzke, 1993). The timing of this report is awkward since it precedes the final report documenting the IPA Phase 2 effort (NRC, 1993), however, the Phase 2 modules are sufficiently described so that this report could be completed in preparation for IPA Phase 3 planning.

1.2 PURPOSE AND SCOPE

As part of the PA Research Project being conducted by the Center for Nuclear Waste Regulatory Analyses (CNWRA), conceptual and mathematical models of disruptive scenarios are being evaluated and advanced for implementation in future IPA exercises and for developing potential guidance to the DOE. This report presents the results of a technical critique of the existing IPA disruptive scenario models. The critique was performed to identify areas for future improvement of the scenario models, with specific focus on: (i) conceptual representations; (ii) mathematical formulations; and (iii) computational algorithms. To aid this critique, a preliminary review was conducted of scenario approaches used by researchers in the United States and other countries. Specific recommendations are presented for further development of IPA scenario models and modules.

1.3 REPORT ORGANIZATION

This report is consists of four major sections. In Section 2, a preliminary review is given of Total Performance Assessment (TPA) and scenario analysis methods used in the United States [i.e., U.S. Department of Energy (DOE) and Electric Power Research Institute (EPRI)] and in other countries. This section also includes a comparison and critique of the various approaches. In Section 3, the four IPA scenario models are described in more detail and critiqued. This section also includes specific recommendations for improvement of the scenario models and modules. The final section of the report, Section 4, summarizes the current state-of-the-art in scenario methodologies, and compares and contrasts them to the NRC/CNWRA approach. Included in the final section is a discussion of the general deficiencies in scenario methodologies.

2 TOTAL-SYSTEM PERFORMANCE ASSESSMENT AND SCENARIO METHODS

In this section, the role of scenarios in TSPA is reviewed as well as alternative scenario methods employed by:

- NRC/CNWRA IPA Phases 1 and 2 (U.S. Nuclear Regulatory Commission, 1992; 1993)
- Sandia National Laboratories (SNL) TSPA (Sandia National Laboratories, 1992)
- SNL Annual PA for Waste Isolation Pilot Plant (WIPP) (Sandia National Laboratories, 1991; 1993)
- Electric Power Research Institute (EPRI) (1990; 1992)
- Atomic Energy of Canada Limited (AECL) (Stephens and Goodwin, 1990)
- Swedish Nuclear Power Inspectorate (SKI) and Swedish Nuclear Waste Management Company (SKB) (Andersson et al., 1989; Andersson and Eng, 1990)
- United Kingdom Department of Environment, Her Majesty's Inspectorate of Pollution (UK/DoE/HMIP) (Thompson, 1988)

The emphasis is on the identification of similarities and differences between the NRC/CNWRA IPA Phase 2 effort and other methods. This section concludes with a summary of key topics which have been identified as being discussed in all of the reviewed methods:

- expert judgment
- alternative conceptual models
- reconciliation of different scenario approaches
- completeness of scenarios
- human intrusion

2.1 TOTAL-SYSTEM PERFORMANCE ASSESSMENT

The formulation and analysis of scenarios can be considered the backbone of PA where the multidisciplinary information and data feed into an overall assessment of system performance. The primary purpose of scenario analysis is to systematically handle the uncertainty in the future evolution of the repository system during the time period of regulatory interest (10,000 yr). Some of the most difficult uncertainties to quantify stem from phenomena which have a low probability of occurrence, yet a potentially high impact on the repository's ability to contain and isolate the radioactive waste.

A generic flow chart for IPA is presented in Figure 2-1. In the figure, a distinction is made between generic features, events, and processes (FEPs) that are internal to the system (and are included in the base-system models), and disruptive events and processes (EPs) external to the system (and are included in the scenario models). In general, generic FEPs are those phenomena which are expected to always (or nearly always) occur and affect the release and transport of radionuclides (e.g., groundwater flow; waste package corrosion; waste form dissolution, mobilization and transport; and sorption).

Disruptive EPs typically (but not always), are discrete events and have a lower probability of occurrence, yet have a potentially higher consequence on the release and transport of radionuclides. A set of important phenomena is developed for both the generic and disruptive EPs. For disruptive EPs, scenarios are generated to describe the characteristics of future events. Because of the large range of

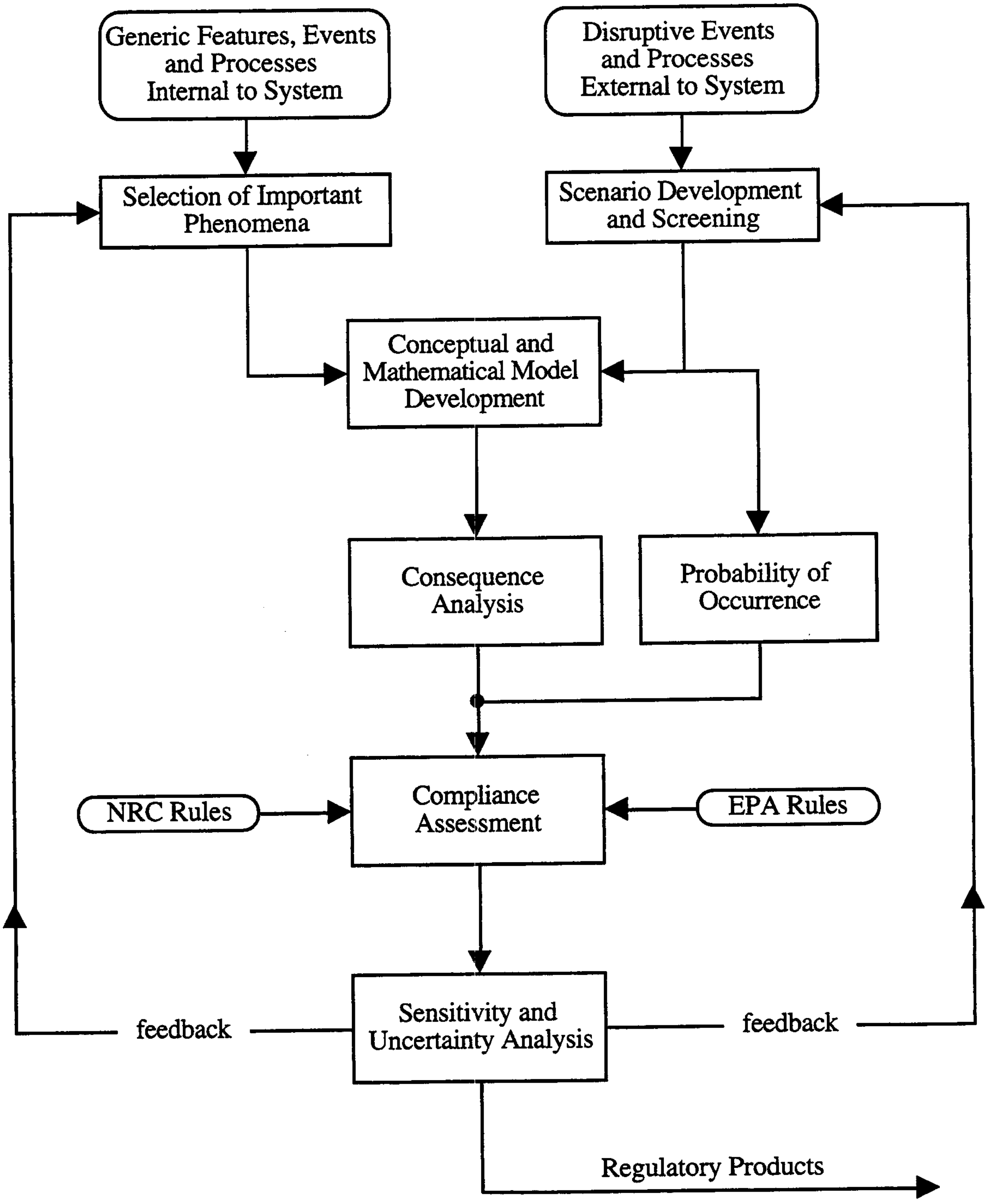


Figure 2-1. Flow diagram for a generic iterative performance methodology which distinguishes between disruptive events and processes, and generic features, events, and processes

potentially different characteristics, a large number of viable future predictions (or realizations) are generated in the process of scenario development. Because of the low probability of occurrence and/or low consequence, certain scenarios may be screened (i.e., deleted from further consideration in PA). The precise criteria for screening varies among implementations.

After scenario development and screening, conceptual and mathematical models are generated, and the probability of occurrence is calculated for each scenario. Similarly for generic FEPs, only the most important phenomena are considered (typically due to time and resource constraints), and conceptual and mathematical models are developed. The mathematical models are used to conduct a consequence analysis. Because the scenario analysis generates a set of possible future realizations, consequence analyses are performed for each scenario and a weighted sum of individual consequences is used to compute the cumulative consequence. The cumulative consequence is compared with regulatory performance measures.

Six regulatory performance measures based on EPA and NRC regulations are shown in Figure 2-2. The compliance assessment is based on a weighting of different predictions of future responses, hence each is based on a probabilistic measure as shown in the examples. In each example of compliance determination, the probability of an outcome is predicted as a function of the magnitude of the outcome. Sensitivity and uncertainty analyses can be performed to determine which generic FEPs and disruptive EPs are the most important to the performance measures.

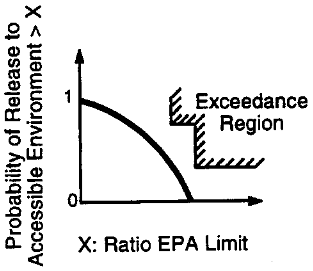
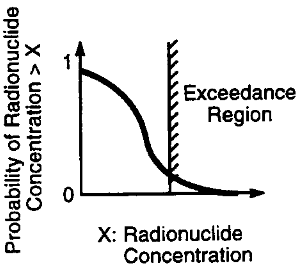
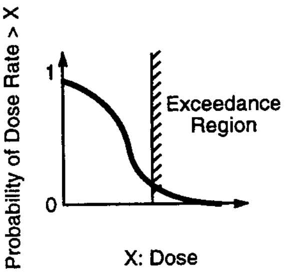
Three major sources of uncertainty must be considered in PA:

- data uncertainty
- model uncertainty (both conceptual and mathematical)
- future-state uncertainty

Each source of uncertainty has different characteristics and is typically handled using a different method. Scenario analysis methods have been developed to handle the uncertainty associated with future behavior. Uncertainty analysis methods (e.g., Monte Carlo, differential analysis) have been developed to accommodate data and model uncertainty. Recently, it has been proposed that scenario analysis methods be extended to account for both disruptive EPs and generic FEPs, and also be extended to account for data and model uncertainty (Barr and Dunn, 1993). For example, the Environmental Simulation Method (ESM) (discussed in Section 2.7) claims to treat all sources of uncertainty similarly so that data, model and future-state uncertainty are handled using the same methods. It is emphasized, however, that the scope of scenario analysis is frequently (yet not always) limited to future-state uncertainties.

2.2 U.S. NUCLEAR REGULATORY COMMISSION/CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

Scenario analysis is a primary tool used by the NRC/CNWRA PA team to quantitatively predict total system performance and compare the predictions against regulatory requirements (Codell et al., 1991; NRC, 1992; 1993). The methodology employed by the NRC/CNWRA team is based on the SNL method, which employs the general steps of identification, classification, and screening of phenomena,

Description	EPA Standard Containment 40 CFR 191.13	EPA Standard Groundwater Protection 40 CFR 191.16	EPA Standard Individual Protection 40 CFR 191.15
Example of Compliance Determination			
Criteria	P (X > 1.0) < 0.1 P (X > 10.0) < 0.001 10,000 yrs	P (X < 15 pCi/liter for alpha emitter) = 1 "Reasonable Expectation" 10,000 yrs	P (X < 25 mRem body, X < 75 mRem Organ) = 1 "Reasonable Expectation" 10,000 yrs

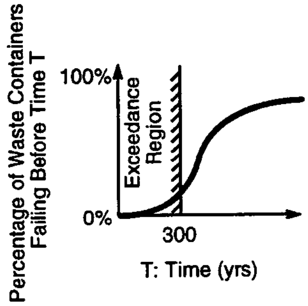
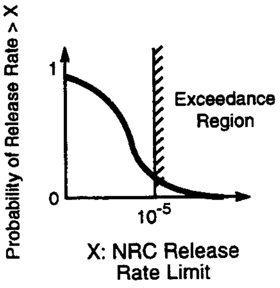
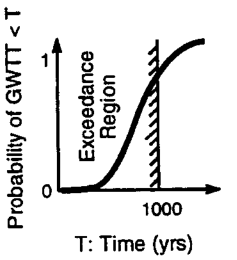
Description	NRC Rule Waste Package Lifetime 10 CFR 60.113(a)(1)(ii)(A)	NRC Rule Release Rate 10 CFR 60.113(a)(1)(ii)(B)	NRC Rule Groundwater Travel Time 10 CFR 60.113(a)(2)
Example of Compliance Determination			
Criteria	P (T > 300 yrs) = 1 "Substantially Complete" 300 yrs	P (X < 10^{-5} per yr of inventory at 1000 yrs) = 1 "Gradual Release" 10,000 yrs	P (T > 1000 yrs) = 1 Pre-Emplacement

Figure 2-2. Six regulatory performance measures used in the compliance assessment task of PA

followed by the formation and screening of scenarios (Cranwell et al., 1990). The SNL method has been extensively discussed in the literature (Hunter et al., 1983; Bonano et al., 1989; Stephens and Goodwin, 1990), hence, it is only briefly reviewed here. For introductory purposes, the NRC/CNWRA application of the scenario methodology for TSPA is presented.

2.2.1 Definition of Scenario and Scenario Classes

A scenario is defined by the NRC/CNWRA team to be

> "any postulated future sequence of processes and events which is sufficiently credible to warrant consideration of its projected effect on repository performance. These sequences represent some of the potential ways in which the repository system environment might evolve. Such alternate evolutions may result from the occurrence of natural events and/or from human-initiated activity and could affect the release and transport of radionuclides from the repository to the accessible environment" (NRC, 1993).

Hence, a scenario is a hypothetical sequence of phenomena which leads to a detrimental consequence on the performance of the high-level waste (HLW) repository. Thus, the purpose of a scenario analysis method is to account for future-state uncertainties (and not necessarily data or model uncertainty which can be considered using other uncertainty analysis methods).

In IPA Phase 2, an EP is classified disruptive if it has a potentially detrimental consequence on the performance of the HLW repository and is initiated outside the repository system; otherwise, the EP is considered one of the generic FEPs. By considering the occurrence/nonoccurrence of each disruptive EP, the concept of a scenario class arises, where a scenario class contains (or originates from) all considered scenarios with the same disruptive EPs. Hence, a scenario class represents a high-level abstraction of the overall system which includes the generic FEPs and zero or more disruptive EPs. A generalized logic diagram is shown in Figure 2-3 and can be used to generate the descriptions and probabilities of scenario classes. Each scenario class is a unique combination (or path) in the logic diagram. An example is the base case which is the combination of no intrusion, no seismo/tectonic events, no climate change, and no volcanic event. The probability of the base case can be calculated as the multiplication of the individual probabilities in the logic diagram [i.e., $(2.3\times10^{-7})\times(4.5\times10^{-5})\times(0.36\times0.97)=3.6\times10^{-12}$]. All events and processes were considered statistically independent, yet it is possible to consider joint probabilities. A matrix of disruptive events is presented in Table 2-1, where the sixteen scenario classes are explicitly enumerated.

2.2.2 Use of Scenario Classes

A maximum of 16 scenario classes can be formed from the 4 disruptive EPs identified in IPA Phase 2. The probability of each scenario class can be generated using the probability of occurrence of the individual EPs. Because of the low probability of some scenario classes, only 9 of the possible 16 scenario classes were modeled (7 scenario classes were screened) in IPA Phase 2 (NRC, 1993).

Drilling and seismic events were assessed to be highly probable during the next 10,000 yr at Yucca Mountain, hence, they were included in each of the most probable scenario classes. Complementary Cumulative Distribution Functions (CCDFs) for the EPA containment performance

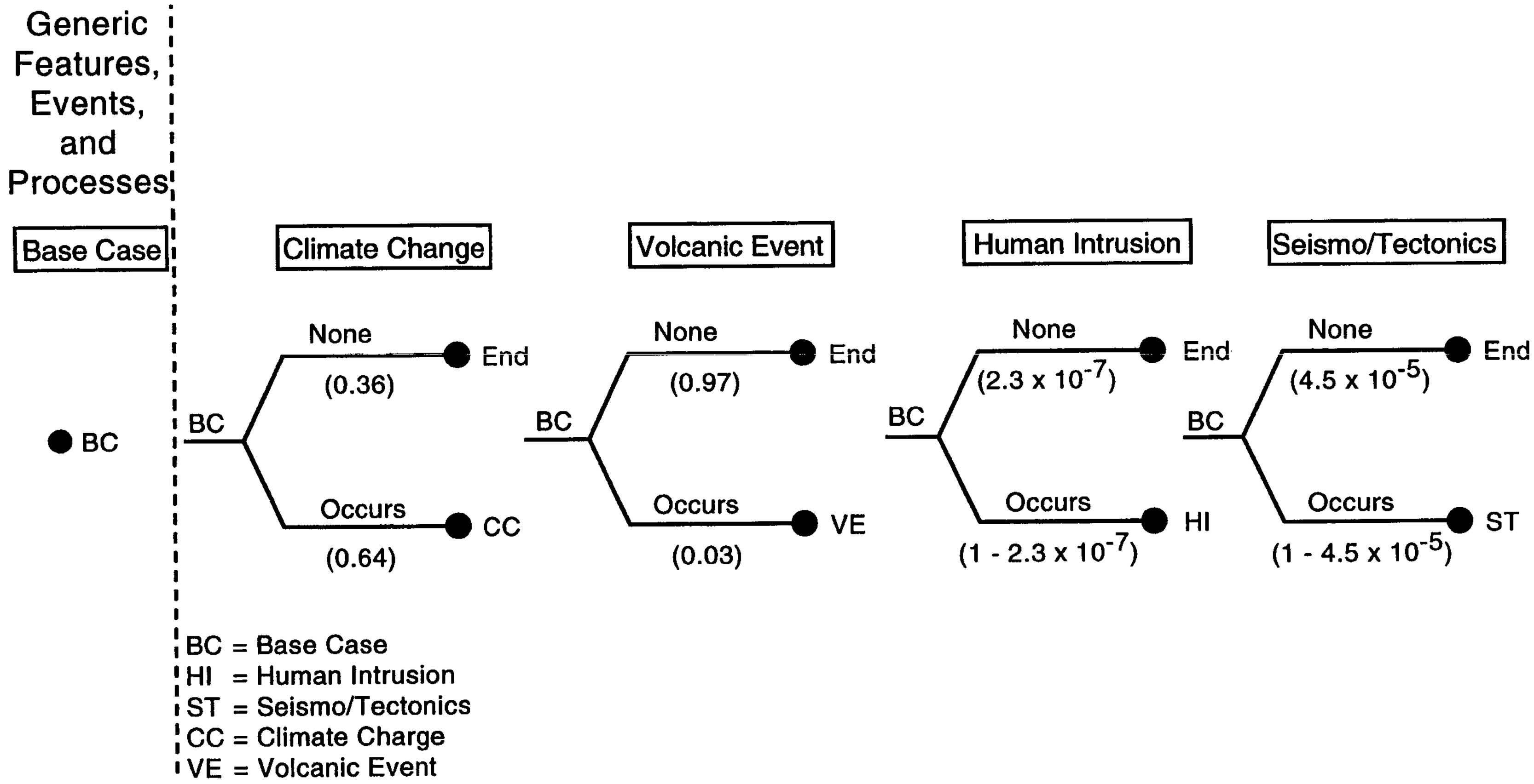


Figure 2-3. Generalized logic diagram for the generation of scenario classes used in the IPA Phase 2 effort (the probabilities of the disruptive EPs are from the Phase 2 effort)

Table 2-1. Combination of disruptive events to form sixteen scenario classes

		nVE		yVE	
		nHI	**yHI**	**nHI**	**yHI**
nCC	nST	(nCC, nST, nVE, nHI) "base case"	(nCC, nST, nVE, yHI)	(nCC, nST, yVE, nHI)	(nCC, nST, yVE, yHI)
	yST	(nCC, yST, nVE, nHI)	(nCC, yST, nVE, yHI)	(nCC, yST, yVE, nHI)	(nCC, yST, yVE, yHI)
yCC	nST	(yCC, nST, nVE, nHI)	(yCC, nST, nVE, yHI)	(yCC, nST, yVE, nHI)	(yCC, nST, yVE, yHI)
	yST	(yCC, yST, nVE, nHI)	(yCC, yST, nVE, yHI)	(yCC, yST, yVE, nHI)	(yCC, yST, yVE, yHI) "fully disturbed"

yVE = yes Volcanic Event
nVE = no Volcanic Event
yHI = yes Human Intrusion
nHI = no Human Intrusion

yCC=yes Climate Change
nCC=no Climate Change
yST=yes Seismo/Tectonics
nST=no Seismo/Tectonics

measure were generated for each of the nine scenario classes and then combined into a single CCDF for TSPA. The combined CCDF is generated by weighting the CCDF of each scenario class by the probability of the class.

Within each scenario class, numerous details were required to characterize the disruptive event; however, these details were considered separate from the scenario class. Typically, the characteristics of an event were randomly selected within the numerical simulation. One realization within a scenario class can be considered a scenario. Scenarios were not explicitly discussed in the IPA Phase 2 implementation, yet were embedded in the scenario class (discussed further in Section 3.7.1).

The IPA Phase 2 implementation did not draw a strong distinction between the description and the consequence of a scenario (discussed further in Section 3.7.2). As implemented, the scenario analysis ended with the assignment of probability of occurrence to each of the four disruptive EPs, and the description of a scenario was embedded in the consequence analysis. This distinction differs from other approaches to scenarios which typically combine both description and consequence in a single event diagram (Sandia National Laboratories, 1992). The rationale for the distinction proposed in the IPA effort was that the scenario analysis was made more transparent (U.S. Nuclear Regulatory Commission, 1993).

2.3 SANDIA NATIONAL LABORATORIES

The DOE is conducting two major deep geologic disposal programs:

- the proposed repository at Yucca Mountain, Nevada, for HLW
- the WIPP in southeastern New Mexico for transuranic waste

A TSPA is being conducted for each of these facilities. Both the Yucca Mountain project and the WIPP project have adopted scenario-based approaches which are discussed next.

2.3.1 Yucca Mountain

Scenario analyses pertaining to the proposed repository located at Yucca Mountain have been conducted by Hunter et al. (1982; 1983), Ross (1987), and more recently by Barr and Dunn (1993). The earliest studies have focused on developing a list of FEPs which constitute the scenarios for the site. As the list of events and processes has developed, the event tree has been adopted as the tool used to organize and convey scenario information (Barr and Dunn, 1993; Barr et al., 1993).

The event-tree method advocated by Barr and Dunn (1993) and applied to volcanic scenarios (Barr et al., 1993) appears to be the most systematic approach to scenarios for the Yucca Mountain site. The method has many of the same features as proposed by Cranwell et al. (1990), including identification of important FEPs and graphically organizing the information in a generalized event tree (where the term generalized is used to signify that the tree contains FEPs and not just events). The tree is organized so that a scenario starts with an initiating event or process and flows in a connected path through the tree until it leads to an effect on the release and/or transport of radionuclides. A scenario is a single connected path through the tree, therefore, the tree contains many scenarios which have the same initiating EP. Barr and Dunn claim that this approach permits the decomposition of the large, complex problem of scenario identification and analysis into a practically solvable problem.

One of the major advantages of the event tree is that it is used as a bookkeeping system to track FEPs that either:

- have been analyzed
- are currently under investigation
- still need to be examined

In comparison, the current NRC/CNWRA approach has not adopted such a tool to keep track of the progress of modeling disruptive FEPs.

In addition, the event tree is reported by Barr and Dunn (1993) to have the advantage of accommodating and retaining alternative conceptual models. The notion that scenarios accommodate alternative conceptual models is a distinction from the NRC IPA Phase 2 implementation where scenario analysis is reserved to account only for uncertainty in the future state of the system (and not data and/or model uncertainty). As will be discussed with other implementations, scenario analysis tools have been used to accommodate data and model uncertainties, as well as future state uncertainties (discussed further in Sections 2.9.2 and 3.7.3).

2.3.2 Waste Isolation Pilot Plant

Since the early 1970s, several studies have been conducted to identify scenarios at the proposed WIPP disposal site. Hunter (1989) examined a wide range of initiating events that have been postulated for WIPP (Clairborne and Gera, 1974; Bingham and Barr, 1979) as well as for disposal in generic sites [Arthur D. Little, Inc. (ADL), 1980; Cranwell et al., 1982; International Atomic Energy Agency (IAEA), 1983] for the first iteration of the annual PA exercise for WIPP (Sandia National Laboratories, 1991, 1993). More recently, Guzowski (1990) has adopted the SNL scenario methodology of Cranwell et al. (1990) for the generation of WIPP scenarios. The starting point for the application of this method was the initiating events identified by Hunter (1989) with one new event for the drilling of pumping wells. During Guzowski's analysis, it was concluded that some initiating events were expected to occur during the 10,000-yr regulatory period, hence, these were folded into the base-case scenario for the WIPP PA. A similar argument could be proposed for some of the disruptive events considered in the IPA Phase 2 effort where the probability of exploratory drilling within the next 10,000 yr was predicted to be essentially certain (~ 0.99999967). In the NRC IPA effort, drilling could be folded into the base-case scenario as other events were folded in the WIPP PA, however, this is not recommended because human activity is viewed to originate externally from the disposal system (hence it is a disruption to the system).

2.4 ELECTRIC POWER RESEARCH INSTITUTE

The EPRI has demonstrated a risk-based methodology to study PA of a hypothetical repository at Yucca Mountain. The work is ongoing with the first two phases being completed (Electric Power Research Institute, 1990; 1992). Scenarios were identified as a key part of the EPRI work. The selection of scenarios was based primarily on the judgments of experts in the following fields: climatology, tectonics, volcanology, rock mechanics, hydrology, geochemistry, waste-package engineering, human factors, nuclear physics, and nuclear engineering. Logic trees were used extensively by the EPRI team to organize, aggregate, and convey the information concerning scenarios. The main advantage of the logic tree is that it structures and documents the interpretations and decisions of the experts in a manner which was considered the most natural and convenient for the participants (Electric Power Research Institute, 1990). In this paper, the logic trees, as used by EPRI, were found to be natural and flexible and are used throughout Section 3.0. In addition to disruptive events, anticipated FEPs were analyzed using logic trees as organizational tools. Scenarios and logic trees were used throughout the TSPA exercises.

2.5 ATOMIC ENERGY OF CANADA LIMITED

The AECL has adopted the scenario-selection methodology of Cranwell et al. (1990) and customized it for their disposal program (Stephens and Goodwin, 1990). During the implementation, two terms were defined:

- factor is any feature, event, or process that could influence the performance of any component of the disposal facility

- scenario is a combination of factors that could affect the ability of the disposal facility to immobilize and isolate the nuclear waste

Factor is a generic and encompassing term which means the same as FEPs used by Barr and Dunn (1993), hence, it is not considered a major distinction. Scenario, however, has been given an expanded definition whereby it specifically encompasses anticipated processes and events, and de-emphasizes the focus on future changes of the system. In contrast, the NRC (1992; 1993) implementation reserves the term scenario (discussed in Section 2.2.1) to account for the large number of plausible future evolutions of the system (the emphasis is on the uncertain prediction of the future).

The Canadians also introduced a central scenario which includes the most probable factors by which waste can be released, migrate through the geosphere, reach the biosphere, and lead to doses to humans. Factors were partitioned to be either central factors or residual factors. The residual factors were used to construct alternative scenarios. In the end, only four scenarios were simulated (the central and three alternatives) due primarily to screening. The low number of scenarios is similar to the low number identified in the IPA Phase 2 effort (U.S. Nuclear Regulatory Commission, 1993), and different from the high number of scenarios identified in other work (i.e., Barr et al., 1993).

2.6 SWEDISH NUCLEAR POWER INSPECTORATE AND SWEDISH NUCLEAR WASTE MANAGEMENT COMPANY

In 1988, the SKI and SKB participated in a joint scenario selection exercise for a hypothetical Swedish repository (Andersson et al., 1989; Andersson and Eng, 1990). The SKI/SKB scenario exercise adopted the method of Cranwell et al. (1990). One important modification to this method, however, was the introduction of the so-called process system. The process system was to include all FEPs that are either continuously active or are in a standby mode (where it may be activated by the occurrence of other causes). Only FEPs that represent the latter (i.e., externally driven causes) were considered in the development of alternative scenarios. This led to the identification of conventional scenarios which affect release and transport through the anticipated barrier systems (e.g., waste package, geosphere, biosphere), and isolated scenarios which short-circuit one or more of the barrier systems (e.g., exhumation of waste due to drilling).

2.7 UNITED KINGDOM DEPARTMENT OF ENVIRONMENT, HER MAJESTY'S INSPECTORATE OF POLLUTION

The UK/HMIP recently conducted a TSPA using the ESM (United Kingdom, Her Majesty's Inspectorate of Pollution, 1992). The ESM stems from the earlier work on the geologic simulation model proposed by Petrie et al. (1981) and INTERA (1983) and has been proposed as an alternative to discrete scenario methods (Thompson, 1988). The main features of the ESM are:

- the simulation is run in a transient mode (in contrast to most scenario analysis methods which have been described as being run in a steady-state mode)
- all identifiable uncertainties are accounted for using Probability Distribution Functions (PDFs), which are based on available data and/or expert judgment
- Monte Carlo sampling is used to select values from the PDFs for each simulation

The primary advantages of the ESM are (as described by Petrie et al., 1981) that it:

- is more natural than traditional scenario methods to model time-dependent phenomena

- allows interaction between disruptive phenomena in a synergistic fashion without hard-wiring the type of interactions to be considered

- accounts for all sources of uncertainty (data, model, and future state) in a uniform manner using Monte Carlo sampling from PDFs

More recently, Thompson (1988) has advocated the ESM and claims:

- environmental changes, their sequence, and their duration need to be explicitly considered in PA

- most scenario approaches do not allow capturing the major effects of environmental changes, thus resulting in lower risk estimates

To date, the ESM has concentrated on effects due mainly to climate change (Boulton, 1990; Nuclear Energy Agency, 1992). The main disadvantages of the ESM appear to be:

- the reliance on a black box simulator which gives the impression of complex calculations without significant user input

- the requirement of a large amount of computational effort to characterize low probability/high-consequence events (i.e., the types of events that scenario methods have traditionally targeted)

The first disadvantage of ESM results from the reliance on PDFs to mathematically describe the couplings and interrelationships between processes. In essence, the PDFs constitute the backbone of the method, and numerous PDFs are required as user inputs to fully describe the future occurrence of phenomena and couplings between phenomena. Although this approach is reported to have the advantage of not requiring hard-wiring of interactions (Petrie et al., 1981), it effectively requires that modeling assumptions be embedded in a less obvious location in the simulation process (i.e., deep within the simulator). In contrast, most scenario methods use an event tree format to organize and convey the modeling assumptions and approximations. The event tree format is considered (by the authors) to more clearly communicate this information. Clear identification and traceability of modeling assumptions is an advantage of discrete scenario methods when compared to the ESM.

The second disadvantage stems from the reliance on Monte Carlo sampling from the many PDFs to determine the evolution of the system. It is widely recognized that Monte Carlo sampling requires a large number of simulations in order to provide accurate approximations of repository performance, especially at the tails of the predictions where low-probability/high-consequence events dominate the shape of the curves (U.S. Nuclear Regulatory Commission, 1992). More efficient sampling strategies can be adopted than pure Monte Carlo [e.g., importance sampling or Latin hypercube sampling (LHS)]. Overall, ESM appears to be well adapted for modeling high-probability EPs, while scenario methods are well adapted to low-probability EPs. Scenario methods typically focus on modeling future evolutions of the system which do not necessarily have a high probability of occurrence. In contrast, the ESM (without acceleration strategies such as LHS or importance sampling) will focus most of the computational effort on high probability EPs.

2.8 OTHER APPLICATIONS

Scenario analysis has also been addressed in studies conducted in other countries, such as:

- French initiatives by ANDRA (France's national agency for radioactive waste management) (Raimbault et al., 1992)
- Project Gewahr in Switzerland (Nuclear Energy Agency, 1992)
- PAGIS Program sponsored by the Commission of European Communities (CEC) (Cadelli et al., 1988)
- Project EVEREST sponsored by the CEC (Raimbault et al., 1992)

The main distinctions between these other approaches and that adopted in the IPA Phase 2 effort are:

- adopting or creating classification and organization schemes for all of the multi-disciplinary information needed to describe scenarios
- increasing the scope of scenarios to handle future-state uncertainties and/or other sources of uncertainty (data and model uncertainty)
- adopting either low- or high-level abstractions where either each sequence of features is called a scenario (low-level abstraction) or each sequence originating from a single cause is called a scenario (high-level abstraction)

A more detailed review of these approaches is currently being conducted and is expected to be submitted as a companion paper.

2.9 KEY TOPICS

In the preceding sections, different scenario methods were reviewed, including those applied to the proposed repository at Yucca Mountain, WIPP, and also the activities in other countries (e.g., Canada, United Kingdom, Sweden). In this section, key topics associated with scenarios are discussed. Based on the preceeding review, the following items have been identified as key topics:

- expert judgment
- reconciliation of different scenario approaches
- completeness of scenarios
- human intrusion

2.9.1 Expert Judgment

The selection of scenarios for the most part will depend on the use of expert judgment. Every example presented in this report (whether within the NRC HLW program, the DOE programs, or programs in other countries) has cited the extensive, and in some cases the exclusive, use of expert judgment in scenario selection. In some cases, the expert judgments have been used in the context of a well-documented, structured scenario-selection methodology, while in others they have not. In several applications, the judgments have been obtained using a fairly formal approach, and in others they seem to have been elicited in an *ad-hoc* manner. In some cases, the judgments have been provided by only one individual, while in others, they have been obtained from one or more groups of experts. Clearly, the issue is not whether expert judgments will be used, for the nature of the problem does not seem to allow for any other means to be applied reliably to the selection of scenarios. Rather, the issue is will the expert judgments be obtained using a systematic and documented approach which is designed to avoid some accepted pitfalls of expert elicitation (e.g., expert overconfidence or biasing of results due to strong-willed experts).

It seems reasonable that, given: (i) the very important role of scenarios in the PA; (ii) the complexity of developing scenarios and assigning a likelihood or probability of occurrence; (iii) the lack of uniqueness in a method for selecting scenarios; and (iv) the already extensive use of expert judgments in scenario selection, the judgments should be elicited and used following a formal and rigorous procedure. Regardless of the method used (event trees, fault trees, logic trees, individual expert versus one or more groups of experts, etc.), a great deal of interpretation and subjectivity will permeate the selection of scenarios. Therefore, the approach used to establish a set of scenarios for PA should be logical, systematic, well-documented, and transparent to allow it to be scrutinized in a manner that those reviewing the approach and the results of its application can extract the foundation for the judgments. Bonano et al. (1990) describe approaches, procedures, and techniques for the elicitation and use of formal expert judgments in various aspects of PA, including scenario selection. These procedures appear to be sound and have been applied successfully (with a few adaptations) by DeWisplare et al. (1993) in the demonstration of a formal expert elicitation for future climate at Yucca Mountain.

2.9.2 Reconciliation of Different Scenario Approaches

The reconciliation of different scenario approaches is an issue. Many programs have anchored on the scenario-selection methodology of Cranwell et al. (1990); however, this seems to have been more out of convenience than out of uniqueness. Other programs, most notably the United Kingdom Nirex (Billington et al., 1990) and the UK/HMIP (1992), have chosen fundamentally different approaches.

In the United States, the DOE has proposed a scenario-selection approach for Yucca Mountain using event trees (Barr and Dunn, 1993; Barr et al., 1993). Barr and Dunn (1993) have noted that their approach is different from that proposed by Cranwell et al. (1990), which was adopted for the NRC IPA Phase 2 implementation (NRC, 1993). They differ in the definition and function of scenario and in the method used for scenario construction (Barr and Dunn, 1993). In addition there is an apparent lack of consistency within DOE programs (i.e., WIPP and Yucca Mountain) regarding the approach to scenarios for PA. It would be beneficial if agreement could be reached between different implementations to facilitate comparison and reconciliation efforts. In particular, it would be helpful if terms had common definitions, and common tools were used to organize, aggregate, and convey the detailed information necessary to understand the differences between implementations. Sweden seems to be the only country with a major radioactive waste management program where the applicant and regulator have agreed to jointly tackle the scenario-selection process (Swedish Nuclear Power Inspectorate, 1989). Such an approach is likely to have many benefits during the licensing process, because the focus will be on the probability and consequences of scenarios selected, and not on the approach used to select them.

2.9.3 Completeness of Scenarios

The issue of completeness regarding the selection of scenarios is not new. Many publications related to uncertainty analysis in PA specifically mention completeness as an issue. Although completeness appears intuitively necessary, it is believed that current methods dictate that an undue effort be required to assess all potentially important events and processes. Completeness should always be considered an impossible task given (i) an infinite number of potentially important phenomena, and (ii) a finite amount of resources (time and money) required to assess each potentially important phenomenon. Hence, it is impossible to completely assess all phenomena. The most that reasonably can be expected is the modeling of all phenomena which have both: (i) a detrimental impact on the performance of the disposal system; and (ii) a sufficiently large likelihood of occurrence. To this end, a large amount of effort has been devoted to developing a consensus on those phenomena which are perceived to be important, including the recent effort by Stenhouse et al. (1993).

2.9.4 Human Intrusion

There is considerable debate within the waste management community regarding the context in which human intrusion should be considered in PA. In 1989, the NEA conducted a workshop in which leading international experts were gathered to discuss methods used to estimate risks associated with human intrusion (Nuclear Energy Agency, 1989). During that workshop more issues were raised than resolved. As a result, the NEA established a working group to address some of those issues, yet most of the issues still remain open.

There are some within the waste management community who advocate that human intrusion scenarios be treated differently from other scenarios (Nuclear Energy Agency, 1993). This position stems primarily from the two arguments that:

- the highly speculative nature of forecasting human actions should not be put in the same context as scenarios due to naturally occurring events
- risks due to human intrusions are not discriminatory between sites (i.e., all disposal systems are likely to fail meeting the regulatory requirements when human intrusion is considered)

How to incorporate human intrusion scenarios into PA continues to be a controversial and difficult issue that fosters much debate. The debate not only has focused on the technical difficulties associated with forecasting human actions, but also has brought societal and philosophical issues, such as this generation's responsibility towards future ones and the distinction between inadvertent and advertent intrusion, to the forefront. The most comprehensive study of human intrusion to date was that conducted by Hora et al. (1991) for the WIPP site. The rigor with which the study was carried out notwithstanding, the study has been the subject of criticism due to the highly speculative and subjective nature of the judgments expressed by the experts utilized.

3 U.S. NUCLEAR REGULATORY COMMISSION/CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES MODULES FOR SCENARIO CLASSES

In this section, the modules for each disruptive EP modeled in IPA Phase 2 are described and critiqued. In particular, the four disruptive EPs considered are:

- climate change (pluvial)
- volcanism
- human intrusion (drilling)
- seismo/tectonics (seismic)

3.1 BASIS FOR DISRUPTIVE EP SELECTION

In Table 3-1, the different implementations of disruptive events in recent TSPAs for Yucca Mountain are summarized. This summary includes two IPA phases of the NRC (1992, 1993), two phases by EPRI (1990, 1992), the first phase by SNL (1992), and Pacific Northwest Laboratory (PNL) (1993). Each of the four disruptive EPs were selected on their ability to detrimentally affect repository performance through either enhanced release of radionuclides from the Engineered Barrier System (EBS), or enhanced transport of radionuclides through the GS. The rationale for each of the EPs is summarized here.

Climate change is most frequently represented by a change in the infiltration rate, and in the elevation of the water table. Increased infiltration and water table rise indirectly affect release of radionuclides from the repository by accelerating the corrosion of waste packages and accelerating the liquid transport through the geologic medium. From the IPA Phase 1 and 2 efforts, it was determined that the infiltration rate had a significant impact on repository performance (U.S. Nuclear Regulatory Commission, 1992; 1993).

Volcanic events have the potential of occurring at Yucca Mountain and leading to magma interactions with waste packages. The primary effect of volcanic activity is waste entrainment in ascending magma which for extrusive events leads to ejection of waste at the ground surface. For intrusive events, the magma may interact with waste packages to accelerate their failure and release of radionuclides into the GS.

Human intrusion is most frequently represented by exploratory drilling through the repository. Drilling may cause a direct release of radionuclides to the ground surface or rapid transport of waste to the saturated zone (e.g., Sandia National Laboratories, 1992; Pacific Northwest Laboratory, 1993). Direct release is caused by drilling through a waste package, thereby mobilizing and mixing the waste with the drilling fluid and exhuming the waste and distributing the contents onto the ground surface. Even if a drill hole misses a waste package, it may exhume radionuclides by removing contaminated rock.

Table 3-1. Different implementations of disruptive scenarios for Yucca Mountain

	Climate Change	Volcanism	Human Intrusion	Seismo/ Tectonics
NRC Phase 1 (1991)	• Increased Infiltration • Water Table Rise	—	• Drilling - Exhume WP - Exhume CR	—
NRC Phase 2 (1993)	• Increased Infiltration • Water Table Rise	• Waste Entrainment in Magma	• Drilling - Exhume WP - Exhume CR	• Vibratory WP Failure - WP Impingement onto Borehole Wall - WP Stress Exceeds Material Yield stress
SNL TSPA 91 (1992)	• Increased Infiltration	• Waste Entrainment in Magma	• Drilling - Exhume WP - Waste into Saturated Zone	—
PNL (1993)	• Increased Infiltration	• Waste Entrainment in Magma	• Drilling - Exhume WP - Exhume CR - Waste into Tuff Aquifer - Waste into Carbonate Aquifer	• Literature Review on Water Table Rise
EPRI Phase 1 (1990)	• Increased Infiltration	• Waste Entrainment in Magma • Water Table Rise	—	• WP Failure due to Primary and Secondary Faulting • Water Table Rise
EPRI Phase 2 (1992)	• Increased Infiltration - Current - Greenhouse - Micropluvials • Water Table Rise	• Waste Entrainment in Magma • Water Table Rise	• Drilling - Exhume WP • Excavation - Exhume WP	• WP Failure due to Primary and Secondary Faulting • Water Table Rise

CR = Contaminated Rock, WP = Waste Package

Seismo/tectonic events have been perceived as being the least important for Yucca Mountain, and different implementations have focused on a variety of effects. For example, the EPRI implementation focuses on a different set of failure mechanisms than the NRC implementation. In contrast, there is much more agreement on the importance and/or consequences of the other disruptive scenarios. The recent IPA effort models premature failure of waste packages due to vibratory ground motion resulting in early release of radionuclides from the waste packages. Two modes of waste package failure are considered in the NRC IPA effort: waste package impingement onto borehole wall, and mechanical stresses exceeding the material yield stress as the waste package vibrates in the borehole. In comparison, the EPRI effort concentrated on primary and secondary faulting, which may give rise to sufficiently large rock displacements that waste packages located along slip planes would rupture under the mechanical load. In addition, the EPRI effort modeled the rise in the water table due to seismic events.

In addition to these four disruptive EPs, the base case is considered as a scenario class. The base case includes the release and transport mechanisms which occur in the absence of the disruptive events, and represents a continuation of present day conditions.

3.2 BASE SCENARIO CLASS

In general, PA proceeds by defining a set of FEPs which can affect the release of radionuclides from the repository and transport of the released radionuclides from the repository to the accessible environment. The IPA Phase 2 work differs from the FEP approach used by the DOE and international organizations by subsuming features, such as faults and hydrologic parameters, within the conceptual models, mathematical models, and/or parameters used in consequence analysis. In order that a distinction can be drawn between the repository system (the underground facility and emplaced waste packages, and the GS within the accessible environment) and the environment external to the repository system, repository- and waste-induced EPs are also subsumed within consequence analyses. Therefore, the IPA Phase 2 scenario analysis only creates scenario classes by considering disruptive EPs (EPs which originate outside the repository system and potentially initiate change within the repository system) (see Section 3.3 of U.S. Nuclear Regulatory Commission, 1993).

Scenario classes are formed from each possible combination of occurrence (or lack thereof) of the considered EPs. Each EP has an associated probability of occurrence (calculated by the analysts), thus each scenario class has an associated probability of occurrence. Certain of the scenario classes can be neglected (screened), due to the unlikelihood of the combination occurring, and only a reduced set of interactions need be considered. For each considered scenario class, a LHS scheme is used to determine a CCDF conditional on occurrence of the scenario class. Breaking the EPs into a set of scenario classes in this way concentrates computational effort on combinations of input parameters that might be difficult to evaluate using pure random sampling.

Certain of the EPs representing disruptive change are considered highly likely to occur, such as seismic activity and human intrusion through drilling, thus the probability of the base case scenario class is quite low. It can be argued that high-probability disruptive EPs are appropriately incorporated into the base case scenario when using the PA as a tool for repository design; nevertheless, when identifying high-priority areas for further investigation, a nominal-event base case scenario class provides a standard for assessing the effects of the various disruptive processes.

3.2.1 Description and Critique of Current Modules

For radionuclides to reach the external environment, one or more waste packages must fail, and any escaping radionuclides must be transported through the geologic setting. Thus, a two-part conceptual model of the repository system can be constructed where only processes affecting waste package failure are considered in one part, and only processes affecting transport of released radionuclides are considered in the other part. Once a radionuclide is released to the external environment, further calculations of the human dosage consequences may be performed.

Under base case conditions, it is assumed that waste packages do not fail due to mechanical impacts, but only fail due to corrosion. In general, corrosion rates depend on temperature, moisture, and chemical constituents dissolved in the water contacting the waste packages. The temperature of the waste packages is affected by the generation of heat due to atomic decay within the waste package, and the transport of heat away from the waste package through thermal convection and transport of heat in moving water. Moisture near the waste packages is affected by temperature, with water vaporizing at high temperatures; further, thermal gradients will induce moisture flow. Both processes are affected by the porous medium, which is fractured and possibly highly heterogeneous, resulting in complex three-dimensional (3D) flow fields. As the generation of heat within the waste packages varies with time, temperature-dependent flow of water also varies with time.

Under base case conditions, transport of radionuclides to the external environment occurs primarily through dissolved or colloidal transport in the water phase. Gaseous phase transport is also important for volatile-radionuclide releases. As noted above, moisture flow paths can be extremely complex; gaseous phase transport is affected by similar processes. When considering transport of radionuclides, it is also necessary to consider interactions of the radionuclides with the porous medium, and daughter products from radioactive decay.

For the purposes of TSPA, it is desirable to capture only the most essential aspects of the physics applied to the accessible environment system. In the Phase 2 version of the TPA code, the complex behavior of the moisture flow field is represented by a network of one-dimensional (1D) steady-state flow tubes, abstracted from a two-dimensional (2D) representation implemented with the DCM3D code. As flow is considered steady-state, time-varying infiltration cannot be accommodated. Transient thermal effects are assumed independent of moisture distributions and affect the rate of corrosion. It is assumed that, when temperatures at the waste packages are above the boiling point of water, no corrosion takes place; however, moisture transport is otherwise unaffected by thermal distributions. Waste packages are represented by a few representative average packages. Near the waste packages, the details of moisture movement are abstracted into a funnel factor, representing the fraction of the average moisture flux contacting waste packages. Colloidal transport of released radionuclides is treated mathematically as dissolved transport, and all interactions of released radionuclides with the porous medium are represented by linear adsorption.

3.2.2 Recommendations for Improvement

There are a number of strong assumptions made in the interests of computational efficiency embedded in the abstraction procedure. These include: (i) the assumption of steady-state flow; (ii) the assumption that thermal processes are uncoupled from moisture processes; (iii) the funnel factor representation of local flow around waste packages; (iv) 1D network representation for radionuclide transport; and (v) reduction of radionuclide/porous medium interaction to linear adsorption. It is expected that these simplifications can only capture first-order, or averaged, effects, compared to more detailed analyses; however, quantitative analyses bounding the effects of simplification have not begun, as the IPA Phase 1 and Phase 2 work focused on creation of the TPA code.

In order to justify the simplifications embedded in the TPA code, three auxiliary analyses are recommended:

- assess the appropriateness of the current flow module, particularly the assumptions of isothermal and steady-state flow
- assess estimates of flow past the waste packages, particularly the values for the funnel factor
- examine the effects of the radionuclide transport assumptions, particularly the adsorption characteristics for each radionuclide

The first recommendation is a response to the simplistic nature with which flow processes are treated. The steady-state assumption and the isothermal flow assumption should be assessed for the corresponding effects on transport. In addition, the effects of spatially and temporally varying infiltration should be assessed.

The second recommendation suggests that the source module be addressed in more detail. In particular, corrosion is highly dependent on moisture, thus moisture pathways should be assessed rigorously. This may require that thermal effect simulation be addressed as well.

The third recommendation urges that the linear adsorption isotherm assumption be examined, as the form of the distribution coefficient has a significant impact on radionuclide transport. This point is demonstrated in an auxiliary analysis in IPA Phase 2 (Appendix D of U.S. Nuclear Regulatory Commission, 1993). Based on the auxiliary analyses, it is possible that modifications to the TPA code will be found desirable.

3.3 CLIMATE CHANGE

The Yucca Mountain site is located in an area with a climate which is classified as mid-latitude desert, with annual precipitation less than 150 mm (6 in) and extremes of temperature. Rainfall is sporadic, sometimes torrential, and can lead to local flooding. It has been estimated that only 0.33 percent of the annual precipitation (0.508 mm, 0.02 in) reaches the deeper units of the unsaturated zone (Department of Energy, 1988).

Temperature and precipitation variation impact the performance model through their effects on the net infiltration. Changes in temperature primarily affect evapotranspiration rates. Increasing temperature increases the evapotranspiration potential, thereby decreasing net infiltration. Similarly, decreasing temperature increases net infiltration.

Paleoclimatic studies indicate that, over the past 10,000 yr, climatic conditions were similar to present conditions in the region of Yucca Mountain, with occasional cooler and wetter intervals lasting from years to decades in length. Prior to this, wetter and cooler conditions prevailed for perhaps

20,000 yr, contemporary with large-scale glacial activity in more northern areas. Periodic glacial activity existed prior to this, with sufficient precipitation to form numerous lakes in the Great Basin province (Department of Energy, 1988).

The most probable climate change of significance is thought to be either a trend towards cooler/wetter conditions, or relatively short periods of wetter conditions (tens to hundreds of years). The significance of wetter conditions is that infiltration would increase, thereby increasing both the release (due to increased corrosion of waste packages) and transport (due to high liquid flow rates in the ground) of radionuclides.

3.3.1 Description and Critique of Current Module

In IPA Phase 2, the climate change is modeled as increased infiltration and elevated water table due to the occurrence of a pluvial climate. Increased infiltration and water table rise are considered the primary effects of increased precipitation. The current implementation is relatively straightforward and is depicted in a logic diagram in Figure 3-1. The pluvial climate is assumed to occur immediately after closure of the repository and continue for 10,000 yr. The infiltration is determined by a random sampling between 5 and 10 mm/yr (as compared with the 0.1 to 5 mm/yr in the base case). The water table is modeled to rise 100 m above the present elevation during a pluvial climate. The consequence for a pluvial climate is implemented through the FLOWMOD module which accounts for hydrologic effects on the source term (SOTEC module) and decreased travel time in the unsaturated zone. One conclusion of the IPA Phase 2 effort was that infiltration for the pluvial climate scenario has a large impact on repository performance (U.S. Nuclear Regulatory Commission, 1993).

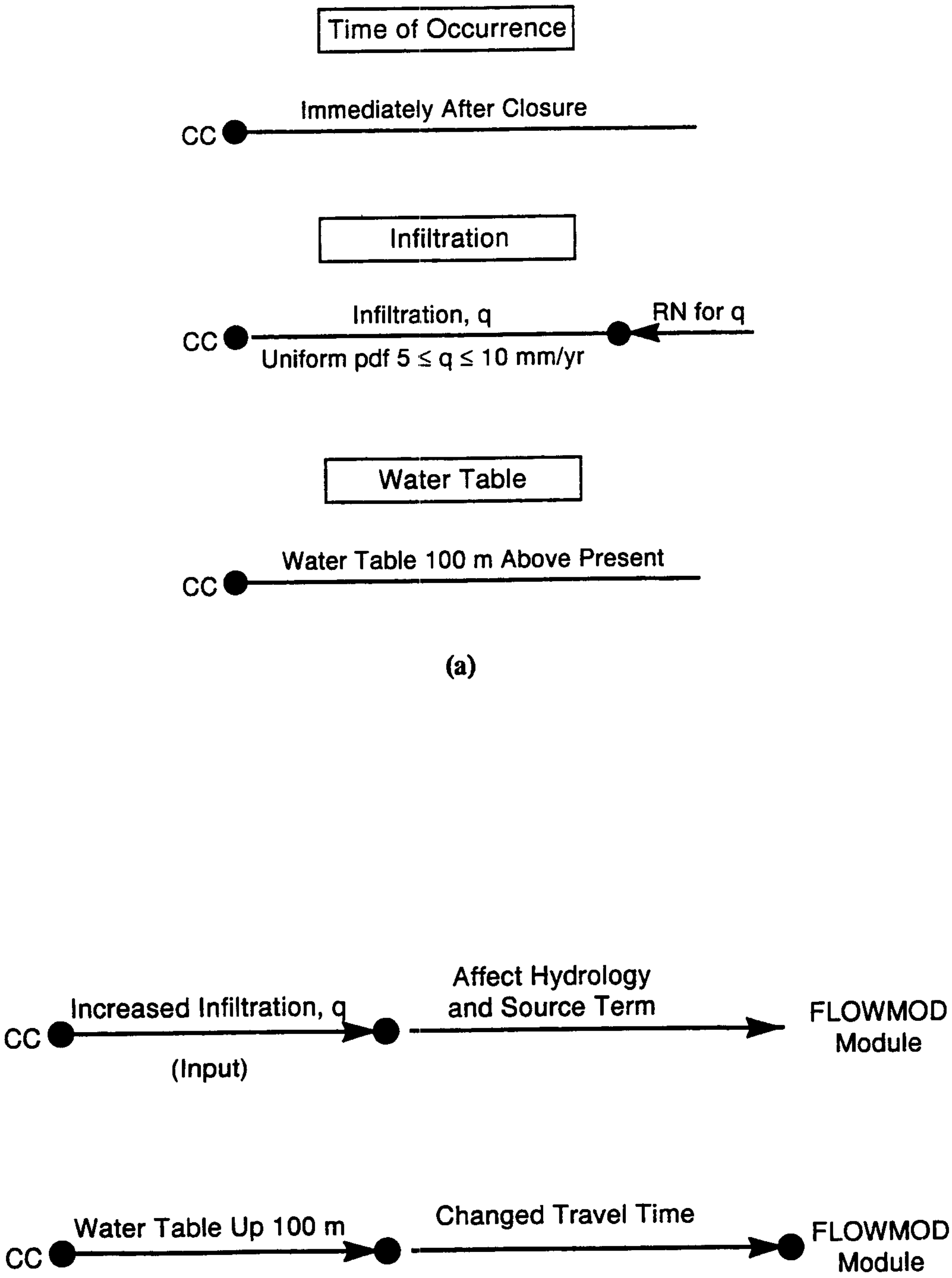
There is no provision in the TPA code for time-varying infiltration, as steady-state conditions are assumed to exist at all times. This restriction on the basic capability of the code implies that the climatic model can only consider steady-state conditions.

Moving toward a capability for time-varying climatic changes was addressed using expert elicitation in a recent report by DeWispelare et al. (1993). Five experts in climatology were assembled, and each provided opinions on climate at Yucca Mountain over the next 10,000 yr. For the categories of average temperature, winter and summer precipitation, maximum precipitation over a decade, and cloud cover, each expert provided expected values and 95 percent confidence bounds for 100, 300, 1000, 3000, 5000, 7500, and 10,000 yr in the future. Although this exercise was mainly a demonstration of expert elicitation procedures, this information can be used to estimate time-varying probability distributions of rainfall for use in future modules. Prediction of net infiltration from this information, however, would need to be performed.

3.3.2 Recommendations for Improvement

The current module is quite simplistic. The simple treatment of flow processes is assumed to be conservative, but the degree of conservatism is uncharacterized. Accordingly, the following are recommended (which are similar to recommendations for the base case):

- investigate the linkages between climate and infiltration



(a)

(b)

Figure 3-1. Logic diagrams for: (a) description; and (b) consequence of climate change as implemented in IPA Phase 2

- assess the importance of temporally and spatially varying infiltration, especially the influence of short-term, torrential thunderstorms on infiltration
- assess the effect of incorporating data from expert elicitations into the climate module

Modeling of these effects should provide a more defensible model of infiltration rate which has been found to be an important parameter in both IPA efforts (U.S. Nuclear Regulatory Commission, 1992; 1993).

3.4 VOLCANISM (VOLCANO MODULE)

Approximately five volcanic events have occurred near the Yucca Mountain area within the last 3.7 million yr (Connor and Hill, 1993). Estimates of the recurrence of volcanic activity in the vicinity of the repository vary from about 10^{-4} to 3×10^{-4} in the next 10,000 yr (Connor and Hill, 1993). Typically, volcanic risk assessment at Yucca Mountain has focused on determining the probability of a direct volcanic occurrence which would directly interact with the waste, thereby altering the physical and chemical properties of the waste, and possibly transporting the waste in the magma. Scenarios have been generated to consider waste transport to the ground surface because surface release of waste has a relatively large consequence. Direct intrusion of magma into the repository, however, has a relatively low probability of occurrence.

Magma intrusion into the vicinity of the repository (within about 10 km) may also lead to accelerated release and transport. Hence, recent analyses do consider proximal volcanic occurrences and indirect consequences (i.e., magma does not directly contact the waste). Possible indirect effects include (but are not limited to):

- changes of the liquid/vapor chemistry around waste packages which may accelerate corrosion of waste containers
- changes of the hydrology and flow fields which may accelerate transport of waste through the geologic media
- development of increased economic resources in the vicinity which may increase the likelihood of human activity in the region, and
- increasing the potential for seismo/tectonic activity in the area which may affect different release and transport phenomena

Increasingly, analysts are considering the indirect consequences of volcanic events as well as direct volcanic effects.

3.4.1 Description and Critique of Current Module

The current NRC/CNWRA volcanism module (called VOLCANO) is primarily devoted to the analysis of the effects of a direct volcanic occurrence which interacts with the waste. Indirect effects are not currently modeled. Direct effects are based on either extrusive or intrusive volcanic activity.

For extrusive events, waste is assumed to be transported in the magma to the ground surface. For an extrusive event, a conservative assumption is adopted so that all of the intercepted waste is released to the accessible environment. For an intrusive event, the waste packages are altered to effectively fail the waste package, and release the waste into the geologic medium for subsequent transport to the accessible environment.

A logic diagram for the description portion of the VOLCANO module implemented in IPA Phase 2 is shown in Figure 3-2 [the node volcanic event (VE) corresponds with that in Figure 2-3]. The current implementation is based on geometric considerations of an upward flowing magma in order to calculate the number of waste packages intercepted by the magma. The following description of a volcanic event are considered:

- time of occurrence
- location of occurrence
- intrusive or extrusive description
- dike geometry
- cone geometry

The time of occurrence is determined by a random number (denoted as RN in Figure 3-2) which is used to sample from a uniform PDF yielding times from 0 to 10,000 yr. Similarly, the location is determined by random sampling from uniform PDFs for both x and y. Intrusive disruptions are considered 10 times more likely than extrusive disruptions. For intrusive events, only a dike is considered. For extrusive events, a coincident dike and cone are considered. The dike geometry is described by width, length, area (area equals the product of width and length), and orientation angle measured from the east and rotating to the north. The cone geometry is described by a radius which is selected from a uniform PDF from 25 to 100 m.

After a volcanic event is described, the consequence analysis can be performed. A FORTRAN-type flow diagram is presented in Figure 3-3 for the consequence analysis a volcanic event as implemented in IPA Phase 2. The first step is to calculate the radionuclide inventory and area of repository intercepted by the waste. These calculations are independent (as shown in Figure 3-3) because the radionuclide inventory only depends on the time of occurrence, and the intercepted area depends on the geometric information (location, dike geometry, cone geometry). The intercepted waste is calculated next as the fractional summation of affected inventory. If the event is extrusive, it is assumed that the affected inventory is released to the accessible environment in the AIRCOM module (see Sagar and Janetzke, 1993 for a description of the TPA code and each module). For intrusive events, the affected inventory is released from the waste packages [this is implemented through the Source Term Code (SOTEC) module] and is available for transport through the geologic medium.

A logic diagram for the consequence analysis of the VOLCANO module implemented in IPA Phase 2 is shown in Figure 3-3. The logic diagram is an alternative graphical format for the same information presented in the preceding flow diagram. Both the logic diagram and flow diagram are used to emphasize that either format is useful.

The current IPA Phase 2 implementation requires a significant number of random numbers to describe the size, location and geometry of an event. The heavy reliance on random numbers is a distinction from the event-tree scenario implementations (e.g., Cranwell et al., 1990; Barr and Dunn, 1993). In event-trees, the events are described without reliance on random number generators (which are

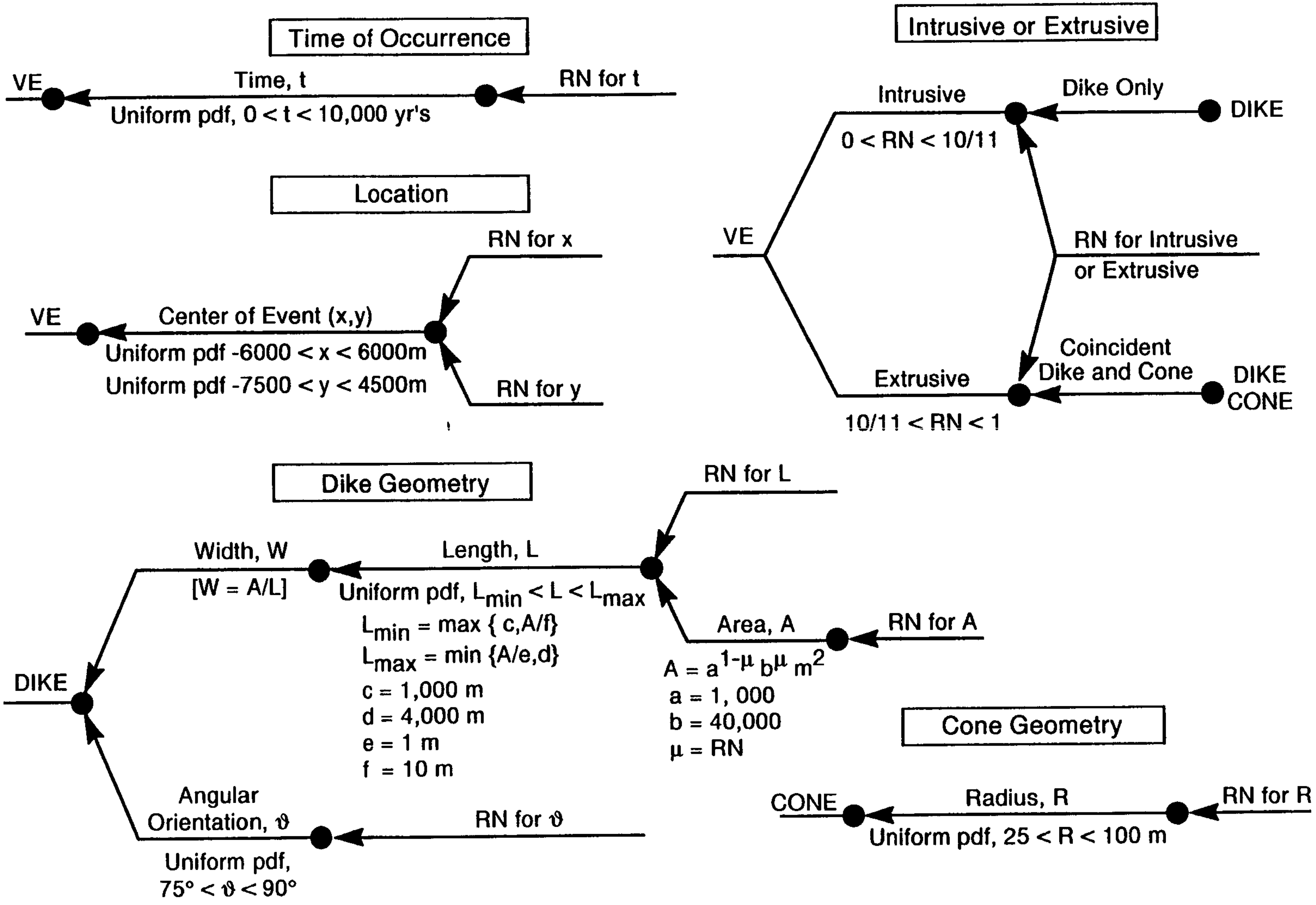


Figure 3-2. Logic diagram summarizing the description of volcanic events implemented in IPA Phase 2

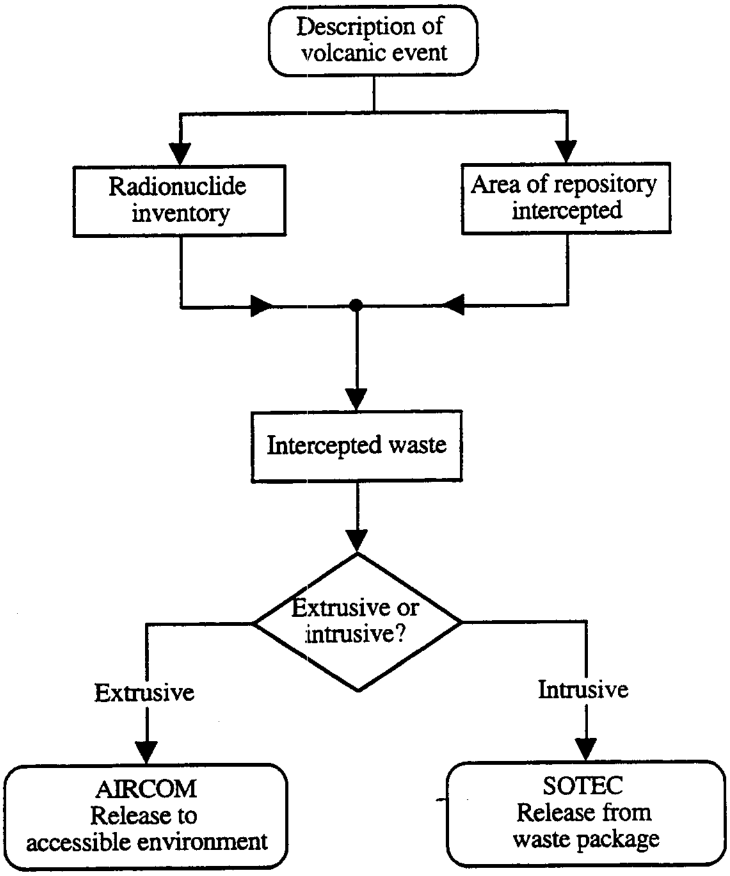


Figure 3-3. Flow diagram summarizing the consequence of volcanic events implemented in IPA Phase 2

used primarily to account for parameter uncertainties). In the diagram, the probability of alternative descriptions is explicitly described by the analysts. In doing so, the analysts are encouraged to proceed in a logical, step-wise description of the problem. The increased detail of description frequently yields benefits such as the identification of scenarios which are not of consequence and need not be modeled. In the current IPA implementation, the center of events can range over 144 km^2 area (12000 × 12000 m), yet the maximum radius of a cone is 100 m and the maximum length of a dike is 4000 m. Hence the vast majority of cones, and a large fraction of dikes, will not contact the repository. In the current implementation, a volcanic event has a consequence if and only if the magma contacts the waste. Hence, it appears that a significant computational effort is devoted to individual volcanic events which have no consequence.

3.4.2 Recommendations for Improvement

The following improvements are recommended for the VOLCANO module:

- Increase usage of volcanologic experts to generate conceptual and mathematical models of volcanic events and their consequence. In particular, the expert(s) should either concur or improve estimates of:

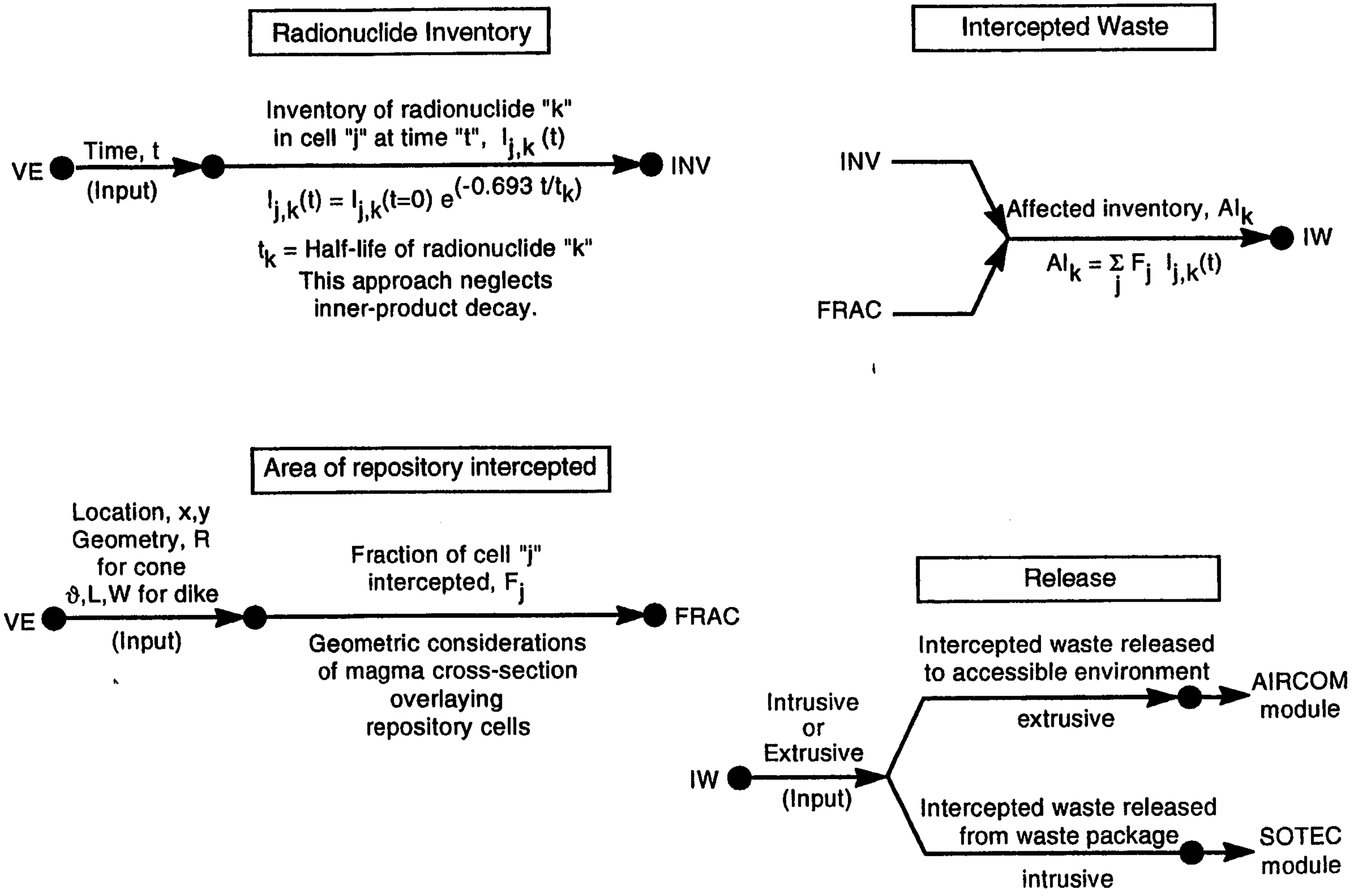


Figure 3-4. Logic diagram summarizing the consequence analysis for volcanic events implemented in IPA Phase 2

  - probability of occurrence (i.e., recurrence probabilities)
  - descriptions (e.g., dike versus cone, intrusive versus extrusive)
  - anticipated consequences (e.g., waste entrainment, waste release, near-field water chemistry, regional hydrology)

- Expand the consequence analysis to include indirect effects of nearby volcanic events on the accelerated corrosion/failure of waste packages.

These recommendations are based on discussions with volcanologic experts who were not involved in the design of the current module. As one might expect, these experts have new ideas and perspectives on what should be modeled and what are acceptable models. It is only logical, therefore, that the most defensible models be incorporated in future modules.

3.5 HUMAN INTRUSION (DRILLO MODULE)

Human activity can lead to disruption to the repository. Analyses of human intrusion neglect advertent human activity (Miklas et al., 1992) and concentrate on inadvertent activity such as surface-based drilling and subsurface mining (Nuclear Energy Agency, 1989). For the IPA effort, only inadvertent exploratory drilling was considered.

3.5.1 Description and Critique of Current Module

Drilling is the sole direct human intrusion mechanism investigated in IPA Phase 2. Two modules were developed for drilling: DRILLO and DRILL1. The first module describes the drilling events, and the second calculates the consequence of the events. A logic diagram is presented in Figure 3-5 for the description of drilling events as implemented in DRILLO. The important characteristics of drilling events are:

- number of holes drilled
- time of drilling occurrence for each hole
- cell of the repository which is intruded by the drilling event
- drill hole radius
- hit or miss waste package determination

For each realization (or execution of the DRILLO module) the number of drilling events, *n*, is calculated using a random number sampling from a Gaussian PDF which has a mean of 15.4 events and a standard deviation of 15.4 (the standard deviation was chosen to be equal to the mean because this is a characteristic of a Poisson distribution which indicates the drilling event are rare and have no correlation). The number of events is limited to not be less than 0 and not greater than 30, hence, it appears that no drilling (i.e., 0 events) occurred ~1/6 of the time and 30 events occurred ~1/6 of the

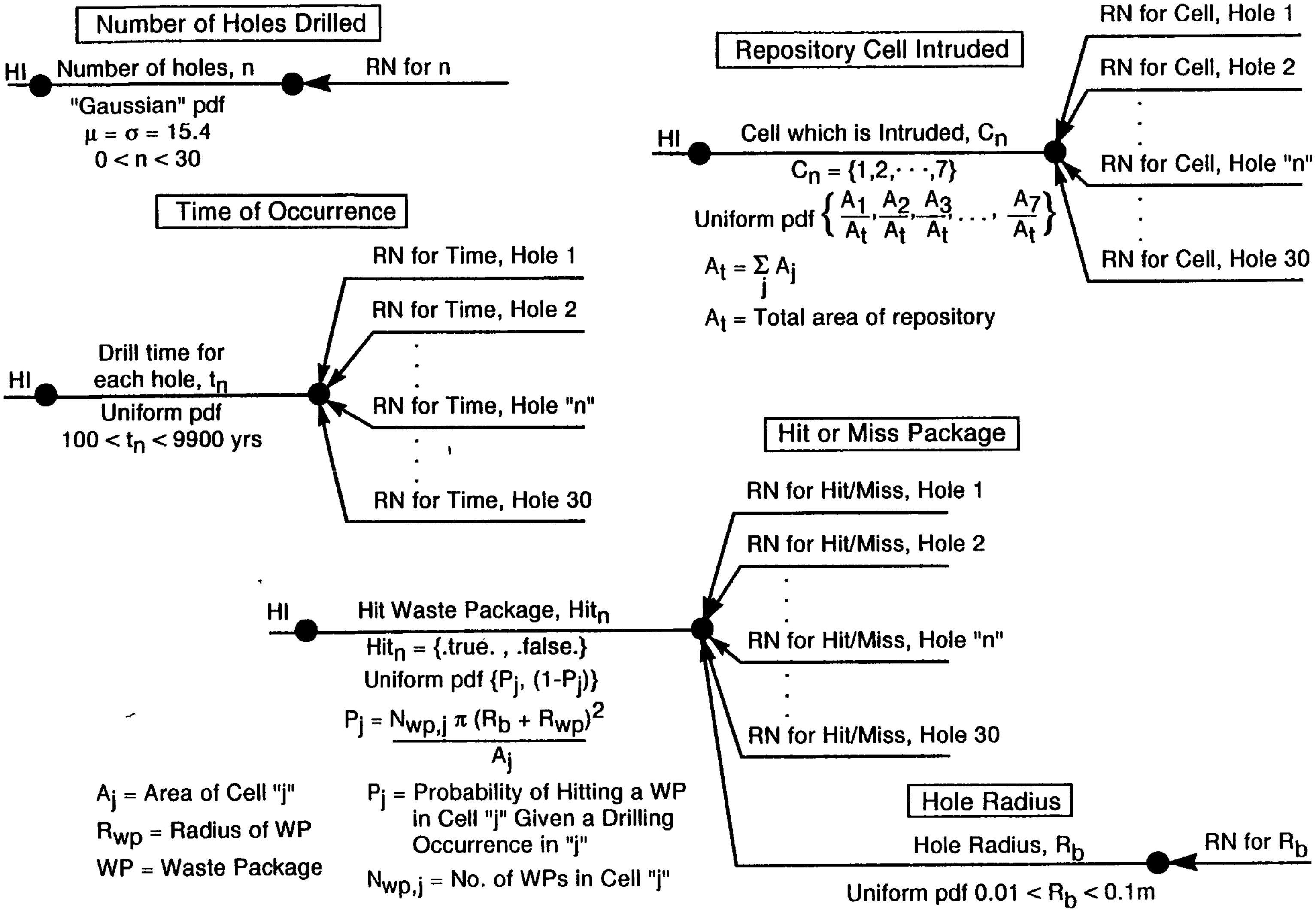


Figure 3-5. Logic diagram summarizing the description of drilling events as implemented in IPA Phase 2

time. The mean number of drilling events was determined using the drilling rate suggested in 40 CFR Part 191 for nonsedimentary rocks (3 boreholes/sq km/10,000 yr), and the area of the repository (5.1 sq km). The average number of drilling events is then estimated to be 15.4 events within the 10,000-yr time period.

The time of occurrence is determined for each drilling event using a random number to sample from a uniform PDF from 100 to 9900 yr. This requires 30 random numbers for the maximum of 30 drill holes, however, only the first *n* drill times are of interest in the simulation. Institutional control is assumed to exist and prohibit drilling for the first 100 yr. The restriction of no drilling events from 9900 to 10,000 yr appears to be a limitation of the implementation. Although not very aesthetic, this limitation has essentially no effect on the consequence.

Each drill hole is assumed to be within the repository area, therefore, each hole will intrude one of the seven repository cells used to discretize the repository in IPA Phase 2. The cell number which is intruded is determined using random numbers. This requires a total of 30 random numbers of which only the first *n* are of interest in the simulation.

Although the drill hole radius is assigned a random value from 0.01 to 0.1 m, the radius of each hole is assumed to be the same for each realization of the DRILLO module. For example, if multiple holes were assumed to be drilled at different times, each hole is assumed to have the same radius. This assumption implicitly contradicts the previous modeling assumptions that the drill holes are uncorrelated in time and space. Again, this appears to be an assumption driven by implementation convenience. It would be more consistent with the current implementation if each drill hole had a distinct radius.

For each drill hole, a calculation is performed to determine if it hits (or misses) a waste package. The drill hole is assumed to hit a waste package if a random number is less than the probability for the cell intruded, and conversely it misses if the random number is larger. The probability of a hit for the cell is determined using the number of waste packages for each cell, the drill hole radius, the waste package radius, and the total area of the cell (the equation is given in Figure 3-4 and in U.S. Nuclear Regulatory Commission, 1992).

As implemented, the DRILLO module requires 92 random numbers to fully describe a realization of drilling events. It should be noted that many of the random numbers are not used in the simulation because only the first *n* are used to determine time of occurrence, hit or miss, and cell intruded.

A flow diagram for the consequence analysis of drilling events is presented in Figure 3-6. In DRILL1, three items can initially be determined independently: the earliest drill time, the cumulative number of holes in each cell, and the cumulative number of waste packages hit in each cell. The radionuclide inventory is calculated in each cell based on the earliest drill time for the drill holes (regardless of the cell intruded). It is assumed that the radionuclide inventory is located in either of two locations: in the waste packages or in the geologic medium beneath the repository. This is based on the assumption that only a negligible quantity of radionuclides are in other locations such as in the rock outside of the region beneath the repository. Hence, two sources of intercepted waste are calculated: in the intercepted waste packages, and in the rock column due to drilling through contaminated rock. Each of these two components is calculated and summed to predict the total intercepted waste. The intercepted waste is assumed to be promptly released to the accessible environment at the earliest drill time (this includes those occurring at later times) and this is implemented through the AIRCOM module.

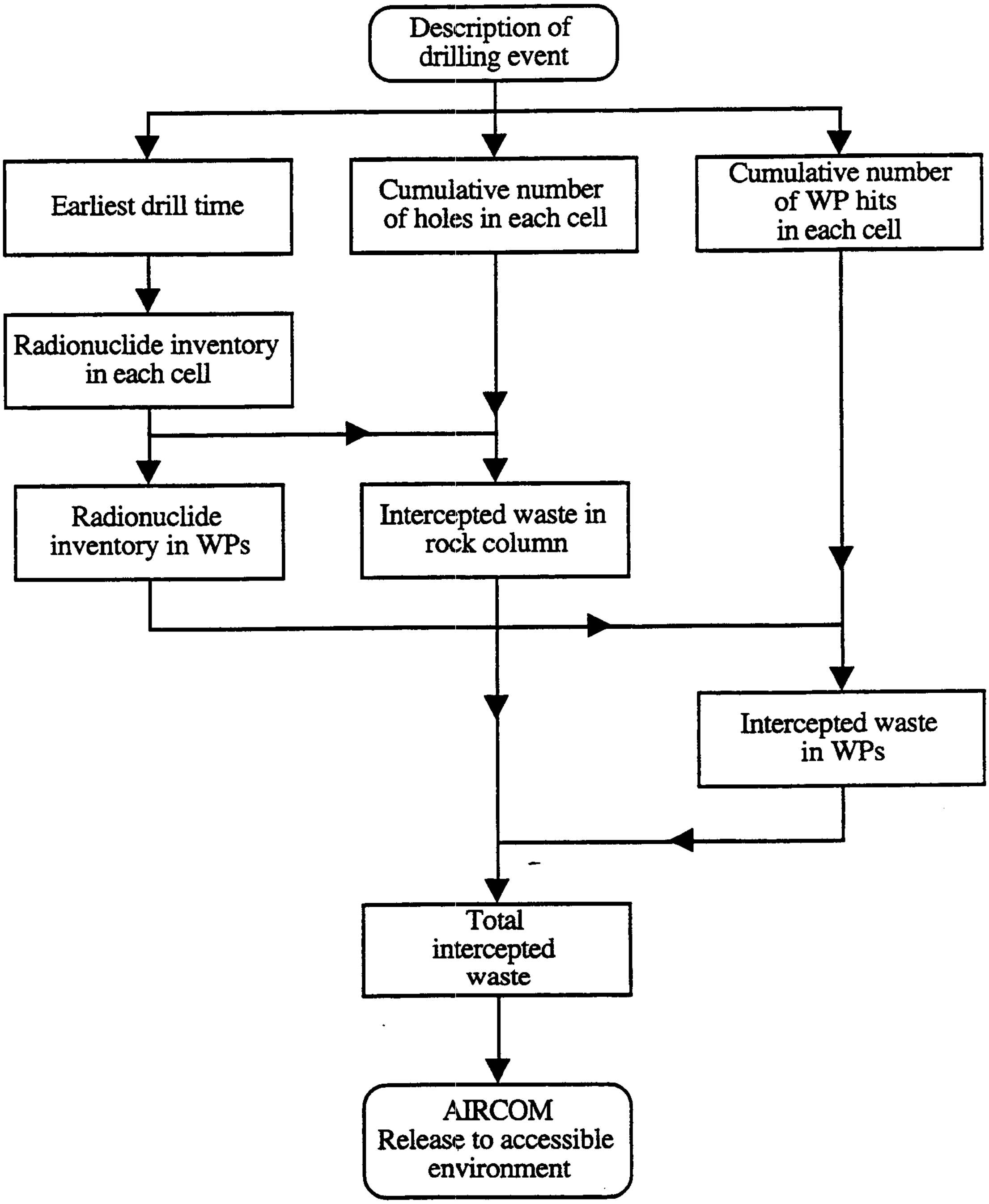


Figure 3-6. Flow diagram summarizing the consequence analysis of a drilling event as implemented in IPA Phase 2

A logic diagram has been constructed for the consequence analysis of drilling events and is presented in Figure 3-7. The logic diagram expresses the same information as presented in Figure 3-7; however, more of the mathematical details are presented in the logic diagram.

A number of assumptions have been employed in the consequence analysis of drilling events:

1. A boring is considered to extend to the water table (i.e., not stop above the repository).
2. Any contact with a waste package releases the entire contents of the package.
3. All waste packages hit during a 10,000-yr simulation release their contents at the time the first package is hit.
4. The probability of drilling is uniformly distributed over the repository.

The first two assumptions appear reasonable and conservative. The third assumption is overly conservative and appears to be motivated by implementation convenience or module limitations. The fourth assumption is unrealistic, as most drill holes are presumably vertical so that drilling rates are lower in areas of steep surface slopes. Much of the repository is overlain by steep surface slopes.

Other assumptions are not conservative:

- a hole drilled near, yet not directly over, the repository has a negligible effect on repository performance
- no consideration is given to the effects of drilling fluids
- no consideration is given to preferential gas and fluid pathways created by boreholes which may lead to accelerated release and transport
- no releases to the saturated zone (as is considered in other implementations, see Table 3-1) are considered

As implemented in IPA Phase 2, drilling is reported to have an insignificant impact on the cumulative release CCDF (i.e., the conditional CCDFs for the base-case and drilling-only scenario classes are indistinguishable). (U.S. Nuclear Regulatory Commission, 1993). The lack of a significant effect may be attributed to the relatively low probability of such an event occurring, and the neglect of secondary effects due to drilling. In addition, human activities other than exploratory drilling were not considered.

In order to avoid defensibility issues when predicting human intrusion, the 40 CFR Part 191 regulatory standard allows the assumption that current practices continue in the future, once institutional control on the site lapses (i.e., 100 yr after closure). The frequency of drilling required by 40 CFR Part 191, Appendix B, is believed to be based on the exploration rates for oil prospecting, with a frequency ten times larger for repositories located in sedimentary formations than for nonsedimentary formations. Apostolakis et al. (1991) reports that, using procedures for gold prospecting common to Nevada, drilling rates may be several orders of magnitude higher than suggested by 40 CFR Part 191, yet the typical depth

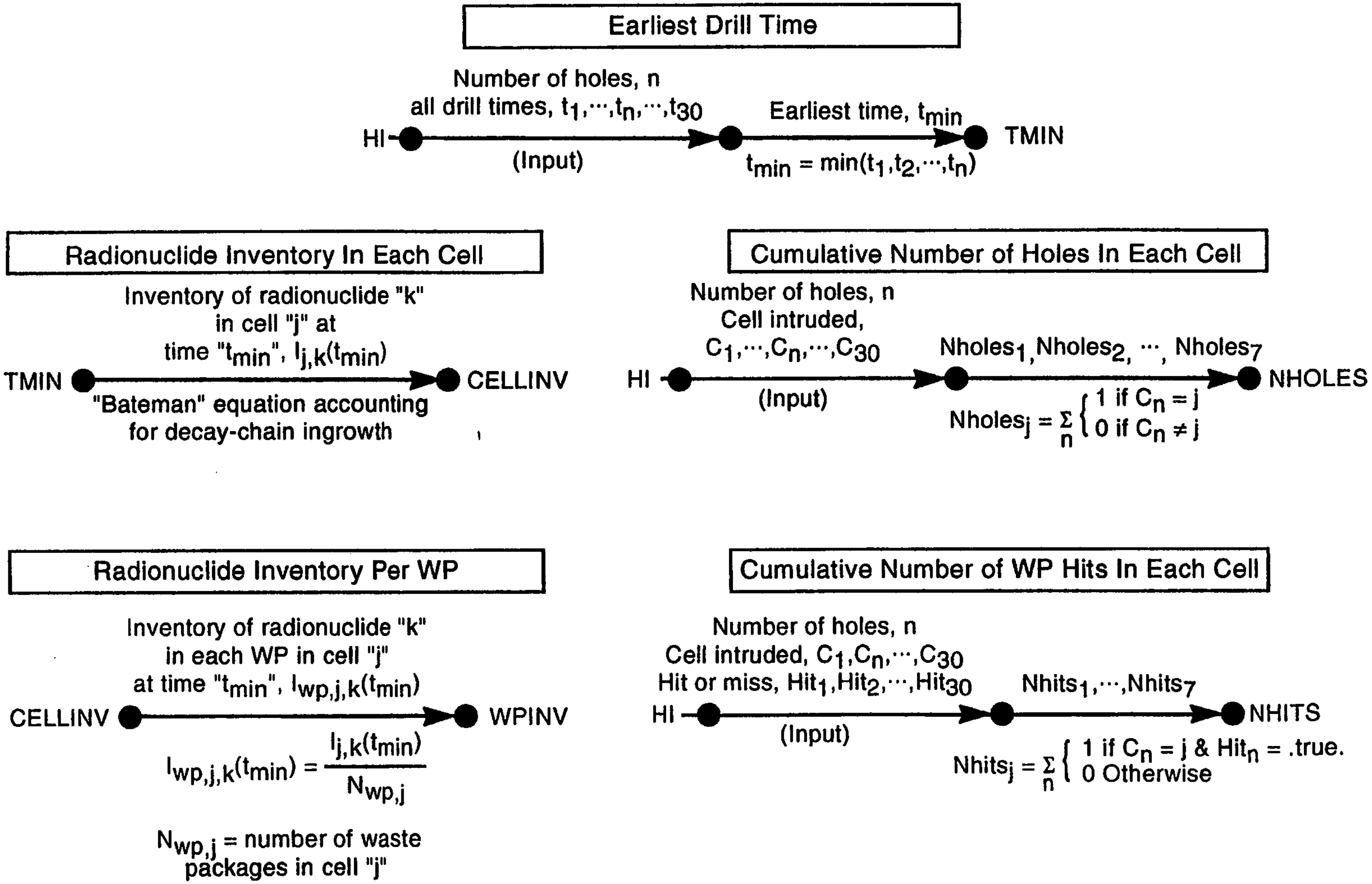


Figure 3-7. Logic diagram summarizing the consequence analysis of a drilling event as implemented in IPA Phase 2

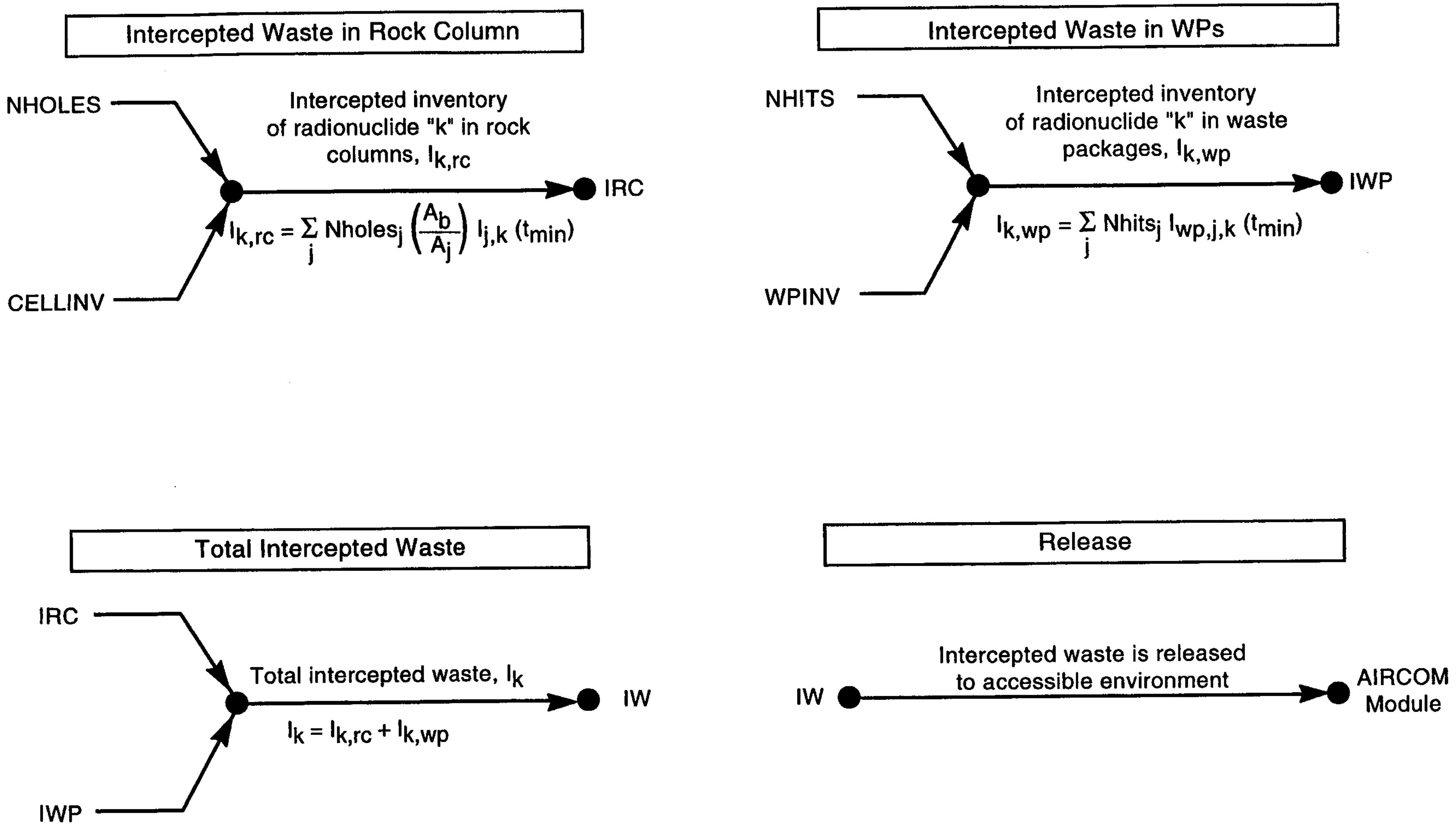


Figure 3-7. Logic diagram summarizing the consequence analysis of a drilling event as implemented in IPA Phase 2 (Cont'd)

of prospecting drill holes may not be as deep as exploratory holes (hence these drill holes may not reach repository depths).

Sandia National Laboratories has also considered human intrusion by drilling in the context of their TSPA for Yucca Mountain (Sandia National Laboratories, 1992). The SNL study examines both surface releases and saturated-zone releases. The surface release scenario is similar to the IPA Phase 2 approach. The SNL report concludes that human intrusion due to drilling does not have a large impact on the compliance CCDF using the drilling frequency specified in 40 CFR Part 191. As the drilling frequency increases, however, the impacts become more significant. It was also indicated that direct releases are orders of magnitude larger than releases due to saturated-zone transport (Sandia National Laboratories, 1992). Although the mechanisms for saturated-zone transport are necessarily represented in a crude way, it is expected that dilution and delay effects inherent in saturated-zone transport are sufficient to make saturated-zone transport pathways considerably less significant than direct-release pathways when considering drilling disruptions. Accordingly, unless some plausible conceptual model is offered to release larger radionuclide quantities to the saturated zone due to drilling than are released to the surface, saturated-zone transport presumably is not significant unless direct surface releases are shown to be significant.

3.5.2 Recommendations for Improvement

The most important issue to be addressed in the human intrusion scenario class is whether the drilling frequency suggested in 40 CFR Part 191 for exploratory activity is appropriate, or should a higher frequency be assumed to reflect the possibility of mineral prospecting (Miklas et al., 1992; Miklas and Lefevre, 1993). It is anticipated that an elevated rate of drilling will yield significant effects on the cumulative release performance measure (as observed by Sandia National Laboratories, 1992).

A second issue to be addressed is indirect effects of drilling. It is anticipated that the introduction of drilling fluids and boreholes can accelerate the release and transport of radionuclides, and should be considered in future calculations.

The drilling scenario is probably one of the easiest to graphically describe using either a logic or a flow diagram. In this work, both diagrams were used to describe the implementations in IPA Phase 2. Without such diagrams, it was difficult to determine what exactly was being implemented in the DRILLO and DRILL1 modules. It is, therefore, recommended that either logic and/or flow diagrams be used in the design and documentation of future modules.

3.6 SEISMO/TECTONICS (SEISMO MODULE)

Yucca Mountain is located in a region where a number of earthquakes have occurred in the recent past due to the extensional faulting which is present in the Basin and Range tectonic province. In addition to large earthquakes, numerous small-scale movements along strike-slip fault zones northwest and southwest of Yucca Mountain have been recorded. The potential impact of faulting and seismicity on the repository has traditionally focused on the premature failure of waste packages due to vibratory ground motion (i.e., shaking) or failure due to secondary faulting (Electric Power Research Institute, 1992). Shaking may lead to package failure through (i) waste package impingement on the borehole wall, (ii) borehole wall failure, or (iii) failure of waste package support (typically at the base of a package).

In addition to vibratory ground motion, a seismic process (i.e., ground shearing) may rupture waste packages inadvertently located in fault zones.

In addition to direct effects, secondary effects of seismic events may lead to accelerated release and transport of radionuclides. In particular, seismic events may change the regional groundwater flow, lead to short-term elevation of the water table near Yucca Mountain, and possibly change the ground surface infiltration characteristics.

3.6.1 Description and Critique of Current Module

SEISMO is the module which describes and calculates the effects of a seismic event on the physical integrity of a waste package. In SEISMO, the strength of the waste package is influenced by the amount of pitting and crevice corrosion, hence highly-corroded packages are susceptible to failure at lower earthquake magnitudes. SOTEC is used to communicate the amount of waste package corrosion, and SEISMO then communicates the seismically-induced failure of packages.

Two modes of failure have been modeled in SEISMO: (i) base failure; and (ii) impingement failure. Base failure is due to the vibration-induced stresses exceeding the yield strength of the waste package at the base, which is assumed to be rigidly attached at the bottom of the borehole. For base failure calculations, the waste package is modeled as a cantilever beam attached at the bottom. The second failure mode is impingement failure which is due to the motion of the free end of the waste package which may oscillate far enough to strike the side of the emplacement borehole (for simplicity, any contact with the side of the borehole is assumed to lead to package failure). In most cases, it was found that the packages failed by the base failure mode (U.S. Nuclear Regulatory Commission, 1993).

A flow diagram for the SEISMO module is presented in Figure 3-8. The SOTEC module provides information on the wall thickness of the waste package. This is used to determine the minimum ground accelerations needed to fail the package for either of the two failure mechanisms. The lowest failure threshold of the two failure modes is then calculated. The annual frequency of seismic events with magnitude greater that the minimum acceleration for failure is then calculated based on recurrence curves for Yucca Mountain. The probability of failure is then calculated for the next time step of interest in the simulation. The accumulation of probabilities dictates that the waste package will eventually fail due to seismic events (or sooner due to other causes such as corrosion). If the waste package fails, then this information is communicated to the SOTEC module to begin transport calculations. If not, then this information is communicated to the SOTEC module to allow for increased corrosion and the next time step of interest.

A logic diagram for the SEISMO module is presented in Figure 3-9. The logic diagram has more information about the implementation details than the flow diagram. Either the logic or flow diagram are useful to graphically describe the SEISMO module. The logic diagram is one long connected stream which is very similar to the flow diagram. Frequently, the description of a disruptive event is more easily presented using a logic diagram, and the consequence is more easily presented using a flow diagram. For this module, however, there is no clear distinction between description and consequence. The implementation is based on an engineering analysis which calculates the time of failure. Hence, the current implementation does not emphasize the uncertainty associated with the future-state of the repository. The uncertainty is implemented in the random number used to determine the time of failure due to the cumulative waste package failure probability. As implemented, this uncertainty could be

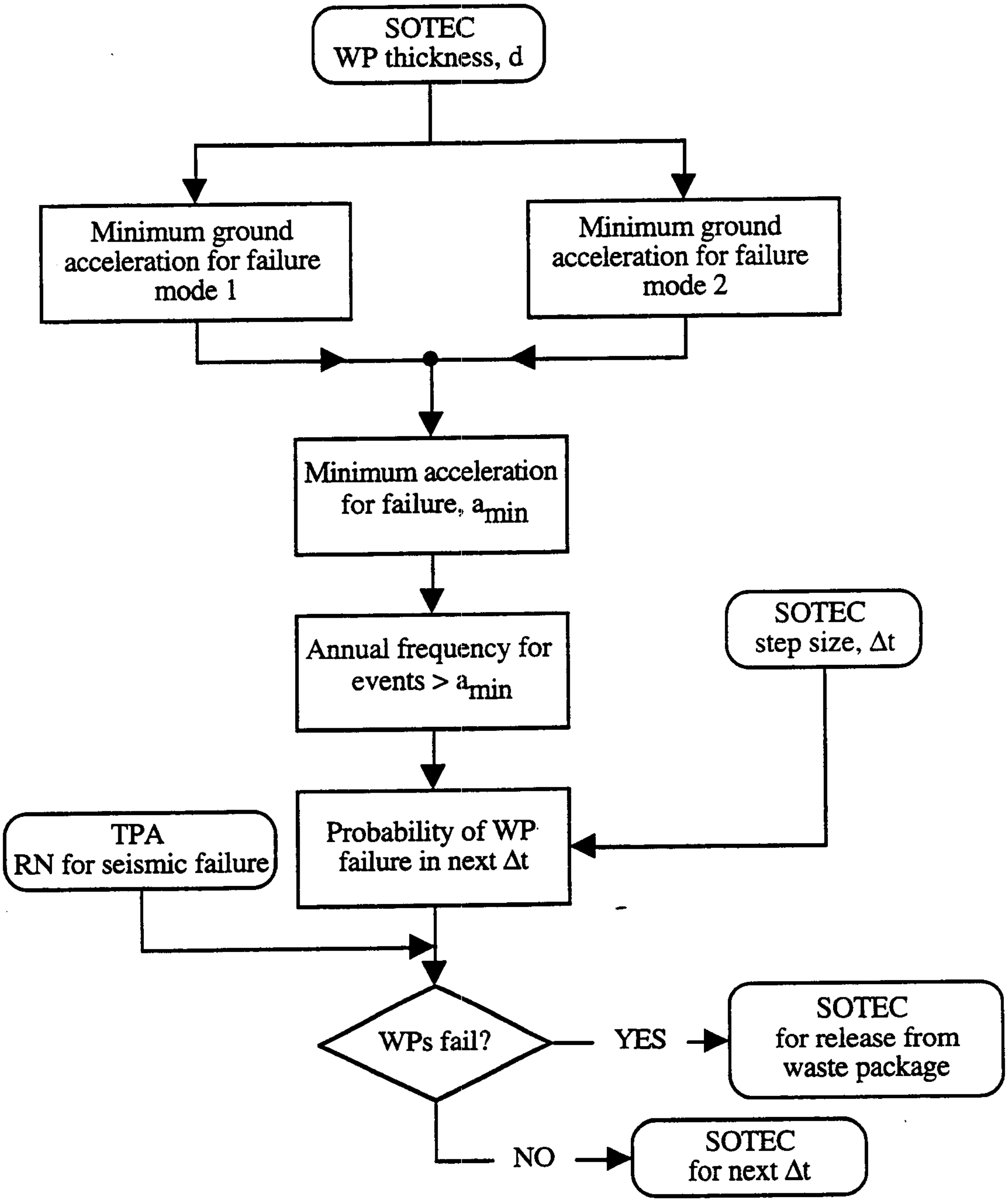


Figure 3-8. Flow diagram summarizing both the description and consequence of seismic events as implemented in IPA Phase 2

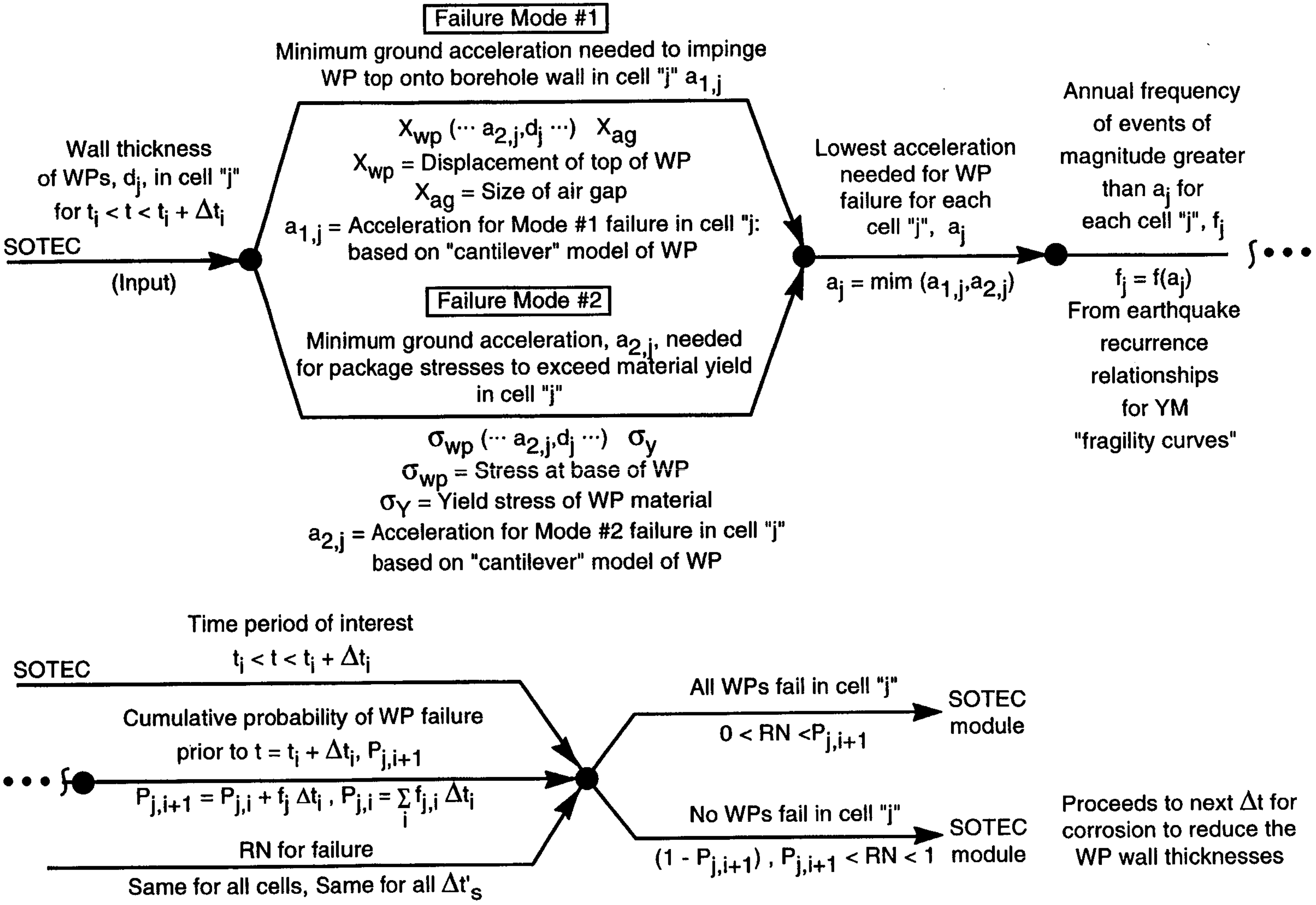


Figure 3-9. Logic diagram summarizing both the description and consequence of seismic events as implemented in IPA Phase 2

interpreted as modeling the uncertainty in the seismically sensitive, corrosion-reduced thickness of the waste package, or another parameter.

Other attempts to cast seismic activity in a scenario analysis can be found in the literature. For example, EPRI has included disruptive seismic events in their demonstration of repository PA (Electric Power Research Institute, 1992). In Figure 3-10, seismic activity within the Ghost Dance fault is progressively described, especially the magnitude of activity, slip rate, and recurrence model. Similarly, one could include time of occurrence, effect on water table, effect on waste package integrity, etc. Hence, the EPRI example demonstrates the utility of tree diagrams and scenario analysis methods for seismic events.

It should be highlighted that the recent PA efforts by SNL (1992) do not include seismic disruptive events. Although the IPA Phase 2 implementation is quite simple, it remains beyond that of other implementations.

3.6.2 Recommendations for Improvement

It is recommended that seismo/tectonic issues be investigated in order to ferret out the irrelevant details and concentrate on the important issues related to radionuclide release and transport. The overall importance of seismic and/or a seismic effects on waste package integrity and isolation remains unclear. The consequences of other disruptive events appear better defined. In comparison, a recent TSPA conducted by SNL did not include seismic events in their analyses (Sandia National Laboratories, 1992). The importance of seismo/tectonic events remains uncertain in total system performance.

In order to more fully assess disruptive seismic events, it is recommended that future analyses consider:

- aseismic effects, especially along the Ghost Dance fault
- secondary faulting effects
- seismic effects on seals for shafts/ramps
- seismic effects on near-field hydraulic conductivity which may provide preferential flow paths for increased infiltration and/or radionuclide transport

Modeling of these effects should more fully reveal the importance of seismo/tectonic events.

3.7 KEY TOPICS

In the preceding sections, the NRC/CNWRA IPA Phase 2 effort for each of the four disruptive EPs was reviewed. A number of reccurring themes have been identified:

- use of scenario classes
- distinction between description and consequence

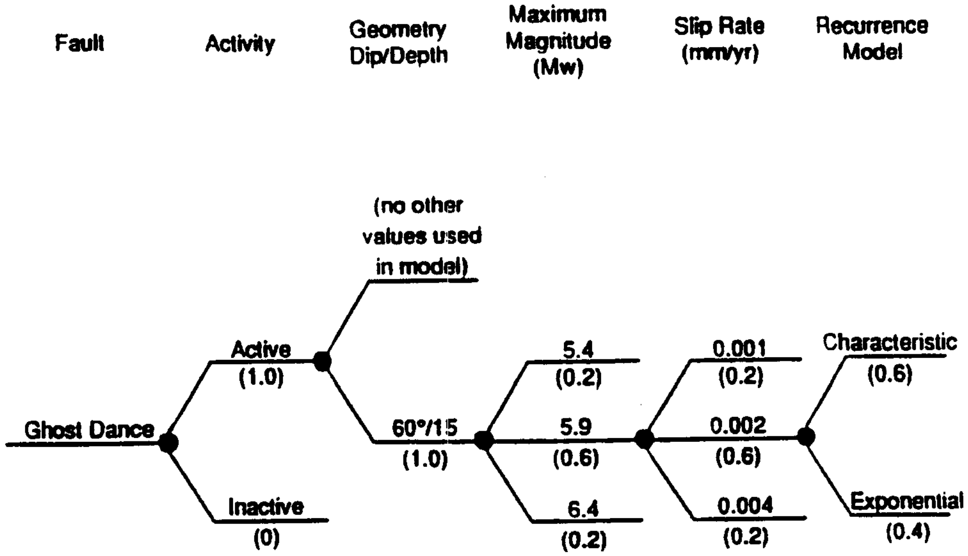


Figure 3-10. Example of a logic diagram for seismo/tectonic disruptive analysis of the Ghost Dance fault (Electric Power Research Institute, 1992)

- consistency between modules
- use of technical experts as module leads
- use of tools to organize, aggregate, and convey information
- use of random numbers

3.7.1 Use of Scenario Classes

The most significant difference between the IPA Phase 2 scenario method and other methods (e.g., Sandia National Laboratories, 1992; Electric Power Research Institute, 1990; 1992) is the adoption of scenario classes. The scenario classes capture the essence of a scenario, yet relegate the detailed descriptions and consequence analyses to the implementation (i.e., CMs). For example, the scenario analysis for volcanic events consisted primarily of assessing the probability of a future occurrence within the region within the next 10,000 yr. After assessing this probability to be 0.03, the scenario analysis ceased and the consequence analysis began. This approach has been recognized by the NRC (1993) to be distinctly different from approaches used by the DOE and other international organizations. In contrast, the recent SNL scenario report on volcanic events goes into great detail about alternative descriptions and hypothetical consequences of volcanic events (Barr et al., 1993). Hence, scenario analysis in the IPA effort has a much narrower interpretation than in other efforts.

As implemented, the scenario class approach yields only one value for the probability of a disruptive event occurring within the next 10,000 yr. For example, a pluvial climate is given the probability of 0.64 (see Figure 2-3). As implemented, there is no way to account for the uncertainty in the probability of occurrence for each of the four disruptive events. This appears to be a necessary limitation due primarily to the implementation of the scenario class.

One of the main reasons that the IPA effort adopted a narrow definition of scenario analysis is that a clear distinction was maintained between scenario analysis and consequence analysis. This distinction is believed to have initiated in much of the earlier work on scenarios (esp. Burkholder, 1980; Hill, 1980; International Atomic Energy Agency, 1981). This classification scheme has merit in that it focuses attention on two separate parts of the problem (summarized in two questions about the disruptive event): (i) what is it? and (ii) why is it important? As with many classification schemes, the scheme should not be considered rigid and inflexible because invariably there exist exceptions. As different research teams performed scenario studies, many of the earlier ideas were modified and adapted. Hence, the notion of a clear distinction between scenario analysis and consequence analysis is not as rigid in other scenario approaches as in the IPA Phase 2 implementation.

3.7.2 Distinction Between Description and Consequence

In this work, an attempt is made to discriminate between description and consequence where the description of an event does not require the knowledge of the repository, and the consequence includes the effects of an occurrence on the repository. It has been observed that many features which have been relegated to the consequence analysis can be considered information pertinent to scenario analysis (and not consequence analysis) because these features describe many of the possible future states of the system. For example, the description of a volcanic event begs the additional information of: (i) when it occurs; (ii) where it occurs; (ii) what type of event (extrusive or intrusive); and (iv) what type of geometry (cone or dike, large or small), etc. This additional information more clearly describes the future state of the system without regard to the presence of the repository and should be considered in the scenario analysis and not in the consequence analysis. In contrast, the consequence analysis involves the accelerated release of waste from the EBS (due to, for example, magma contacting and disintegrating waste packages), and accelerated transport of waste through the GS (due to waste entrainment in the magma and possible ejection at the ground surface). The purpose of the consequence analysis is to determine the detrimental effects of the disruptive event on the performance of the repository system. The purpose of the scenario analysis is to describe the many plausible future-states of the system and subsequently assess their relative probability of occurrence. In the current IPA implementation, the vast majority of work is relegated to consequence analysis.

3.7.3 Consistency Between Modules

During the review, it became apparent that there were significant conceptual and implementation inconsistencies among the four modules. Probably the most significant is the lack of modularization of common functions. The most notable example is the radionuclide inventory, which is calculated differently in the VOLCANO and SOTEC modules. The implementation in the VOLCANO module is extremely simple and is only a decay model for each of the radionuclides initially in the inventory, therefore it fails to capture any of the decay-chain in growths (i.e., daughter products). The implementation in the SOTEC module (used by DRILL1) is much more sophisticated and does account for decay-chain in growths. This is a significant inconsistency that should be corrected (by having a single inventory module) in the next phase of IPA.

Conceptual differences also exist between modules. The most notable example is the SEISMO module that has a different approach to the problem than the other modules. This is primarily due to the difference in the technical details needing to be implemented; however, it is also due to different personnel being responsible for each module. Another example is the different conceptual implementation for location of drilling events (in DRILLO) and location of volcanic events (in VOLCANO). The current implementation in DRILLO is confusing and, in contrast, the implementation in VOLCANO is rather straightforward. The location of a drilling event could have been calculated using two random numbers to determine the x,y coordinates, and then the DRILL1 CM could subsequently calculate which cell was intruded (if any) and if a waste package was intercepted (these calculations would be similar to the geometric calculations in VOLCANO). The adoption of similar techniques among the modules would greatly enhance clarity.

3.7.4 Use of Technical Experts as Module Leads

Although it is apparent that competent technical personnel were selected to design and implement the current modules, it appears that some questionable modeling assumptions were employed (such as the PDF for the area of a dike or radius of a cone in the VOLCANO module). In many cases, it appears that persons primarily responsible for the contents of a module were not subject-matter experts. Although this may be sufficient, it is recommended that experts in the respective fields be responsible for establishing the conceptual and mathematical contents of a module (this is also emphasized by Barr and Dunn, 1993). The role of the PA program element should be to convey the information needs of PA and assist the technical expert in developing technically defensible models which are useful in TSPA. It is recommended that technical experts be assigned as module leads and given sufficient support from PA program element personnel to develop the most credible models of these disruptive events.

3.7.5 Use of Tools to Organize, Aggregate, and Convey Information

One of the major themes in the literature is that scenarios must be developed and analyzed in a systematic, logical, and defensible manner, and that all analyses need to be documented and traceable (Nuclear Energy Agency, 1992). Scenario analysis tools have been developed to help generate, organize, analyze, and document scenarios. In particular, influence (or logic or flow) diagrams are particularly useful in conveying the plethora of multidisciplinary information. However, in the documentation of the IPA Phase 2 effort, the descriptions were frequently insufficient. In the conduct of this research, it was necessary to call the responsible person to understand the implementation, or extrapolate beyond the documentation to determine the implementation. In many cases, the logic behind the implementations was not understood until a logic diagram or a flow diagram was constructed. Because it is important that TSPA be fully documented to facilitate understanding, comparison, and reconciliation between different implementations, it is recommended that appropriate tools be used to organize, aggregate, and convey the descriptions of the modules. In particular, graphical logic and flow diagrams (as used throughout Section 3) have been found to be extremely informative and are recommended to be adopted in future IPA efforts.

3.7.6 Use of Random Numbers

In the sensitivity studies conducted in IPA Phase 2, random numbers were used as LHS parameters. As a result, it was determined that infiltration rate was very important and that neither seismic effects nor volcanic events had a significant effect on the total CCDF (U.S. Nuclear Regulatory Commission, 1993). It is recognized that the modeling assumptions in the TPA code greatly influence which parameters and/or phenomena are found to be important (this is true for any code). Similarly, the choice of LHS parameters (i.e., random numbers) can also have an impact on sensitivity conclusions from TSPA.

The use of random numbers varied significantly between disruptive modules, as shown in Table 3-2. In the table, the quantity of random numbers is presented as well as how the random numbers were used to either describe the event or assess the consequence of the event. Two conclusions can be drawn from the table:

1. A majority of random numbers were devoted to describing a disruptive event (and not calculating its consequence).

2. There is a significant imbalance between the quantity of numbers used in each module.

The first conclusion indicates that the random numbers can most probably be eliminated from the CMs. This is believed because the description of a scenario can logically be summarized in an event tree structure which eliminates the use of random numbers.

The second conclusion is demonstrated by the DRILLO module which uses a large quantity of random numbers (i.e., 92) to describe the exploratory drilling scenario, while the climate scenario uses only one random number to determine the pluvial infiltration rate. These random numbers were used as LHS parameters to assess the importance of the scenarios and their parameters on system performance. It appears that these random numbers were chosen with minimal consideration as to how they would be used as LHS parameters in overall sensitivity and uncertainty studies. It is conceivable that the large quantity of random numbers chosen for the drilling scenario acted to dilute the importance of drilling, and that the choice of only one random number for climate acted to enhance the importance of pluvial infiltration rate. Therefore, it is recommended that future implementations assess the use of random numbers to facilitate sensitivity studies so that the quantity of random numbers neither dilute the importance of a scenario nor bias the importance of a parameter.

Table 3-2. Random numbers used in either description or consequence analysis of disruptive modules as implemented in IPA Phase 2

	Quantity of Random Numbers Used		
	Description	Consequence	Total
Volcanic Event (VOLCANO module)	8	0	8
Human Intrusion (DRILLO and DRILL1 modules)	92	0	92
Seismo/Tectonics (SEISMO module)	(1/2)*	(1/2)*	1
Climate Change (implement in EXEC module)	1	0	1

* There is no clear distinction between description and consequence in the SEISMO module

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 RECOMMENDATIONS FOR IMPROVEMENT OF SCENARIO ANALYSIS

In Section 2, the role of scenario analysis in TSPA was reviewed, as well as recent applications by:

- NRC/CNWRA (Section 2.2)
- SNL for Yucca Mountain (Section 2.3.1)
- SNL for WIPP (Section 2.3.2)
- EPRI (Section 2.4)
- AECL (Section 2.5)
- SKI/SKB (Section 2.6)
- UK/HMIP (Section 2.7)

Many key topics were identified in the review of these methods, and found to be generally applicable to all scenario analysis methods. In this section, specific recommendations are presented to address key topics and improve scenario analysis.

- Expert Judgment (Section 2.9.1)
  - It was concluded that expert judgment is ubiquitous and essential in PA. Recent work has focused on methods and procedures to avoid some of the pitfalls of expert elicitation (e.g., expert overconfidence or biasing of results due to strong-willed experts).
  - Hence, it is recommended that if expert opinion is to be used, it should be acquired using a formal, well-documented, structured expert elicitation procedure.
- Reconciliation of Different Scenario Approaches (Section 2.9.2)
  - It was concluded that reconciliation of different scenario approaches is highly desirable, especially in a contentious regulatory environment. It was concluded that differences can be reduced and/or avoided through the use of common definitions, methods, and tools. It was noted that the SKI and SKB have adopted a proactive approach to scenario analysis where the applicant and regulator have agreed to jointly pursue scenario identification and selection. Many benefits appear likely during the licensing process where attention will not be focused on reconciliation of different approaches but on comparison of different conclusions.
  - Hence, it is recommended that efforts be devoted to developing a consensus of affected parties in the United States HLW program on scenario identification, selection, analysis, and documentation.

- Completeness of Scenarios (Section 2.9.3)
  - It was concluded that it is impossible to achieve completeness whereby all potentially detrimental and sufficiently likely EPs are considered. The most that reasonably can be expected is the modeling of all demonstrably important EPs where a consensus of either data or opinion support the conclusion that the EP is both viable and detrimental.
  - Hence, it is recommended that efforts be devoted to developing a consensus of either data or opinion which identifies the EPs that need to be included in a TSPA. This consensus should be pursued through both international activities and activities focused on the United States HLW program.
- Human Intrusion (Section 2.9.4)
  - It was concluded that the prediction of human activity is highly speculative and highly controversial. It appears that predictions can vary by orders of magnitude due to the assumptions employed (e.g., whether exploratory or exploitation activity, whether based on current technology or speculated future technology).
  - Hence, it is recommended that cooperative efforts be pursued to develop a consensus on how human intrusion should be modeled. In particular, it is recommended that predictions of future human activity be based on current technologies and current activities in the vicinity of Yucca Mountain, and not based on highly speculative assessments of future human endeavor.

4.2 RECOMMENDATIONS FOR IMPROVEMENT OF IPA MODULES

In Section 3, the CMs considered in IPA Phase 2 were reviewed and critiqued for the following:

- base case (Section 3.2)
- climate change (Section 3.3)
- volcanism (Section 3.4)
- human intrusion (Section 3.5)
- seismo/tectonics (Section 3.6)

A number of module-specific recommendations were identified and presented. In addition, a number of key topics were identified that are applicable to at least two of the modules. In this section, specific recommendations are presented to improve future modules.

- Use of Scenario Classes (Section 3.7.1)
  - It was concluded that the IPA Phase 2 implementation of a scenario analysis method is distinct from any other implementation primarily due to the use of scenario classes.

Although the logic behind the distinction is laudable, it is not a natural distinction. It is believed to unduly encumber the scenario analysis method and diminish the role of scenario analysis (which is primarily subsumed in consequence analysis).

- — Hence, it is recommended that the scenario class distinction be abandoned or revamped to be more consistent with other methods.

- Distinction Between Description and Consequence (Section 3.7.2)
  - — It was concluded that the IPA Phase 2 implementation does not discriminate between description and consequence of disruptive EPs. This distinction, however, appears both intuitive and useful in scenario methods.
  - — Hence, it is recommended that the distinction between the description and the consequence of a disruptive EP be adopted and used to distinguish between scenario analysis and consequence analysis. An acceptable criteria is that the description of an EP includes all of the information which makes the EP important — excluding the interaction or effect on the repository. The consequence includes all information on how the EP interacts with the repository system and affects the performance.
- Consistency Between Modules (Section 3.7.3)
  - — It was concluded that significant differences exist in the conceptual approach and implementation among modules. These differences deter clarity and uniformity within the TSPA. The sources for these differences are due to different personnel being assigned to modules, insufficient communication between module development teams, and lack of adherence to module development guidelines.
  - — Hence, it is recommended that uniform guidelines, tools, and techniques be developed and provided to each module development team.
- Use of Technical Experts as Module Leads (Section 3.7.4)
  - — It was concluded that some questionable modeling assumptions were employed in specific modules. These assumptions may not be considered defensible to experts in the field.
  - — Hence, it is recommended that recognized technical experts be assigned as module leads, whereby the technical expert is responsible for the defensibility of the conceptual and mathematical models.
- Use of Tools to Organize, Aggregate, and Convey Information (Section 3.7.5)
  - — It was concluded that analyses need to be traceable, and that tools have been developed to help generate, organize, analyze, and document the analyses. In particular, influence (or logic or flow) diagrams have been used by other organizations and have been found to be very useful in conveying the plethora of multidisciplinary information.

- Hence, it is recommended that organization tools (e.g., logic diagrams, flow diagrams) be adopted and consistently used throughout the IPA effort.

- Use of Random Numbers (Section 3.7.6)

  - It was concluded that random numbers were used as LHS parameters, however, the use of random numbers varied significantly between modules. More importantly, the LHS parameters were used in sensitivity and uncertainty analyses, yet it does not appear that these parameters where chosen based on their eventual usage. It appears that random numbers were chosen without explicit recognition of their eventual use as LHS parameters. It is conceivable that a poor choice of LHS parameters could either dilute or enhance the predicted importance of an EP.

  - Hence, it is recommended that future implementations assess the use of random numbers and LHS parameters to facilitate sensitivity and uncertainty studies.

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