NUREG/CR-1667
SAND80-1429
GF
Printed December 1982

Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure

R. M. Cranwell, R. V. Guzowski,
J. E. Campbell, N. R. Ortiz

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Prepared for
U. S. NUCLEAR REGULATORY COMMISSION

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

and

National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-1667
SAND80-1429
GF

Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure

R. M. Cranwell
R. V. Guzowski*
J. E. Campbell+
N. R. Ortiz

December 1982

Sandia National Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
U.S. Department of Energy

Prepared for
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Memorandum of Understanding DOE 40-550-75
NRC FIN No. A-1192

*Energy Management & Technology
+INTERA Environmental Consultants, Inc.

ABSTRACT

This report contains the description of a procedure for identifying and screening those events, features and processes, both natural and human induced, felt to be important to the isolation of radioactive wastes in deep geologic formations. In this report, the term "scenario" is used to represent a sequence of these events, features and processes. The scenario selection and screening procedure discussed in this report is demonstrated by applying it to the analysis of a hypothetical waste disposal site containing a bedded salt formation as the host medium for the underground facility (repository). A final set of 12 scenarios is selected for this hypothetical site. Detailed risk calculations will be performed on these 12 scenarios in a later report.

TABLE OF CONTENTS

TABLE OF CONTENTS (Con't)

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

TABLES

ACKNOWLEDGEMENTS

Several individuals made valuable suggestions and comments during the development and demonstration of the scenario selection and screening procedure discussed in this report. In particular, the authors would like to acknowledge the suggestions of Joe Pearson of INTERA Environmental Consultants, Inc., Herb Shaw of the U.S. Geological Survey, Fred Donath of CGS, Inc. and Mark Reeves of GeoTrans, Inc.

1. INTRODUCTION

The Fuel Cycle Risk Analysis Division of Sandia National Laboratories, Albuquerque (SNLA), is currently funded by the U.S. Nuclear Regulatory Commission (NRC) to develop a methodology for use in assessing the risk from geologic disposal of radioactive waste. An important part of this methodology includes a procedure for identifying and screening those events, features and processes, both natural and human induced, that could conceivably alter the natural state of the disposal site and result in human exposure to radionuclides released from the underground facility. As used in this report, the term "scenario" will refer to the hypothetical occurrence of a sequence of these events, features and processes, either singly or in combination.

Scenario identification is important not only in evaluating the safety of a site but also as a guide to data collection. Identification of potentially disruptive events and processes, in conjunction with sensitivity analyses, can indicate which data are most significant in assessing the performance of a potential disposal site.

1.1 Purpose of This Report

This report contains that portion of the SNLA/NRC Risk Assessment Methodology describing a procedure for arriving at a representative set of scenarios for use in evaluating a potential waste disposal site. The use of this procedure has been demonstrated by applying it to the analysis of a hypothetical radioactive waste disposal site containing a bedded salt formation as the host medium for the underground facility (Chapter 3). In this demonstration, a set of representative scenarios was selected which were felt to be important to the isolation of radioactive wastes at this site. These scenarios will be used in the demonstration of the SNLA/NRC Risk Assessment Methodology which is described in Cranwell et al. (1982). Since the site is hypothetical, the scenarios selected in the demonstration may not be the same as those selected in a real site analysis. In fact, the most significant scenarios will undoubtedly vary from site to site and from geologic formation to geologic formation.

1.2 Summary of Report Contents

Chapter 2 of this report contains a description of the scenario selection procedure used to arrive at a set of scenarios for the hypothetical site. This description includes: (1) criteria for selecting and screening events, features and processes (Section 2.3), (2) an illustration of how scenarios are formed by taking sequences of various events, features and processes (Section 2.4), and (3) a discussion of scenario probabilities (Section 2.5).

In Chapter 3, the scenario selection procedure is demonstrated by applying it to a hypothetical site containing a bedded salt formation as the host medium for the waste repository. A description of this site can be found in Sections 3.1 and 3.2. The final set of scenarios selected for this site can be found in Section 3.9.

Summary and conclusions are given in Chapter 4. The appendices contain procedures for determining probabilities of various events and processes.

2. PROCEDURE FOR SCENARIO SELECTION

The selection of those scenarios considered to be important in the disposal of radioactive waste in deep geologic formations should be accomplished by means of an objective and consistent procedure. Firm and useful criteria become essential in the selection of relevant scenarios for use in a potential disposal site analysis.

This chapter presents a systematic procedure for arriving at a set of scenarios for use in the analysis of a potential radioactive waste disposal site. Briefly, this procedure consists of the following steps: (1) an initial comprehensive identification of those events, features and processes felt to be important to the long-term isolation of radioactive waste in deep geologic formations, (2) a classification of these events, features and processes to aid in completeness arguments, (3) an initial screening of these events, features and processes based on well-defined criteria, (4) the formation of scenarios by taking specific combinations of those events, features and processes remaining after the initial screening process, (5) an initial screening of these scenarios, and (6) the selection of a final set of scenarios for use in evaluating a potential disposal site. Each of these steps is discussed in more detail below. The screening criteria mentioned in step (3) are discussed in Section 2.3.

Figure 2.1.1 provides a simplified graphical illustration of the scenario selection procedure. A loop connecting classification back to identification is indicated in Figure 2.1.1 to point out the fact that classification provides a valuable logical test to assure that potentially important events, features and processes have not been overlooked. The procedures and criteria for scenario selection presented here will be demonstrated in Chapter 3 by application to a hypothetical radioactive waste repository in bedded salt. A final set of scenarios, selected for this hypothetical site, will be discussed in Section 3.9. No claim is made that the methods presented are the only methods available for scenario selection, nor that the scenarios selected for the hypothetical bedded salt site are those that would be selected in a real site analysis. It is felt, however, that the methods presented can be applied, in principle, to any geologic site being considered for radioactive waste disposal.

2.1 Identification of Events, Features and Processes

The first step in any scenario selection procedure should be the identification of a comprehensive set of

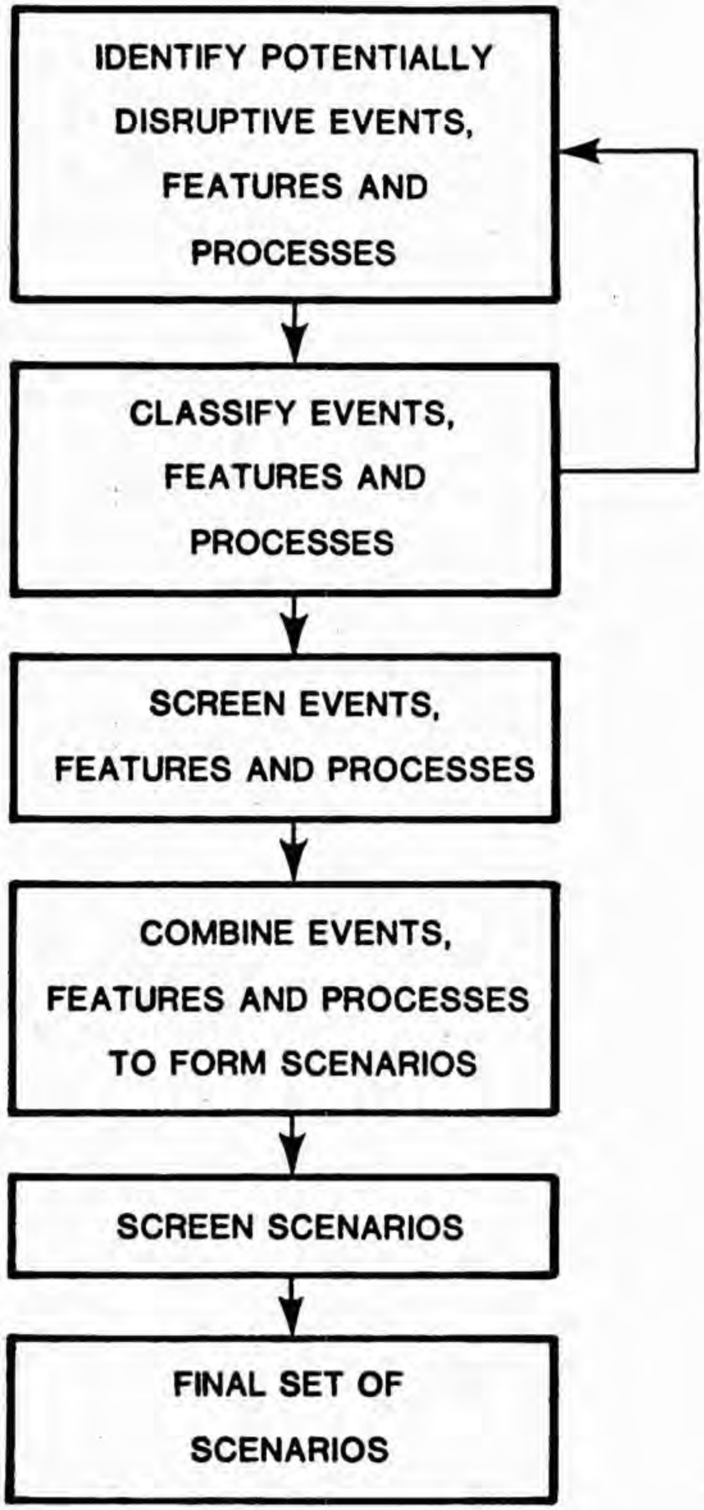

Figure 2.1.1. Graphical Illustration of Scenario Selection Procedure

events, features and processes, both natural and human induced, felt to be important to the isolation of radioactive waste at the site being considered. This identification would generally be accomplished through discussions among persons knowledgeable in the areas of earth science and waste-management analyses. The use of knowledgeable and experienced individuals helps assure that potentially important scenarios are not overlooked. For the demonstration of the SNLA/NRC Risk Assessment Methodology, a panel of knowledgeable earth scientists was convened for the purpose of identifying those events, features and processes (phenomena) considered to be important to the isolation of radioactive waste in a bedded salt repository (See Section 3.2). These phenomena are listed in Table 3.3.1.

2.2 Classification of Events, Features and Processes

The classification of events, features and processes provides a logical aid to help assure that important scenarios will not be overlooked. The initial list of phenomena specified in Table 3.3.1 was classified into the categories of: (1) natural, (2) human induced, and (3) repository induced. This classification was based on the origin and physical characteristics of these phenomena. A procedure for further classification is presented below. In addition to addressing the question of completeness, this classification also provides the organization needed to begin developing and analyzing scenarios.

Events, features and processes will be classified based upon the manner in which they influence the waste repository system consisting of the underground facility and the surrounding geology. Those phenomena in the near vicinity of the underground facility, whose major effect is to influence the movement of radionuclides from the underground facility to a nearby aquifer or directly to the surface, will be referred to as <u>release phenomena</u>. Similarly, those phenomena in the far field (i.e., at the site but not in the near vicinity of the underground facility), whose major effect is to influence the transport of radionuclides in ground water, will be referred to as <u>transport phenomena</u>.

The distinction between those events, features and processes included as release phenomena and those included as transport phenomena is not always obvious. For example, faulting may be classified as either a release or transport phenomenon, depending on the proximity to the site. If the fault should pass through or very near the underground facility, its primary effect would be to influence movement of radionuclides from the underground facility to a nearby aquifer. In this case, the fault would be classified as a release phenomenon. On the other hand, if the fault should occur at some distance away from the underground facility so that its primary effect is to influence the transport of radionuclides in ground water once they are released from the underground facility, then it would be classified as a transport phenomenon. Thus the distinction between release and transport phenomena may seem somewhat arbitrary. Furthermore, regardless of its classification, a given event, feature or process may influence both radionuclide release and transport, depending on its effect on the site hydrology. Despite the seemingly arbitrary division of phenomena into release and transport categories, the reasons for this division become more apparent when one considers the complex thermal, mechanical, geochemical and hydraulic analyses that may be required for near-field (release) phenomena analysis compared to the more straightforward flow and transport analyses required for far-field (transport) phenomena analysis.

2.3 Initial Screening of Events, Features and Processes

Many of the events, features and processes from the initial list considered for a potential disposal site can be eliminated based on firm and well-defined screening criteria. An initial screening of these events, features and processes is not only desirable but also essential if one considers the thousands of scenarios that could be defined by taking specific combinations of these phenomena.

Initial screening criteria should, in our view, consist of the following:

(1) physical reasonableness of the events, features and processes being considered

(2) probability of significant release of radionuclides from these events, features and processes

(3) potential consequences associated with the occurrence of these events, features and processes.

Once the initial list of events, features and processes has been reduced using the above criteria, an additional level of screening of the scenarios defined by taking combinations of the remaining phenomena can be accomplished by using any of the above criteria as well as a fourth criterion:

(4) risk associated with the occurrence of these scenarios.

Risk, as used in this report, refers to probability times consequences. Further discussions of these criteria follow below. Although reference is made specifically to events, features and processes, the topics discussed also apply to the scenarios formed by taking specific combinations of these phenomena.

Physical Reasonableness

Events, features and processes whose occurrence is practically impossible due to the physical and chemical characteristics of the waste and characteristics of the engineered facility or geologic site can be eliminated by this screening criterion. Some examples of phenomena that could be eliminated based on the test of physical reasonableness are

-- a nuclear explosion in an underground facility designed to prevent criticality

-- formation of dissolution cavities in crystalline rock

-- tsunamis for a repository far removed from coastal regions.

Clearly, the elimination of phenomena due to this criterion would be largely site specific. Therefore, this step in the screening process should be repeated for each repository site.

Probability

Events, features and processes with very "small" probability can generally be rejected. The specification of "small" should be the responsibility of the regulator or the applicant(s) and should be consistent with the appropriate regulations. Once a value has been selected, judgmental decisions will undoubtedly still have to be made as many probabilities associated with various phenomena will have large uncertainties. The value selected in the demonstration analysis of this report was 10^{-8}/year.

In several safety studies, numerical probability criteria have been used to reject scenarios. For example, WASH-1400 (Reactor Safety Study, 1975) uses a limit of 10^{-9}/year to reject accident sequences. Other references (Griesmeyer and Okrent, 1981) suggest larger numbers (e.g., 10^{-7}/year). The EPA draft standard (Egan & Golden, 1981) does not include releases with probability of occurrence smaller than 10^{-8}/year.

Consequence

As used in this report, "consequences" can have different interpretations, depending upon the stage of the screening process in which one is involved. For example, in the earlier stages of the screening process, "consequences" generally refers to the effects that a certain event, feature or process might have on the natural properties of the site (e.g., hydraulic head distribution). Thus, only flow and possibly thermomechanical analyses are needed at this point. Later in the screening process, "consequences" generally refers to the amount of radionuclides being discharged to the biosphere and the health effects associated with these discharges. Thus, radionuclide transport and health effects calculations are also needed at this point. The reason for this breakdown is that in the early stages of the screening process, it is felt that detailed transport and health effects calculations should be avoided because of the higher computer and man-time costs associated with these efforts. It is desirable to first reduce the total scenarios to a reasonable number before undertaking detailed risk calculations.

At any rate, screening based on consequences can occur in several ways. For example, events, features and processes having similar consequences (e.g., effects on hydraulic head) could conceivably be grouped together provided the probabilities of these phenomena are appropriately combined. Also, events, features and processes with relatively low consequences (e.g., less than 0.01 of the proposed release limits in the EPA draft standard

(40CFR191, draft #20)) could be eliminated. However, before eliminating phenomena based on insignificant consequences, their potential maximum consequence should be considered.

The screening of events, features and processes based on consequences could be either direct or indirect. Assume, for example, that the analyst determines that the effect of a given transport phenomenon on the flow system is negligible or does not provide for a shortened path to the surface environment (e.g., withdrawal wells). If consequences are known to be insignificant without the transport phenomenon, then consequences with the transport phenomenon can be assumed to be insignificant. In other cases, the analyst may decide to calculate consequences before deciding whether to reject certain events, features and processes.

The application of the above three criteria should reduce the number of scenarios to be considered from hundreds or thousands down to a few tens or less. A "final set" of scenarios can then be ranked based on their contribution to public risk. These screening procedures, if properly applied, can dramatically reduce the cost and effort required to perform repository risk analysis.

2.4 Scenario Development

The next step in the scenario selection procedure involves the formation or development of scenarios by taking meaningful combinations of those phenomena remaining after the initial screening process. Recall that at this point, the events, features and processes have been classified as to "release" and "transport" phenomena as discussed in Section 2.2. The development of scenarios by taking combinations of the various release and transport phenomena is illustrated by a simple example.

Consider the simple case of two basic release phenomena (R1, R2) and three basic transport phenomena (T1, T2, T3). The possible scenarios that can be created by taking combinations of these phenomena are shown in Figure 2.4.1. As can be seen, there are $2^5 = 32$ possible combinations in this example. The use of the tree diagram as illustrated in Figure 2.4.1 helps assure that all possible combinations are identified. Furthermore, this approach is helpful in eliminating illogical combinations. For example, consider a site having aquifers above and below the underground facility. Further assume that these aquifers are not hydraulically connected. Without speculating on how such phenomena might occur, let R1 represent release to the overlying

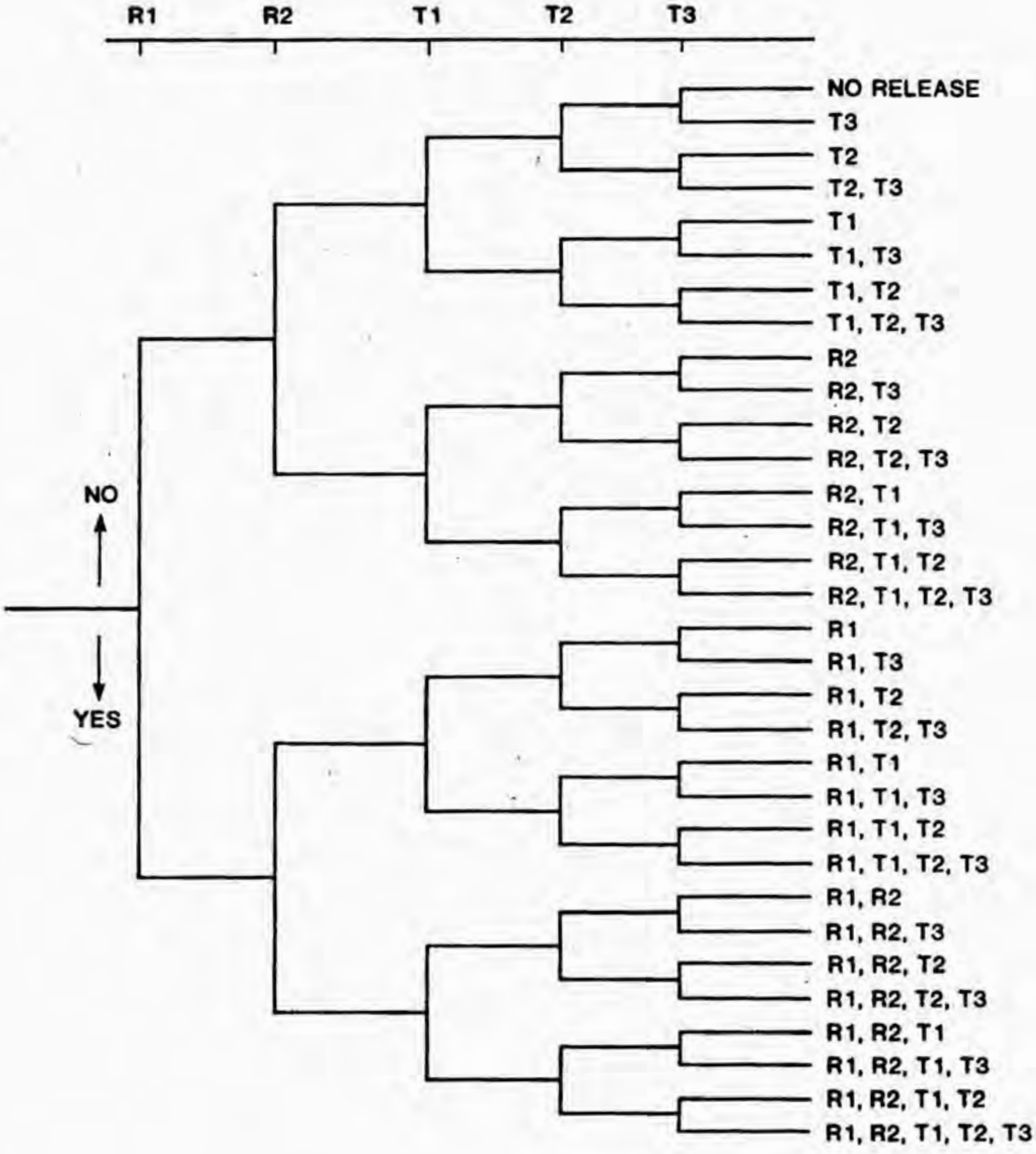

Figure 2.4.1. Potential Combinations of Two Release and Three Transport Phenomena

aquifer and R2 represent release to the underlying aquifer. To complete the example, let T1 represent withdrawal wells placed into the overlying aquifer and T2 represent wells placed into the underlying aquifer and assume that these wells do not significantly alter the flow system. Then the tree diagram presented in Figure 2.4.1 simplifies to that shown in Figure 2.4.2 and 32 scenarios have been reduced to 17. The reason for this reduction is that combinations R1,T2 (release to overlying aquifer, wells in underlying aquifer) and R2,T1 (release to underlying aquifer, wells in overlying aquifer) need not be considered as they are equivalent to R1 and R2. Thus, this type of approach for combining release and transport phenomena to form scenarios can help assure that all meaningful combinations are identified.

2.5 Initial Screening of Scenarios

The next step in the scenario selection procedure would be to screen the scenarios developed from taking appropriate combinations of the various release and transport phenomena. An initial screening of these scenarios can be based on the criteria discussed in Section 2.3. Because of the difficulty in always being able to assign accurate probabilities to every scenario, it is felt that physical reasonableness and consequence

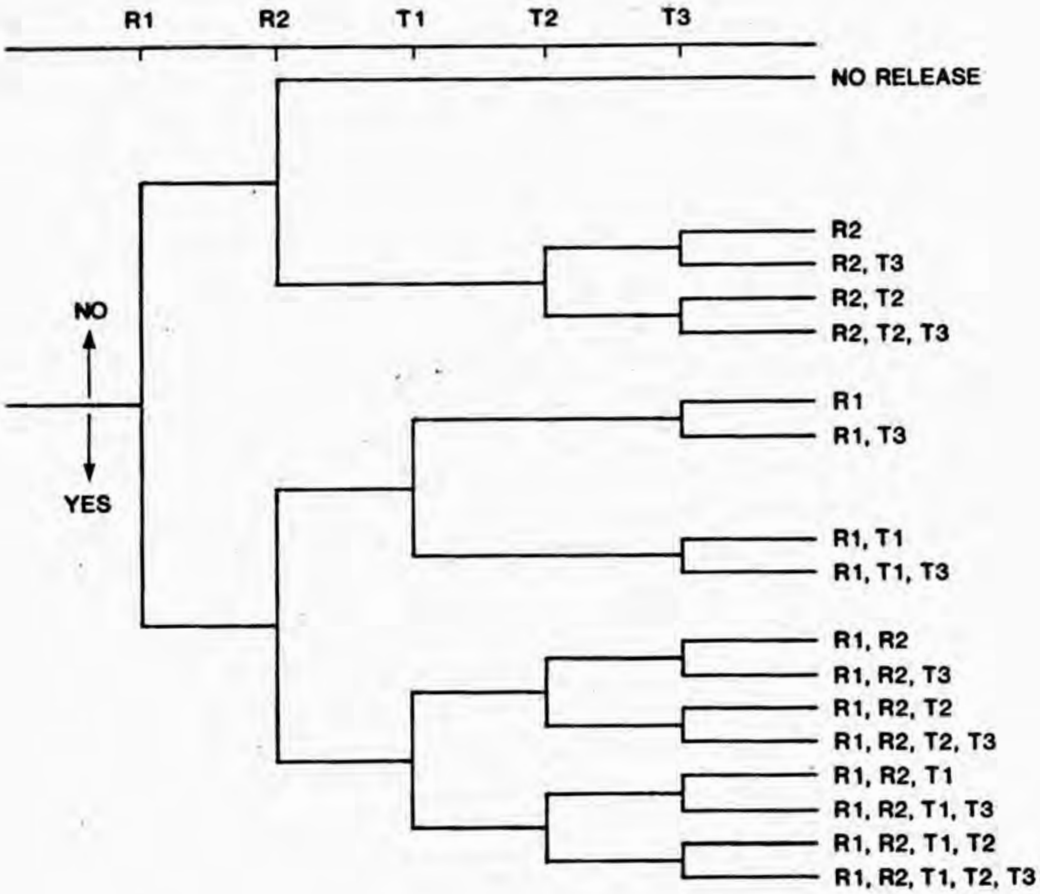

Figure 2.4.2. Meaningful Combinations of Two Release and Three Transport Phenomena

arguments should be applied first. Before proceeding with the screening of scenarios, the topic of scenario probabilities is discussed in more detail.

Scenario Probabilities

Assuming probabilities have been assigned to the various release and transport phenomena (components) comprising a scenario, a probability for that scenario can be arrived at by simply multiplying the probabilities of each of the components (assuming, of course, independence among the components). For example, assume that the probability of release phenomenon R2 is p_1, the probability of transport phenomenon T2 is p_2, and the probability of transport phenomenon T3 is p_3. Then the probability of Scenario R2,T2,T3 in Figure 2.4.2 would be $p_1 \cdot p_2 \cdot p_3$. If for some reason the components of a scenario are not independent, then conditional probabilities can be used. For example, if T2 and T3 are not independent, let p_3 be the probability of T3, given that T2 has occurred. Then the probability of Scenario R2,T2,T3 is still the product of the individual component probabilities. If this probability falls below the agreed upon cut-off (e.g., 10^{-8}/year), and one is relatively confident in the probability estimates for each component comprising the scenario, then this scenario could be eliminated from any further consideration.

The assigning of probabilities to scenarios representing future geologic and human activity is a difficult problem. For example, many geologic events and processes are not random in nature, either temporally or spatially (e.g., glaciation). Thus, to develop probabilistic models and procedures for use in assigning probabilities to these events and processes would be unrealistic. Furthermore, because of the site-specific nature of many geologic events and processes, the development of generic probabilistic procedures and models for these events and processes would not be meaningful. In many cases, even if realistic probability models could be developed, lack of data and the time frames involved in the analysis of radioactive waste disposal would make the use of such models of limited value. Many assignments of scenario probabilities will have to be totally subjective (because of lack of data) and obviously evaluated on a site by site basis. In many cases, the absolute best that can be hoped for is a conservative upper bound estimate of these probabilities.

Because of the difficulties involved in arriving at accurate probabilities for scenarios, the use of these probabilities in risk analyses should be done with extreme care. Initially, scenario probabilities should only be used to screen and rank scenarios for purposes of additional modeling. It could be misleading to use these probabilities in risk analysis; that is, to multiply them by consequences in an effort to predict risk. For many scenarios, the probabilities are too uncertain to provide meaningful risk estimates. Furthermore, the need for a definitive probability for each and every scenario is not apparent considering the format of the current federal regulations. For example, the current EPA draft standard (Egan and Goldin, 1981) groups releases into two categories; those with probabilities in the range from 10^{-2} to 1 and those with probabilities in the range from 10^{-4} to 10^{-2}. Thus, all that is necessary is an estimation of which category (range) a scenario would fall.

2.6 Final Screening of Scenarios

A final screening of the scenarios remaining at this point can be accomplished using probability and consequence arguments. Here, consequences generally refer to either radionuclide discharges at some specified point or the health effects resulting from these discharges.

To avoid the problem of scenario probabilities as discussed in the previous section, the initial screening at this stage should be based on consequences. If, in performing transport calculations for a scenario, no discharges are observed for the period of time used in the analysis, or the releases are below those specified by, for example, the EPA draft standard, then no additional health effects or risk calculations are necessary. Thus, the concern for a scenario probability is immaterial. However, if discharges are significant, then the need for a scenario probability becomes more important and the screening of the scenario would have to be based on an estimate of its risk.

2.7 Applicability of Event-And Fault-Tree Analysis in Geologic Waste Isolation

As was discussed in previous sections, the events, features and processes felt to be important with respect to the long-term isolation of radioactive waste in deep geologic formations are categorized into two groups: release and transport phenomena. Scenarios are then formed by taking meaningful and appropriate combinations of these release and transport phenomena. This procedure was displayed in the form of a logic diagram (Figure 2.4.1).

It is felt that this organizational method is preferable to the classical event-tree, fault-tree techniques frequently used in the analysis of engineered systems. This statement is made for the following reasons: (1) many of the so-called "events" associated with geologic environments do not represent immediate or abrupt changes in the system but rather slow, continuous changes over hundreds to thousands of years (e.g., dissolution cavities in bedded salt formations, shaft or borehole seal degradation, formation of geologic dikes, etc.). Hence their occurrence cannot be represented by a simple "yes" or "no" statement; (2) the existence of feedback loops frequently appear in the investigation of the processes that could affect the release of radionuclides from the underground facility. Event trees and fault trees do not adequately incorporate interactions between various factors influencing radionuclide movement; (3) for a given set of conditions, many of the processes are basically deterministic. Thus, the question of when and if a certain "barrier" will be breached is answered when a given set of conditions is specified. The real question is "what conditions exist?"; (4) event trees and fault trees force artificial divisions in the representation of processes. The important question is how the entire system behaves.

Other studies (Burkholder, 1981 and Koplik et al., 1982) have also concluded that event and fault trees are not useful for analyzing the processes themselves or their interactions. They recommend the use of simulation techniques with models to describe the evaluation over time of a set of variables representing the scenarios. The latter method is used in this study as described in the next chapter.

3. APPLICATION OF THE SCENARIO SELECTION PROCEDURE

In this chapter we demonstrate the use of the scenario selection procedure discussed in the previous chapter by applying it to a hypothetical reference site containing a bedded salt formation as the host medium for the radioactive waste repository. Since the stratigraphic layering of any disposal site is an important consideration in developing and analyzing the release and subsequent transport of radionuclides to the biosphere, a description of the reference site which provides the geologic setting for the demonstration is given below.

3.1 The Reference Site

While the reference site used in the demonstration is hypothetical, the physiographic setting and geologic and hydrologic properties are real in the sense that they were chosen as representative of several regions in the United States. The site is located in a symmetrical upland valley, half of which is shown schematically in Figure 3.1.1. Surrounding the valley is a ridge having an elevation of 6,000 feet. The crest of the ridge is a divide for both surface drainage and ground-water flow with the result that the only water moving within the valley falls in the valley itself. River L is the major source of drainage for the valley. The elevation of River L at the point of cross-section (Figure 3.1.1) is 2,500 feet. Tributaries to River L exist, such as River U, but these are intermittent.

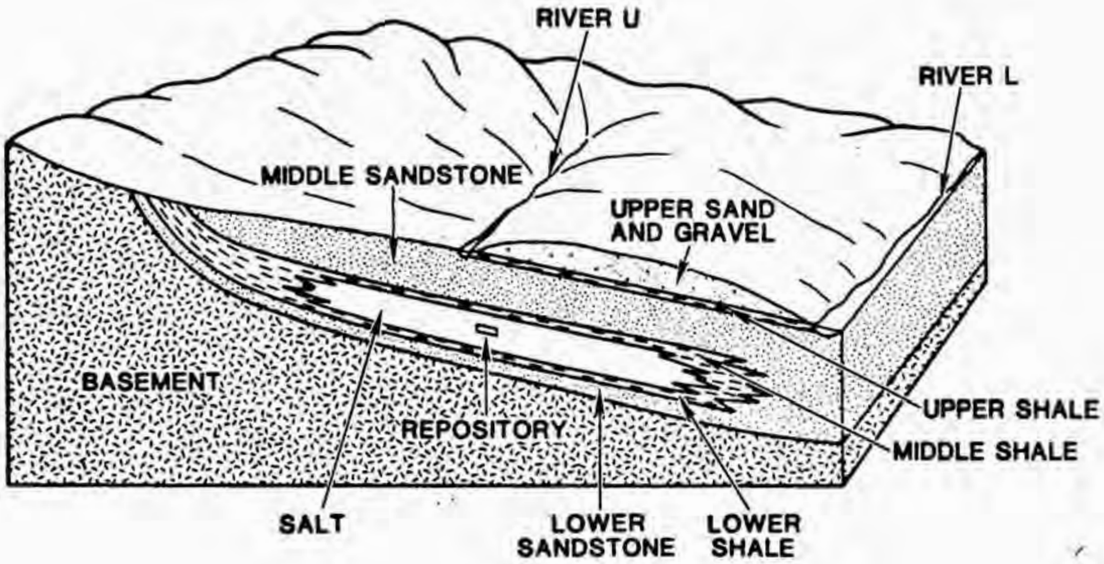

Figure 3.1.1. Schematic Diagram of the Reference Site. One side of the symmetric basin is shown. The upper end of the valley is approximately elliptic with the repository located on the minor axis; the sides of the valley are parallel below the repository. The vertical exaggeration of scale is approximately 20.

The valley receives an average of 40 inches of rainfall per year, of which 16 inches are lost by evapotranspiration and the remaining 24 inches recharge the ground-water system.

Underlying the valley is a basement of crystalline bedrock that crops out over a narrow width at the ridge crest surrounding the valley. This basement is assumed to be impermeable to ground-water flow and is overlain by a sequence of sedimentary rock as shown in Figure 3.1.1. The layered sequence is typical of sedimentary basins in which shale, siltstone, sandstone and salt are the dominant rock types. A bedded salt deposit having a low permeability is located within the sedimentary sequence and is considered to be the host rock for the radioactive waste repository. A detailed description of the reference repository can be found in Campbell, et al., (1978).

3.2 Hydraulic Characteristics of the Reference Site

Hydraulic properties of the rock units shown in Figure 3.1.1 are given in Table 3.2.1. The properties of the sandstone and shale units are representative of these rock types (Franke and Cohen, 1972). However, as the site studied by Franke and Cohen did not contain a bedded salt formation, the hydraulic conductivity and porosity of the salt were arbitrarily assumed to be factors of 10^3 and 10 lower, respectively, than those values for the middle/lower shale units. These values are at the upper section of the range of representative salt formations.

Table 3.2.1

Hydraulic Properties for
Geologic Units Comprising the Reference Site

	Upper Sand and Gravel	Upper Shale	Middle Sand-stone	Middle/ Lower Shale	Salt	Lower Sand-stone
Hydraulic Conductivity (ft/day)						
Horizontal	270	10^{-2}	50	10^{-2}	10^{-5}	40
Vertical	27	10^{-5}	1.4	10^{-3}	10^{-6}	7
Porosity	0.3	0.3	0.3	0.3	0.03	0.3

The location of the repository, as may be inferred from the elevation contours of Figure 3.2.1, is far enough from the head of the valley that ground-water flow near the repository is perpendicular to River L and to the valley axis. This suggests that, for purposes of analyzing conditions around the repository, a two-dimensional simulation of the reference site would be sufficient. Furthermore, three-dimensional analyses of the reference site have shown that a two-dimensional representation of the flow system is adequate.

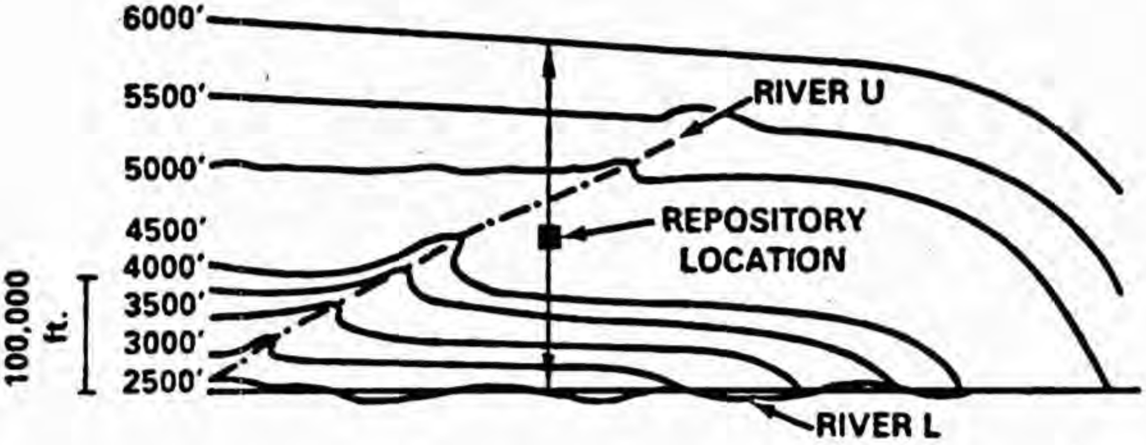

Figure 3.2.1. Physiographic Setting of the Reference Site

Contoured hydraulic head data and interstitial velocity fields for the reference site are calculated in two dimensions using the Sandia Waste Isolation Flow and Transport (SWIFT) model. SWIFT is a three-dimensional, finite-difference code that solves conservation equations for fluid flow, heat transport (possible nontrace), solute mass, and radionuclides in trace quantities (Reeves and Cranwell, 1981). Figure 3.2.2 shows the two-dimensional representation of the reference site used in the SWIFT simulations.

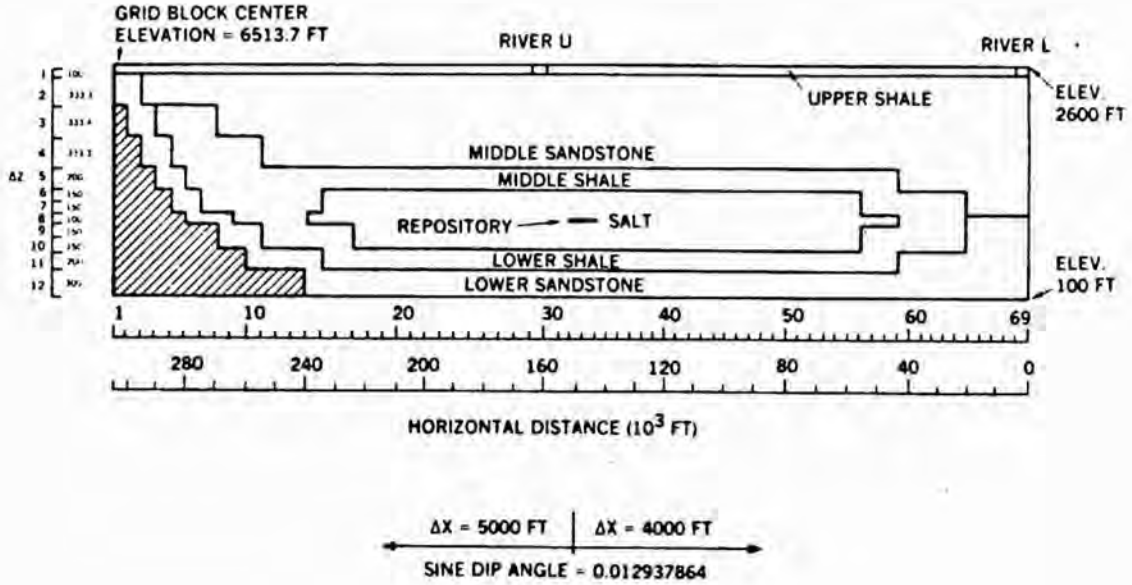

Figure 3.2.2. Two-Dimensional SWIFT Setup for Reference Site

The distribution of hydraulic head, as calculated by SWIFT, is shown in Figure 3.2.3. This figure indicates that flow in the middle and lower sandstone aquifers (also referred to as overlying and underlying aquifers, respectively) is essentially one-dimensional. A downward gradient exists across the repository, which would be more apparent if not for the vertical exaggeration of scale (x20). Thus, should a hydraulic connection be established between the overlying and underlying aquifers, fluid flow would be downward through this connection.

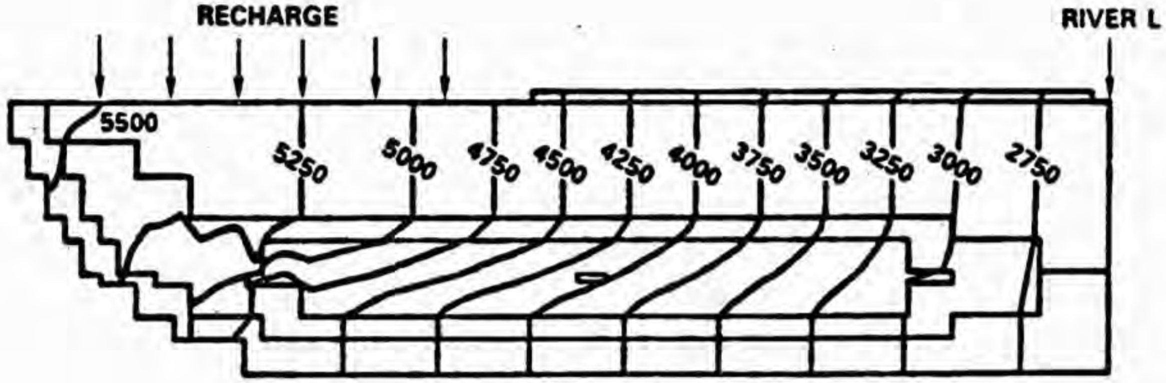

Figure 3.2.3. Hydraulic Head Distribution of the Reference Site

Upward ground-water movement exists in the vicinity of River L. This upward movement is not apparent in Figure 3.2.3 because of the absence of detail in the plotting of the lines of constant potential. (This absence of detail was intentionally incorporated to avoid clutter in the figure.) Figure 3.2.4, on the other hand, shows an enlarged isolated segment of the reference site near River L. Here, more detail was incorporated and the upward movement of the ground water is apparent.

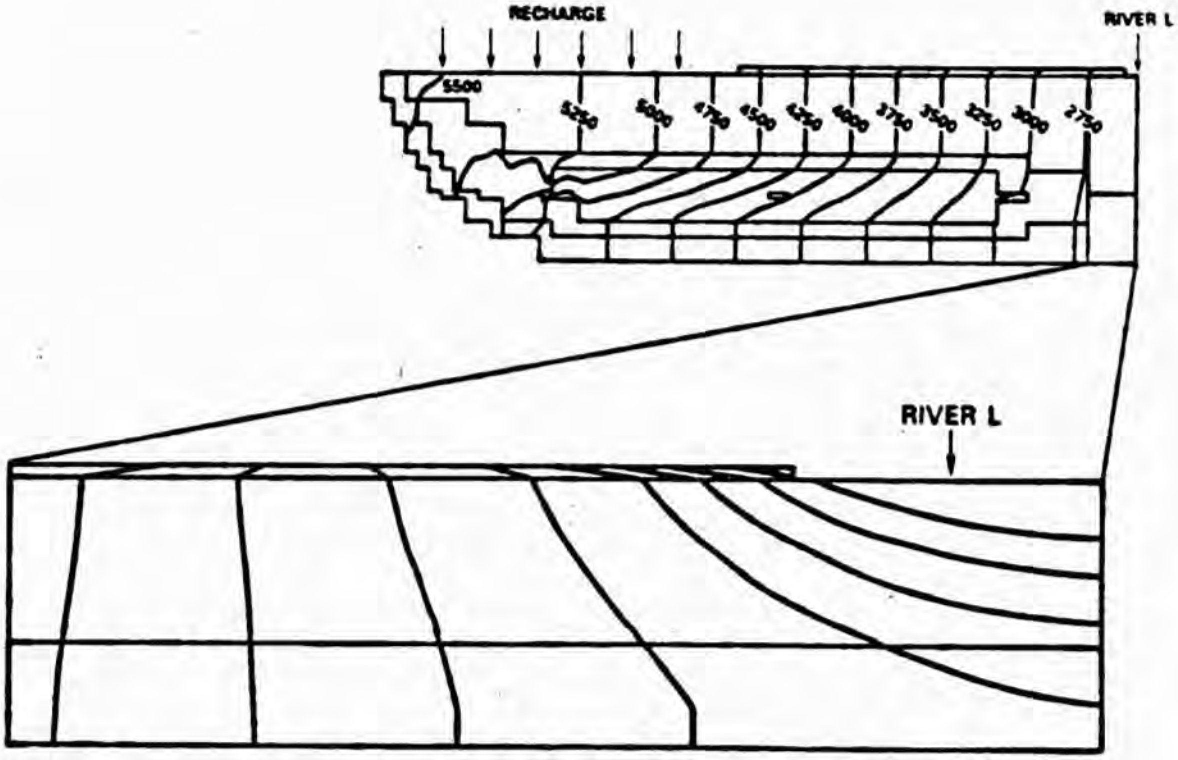

Figure 3.2.4. Hydraulic Head Distribution Near River L. Enlargement was more in the horizontal direction than in the vertical. Thus, the vertical exaggeration of the two figures is not equivalent.

Fluid velocities, as calculated by SWIFT, are shown in Figure 3.2.5. The one-dimensional nature of fluid flow in the aquifers is clearly shown in this figure. Fluid velocities below 5 x 10^{-5} ft/day were not plotted, which explains why no vectors are shown in the salt layers. Figure 3.2.5 begins to show some movement upward toward River L. However, here as in Figure 3.2.3, detail was sacrificed to avoid cluttering the figure. To better illustrate this upward movement, velocity vectors were plotted for an enlarged, isolated segment of the reference site near River L. These are shown in Figure 3.2.6, where the upward movement to River L is more evident.

Plots of both the distribution of hydraulic head and fluid velocity field will be used in the next chapter to show the effects of various features on the natural flow patterns of the reference site. However, in most cases, changes in the ground-water flow pattern are illustrated adequately by the fluid velocity field. Thus, plots of the hydraulic head distribution will be used only to show changes in flow trends that are not necessarily obvious from the fluid velocity field plots. For example, certain geologic features could change the direction of flow from downward across the salt and shale to upward across these units (see, e.g., Transport Phenomenon T11). This upward movement may not be seen

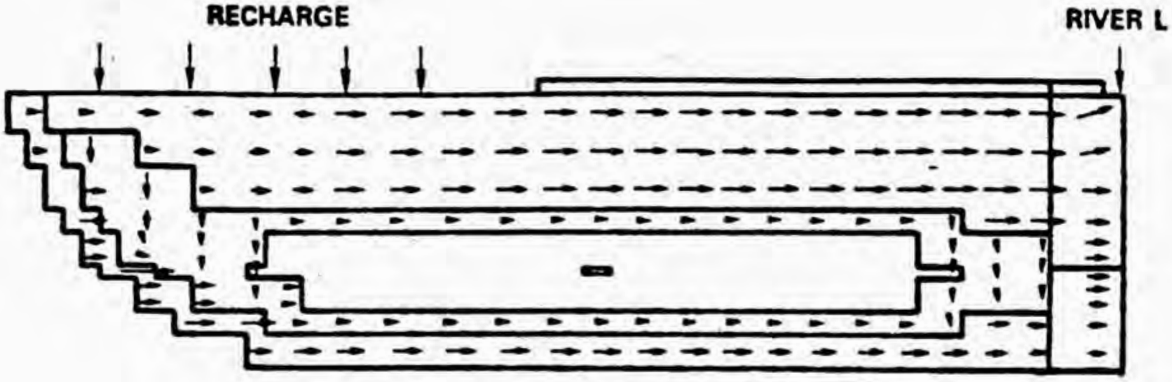

Figure 3.2.5. Fluid Velocity Vectors of the Reference Site

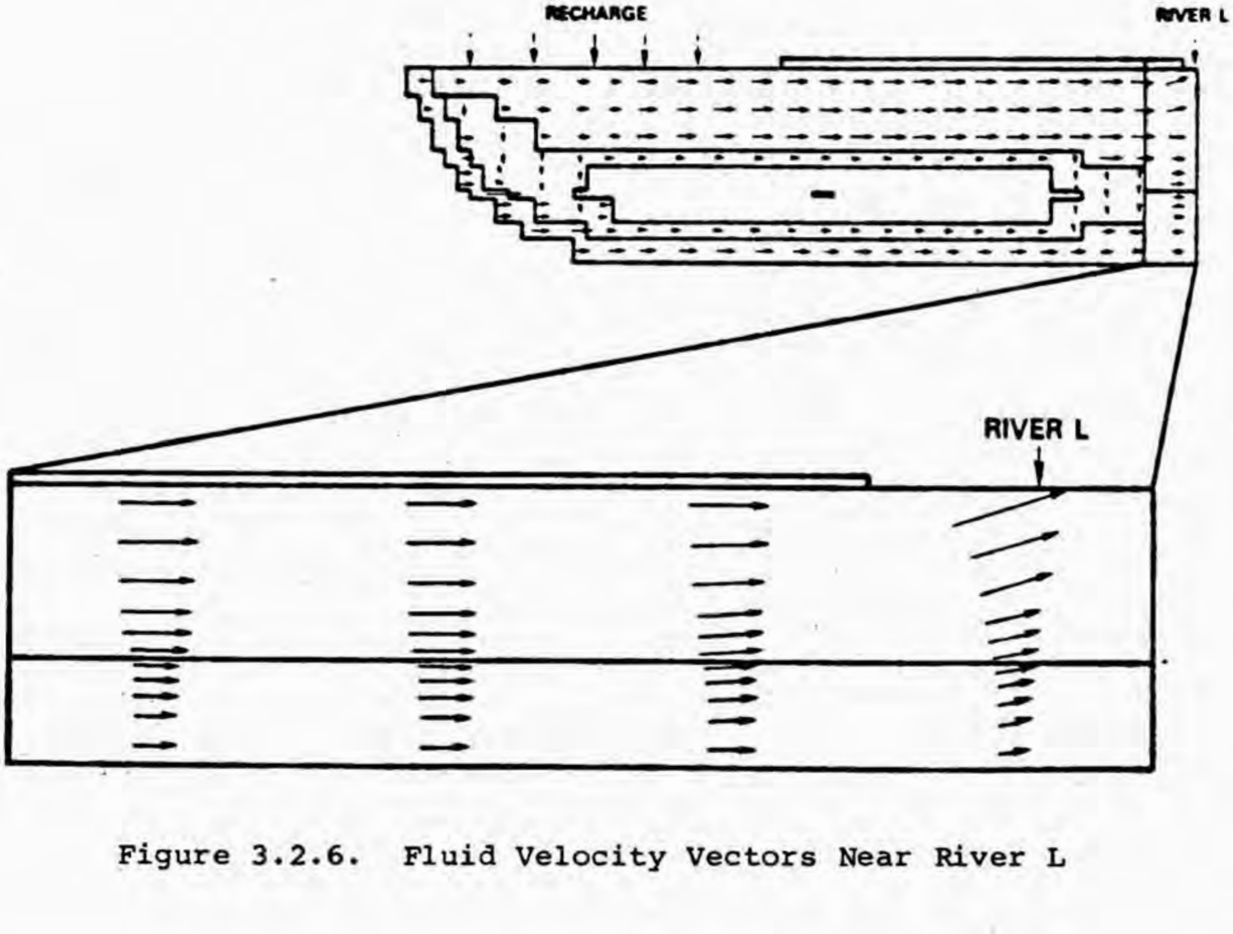

Figure 3.2.6. Fluid Velocity Vectors Near River L

in the velocity vector field plots since these vectors do not normally appear in the salt. Therefore, plots of the hydraulic head distribution would be used to show this change in the head gradient.

3.3 Identification and Classification of Events, Features and Processes for Reference Site

In 1976-77, a panel of knowledgeable earth scientists was convened for the purpose of identifying events, features and processes which could potentially disrupt a radioactive waste repository (Panel Members, 1976-77). Other studies (Bingham, F. W. & G. E. Barr, 1979; Arnett, R. C., et al., 1980; and WIPP, 1979) discussing scenario identification have been reviewed to verify that the list is as complete as possible. Phenomena identified by the panel are listed in Table 3.3.1 and are classified into the following categories: 1) natural, 2) human induced, and 3) repository induced. This list includes a wide variety of events and processes and represents an attempt to establish a comprehensive base from which a final set of scenarios will be selected. As the list is somewhat general, it could probably be shortened in a site-specific analysis.

TABLE 3.3.1

Potentially Disruptive Events, Features and Processes

NATURAL PHENOMENA AND PROCESSES

Celestial Bodies

- Meteorites

Surficial Phenomena and Processes

- Erosion/Sedimentation
- Glaciation
- Pluvial Periods
- Sea Level Variations
- Hurricanes
- Seiches
- Tsunamis
- Regional Subsidence or Uplift (also applies to subsurface)
- Landslides

Subsurface Phenomena and Processes

- Earthquakes
- Volcanic Activity
- Magmatic Activity
- Dissolution Cavities
- Interconnected Fracture Systems
- Faults

HUMAN INDUCED PHENOMENA AND FEATURES

Inadvertent Intrusions

- Explosions
- Drilling
- Mining
- Waste Disposal (Injection Wells)

TABLE 3.3.1 (Cont.)

Undetected Features

- Boreholes
- Mines

Hydrologic Stresses

- Irrigation
- Dams

WASTE AND REPOSITORY INDUCED PHENOMENA AND PROCESSES

- Subsidence and Caving
- Shaft and Borehole Seal Degradation
- Thermally-Induced Stress/Fracturing in Host Rock
- Excavation-Induced Stress/Fracturing in Host Rock

A classification of these events, features and processes into release and transport phenomena is discussed in Section 3.5.

3.4 Initial Screening of Phenomena Based on Physical Reasonableness and Probability Arguments

The initial screening of the list of phenomena presented in Table 3.3.1 can be accomplished by using straightforward elimination procedures such as probabilistic and physical justification arguments. For example, most of the surficial phenomena and processes listed in Table 3.3.1, with the exception of those having long-term hydrologic effects, can be expected to have no significant effects on the release of radioactive material from a repository located at least two thousand feet below the ground surface. Furthermore, certain geologic and natural phenomena and processes, such as meteorite impacts, are shown to have small enough probability of occurrence that their contribution to risk is of little importance.

The following paragraphs contain arguments for eliminating certain of the phenomena listed in Table 3.3.1. These arguments represent the first step in the screening procedure to arrive at a list of phenomena that portray the most significant scenarios in terms of risk. To the extent possible, the arguments apply to the generic aspects of waste disposal in deep geologic media. However, in certain instances, reference will be made specifically to bedded salt and to the hypothetical reference site used in the methodology demonstration.

As was mentioned in Chapter 2, a probability of 10^{-8}/yr (or 10^{-3} for a 10^5 year period) is used as the cut-off for the elimination of phenomena based on probabilistic arguments. The 10^5 year time period was the length of time used in the demonstration of the SNLA/NRC Risk Assessment Methodology (Cranwell et al., 1982).

Meteorite Impact

It is generally agreed that meteorite impacts occur with such infrequency that it is of little importance with respect to the risk from radioactive waste disposal in deep geologic formations. Several estimates have been made of the probability that a meteorite impact could either excavate a repository located at varying depths below the land surface or severely fracture the overlying protective rock strata. Hartmann (1979) estimates the probability that a catastrophic impact would completely exhume part of a repository with an area of 10 km^2, buried 600 meters deep, to be 6 x 10^{-13}/yr. The Swedish KBS (Karnbranslesakerhet, 1978) study determines a rate of $10^{-13}/km^2/yr$ for craters at least 100 meters deep. Logan and Berbano (1978) estimate a probability of 1 x 10^{-13}/yr for a direct strike by a meteorite of enough energy to exhume material from a depth of 800 meters for a 10 km^2 repository. Claiborne and Gera (1974) estimate the chances of excavation to be 2 x 10^{-13}/yr for a 8 km^2 repository located 600 meters below the land surface.

The dimensions of the Sandia hypothetical waste repository are approximately 8 km^2 and located at a depth of about 625 meters (Campbell, et al., 1978). The probability of excavation for this repository has been estimated as 8 x 10^{-13}/yr (see Appendix A). This probability value, as well as the others listed above, is several orders of magnitude smaller than the cut-off value (10^{-8}/yr). Therefore, this event is rejected based on its small probability of occurrence.

Erosion/Sedimentation

Because of the depths being considered for deep geologic waste repositories, erosion is generally considered not to be important as a potential mechanism for releasing radionuclides from the repository. Erosion alone, at a U.S. average of approximately 2×10^{-4} ft/yr (Judson and Ritter, 1964), is unlikely to be a hazard for emplacements ranging from 2,000 to 3,000 feet below the land surface. In areas dominated by limestone and having a relatively high rainfall, the average erosion rate, predominantly the result of chemical weathering, is approximately 5×10^{-4} ft/yr (Bloom, 1969). The more resistant rocks of the Columbia River drainage system, which undergo primarily mechanical weathering, have an average erosion rate of 1×10^{-4} ft/yr (Gilluly, Waters, and Woodford, 1968). Mountainous regions typically have erosion rates of approximately 3×10^{-3} ft/yr (Bloom, 1969). The average rate of downcutting of the Colorado River in the Grand Canyon, one of the highest for any major river system, has been from 5×10^{-4} ft/yr to 3×10^{-3} ft/yr (Gilluly, Waters, and Woodford, 1968). Even at these accelerated rates, it would take over 700,000 years to remove the overburden above a repository located at depths of 2,000 feet.

Since the principal effect of sedimentation is to increase the thickness of the overburden above the repository, this process is, in most cases, beneficial. Sedimentation can, however, have certain negative effects. For example, sedimentation can influence the distribution of surface waters and increase the static loading over the repository. This increase in loading could induce fracturing or plastic deformation of the protective rock units encompassing the repository. Such effects are, however, considered in other scenarios in this study. Sedimentation is also a factor in diapirism, a process that could result in upward movement of waste. However, certain conditions need to exist before this process can occur. For example, model studies of salt dome formation have shown that an overburden of about 3,300 feet and a thickness of at least 900 feet of salt were necessary to initiate the salt-flow process (Halbouty, 1979). The thickness of the salt layer in the reference site used in this demonstration is only 700 feet, with an overburden of approximately 2,050 feet. Since only the overburden can increase, it is felt that sedimentation, as a potential mechanism for containment failure, can be neglected in this analysis. Thus, both erosion and sedimentation are eliminated from any additional consideration based on the criteria of physical reasonableness.

Glaciation

During the Pleistocene period, four major glacial advances covered the northern portion of North America. The latest advance began about 70,000 years ago, and after several pulses, finally retreated from the United States about 10,000 years ago. Considerable controversy surrounds what conditions cause continental glaciation, whether the present climate is postglacial or interglacial, and what long-term effects industrialization will have on world climate. Based on the history of glaciation in the Pleistocene, renewed growth of continental glaciers is expected within the next 100,000 years (Bloom, 1969). Thus, depending on its location and the period of time considered to be of concern, the effects of glaciation on a geologic radioactive waste repository could be realized.

For those sites that would be overridden, the effects of glaciation are uncertain. For example, the deposit of glacial till beneath the glacier could result in a positive effect since this material tends to be impermeable. On the other hand, glacial movement can result in erosion of the land surface beneath the glacier. The rate of this erosion, however, depends upon several factors: (1) the thickness and rate of movement of the glacier; (2) the abundance, shape, and hardness of the rock particles within the base of the glacier; and (3) the erodibility of the rocks beneath the glacier. Furthermore, the depth of erosion can vary depending on the local topography and climatic conditions. For example, it is believed that glacial scour deepened the large valleys of northern British Columbia and southern Alaska by at least 1,960 feet (Flint, 1971). Reid (1892) concluded that the average erosion rate beneath the Muir Glacier in southern coastal Alaska amounted to 6 x 10^{-2} ft/yr. At this rate, 2,000 feet of overburden could be removed in about 32,000 years. However, these regions provide optimum conditions for glacial erosion. They are high and steep and have climates which, during a glacial period, would provide abundant snowfall. The Canadian Shield is an example of the other extreme. Here, evidence indicates that glaciation did little more than modify the details of the existing relief (Flint, 1971).

In addition to the erosional effects of the glacier itself, increased fluvial erosion in advance of the ice can result from the increase in precipitation often associated with interglacial periods. Furthermore, the tremendous weight of the glacier itself and the presence of ice and accompanying water could result in fracturing and renewed movement on existing faults as well as alterations in the surface and ground-water hydrology.

It is generally agreed that those regions for which no evidence exists of glaciation in the Pleistocene period probably will not be glaciated during future advances. Thus, the long-term risk from glaciation could probably be controlled by selecting repository sites some distance from the glaciated areas of the Pleistocene period. The reference site described in Section 3.1 and used in this analysis is assumed to be located in a region not affected by future glaciation. Thus, glaciation is eliminated from additional consideration based on the criteria of physical reasonableness and/or probability.

Pluvial Periods/Sea Level Variations

Pluvial periods and sea level variations could be important for disposal in unsaturated zones (arid lands) and in rock structures showing evidence of dissolution. Pluvial periods could increase the amount and rate of aquifer recharge, thus increasing hydraulic gradients in drainage systems. In fully saturated systems, such as the reference bedded salt site, increased rainfall would probably not have adverse effects except to increase runoff and thus erosion. In instances of disposal in unsaturated zones, pluvial periods must be assessed on a site-specific basis. In the analysis of the reference site, the problem of pluvial periods is handled in part by varying the hydraulic properties of the overlying and underlying aquifers. That is, allowing for uncertainty in aquifer hydraulic conductivity has the effect of allowing for variation in aquifer recharge rates.

Sea-level variations can alter processes such as erosion, sedimentation, and the regional hydrology. However, most effects from sea-level variations would not be felt by a repository located inland. A substantial rise in sea level would flood coastal areas. This flooding could affect a repository located in the salt dome regions of the Gulf Coast, depending on its depth of burial above the present sea level. Extrapolation of recorded sea-level fluctuations indicate that between 10,000 and 9,000 years ago the sea level was rising at an average rate of approximately 3 x 10^{-2} ft/yr, whereas during the last 3,000 years the average rate has slowed to approximately 1 x 10^{-3} ft/yr (Flint, 1971). At this latter rate, the sea level could rise as much as 115 feet in the next 100,000 years.

Considering the elevation of the reference repository (approximately 2,800 ft above sea level), the effects of such sea-level changes would be minimal.

Based on the above arguments, the phenomena of pluvial periods and sea-level variations can be eliminated because of physical reasonableness and/or probability of occurrence.

Hurricanes/Seiches/Tsunamis

These phenomena may be important to the safety of disposal sites located on the margins of the Gulf of Mexico or on the coastal regions of the United States during the operational phase. In the post-closure phase, adverse effects from these phenomena might conceivably arise from alteration of ground-water flow patterns and from imposed hydrostatic loading on the site. However, such effects are likely to be transient and of no long-term consequence.

As the reference site is not located near coastal regions, the phenomena of hurricanes, seiches and tsunamis are eliminated based on physical reasonableness and/or probability of occurrence.

Regional Uplift and Subsidence

Regional uplift or subsidence is of little consequence to the integrity of a bedded salt repository. One reason for this lack of effect is the long times required to produce significant uplift or subsidence. Furthermore, the expected epeirogenic nature of the movement would probably not cause faulting and folding.

Uplift could result in an increase in stream gradients, therefore an increase in rates of stream erosion. With the exception of active orogenic belts and recently deglaciated areas, the maximum rate of uplift in the United States is approximately 5 x 10^{-2} ft/yr (Press and Siever, 1974), with most areas of uplift experiencing substantially lower rates. Even at lower rates of uplift, stream erosion will not match uplift for most rock types.

Subsidence could result in a decrease of stream gradients and erosion rates. Deposition of sediments in the region may contribute to the isolation of the repository. Maximum rates of epeirogenic subsidence are approximately 3 x 10^{-2} ft/yr (Press and Siever, 1974). Most subsiding areas have rates substantially lower than this.

The bedded salt locations under consideration for nuclear waste disposal sites are in regions undergoing epeirogenic uplift at rates of 3 x 10^{-3} to 2 x 10^{-2} ft/yr (Press and Siever, 1974). Because of the low rate of movement, along with the limited amount of folding and faulting associated with the movement, regional uplift and subsidence are not expected to result in significant effects on the reference site system. Thus, these phenomena are eliminated based on physical reasonableness and/or probability of occurrence. It should be noted that 10CFR60 (U.S. Nuclear Regulatory Commission, 1981) classifies uplift and subsidence as adverse conditions and, thus, requires that the applicant demonstrate that these conditions do not impair significantly the ability of the repository to isolate the waste.

Landslides

In certain areas, a landslide could conceivably divert or dam a river resulting in the presence of water above the repository. Impounded water behind the dam could exert sufficient pressure to result in displacement along fractures and faults. However, for the reference site used in this analysis, diversion of water or damming by a landslide resulting in surface water being present above the repository would require the diversion or impoundment of water a distance of about 25 miles laterally from an existing river (River L). No evidence of the diversion or impoundment of a body of water by landslide for a distance this great can be found in the literature. Thus, for the site considered in this demonstration, landslides can be eliminated based on physical reasonableness and/or probability of occurrence. However, this phenommenon should be considered for different sites. 10CFR60 classifies landslides as an adverse condition and requires the applicant to demonstrate that this condition does not impair significantly the ability of the geologic repository to isolate the waste.

Earthquakes

The frequency and magnitude of earthquakes in a region may affect the stability of a repository during the operational phase. After closure of the repository, ground motion caused by earthquakes will have no effect on the repository beyond possibly contributing to the failure of borehole and shaft seals. Movement along faults, fracture formations, and changes in rock properties that are associated with faults could affect groundwater flow, and thereby influence radionuclide release and transport. The proposed rule on high-level waste disposal (10CFR60) lists earthquakes as an adverse condition and requires a careful analysis from the applicant to demonstrate that it does not significantly impair the ability of the geologic repository to isolate the radioactive waste. Nevertheless the effects of earthquakes (e.g., faulting) are considered in other sections of this report.

Volcanism and Magmatism

Volcanic activity occurs primarily in tectonically unstable areas. These areas are rift zones, spreading centers along plate boundaries, subduction zones, and locations above deep-mantle plumes. The quaternary volcanism evident throughout much of the western United States probably is the result of the North American Plate overriding a previously active spreading center.

Areas underlain by bedded salt are generally either tectonically stable or undergoing epeirogenic uplift. Volcanic activity would not be expected in either of these settings. In the areas of uplift, occasional fractures may provide pathways for intrusion of magma resulting in the formation of dikes or sills. Areas of possible future dike intrusion should have anomalously high heat-flow associated with magma at depth. Such anomalies would probably be detected during site evaluation.

The formation of a dike or sill could disrupt the ground-water flow system of the site. Due to the generally low-permeability characteristics of these features, the effects are to act as a low-conductivity "dam," resulting in the redirection of the flow of ground water. The effects of the change in ground-water flow on the reference site depend in part on the orientation and size of the feature and the geologic setting into which the feature intrudes. These features and their effects on the reference site flow patterns are investigated in the next section.

The low probability of volcanic activity in bedded salt regions essentially eliminates this geologic process from additional consideration. Several estimates have been made as to the probability of this process disrupting a repository site. Logan (1978) estimates the probability of volcanism affecting a 10 km^2 repository in the Delaware Basin to be from approximately 8×10^{-11} to 8×10^{-12} per year. Arthur D. Little, Inc. (1980), arrived at estimates ranging from 1×10^{-10} to 1×10^{-8} per year. For a repository with the dimensions of those of the hypothetical reference repository used in this analysis, a probability of 6×10^{-9}/year was estimated using a model described in Beckman and Johnson (1981). For reasons given in Appendix C, this estimate is conservative. Thus, probabilities discussed above indicate that this phenomenon can be eliminated based on probabilistic arguments.

Explosions

Because of repository-design technology and the understanding of radionuclide-host rock interactions, a nuclear explosion originating in the repository is highly unlikely. Furthermore, 10CFR60 requires that the system be designed for nuclear-criticality safety.

The possibility of a disruption of the repository owing to the effects of nuclear warfare is highly speculative, as much of this subject requires subjective judgments concerning the actions of humans in the future. In the event of nuclear warfare, empirical relations between crater dimensions and explosive yield (Glasstone, 1962) indicate that a surface explosion of 635 MT yield would be required to excavate a crater 2063 feet deep (the repository is 2050 feet below the land surface). To excavate through the shale layer (1700 feet depth) would require a 365 MT yield. Most thermonuclear weapons of the kind that might be deployed against strategically important targets would have a yield of 200 KT to 10 MT.

The more likely scenario would be the explosion (either accidental or in the event of war) of one or more nuclear weapons in the 10 MT yield range on or near the surface of the reference site. These explosions could cause some fracturing in the middle shale layer allowing the infiltration of water to the salt layers and the formation of a dissolution cavity that may in time reach the repository. The possibility of this phenomenon is considered in a later section of this report (see Phenomenon R4).

Sabotage needs to be considered only during the operational phase of the repository. After closure, access to the radioactive waste requires a massive drilling and excavating program. For this reason, sabotage is not considered in this report. Furthermore, explosion due to combustible material (e.g., gas) after closure of the facility is highly improbable. The existence of such material would undoubtedly be detected during the operational phase of the programs and, therefore, be adequately compensated for as required by 10CFR60.

Irrigation and Dams

Irrigation by well water in a region presupposes the presence of aquifers with sufficient yield and water of adequate purity to support such activity. In bedded salt areas, the aquifers beneath the salt beds tend to be saline, whereas the aquifers above the salt usually contain relatively pure water. As a result, irrigation would affect the aquifers above the repository horizon. The pumping and infiltration of water could alter the hydraulic properties of the region. However, these changes are considered in the analysis by varying the hydraulic properties of the aquifer. A large-scale irrigation project could decrease hydrostatic pressure in the pumping area. Such changes in pressure may result in minor displacements along fractures in the underlying units. This movement would be small and have no effect on the repository or the ground-water flow system. Furthermore, large irrigation projects for the reference site used in this analysis are not considered due to the relatively large rainfall assumed (40 in/yr). Irrigation wells are considered as shortened paths to the environment (see Transport Phenomenon T1) and also in the Pathways Model (Helton and Kaestner, 1981) to determine surface concentrations for use in estimating health effects. The effects of irrigation on radionuclide transport in ground water (other than varying the hydraulic properties of the site) are not considered. In a real site analysis, estimates should be made as to the potential impact of large irrigation projects on the hydrologic system.

Regional changes in the ground-water system associated with dam construction could alter the hydraulic properties of the aquifers. These variations are included in the analysis by varying the hydraulic properties of the aquifer. Other than varying these properties, it is assumed that no dams exist or are constructed at some later date at the reference site.

It should be noted that 10CFR60 requires that the applicant demonstrate that these phenomena do not impair significantly the ability of the repository to isolate the waste.

3.5 Additional Screening of Phenomena Using Consequence Arguments

In the previous section a preliminary screening of the initial list of events, features and processes was performed based on straightforward physical reasonableness and probabilistic arguments. A detailed analysis of their effects on the flow properties of the reference site was not required. In this section, additional screening of the initial list of events, features and processes will be performed based not only on physical reasonableness and probabilistic arguments but also on consequence arguments. Here, consequence is in terms of the effects that these phenomena have on the natural properties of the reference site. The discussions of the events, features and processes in this section are in the context of release (R) and transport (T) phenomena as defined in Section 2.2.

Release Phenomena

Release Phenomenon R1: Release Phenomenon R1 consists of a high-permeability region extending from the ground surface to the repository having a horizontal cross-sectional area ranging from a few square feet to a few tens of square feet (Figure 3.5.1). This feature is meant to represent a drill hole or mining shaft, present at time of repository closure or emplaced at some future time, that was never sealed or in which the sealing material has deteriorated. The effects of such a feature on the flow system are shown in Figure 3.5.2. This figure indicates that water in the middle sandstone aquifer would tend to migrate into the feature to the repository. It is assumed that the width of the feature in the direction of the hydraulic gradient is sufficiently small so as to avoid the formation of a U-tube connection to the middle sandstone aquifer (see Release Phenomenon R3).

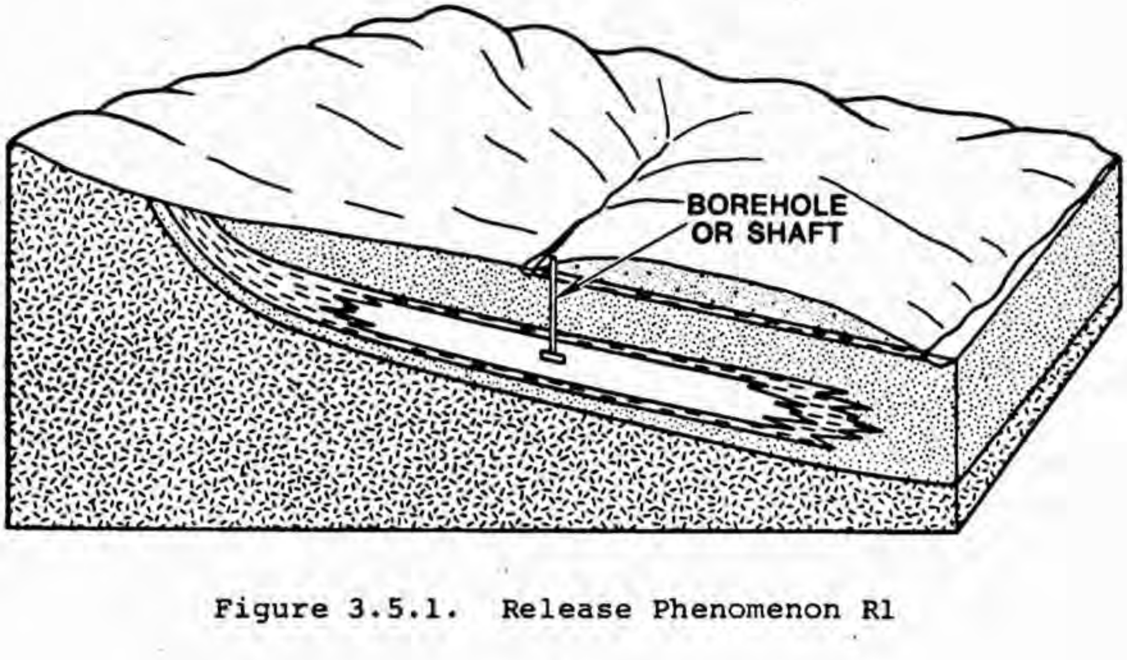

Figure 3.5.1. Release Phenomenon R1

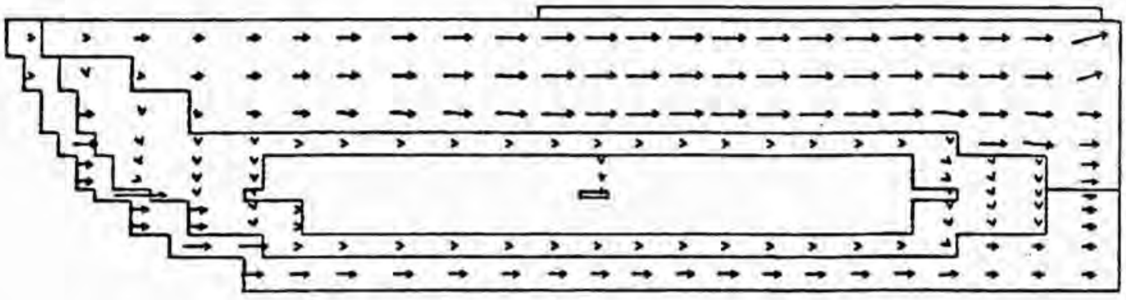

Figure 3.5.2. Fluid Velocity Vectors for R1

Drilling into the repository could result in release of radioactive material directly to the ground surface if a waste canister is penetrated or leached radionuclides are encountered. However, the small amount of material that would be transported to the surface under these conditions would result in limited population exposures. The more significant long-term effects from a drill hole or mining shaft emplaced to the repository level would come from the dissolution and transport of radionuclides in ground water. Large-scale releases to circulating ground water would have to be preceded by dissolution of all or portions of the salt layers surrounding the waste. Heat generated by the radioactive waste would tend to enhance salt dissolution along this feature. Thermal convection and thermally-enhanced diffusion provide mechanisms for movement of dissolved salt away from the repository thereby allowing further salt dissolution. However, heated fluid rising in the drill hole or shaft will cool as it moves away from the repository. Thus, salt may precipitate in the upper portions of the drill hole or shaft and reduce the effective permeability of the feature.

Salt creep is another mechanism that would tend to reduce the long-term effects from a drill hole or mine shaft. Without the offsetting process of salt dissolution, salt creep would have the effect of closing such a feature in the salt. Thus the predominant risk from this phenomenon appears to be the inadvertent drilling into a waste canister or leached radionuclides and transportation of the material directly to the surface. Despite the limited population exposure from this event, Phenomenon R1 is retained for further analysis.

Release Phenomenon R2: Release Phenomenon R2 is similar in structure to R1 with the exception that the high-permeability region extends to the lower sandstone aquifer (see Figure 3.5.3). This feature represents a drill hole or mining shaft extending from the ground surface to the lower sandstone aquifer and passing through the repository. This high-permeability region would result in flow downward into the lower sandstone aquifer (Figure 3.5.4). Any radionuclides dissolved at the repository would be transported to the lower aquifer for eventual discharge at River L. Should this feature be combined with a transport phenomenon that causes an upward hydraulic gradient across the salt and shale, transport of dissolved radionuclides would be upward into the middle sandstone aquifer. The fact that the drill hole or shaft is completed through the repository to the lower sandstone aquifer means that radionuclide migration times to the aquifer will be substantially shorter for R2 than for R1. The migration pathway is along the lower sandstone aquifer to River L.

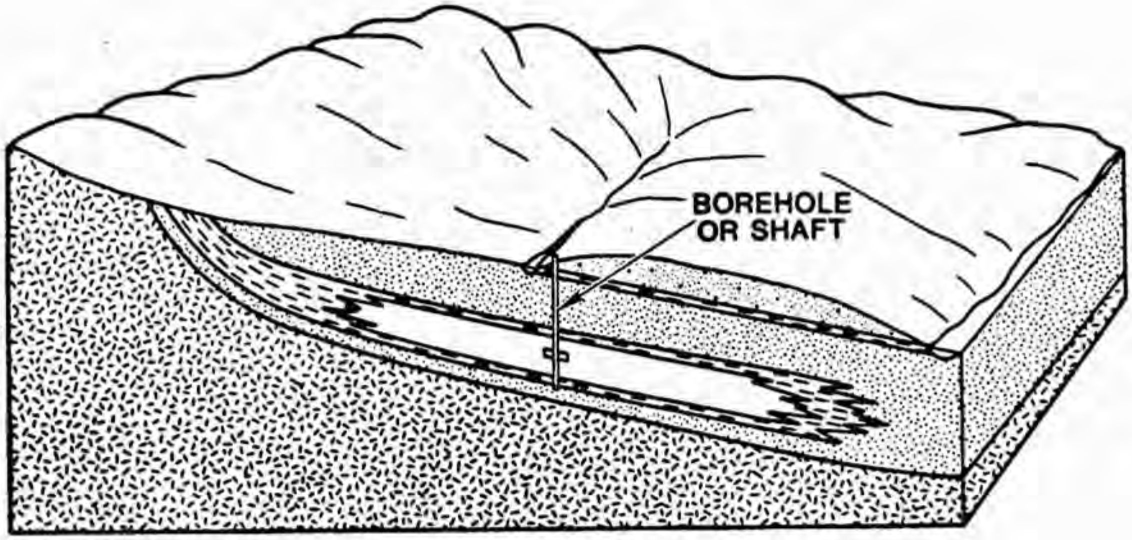

Figure 3.5.3. Release Phenomenon R2

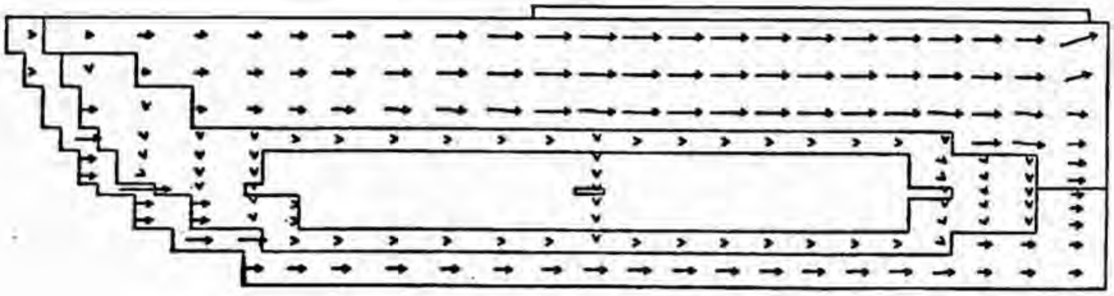

Figure 3.5.4. Fluid Velocity Vectors for R2

It is felt that this phenomenon cannot be eliminated based on physical reasonableness and/or probabilistic arguments as the probability of inadvertent intrusion is above the 10^{-8}/yr cut-off (see Appendix B). The effects of this feature on the overall flow properties of the site are minimal. However, depending on the size and number of boreholes considered, drilling would result in substantial releases of radionuclides to circulating ground water. Thus, R2 is retained to perform additional analysis of the possible discharges to the surface environment and health effects resulting from these discharges.

Release Phenomenon R3: Release Phenomenon R3 postulates the existence of two hydraulic communications between the middle aquifer and the repository and downdip from each other (Figure 3.5.5). The horizontal cross-sectional area of each zone is on the order of a few square feet to a few tens of square feet. This feature could result from exploratory drill holes or mining shafts, present at the time of repository closure or emplaced at some future time, that were never sealed or in which the sealing material has deteriorated. Because of the density difference between fresh water and brine, the hydraulic gradient will not be sufficient to drive water through the repository and out the downdip communication unless a minimum separation distance (approximately 3,000 ft. for the reference site) between the two communications is exceeded.

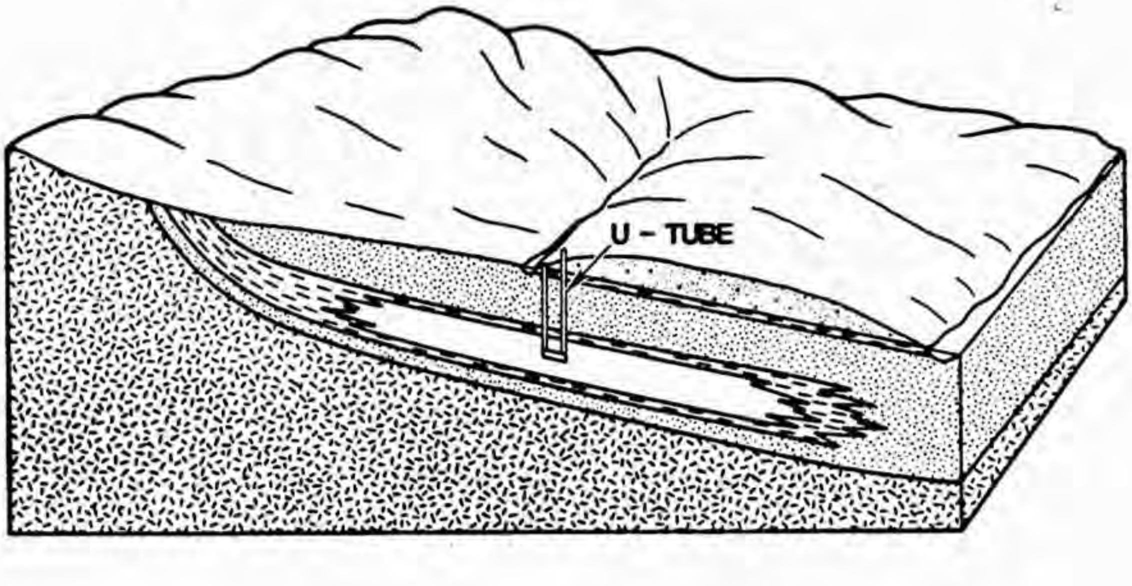

Figure 3.5.5. Release Phenomenon R3

Assuming the horizontal conductivity of the repository is higher than the intact salt, the presence of these two hydraulic communications results in ground water circulating from the middle sandstone aquifer through the repository and returning to the middle aquifer (Figure 3.5.6). Such a communication is generally referred to as a "U-tube". Radionuclides transported to the middle aquifer could reach the surface environment through withdrawal wells placed into the middle sandstone aquifer downdip from the repository or discharged at River L. Design criteria could reduce the probability of this feature by requiring that the separation, in the direction of the gradient, of exploratory holes or shafts emplaced during repository construction, be sufficiently small so as to avoid formation of a U-tube.

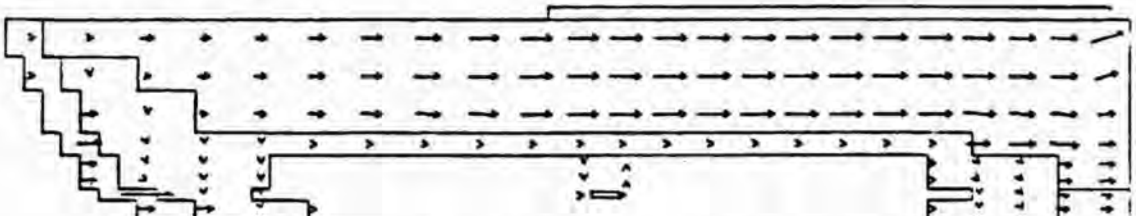

Figure 3.5.6. Fluid Velocity Vectors for R3

The consequences of such a feature could be significant, particularly if other features, such as withdrawal wells into the middle sandstone aquifer, provide a shortened path to the surface environment. Travel times from the repository to withdrawal wells located one mile downdip from the repository can be as short as a few tens to hundreds of years.

As was mentioned earlier, this feature could be formed by failure of the sealing material in two or more of the access shafts emplaced at the time of construction of the repository or from future drilling or mining. Very little data exist on the long-term integrity of sealing materials for boreholes or shafts. Therefore, it is extremely difficult to arrive at a probability that this feature will occur from failure of sealing materials. Probabilities associated with inadvertent intrusions due to drilling are, however, above the 10^{-8}/yr cut-off imposed on this demonstration. Thus, it is felt that this phenomenon cannot be eliminated based on probability arguments. Therefore, based on the potential consequences, R3 will be retained for further analysis.

Release Phenomenon R4: This release phenomenon postulates a massive dissolution cavity having a horizontal cross-sectional area approximately equal to that of the repository (Figure 3.5.7). Formation of such a cavity could result from the development of a hydraulic communication between the middle aquifer and the salt followed by dissolution of the salt layers above the repository. Events which might lead to a dissolution of the salt above the repository are: (1) thermally- or impact-induced fracturing of the overlying shale, (2) drilling or mining at some future date after repository closure, and (3) degradation of the sealing material in shafts or boreholes emplaced at the time of repository excavation.

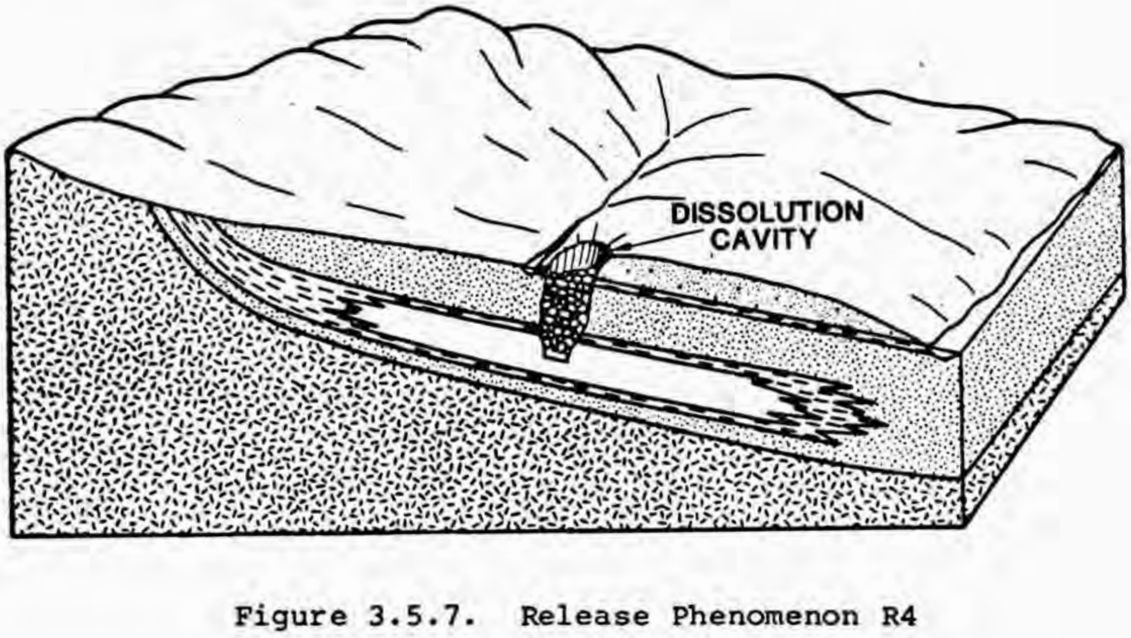

Figure 3.5.7. Release Phenomenon R4

Fracturing of the overlying shale would provide a communication for water from the middle sandstone aquifer to flow downward into contact with the salt. If the width or separation of the communication in the direction of the gradient is large, interstices at the salt/shale interface could allow for convective flow along this interface forming a dissolution cavity in the salt (Figure 3.5.8). Subsequent growth of the cavity to the depth of the repository would result in radionuclides being dissolved in circulating ground water. These radionuclides would then be transported in the middle sandstone aquifer where release to the surface could result from water wells placed into the middle sandstone aquifer or discharge at River L. The projected size of this disruptive feature ensures that collapse of the overlying rock will extend to the land surface.

Because of the several mechanisms that could lead to a disruption of the middle shale above the repository and the subsequent dissolution of the overlying salt layers (e.g., thermal effects, impact fracturing, inadvertent intrusions, etc.), it was felt that this phenomenon should not be eliminated based on probabilistic arguments. Given the existence of hydraulic communications between the middle sandstone aquifer and the salt, rates of growth of dissolution cavities were modeled using the Dynamic Network (DNET) model (Cranwell, Campbell and Stuckwisch, 1981). Varying the properties of the hydraulic communications and the middle sandstone aquifer, and considering offsetting effects such as salt creep, it was found that dissolution cavities reached the depth of the repository about 50% of the time over a 10^5 year period. The consequences of this phenomenon (in terms of discharge rates to the biosphere and health effects) could potentially be large because of the size of the disruptions and the inventory accessed. Therefore, R4 is retained for further analysis.

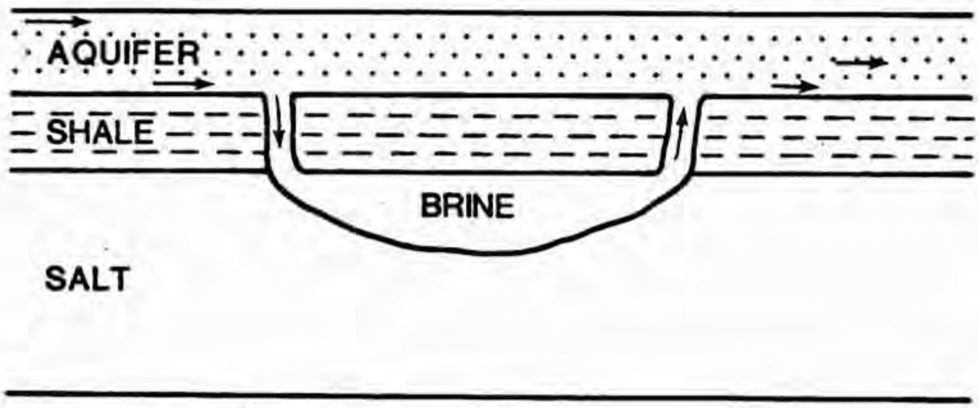

Figure 3.5.8. Dissolution Cavity at Salt/Shale Interface

Release Phenomenon R5: This phenomenon is similar in nature to R4 with the exception that the disrupted region is below the repository (Figure 3.5.9). Such a region would require extensive fracturing of the shale beneath the repository allowing water in the lower sandstone aquifer to flow upward into contact with the salt and then returning to the lower aquifer (Figure 3.5.10). Long-term dissolution of the salt could result in a dissolution cavity extending into the repository with a subsequent release of radionuclides to circulating ground water.

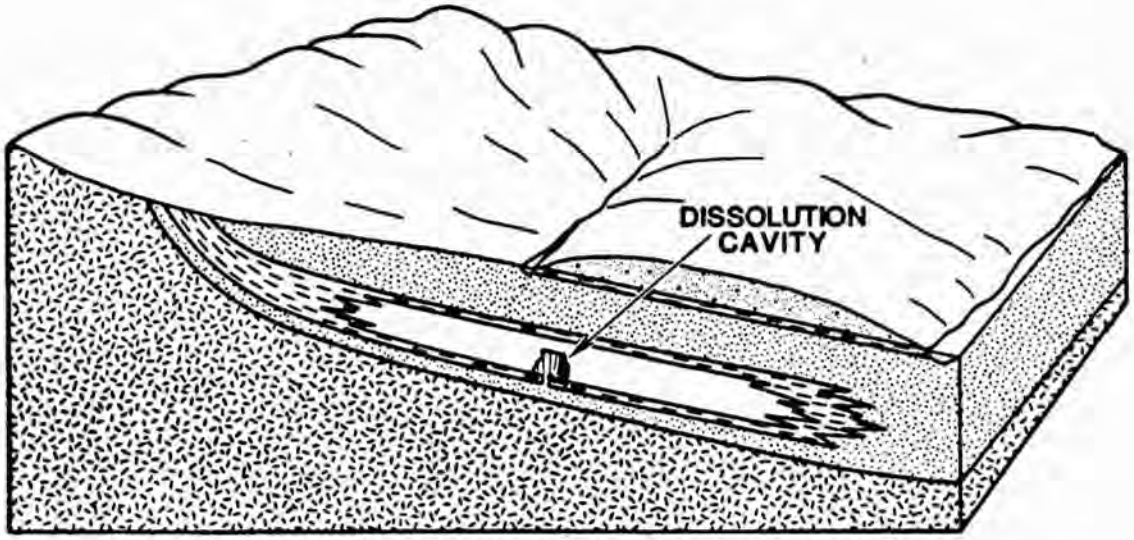

Figure 3.5.9. Release Phenomenon R5

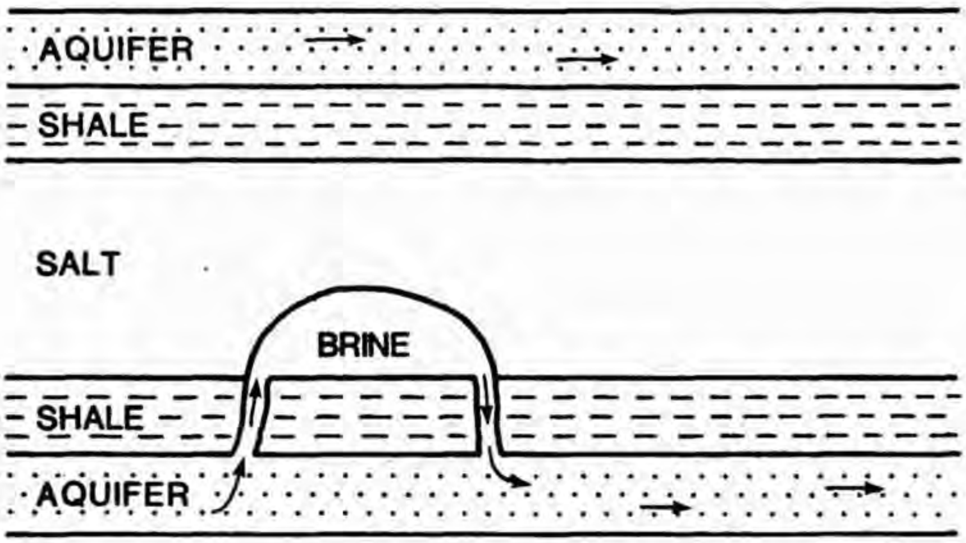

Figure 3.5.10. Formation of a Dissolution Cavity Below the Repository

Release Phenomenon R5 is included here for completeness. However, it is difficult to identify physically reasonable mechanisms that could cause this type of disrupted zone. Drilling or failed seals on shafts would affect both the shale above and below the salt, not just the lower shale. Thermal expansion of the shale is a possibility, but results from thermomechanical calculations indicate that the shale beneath the repository undergoes little thermal stress. Any horizontal thermal expansion meets the resistance of the surrounding rocks and results in compressional stresses such that, even if fractures were to develop, the compressive forces would keep them closed. Expansion downward would be prevented by the greater confining pressure in that direction, whereas expansion upward would be insufficient to cause fracturing of the shale.

Based on the physical reasonableness arguments discussed above, Release Phenomenon R5 is eliminated from any additional consideration.

Release Phenomenon R6: This phenomenon assumes the presence of a relatively narrow planar structure oriented parallel to River L and located directly below the repository (Figure 3.5.11). The feature represents a high-permeability fault plane terminating at the contact between the lower shale and salt.

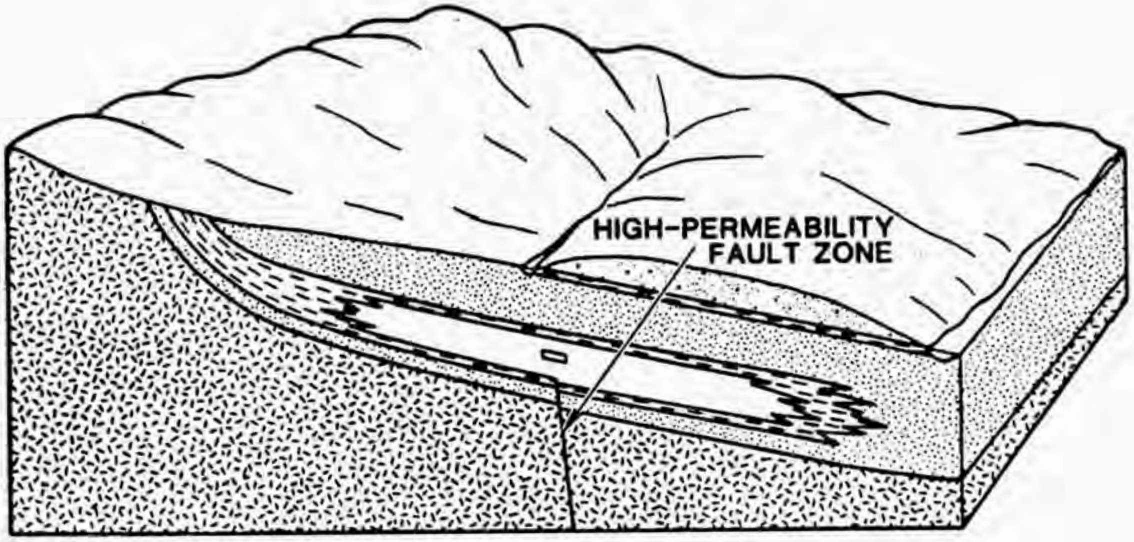

Figure 3.5.11. Release Phenomenon R6

A disturbed zone in this location having a high hydraulic conductivity has very little, if any, effect on either the head distribution or velocity field. This can be seen in Figures 3.5.12 and 3.5.13, where the vertical and horizontal conductivities for the disturbed zone were arbitrarily set at three orders of magnitude higher for that portion in the shale and one order of magnitude higher for the sandstone. Thus units already having a high conductivity are assumed to be influenced less by this high-conductivity zone than those with a lower conductivity.

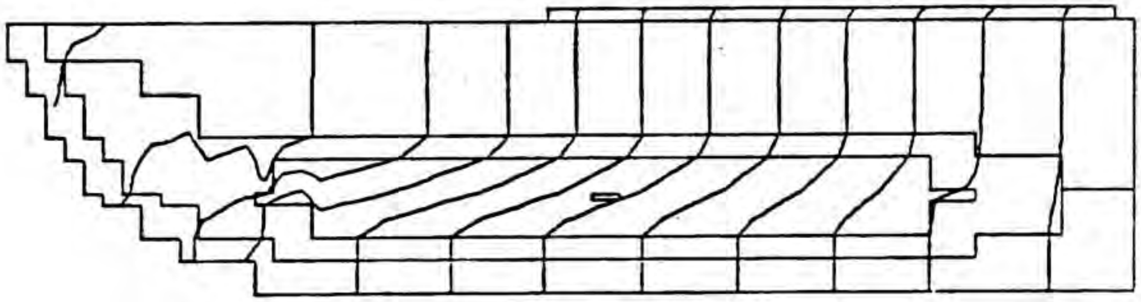

Figure 3.5.12. Hydraulic Head Distribution for R6

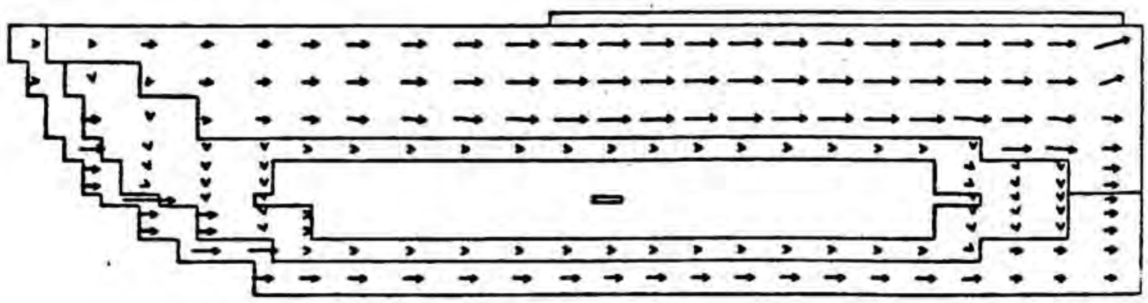

Figure 3.5.13. Fluid Velocity Vectors for R6

At the time of formation of this high-permeability zone, fresh or low-salinity ground water from the lower aquifer could rise in the zone and come in contact with the salt. Density differences between the brine at the salt contact and the underlying fresh water could initiate a convective current, thus resulting in salt dissolution. This process could be enhanced from temperature increases due to the emplacement of hot waste in the repository. Furthermore, if this feature is combined with a transport phenomenon that results in an upward hydraulic gradient, salt dissolution could be enhanced. However, analysis of salt dissolution rates have shown that formation of a cavity of any significant size is extremely difficult in this situation.

If a fault existed in this position prior to repository excavation, any extensive salt dissolution resulting from it would probably be detected during site-suitability studies. Thus the assumption would be that either the fault was present prior to excavation and extensive salt dissolution had not occurred or the disruptive feature occurred subsequent to repository closure. The probability that an existing undetected fault lies directly below the repository depends on the density of faults in the area (see Appendix D). The probability of a new fault developing directly below the repository is extremely small (see Bonilla, 1979). Furthermore, existing data typically show that bedded salt deposits generally exist in regions of low seismic activity (see, e.g., Johnson and Gonzales, 1978) and, thus, the probability of movement on a pre-existing fault would be small (Donath and Cranwell, 1980). Using data on faulting rates from the Delaware Basin in New Mexico (Claiborne & Gera, 1974) or the Palo Duro Basin in Texas (Stone & Webster, 1981), it can be shown (see Appendix D) that the probability of a fault developing directly below the repository is on the order of 10^{-11}/yr. This falls below the 10^{-8}/yr cut-off imposed on this demonstration.

Based on the probabilistic and physical reasonable arguments above, R6 will not be retained for further analysis.

Release Phenomenon R7: This phenomenon assumes the presence of a planar structure similar in orientation and location to that of R6 with the exception that the disturbed zone is now one having a low permeability. Here, the structure represents a fault or igneous dike terminating at the contact between the lower shale and salt.

The effects of this feature on the flow system are somewhat more apparent, as can be seen in Figures 3.5.14 and 3.5.15. These figures were generated by arbitrarily decreasing the vertical and horizontal conductivities of the disturbed zone by two orders of magnitude for the sandstone and one order of magnitude for the shale. The effects of this structure are to form a low-conductivity "dam," thus reducing the flow in the lower sandstone and increasing the tendency for fluid movement up into the salt and over the obstruction. However, the low vertical conductivity of the shale would eliminate any extensive salt dissolution above the obstruction. On the other hand, if vertical, high-conductivity fractures should develop adjacent to this obstruction, the flow of water from the lower sandstone aquifer could be enhanced, the result being a continuous convective current of brine and fresh water from the lower sandstone. If this process should continue, the eventual outcome could be the formation of a dissolution cavity below the repository similar to that discussed in R5.

The probability of R7 is similar to that for R6. However, if the low-conductivity zone is formed by the intrusion of magma into a fault zone, the probability of R7 would be even smaller (Schneider and Platt (1974) given the probability of volcanism as 10^{-4} times that of faulting). Therefore R7 is eliminated based on probabilistic arguments.

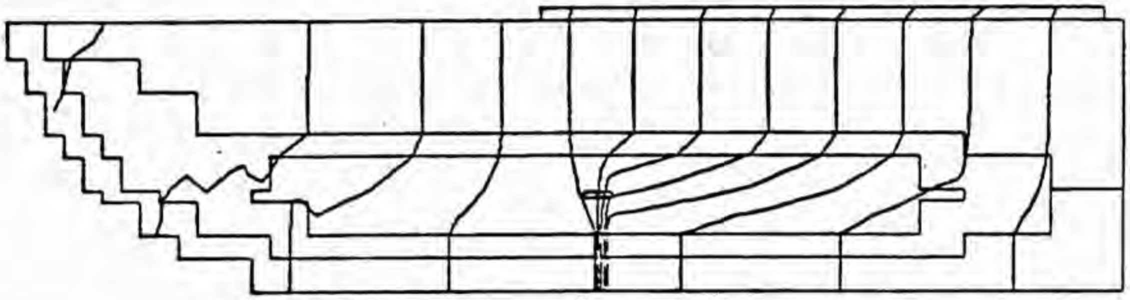

Figure 3.5.14. Hydraulic Head Distribution for R7

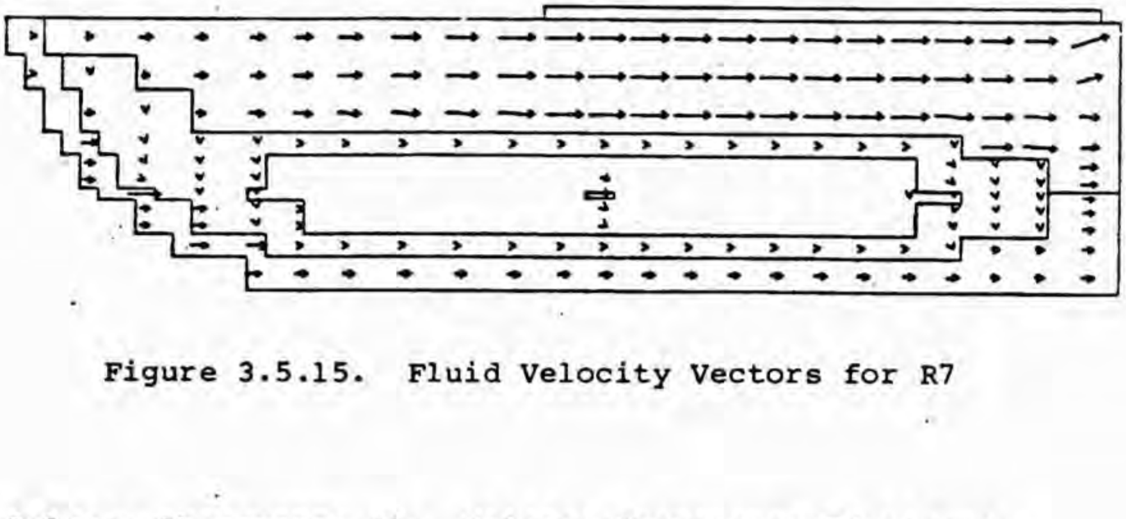

Figure 3.5.15. Fluid Velocity Vectors for R7

Release Phenomenon R8: Release Phenomenon R8 assumes the presence of a narrow planar structure oriented parallel to River L and passing through the repository

(Figure 3.5.16). As was the case with R6, the structure represents a high-permeability fault plane. Geologically, the presence of this high-permeability zone in the salt unit would probably be rare. It is generally accepted that faulting of thick salt formations does not lead to the formation of permeable zones; on the contrary, the plastic deformation of salt is known to heal any fracture or opening in the salt (see, e.g., Thurston, 1961). As a matter of fact, most of the known faults in salt formations confirm the self-healing behavior of halite. Fault breccias, which

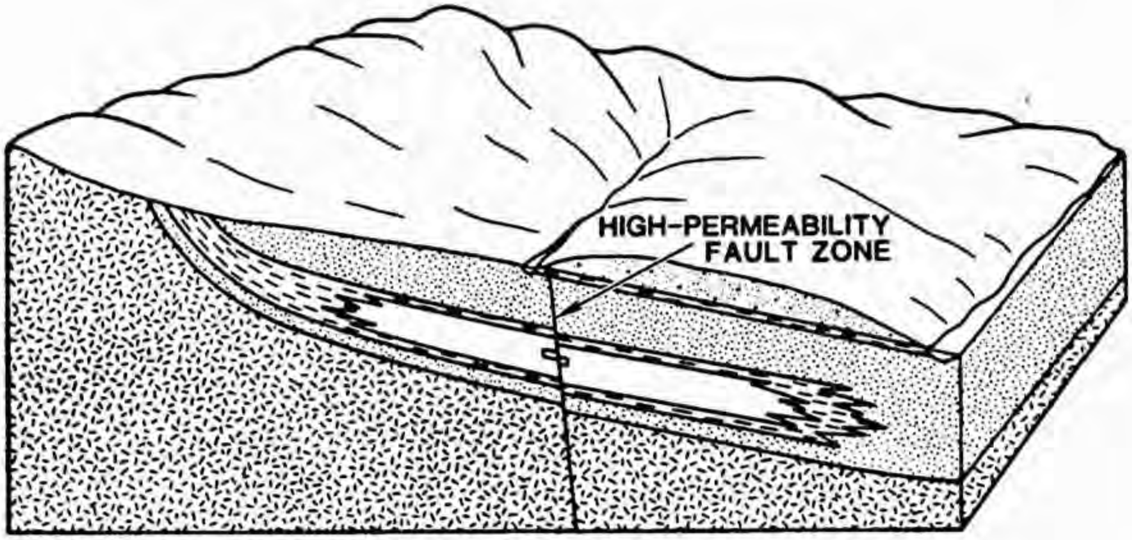

Figure 3.5.16. Release Phenomenon R8

are common in brittle rocks, are unknown in salt formations. However, it might be argued that permeable fracture zones could be found in salt but would eventually be obliterated by salt dissolution or recrystallization. Therefore, the lack of documented examples would not provide the impossibility of the event. A possible example of salt dissolution due to faulting was reported by Jones (1974) in east-central New Mexico.

The effects on the ground-water flow patterns of the reference site due to the presence of this high-permeability zone are shown in Figure 3.5.17. Here, as in R6, the vertical and horizontal conductivities of the disturbed zone were set at three orders of magnitude higher for the shale than in the undisturbed system and one order of magnitude higher for the sandstone. Conductivities of the salt were also set at three orders of magnitude higher than in the undisturbed system. Figure 3.5.17 indicates that this high-permeability zone provides a path for migration of dissolved radionuclides to the lower sandstone. Of course, the permanency of the water circulation through the repository would depend on the relative rates of salt dissolution and fracture healing. The removal of salt would not be uniform along the fault. Salt removal would be

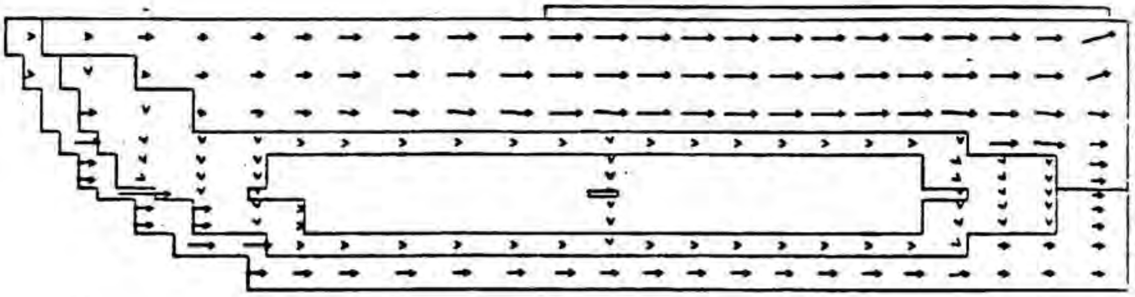

Figure 3.5.17. Fluid Velocity Vectors for R8

highest at the point where the unsaturated water enters the salt formation and would progressively decrease as the circulating brine becomes saturated. In a thick evaporite sequence such as that in the reference site, it is unlikely that salt dissolution would extend throughout the total thickness of the salt. Thus, plastic flow would eventually close the fracture and stop circulation of water. In fact, calculations with the DNET code have indicated that this is exactly what would occur.

If no permeable zone were formed along that portion of the fault in the salt formation, faulting could still result in release of radionuclides to circulating ground water by bringing the waste into contact with either an overlying or underlying aquifer due to offsetting along the fault. However, this would require a vertical displacement of at least 550 feet between the two sides of the fault, since this is the thickness of the salt and shale units above and below the repository.

Movement along fault planes can occur suddenly or in a more or less continuous creep. The greatest displacement known to have taken place in a single event was an offset of almost 50 feet during the Alaskan earthquake of 1899. The slow, continuous rates of vertical movement along a fault plane can be fairly extensive but this usually occurs over very long periods of time. For example, the only faults in the Texas Panhandle known to have affected the Upper Permian salt beds have been reported by Johnson (1976). These faults are located along the Amarillo Uplift and offset the salt by as much as 600 feet. Tectonic activity that formed the Amarillo Uplift began in late Mississippian and early Pennsylvanian time (Stone & Webster, 1981). Earthquake activity in historic time along this uplift indicates that at least some of the faults in this region continue to be active (Stone & Webster, 1981).

Assuming that movement along the faults began at the end of the Permian (225 million years ago), Permian beds being the youngest units offset, and continued to the present, and that the maximum offset of the salt beds is 600 feet, the rate of movement along these faults is 2.6×10^{-6} ft/yr. This would result in only about 0.3 feet of offset in 10^5 years.

A fault intersecting the repository horizon and present at the time of excavation would obviously be detected. Thus, the only other alternative would be that development of the fault occurred subsequent to repository closure. This could be the result of either the formation of a new fault (i.e., the occurrence of faulting where no fault existed previously) or renewed movement on a pre-existing fault below the repository. As was mentioned previously, the probability of a new fault developing is, in itself, very small ($<<10^{-8}$/yr), let alone that it also intersects the repository. Thus, the more likely occurrence would be renewed growth on a pre-existing fault below the repository. The probability of a pre-existing fault lying directly below the repository is on the order of 10^{-3} to 10^{-2} depending on the density of faults (Appendix D). The possibility of renewed movement on such a fault would make the probability of this phenomenon even smaller. Thus, R8 is eliminated from additional consideration based on the physical reasonableness and probabilistic arguments discussed above.

Release Phenomenon R9: R9 is nearly identical to R8, the exception being that the disturbed zone is assumed to have a low permeability. Here, the structure represents a fault plane or an igneous dike passing through the repository.

The effects of this low-permeability zone on the hydraulic head potential are shown in Figure 3.5.18. These equipotential lines were generated by decreasing the vertical and horizontal conductivities of the disturbed zone by three orders of magnitude for the sandstone.

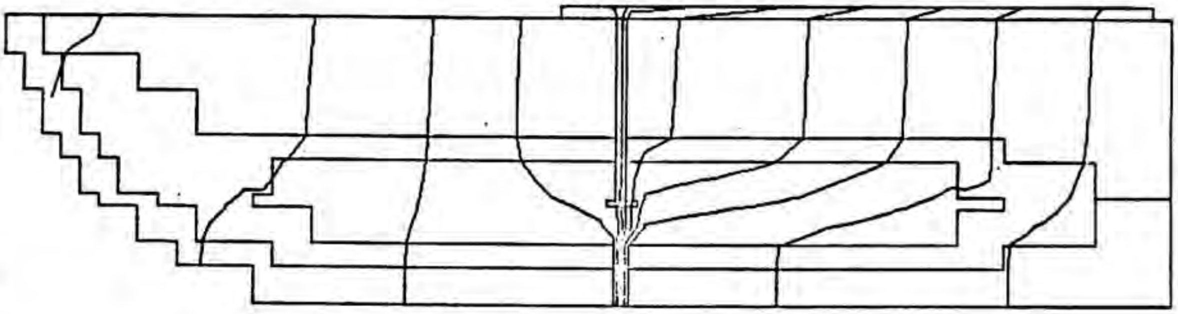

Figure 3.5.18. Hydraulic Head Distribution for R9

Conductivities of the salt were also set at one order of magnitude lower than in the undisturbed system. Updip from the repository, ground water now moves generally upward through the salt and shale into the middle sandstone aquifer. However, downdip from the repository the flow is still downward across the salt and shale units. These flow patterns suggest the possibility of a significant variability in the confining capabilities of the salt. For example, depending on the deformational history of the area, high-permeability fractures may develop parallel to a low-permeability fault plane or dike. As a result, vertical flow along the fault or dike could be enhanced by the presence of these fractures.

Such upward, vertical movement can be observed in Figure 3.5.19, where a high-permeability zone was assumed to exist updip and adjacent to the low-permeability zone. Conductivities for this high-permeability zone were increased three orders of magnitude for the salt and shale units and one order of magnitude for the sandstone units. For a fault or dike passing through the repository, the increased vertical flow could intensify the dissolution of released radionuclides in circulating ground water and result in transport of this aqueous solution along the low-permeability zone. If the fault plane

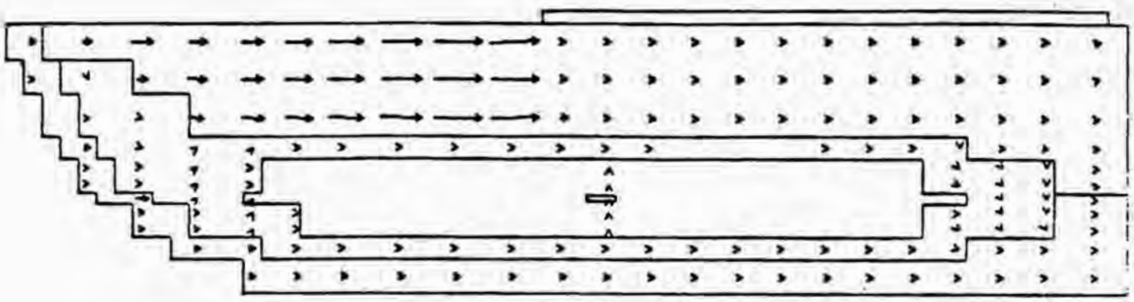

Figure 3.5.19. Fluid Velocity Vectors for R9

or dike should extend to the land surface, dissolved radionuclides could be discharged directly to the biosphere.

A fault or dike that would cause a disruption of the flow system to the extent shown in Figure 3.5.18 would obviously be detected during site-suitability analyses, provided it existed prior to repository excavation. Thus, one would assume that development occurred subsequent to repository closure. As was discussed in R8, the probability of this alternative is small ($\ll 10^{-8}$/yr) and would be even smaller if such a feature resulted from intrusion of magma into a fault zone. Therefore, R9 is eliminated from further consideration based on physical reasonableness and/or probabilistic arguments.

Transport Phenomena

Transport Phenomenon T1: T1 represents the existence of a field of withdrawal wells completed into the middle sandstone aquifer and located downdip from the repository (Figure 3.5.20). These wells represent sources of water for either individual or municipal water supply and for irrigation. Such wells could be contaminated by dissolved radionuclides discharged into the middle sandstone aquifer through several release phenomena (see, e.g., R3). For purposes of analysis, the fractional discharge of released radionuclides via the wells is taken to be the same as the fractional withdrawal of water from the aquifer over the entire well field. To determine concentrations, the radionuclide discharge is distributed to those wells within the width of the contaminant plume.

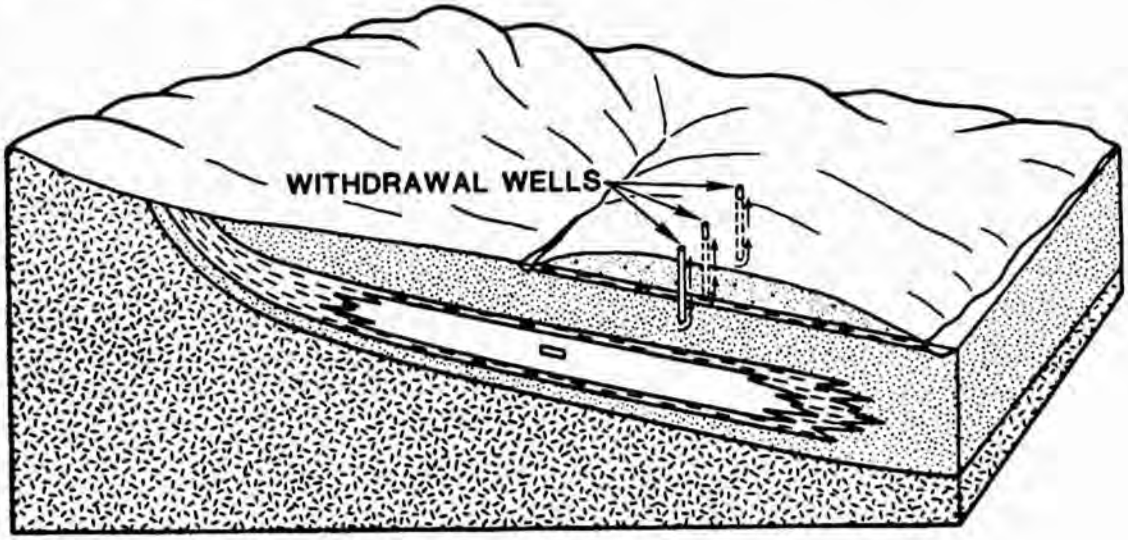

Figure 3.5.20. Transport Phenomenon T1

For release phenomena in which the migration path from the repository to the overlying or underlying aquifer has a small cross-sectional area (e.g., a single shaft or drill hole), the width of the contaminant plume at distance x downdip in the aquifer is taken as

$$W_p = 2.5\ \sigma_y$$

where

$\sigma_y = \sqrt{2\ \alpha_T x}$

α_T = transverse dispersivity.

Ignoring longitudinal dispersion, this plume width will preserve the peak or centerline concentration as the peak concentration is proportioned to $1/(\sqrt{2}\,\pi\sigma_y)$. For release phenomena such as faulting or other major disruptions which extend the full width of the repository, the plume width is taken as the width of the repository. For reasonable values of the transverse dispersivity and downdip distances up to about 10,000 feet, it can be readily demonstrated that the repository width is a good approximation for the plume width.

The probability of wells being emplaced into the middle aquifer at some time in the future after repository closure is larger than 10^{-8}/yr (see Section 3.8). Furthermore, these wells would provide a shortened path to the surface environment for radionuclides released into the middle sandstone aquifer. Thus, T1 will be retained for further analysis.

Transport Phenomenon T2: T2 is nearly identical to T1, the exception being that the wells are completed into the lower sandstone aquifer (Figure 3.5.21). These wells could be contaminated by radionuclides released into the lower aquifer (see, e.g., R2). There are several reasons, based on our hypothetical reference site, why this phenomenon could be eliminated from further analysis. First, since there is some downward movement of ground water through the salt, water in the lower sandstone aquifer is likely to be saline. Second, because wells to the lower aquifer would be drilled through the salt, there is the likelihood of further increasing the salinity. Finally, the lower sandstone is about 2,000 feet below the land surface, whereas an abundant water supply (the middle sandstone aquifer) is available much nearer the land surface. Nevertheless, there are reasons for retaining T2. For example, the mere fact that the lower sandstone is 2,000 feet below the ground surface cannot be taken to preclude its use as an aquifer some time in the future. For example, water supplies to the cities of Phoenix and Tucson used to come from relatively shallow aquifers. These aquifers have long since been pumped dry,

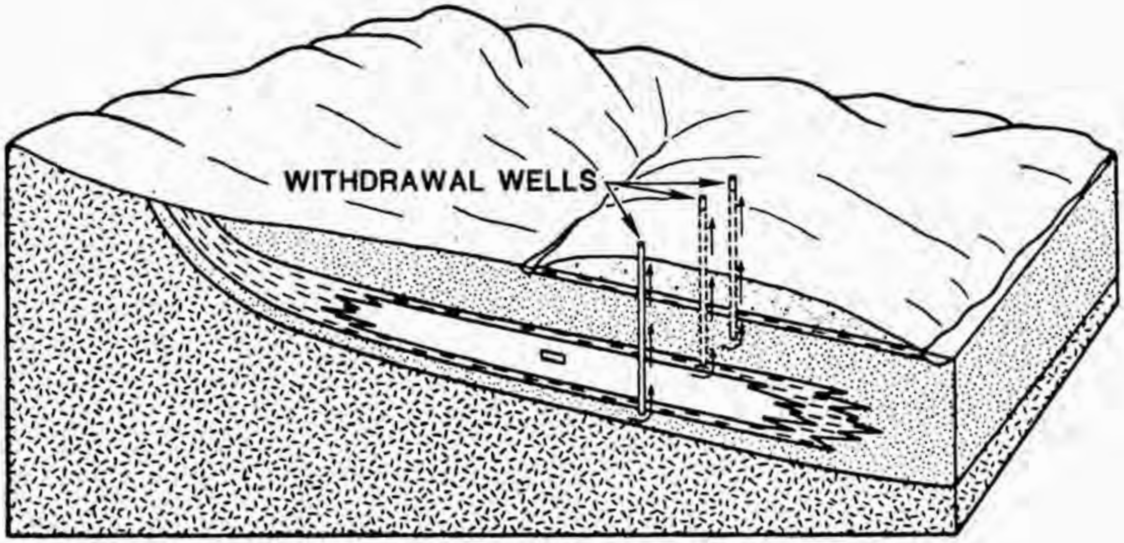

Figure 3.5.21. Transport Phenomenon T2

and present water supplies to Tucson, at least, come from aquifers several thousand feet deep. Furthermore, in our analysis of withdrawal wells, no assumptions are made as to the salinity of the aquifers. Thus, the possibility of the presence of withdrawal wells into the lower aquifer necessitates the inclusion of T2 for further analysis.

Transport Phenomena T3 and T4: These transport phenomena are identical to T1 and T2, respectively, with the exception that the wells are located updip from the repository (Figures 3.5.22 and 3.5.23). The effects on the flow system of withdrawal wells located updip from the repository would be significant only if the amount of water withdrawn were sufficient to significantly alter the

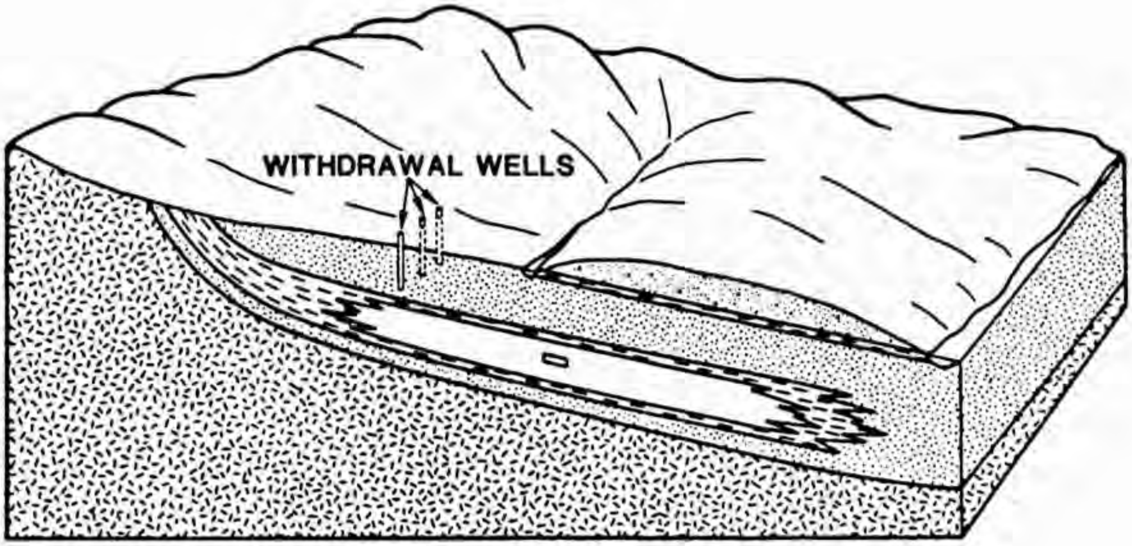

Figure 3.5.22. Transport Phenomenon T3

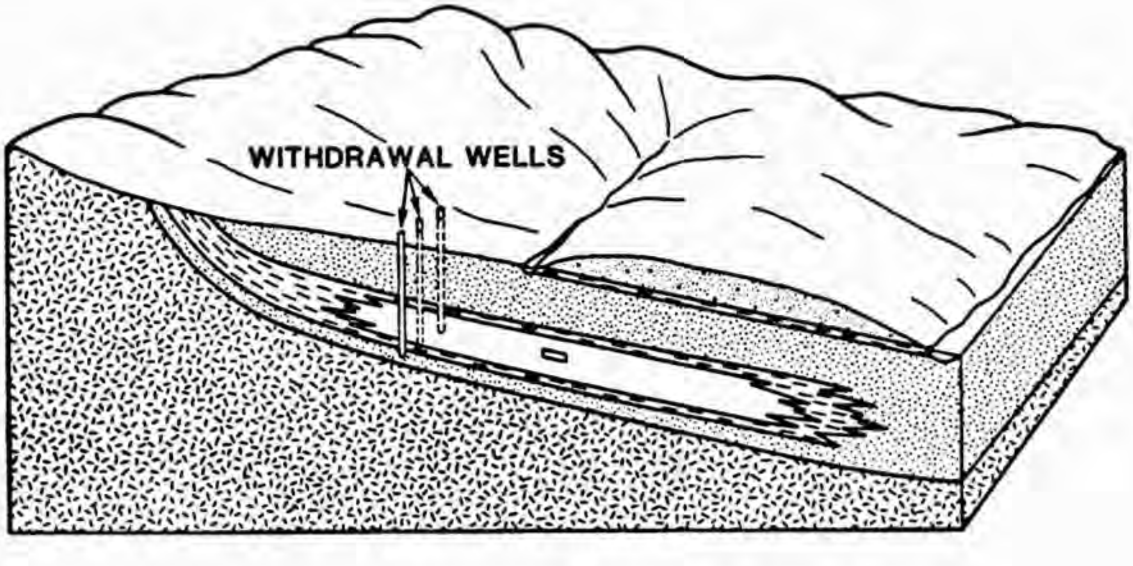

Figure 3.5.23. Transport Phenomenon T4

hydraulic gradients in the flow system, and then only if these altered gradients were maintained for very long periods of time. Furthermore, assuming wells are just as likely to be drilled downdip from the repository as updip, the risk from T3 and T4 would clearly be dominated by wells located downdip from the repository; i.e., T1 and T2. Finally, the effects of wells updip from the repository could possibly be beneficial as they could somewhat reduce fluid velocities near the repository.

Based on the arguments presented above, T3 and T4 will be eliminated from any further analysis.

Transport Phenomenon T5: T5 represents a field of injection wells completed into the lower sandstone aquifer downstream from the repository. Injection wells for disposal of chemical waste or other purposes are likely only into the lower sandstone. The effects would alter the transport of released radionuclides only if the amount of the material injected and the periods of injection were sufficient to alter the hydraulic gradients in the flow system for long periods of time. Figure 3.5.24 shows the hydraulic head distribution plots, where an injection well, injecting fluid at the rate of 1,000 ft^3/day, has been completed into the lower sandstone aquifer. This figure shows no significant change in the hydraulic head distribution from the base case. Thus, T5 is eliminated from further analysis based on low consequence.

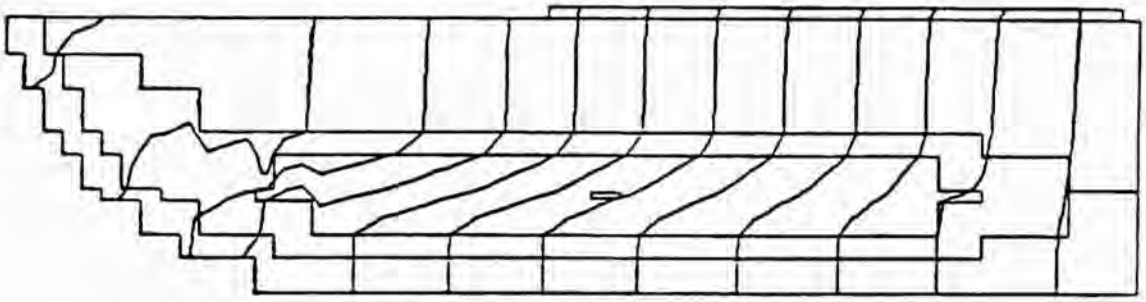

Figure 3.5.24. Hydraulic Head Distribution for T5

<u>Transport Phenomenon T6</u>: T6 is identical to T5 with the exception that the injection wells are updip from the repository. T6 is eliminated on the same basis as T5.

<u>Transport Phenomenon T7</u>: T7 assumes the existence of a narrow, high-permeability planar structure oriented parallel to River L and located downdip from the repository and extending through the lower sandstone and shale (Figure 3.5.25). The feature represents a fault plane terminating at the contact between the lower shale and salt. T7 is identical to R6 with the exception of location; the feature in R6 is located directly below the repository whereas the feature here is located downdip from the repository. A distinction is made

between the two since it is felt that a fault plane directly below the repository would have a greater influence on release of radioactive material from the repository than on its transport in an aquifer once released to that aquifer, whereas a fault downdip would have a greater influence on transport of radionuclides in the aquifer.

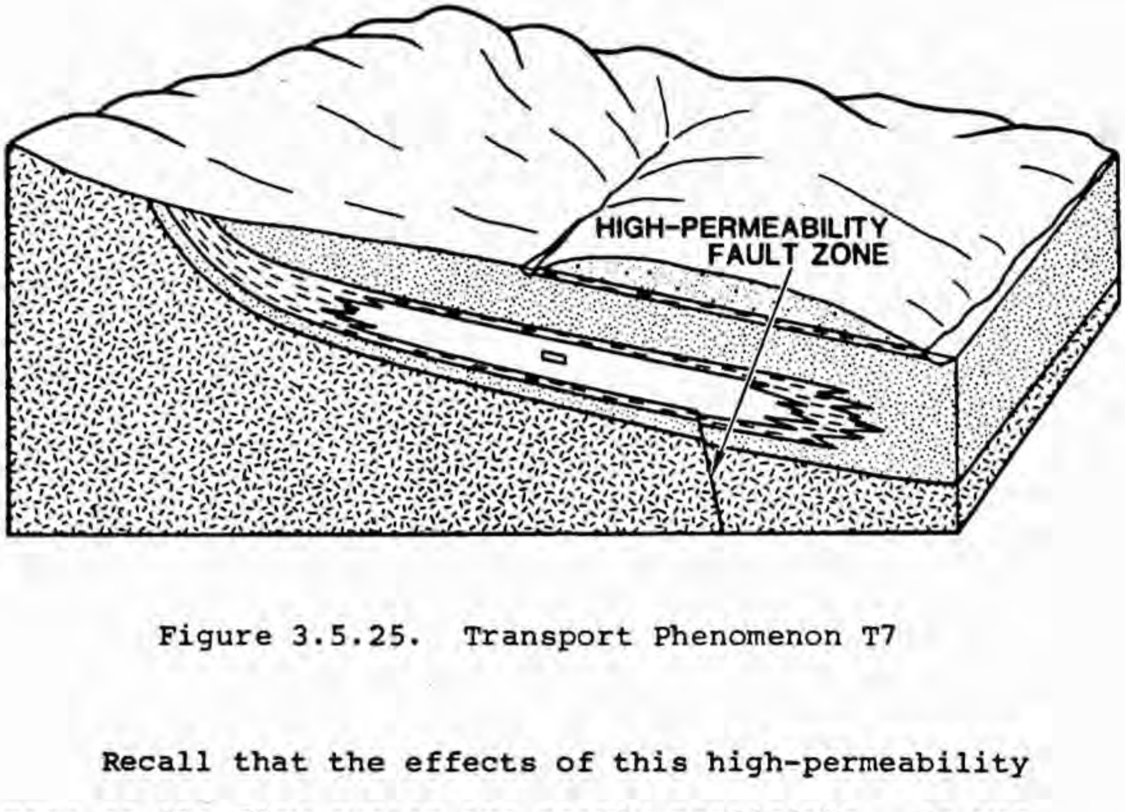

Figure 3.5.25. Transport Phenomenon T7

Recall that the effects of this high-permeability zone on the flow system are nearly negligible. As was the case with R6, a high-permeability zone in this location could result in some long-range effects on the reference site, such as the formation of a dissolution cavity in the bedded salt above the zone. However, the size of this cavity would not be significant to alter the transport of radionuclides released to the lower aquifer. Thus, T7 can be eliminated based on consequence arguments.

Transport Phenomenon T8: T8 is similar to T7, except that the disturbed zone is one of low permeability. Thus, T8 is similar to R7 with the difference being location. The effects of this low-permeability zone on the flow system are similar to the effects produced by R7, namely, to reduce the flow in the lower sandstone and to develop flow around and over the obstruction (Figures 3.5.26 and 3.5.27). Furthermore, the hydraulic

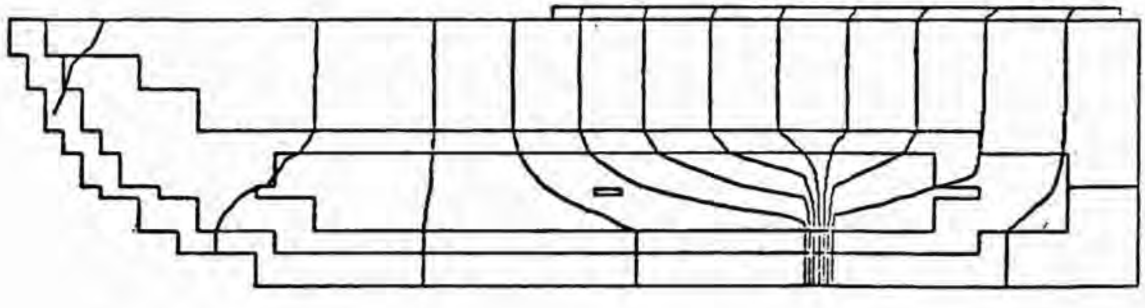

Figure 3.5.26. Hydraulic Head Distribution for T8

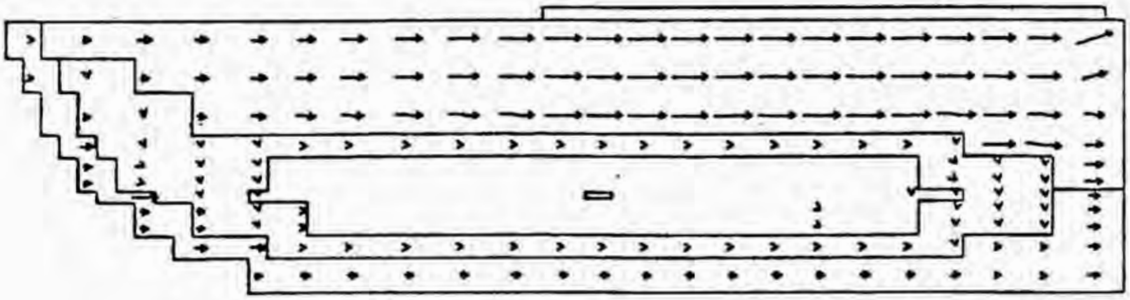

Figure 3.5.27 Fluid Velocity Vectors for T8

gradient on the updip side of the disruption is now upward across the salt and shale.

Arguments used to eliminate R7 could also be used to eliminate T8. However, should this feature be combined with a high-permeability zone passing through the repository and connecting both aquifers, flow in the lower sandstone would be diverted upward through the repository and into the middle sandstone. This can be seen in Figure 3.5.28, where a drill hole through the repository and into the lower sandstone (R2) has been combined with the low-permeability feature of T8. With the more likely possibility of withdrawal wells being placed into the middle sandstone aquifer, and the shorter path for discharge at River I (1,000 feet less) than through the lower aquifer, this possibility could result in a greater risk than that resulting from the usual discharge to the lower aquifer. Thus, despite the fact that the probability of this scenario is likely to be less than the 10^{-8}/yr cut-off, T8 is retained for further analysis.

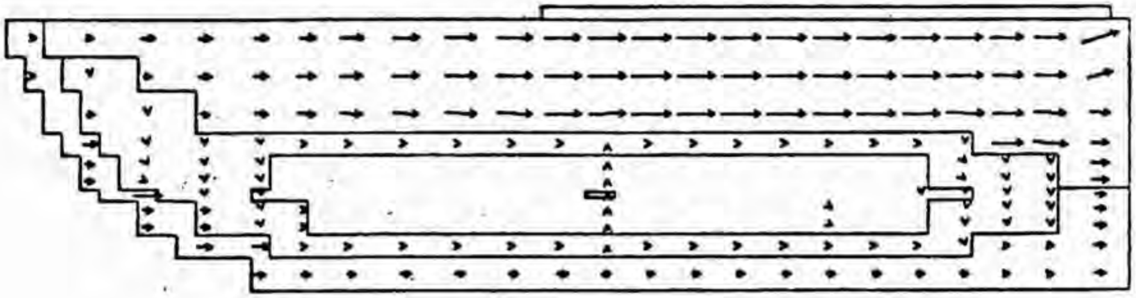

Figure 3.5.28. Fluid Velocity Vectors for R2, T8 Combination

Transport Phenomenon T9: T9 represents the presence of a high-permeability fault plane located downdip from the repository and passing through both the lower and middle sandstone aquifers (Figure 3.5.29). T9 is similar to R8 with the exception of location. Thus, the effects on the flow system of such a feature would be essentially the same. Large-scale salt dissolution along such a high-permeability zone prior to repository construction would probably be detected by site characterization studies, and, thus eliminating the site from consideration. Furthermore, the probability of post-closure faulting on this scale is small and can be minimized by selecting a site with low-seismic activity.

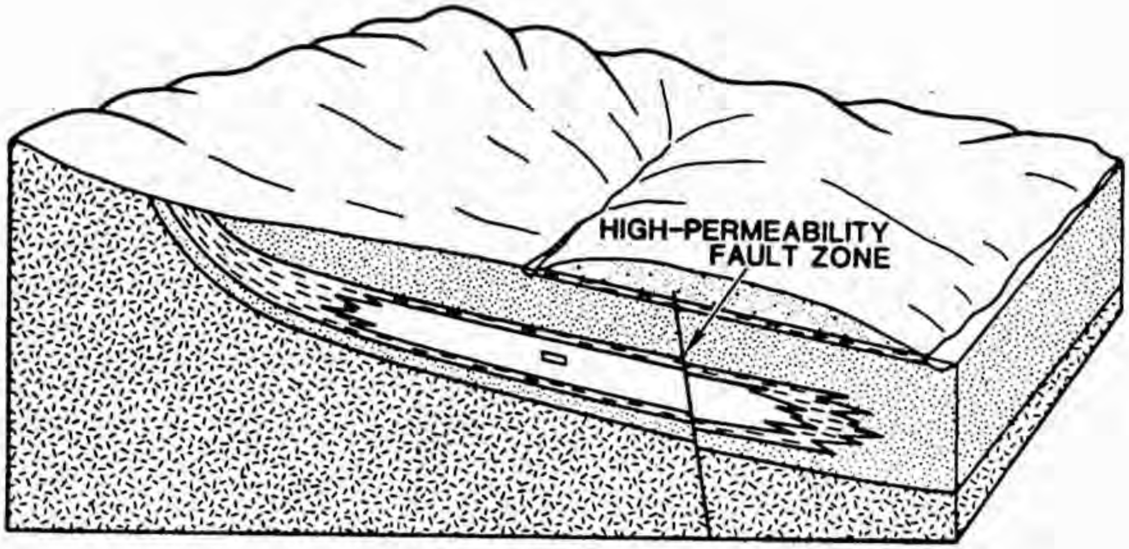

Figure 3.5.29. Transport Phenomenon T9

In addition to large-scale salt dissolution, a high-permeability zone in this position could act as a conduit between aquifers, and therefore spread any released radionuclides from one aquifer to another, depending on the direction of the hydraulic gradient. For releases to the middle sandstone, dissolved radionuclides could be transported to the lower sandstone through this high-permeability zone, resulting in a longer path length for discharge at River I. Thus, in this case, the presence of this zone could actually be beneficial. If release occurred to the lower sandstone, movement to the middle sandstone through this high-permeability zone could occur if a blockage or cementation occurred in one or both of the aquifers downdip from the high-permeability zone. However, the probability of a scenario involving the combination of a release of radionuclides to the lower sandstone, a high-permeability zone downdip connecting both aquifers, and a low-permeability blockage downdip from the high-permeability zone is extremely small ($<<10^{-8}$/yr). Thus, T9 will be eliminated based on probability and consequence arguments.

<u>Transport Phenomenon T10</u>: T10 is similar to T9 with the exception of the hydraulic properties of the disturbed zone. Here, the zone is one having a low permeability and represents a fault plane or igneous dike located downdip from the repository. The effects on the flow system are similar to those for R9. As this feature would create an upward hydraulic gradient across the repository (Figure 3.5.30), the primary concern would be the combination of T10 with a high-permeability zone passing through the repository (e.g., R2). In this case, upward vertical flow could occur through the

high-permeability zone with dissolved radionuclides being discharged either to the middle sandstone aquifer or directly to the land surface. This upward movement can be observed in Figure 3.5.31, where a drill hole from the surface to the lower sandstone and passing through the repository has been combined with the low-permeability zone of T10.

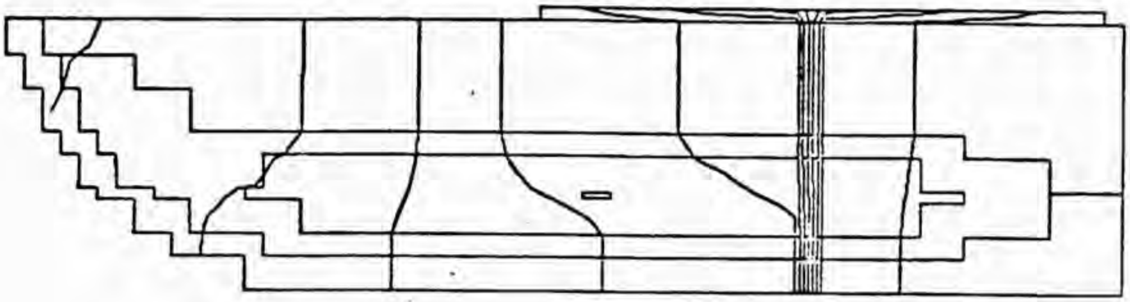

Figure 3.5.30. Hydraulic Head Distribution for T10

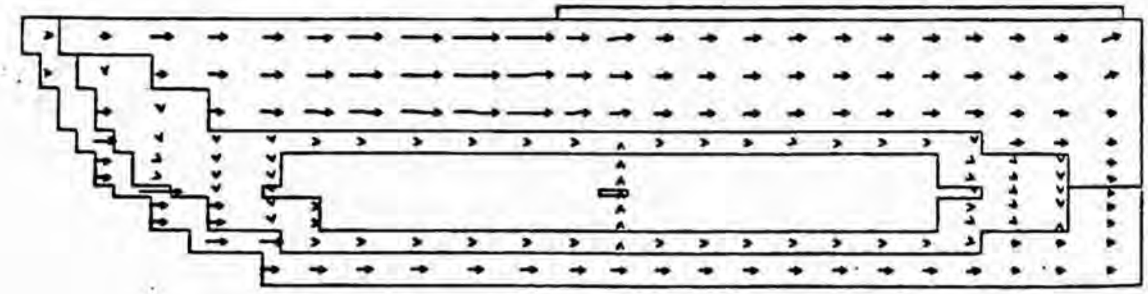

Figure 3.5.31. Fluid Velocity Vectors for R2, T10 Combination

The probability of a new fault occurring in the reference site downdip from the repository is on the order of 10^{-10}/yr. If this low-permeability zone is formed by the intrusion of magma into a fault zone, the probability of such a feature would be even smaller. Nevertheless, with the potential for direct release to the land surface when T10 is combined with R2, T10 is retained for further analysis.

<u>Transport Phenomenon T11</u>: T11 assumes the existence of a high-permeability planar structure in the lower sandstone and shale oriented parallel to River L and located updip from the repository (Figure 3.5.32). The

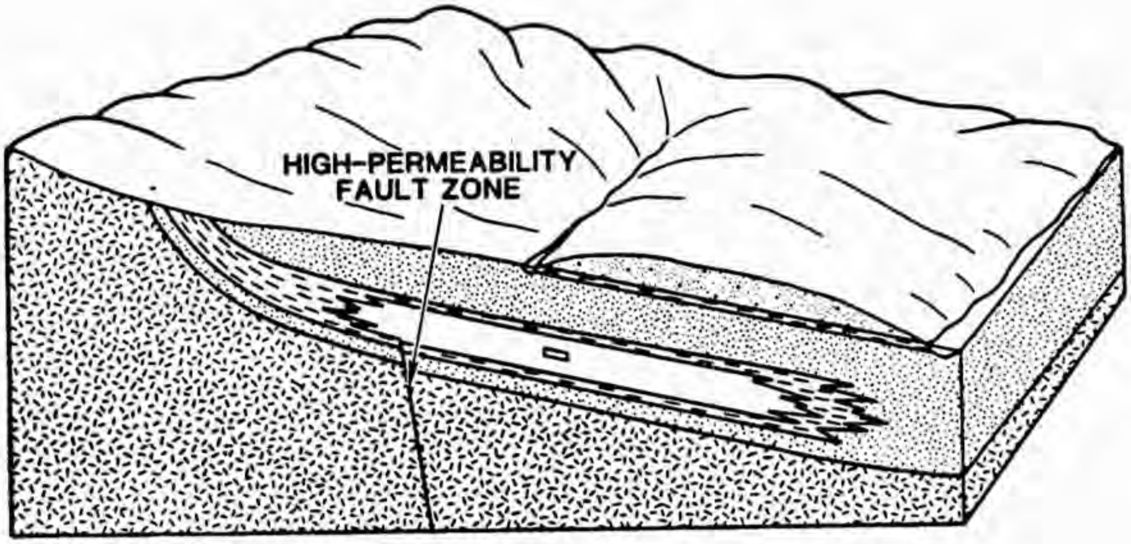

Figure 3.5.32. Transport Phenomenon T11

feature represents a fault plane terminating at the contact between the lower shale and salt. It is similar to T7 and R6 with the exception of location.

As was the case with R6 and T7, the effects of this high-permeability zone on the flow system are felt to be negligible. Thus, like R6 and T7, T11 can be eliminated based on consequence arguments.

Transport Phenomenon T12: T12 is similar to T11, the difference being that the disturbed zone is one of low permeability. Here, the feature represents a fault plane or an igneous dike terminating at the contact between the lower shale and salt.

The effects of this feature on the flow system are similar to those of R7 and T8. However, because the feature is located in the updip portion of the flow system, the increase in the tendency for downward flow downdip from the zone is more apparent than it was in R7 and T8 (Figure 3.5.33). This could have the effect of increasing the rate of migration of radionuclides from the repository to the lower sandstone. However, this effect would be offset by the decrease in fluid velocities in the lower sandstone due to the presence of this low-permeability zone. Therefore, T12 is eliminated based on consequence arguments.

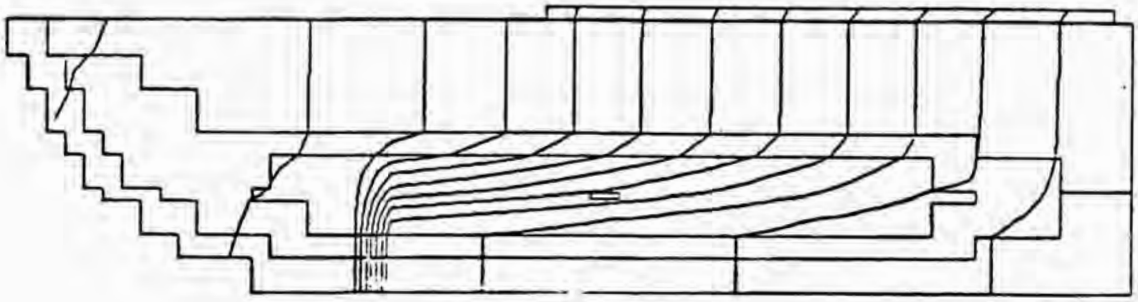

Figure 3.5.33. Hydraulic Head Distribution for T12

Transport Phenomenon T13: T13 represents the existence of a high-permeability fault plane on the updip side of the repository, oriented parallel to River I, and extending to the land surface (Figure 3.5.34). Since it extends to the land surface, it would probably be detected during site-characterization studies. The

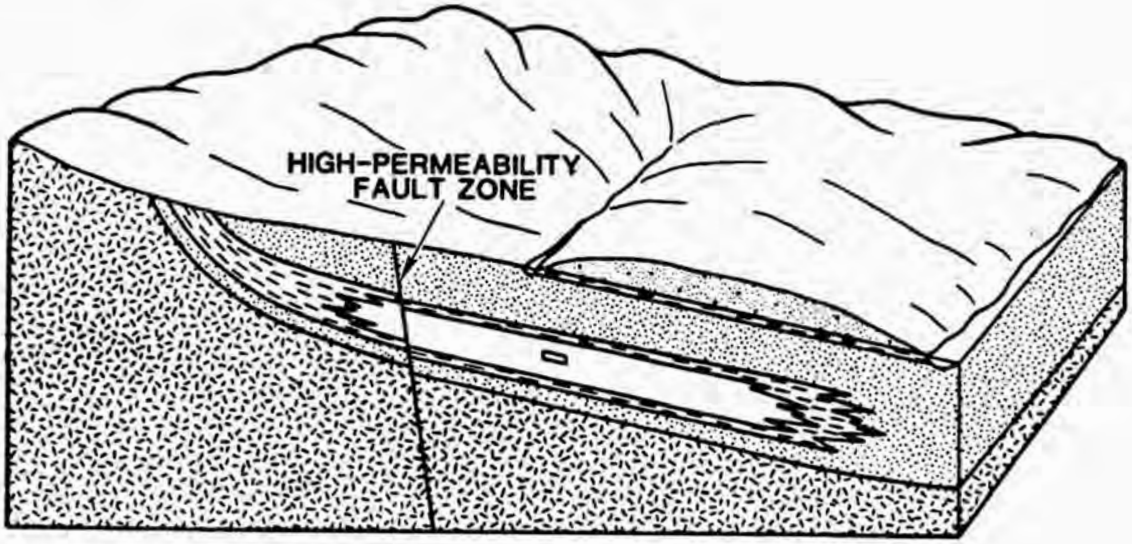

Figure 3.5.34. Transport Phenomenon T13

probability of such a feature occurring at some later date is less than the 10^{-8}/yr cut-off imposed on this demonstration (approximately 10^{-10}/yr). Thus, T13 is eliminated based on probabilistic arguments.

Transport Phenomenon T14: T14 is similar to T13, the difference being that the disturbed zone is now one of low permeability. This feature represents a fault plane or igneous dike extending to the land surface. Since it extends to the land surface, and because of its effects on the flow system (see Figure 3.5.35), it would probably be detected during site-characterization studies. Thus, the assumption would be that development occurred subsequent to repository closure.

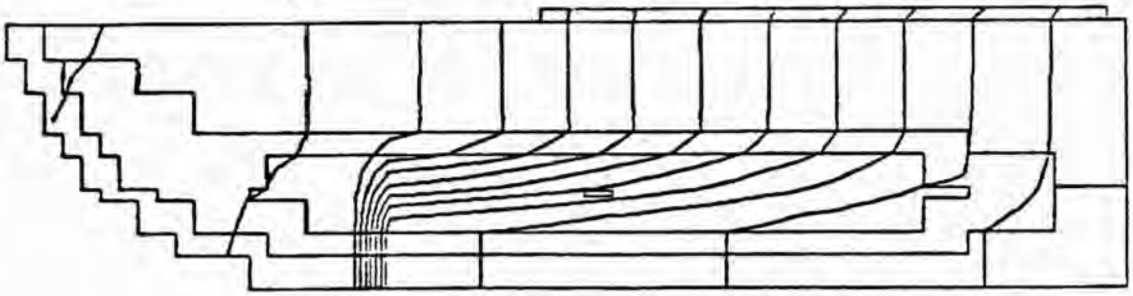

Figure 3.5.35. Hydraulic Head Distribution for T14

The effects of this low-permeability zone on the flow system are similar to those of R9 and T10. However, because of its location, the increase in the downward flow downdip from this feature is more apparent than it was in R9 and T10 (Figure 3.5.35). As was discussed in T12, this could have the effect of increasing the rate of migration of radionuclides from the repository to the lower sandstone. On the other hand, this effect would be offset by the decrease in fluid velocities in the lower sandstone due to the presence of this low-permeability zone. Furthermore, the probability of this feature occurring, let alone subsequent to repository closure, is less than the 10^{-8}/yr cut-off. Thus, T14 is eliminated from further consideration based on probabilistic arguments.

3.6 Final Set of Release and Transport Phenomena

Table 3.6.1 below lists the set of Release and Transport Phenomena remaining after the elimination procedures of Sections 3.4 and 3.5. The "BC" phenomenon listed in Table 3.6.1 represents the reference site without any disruptions and will be referred to in the remainder of this report as the "Base Case Scenario". Since it represents the reference site without any disruptions, it needs to be considered

TABLE 3.6.1

Final Set of Release and Transport Phenomena

Number	Description
BC	Reference Site Without any Disruptions
R1	Borehole or Shaft to Repository
R2	Borehole or Shaft Through Repository to Lower Sandstone
R3	U-Tube to Middle Sandstone
R4	Dissolution Cavity from Middle Sandstone to Repository
T1	Withdrawal Wells Completed into Middle Sandstone Downdip from Repository
T2	Withdrawal Wells Completed into Lower Sandstone Downdip from Repository
T8	Low Conductivity Fault or Dike in Lower Sandstone Downdip from Repository
T10	Low Conductivity Fault or Dike Through Both Aquifers Downdip from Repository

as a possible scenario. Scenarios will be formed by taking meaningful sequences, either singly or in combinations, of these phenomena (Section 3.7). An initial screening of these scenarios can be carried out based on criteria listed in Section 2.3. A final screening of the remaining scenarios can then be performed based on consequence and risk estimates. Recall that consequences at this point refer to radionuclide discharge to the surface environment and the health effects resulting from these discharges.

3.7 Constructing Scenarios from Release and Transport Phenomena

The next step in the scenario selection procedure is to construct scenarios by taking meaningful sequences, either singly or in combination, of the release and transport phenomena listed in Table 3.6.1. One means of illustrating this construction of scenarios is by the use of a logic diagram similar to that shown in Figure 2.4.1. This has the benefit of presenting a diagrammatic representation of each of the various combinations of release and transport phenomena used and aids in assuring that all meaningful combinations have been considered.

A logic diagram, including every possible combination of release and transport phenomena listed in Table 3.6.1, would contain $2^8 = 256$ outcomes. Initially, many of these combinations can be eliminated. For example, R1 (borehole or shaft to repository) could be considered in combination with R2 (borehole or shaft to lower aquifer), and the scenario (R1,R2) analyzed in terms of radionuclide transport and health effects. However, to avoid the complexity of performing transport calculations for scenarios involving multiple transport paths, consequences resulting from scenario (R1,R2) could be determined by adding the consequences from each of R1 and R2. The same reasoning could be applied to any combination of release phenomena involving multiple transport paths. Furthermore, release phenomena involving releases to the upper aquifer would probably be dominated by R4 (massive dissolution cavity to repository). In fact, the long-term outcome of release phenomenon such as R3 (U-tube) would probably lead to a disruption such as that described in R4. Thus, these phenomena do not necessarily need to be considered in combination. In the demonstration presented here, none of the release phenomena are considered in combination when forming scenarios.

Recall that R1 (borehole or shaft to repository) was retained only because of the potential of inadvertent drilling into a waste canister or leached radionuclides and transporting this material directly to the land surface. Thus, in this demonstration, R1 is not considered in combination with any transport phenomena. This eliminates the sequences (R1,T1), (R1,T2), (R1,T8), and (R1,T10). Furthermore, T10 (low permeability fault or dike downdip from repository) was retained only because of its potential of direct release to the land surface when combined with R2. Thus, T10 is not considered by itself.

The diagram in Figure 3.7.1 contains what is felt to be all the meaningful combinations of the release and transport phenomena listed in Table 3.6.1. This diagram contains 16 sequences (i.e., scenarios). These are the scenarios which will be subjected to the next level of screening as discussed below.

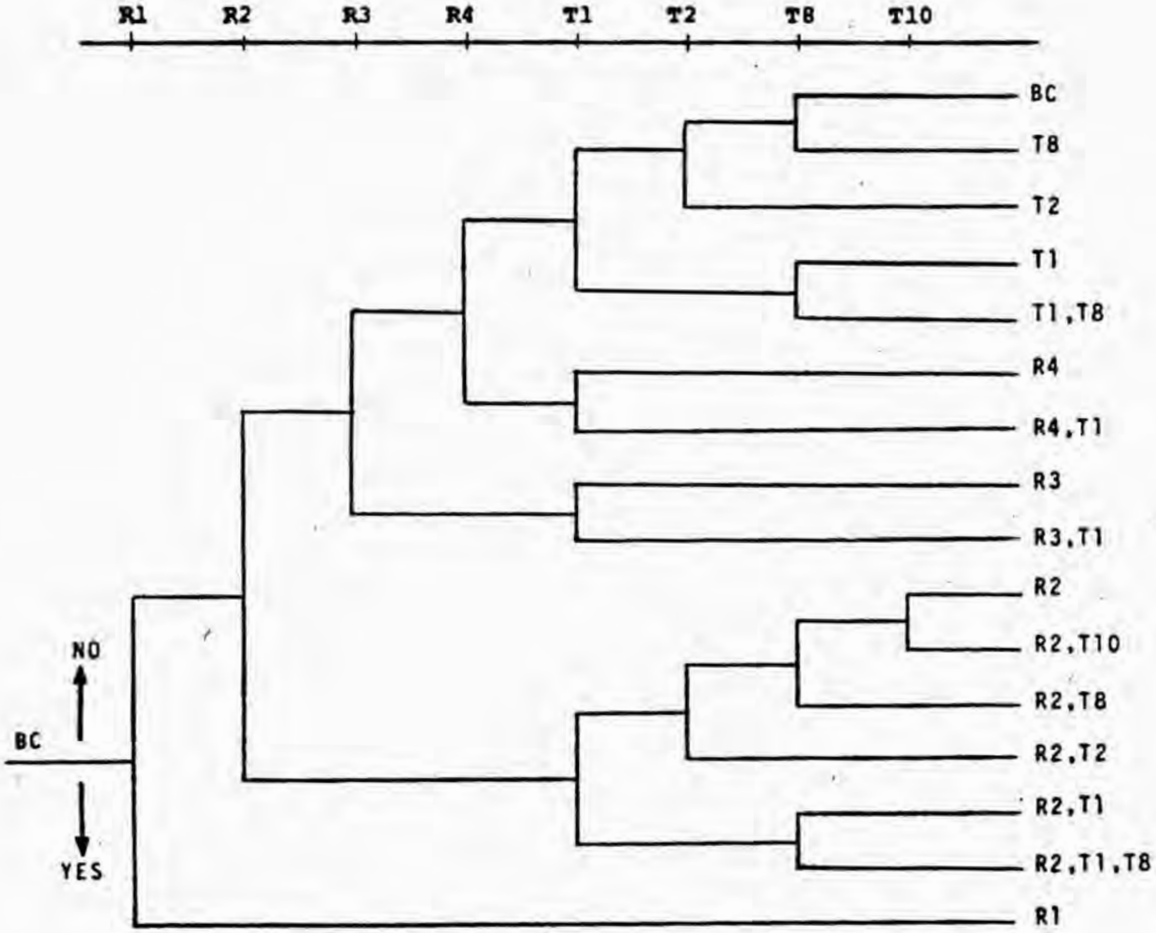

Figure 3.7.1. Scenarios Constructed from Release and Transport Phenomena

3.8 Initial Screening of Scenarios

An initial screening of the scenarios listed in Figure 3.7.1 can be accomplished by means of the criteria listed in Section 2.3. As was discussed in Section 2.5, physical reasonableness and consequence arguments will be applied first. The remaining scenarios will then be quantified in terms of probabilities and screened on the basis of this criterion.

Some of the scenarios in Figure 3.7.1 are included only for completeness of the diagram and thus can be eliminated based on physical reasonableness or consequence arguments. For example, consequences from (R2,T1) would be no different from R2, since withdrawal wells completed into the middle sandstone would not alter the consequences from a release to the lower sandstone. The combination (R2,T1) was necessary in construction of the diagram in order to arrive at (R2,T1,T8). The same is true of T1. The hydraulic gradient in the undisturbed system is downward, and there is assumed to be ample fluid in order for convection to dominate molecular diffusion. Thus, any radionuclides released in the Base Case Scenario (BC) would be discharged to the lower aquifer with eventual transport to River L. Withdrawal wells into the middle sandstone would not significantly alter the consequences from the Base

Case Scenario. T1 was necessary in construction of the diagram in order to arrive at (T1,T8).

The remaining scenarios in Figure 3.7.1 are now quantified in terms of probability estimates (whenever possible) and screened on the basis of the cut-off (10^{-3} for 10^{5} years) imposed on this demonstration. However, due to the uncertainty that frequently exists in these probabilities, scenarios with probabilities below this cut-off may be retained for further analysis. Furthermore, where estimates of realistic probabilities are virtually impossible, no attempt should be made to screen on this basis. Instead, these scenarios should be retained and subjected to further analysis (e.g., transport and health effects calculations).

Probabilistic Evaluation of Scenarios

Probabilities of those scenarios remaining after the above screening process are now discussed in detail. Estimates of probabilities will be assigned to these scenarios whenever possible. The values for these probabilities are obtained from either the models and techniques discussed in Appendices A-D or from other sources such as expert opinion when little or no data is available. In many instances, these probabilities have been unavoidably arbitrary, since the reference site used in the demonstration of the scenario selection procedure is entirely hypothetical. A great deal of site-specific research is required to generate reliable probability data.

It should be noted that the probability associated with each scenario is not the probability that that scenario occurred and nothing else. It is the probability that at least that scenario occurred within the 10^5 year period considered. In that respect, the scenario probabilities are conservatively high.

Base Case (BC) Scenario - Recall that the Base Case Scenario is the reference site without any disruptions other than the emplacement of the repository. Since it is the reference site, the probability associated with this scenario would be 1 (assuming, of course, that one is not considering the probability of the Base Case occurring and nothing else).

Scenario R1 - Scenario R1 represents a high-permeability zone (borehole or shaft) extending from the land surface to the repository. This scenario was retained because of the possibility of inadvertent drilling into a waste canister or leached radionuclides and transporting this material directly to the land surface.

While the repository is operational, and during the administrative control period following sealing and decommissioning of the repository, no drilling into the site would be expected. After this period, it is conceivable that future generations might drill into the formations containing the waste without knowing it was there. For purposes of analysis, the period of administrative control is arbitrarily assumed to be 100 years. Thus, the probability of inadvertent drilling into the waste is 0 for the first 100 years. Following this period several factors enter into determining the probability of this scenario. The first is the probability of drilling at the site. The potential for natural resources such as potash, oil and gas existing at the site influence the possibility of drilling. Also, heat generated by the waste could make the site appear to be a geothermal source to future generations. Because of the unpredictability of future generations, it is difficult to determine when the economic factors that drive the present-day search for these resources will end. Thus, probabilities derived for this scenario are based on current drilling data. Based on drilling data from various bedded salt regions (see Appendix B), the probability of at least one drill hole penetrating the repository in 10^5 years is nearly 1.

Geometric probabilities must also be considered. Given that drilling has occurred at the site, what is the probability that it intersects a room filled with canisters and also intersects a canister or leached waste from a canister? In our calculations, the probability of intersecting leached waste was assumed to be the same as intersecting a canister. The probability of intersecting a room and a canister was found to be approximately 2.5×10^{-3} for the hypothetical reference repository (see Appendix B).

The probability of Scenario R1 is determined by multiplying the two probabilities discussed above. Thus,

Time (yr)	Probability
0-100	0
$100-10^5$	2.5×10^{-3}

Scenario R2 - Scenario R2 represents a high-permeability zone (borehole or shaft) connecting overlying and underlying aquifers and passing through the repository. Since repository design criteria would undoubtedly not allow the drilling of such shafts or boreholes in the construction of the repository, the drilling of this borehole or shaft is assumed to occur subsequent to repository closure and administrative control. Furthermore, no assumption is made as to the sealing or backfilling of this shaft or borehole. Boreholes will probably be drilled outside specified boundaries of the site during site-suitability studies and these boreholes will be sealed. For release of radionuclides to occur from these boreholes, a dissolution front would have to advance to the repository once the sealing material had failed. For this to occur, failure of the sealing material would have to be severe. Furthermore, salt dissolution along the borehole would have to be extreme to extend to the repository. Analyses with salt dissolution rates along boreholes (see, e.g., Cranwell, Campbell and Stuckwisch, 1982) have shown that such dissolution rates are highly unlikely.

The probability of drilling into the repository is assumed to be the same as that for Scenario R1. The probability of intersecting a canister is not considered here, only the probability of intersecting a room. For the hypothetical waste repository, this was determined to be 0.25 (see Appendix B). Thus, the probability of R2 is estimated as

Time (yr)	Probability
0-100	0
$100-10^5$	0.25

Scenario R3 - Recall that Scenario R3 postulates the existence of two high-permeability zones extending from the overlying aquifer to the repository and downdip from each other. Flow through this "U-tube" feature would involve entry of fresh water from the overlying aquifer through the updip communication, flow through the repository, and discharge into the overlying aquifer through the downdip communication. Because of density differences between fresh water and brine, the hydraulic gradient at the reference site will not be sufficient to drive water through the repository and out the downdip communication unless a minimum separation distance is maintained. For the reference site, this distance was found to be approximately 3000 feet. Thus, if the U-tube formation was due to future drilling, the target area would have to be reduced accordingly.

Realization of the need for a minimal separation of the vertical connections in the U-tube scenario would clearly be recognized during construction of the repository. Thus, repository design criteria would eliminate the formation of this scenario from boreholes and shafts placed at the time of repository construction. Therefore, it is assumed that this scenario results from an existing borehole or shaft (emplaced at time of repository construction) and drilling at some future date.

Boreholes and shafts emplaced at the time of repository construction would clearly be sealed. Thus, the estimation of the probability of seal failure is needed.

Estimation of the probability of a shaft or borehole seal failure is difficult because of the lack of data describing the long-term behavior of sealing materials. Schneider and Platt (1974) arrive at an estimate of 10^{-4} as the probability of an original flaw in a seal based on a study of borehole seals by the oil and gas industry. Depending on the material used, seals may either deteriorate with time or improve. Thus, due to the lack of additional data, a probability of 10^{-4} will be used for this event for all time.

The probability that the two vertical communications of the U-tube are formed by two drill holes emplaced at some future date and at least a distance of 3000 feet apart in the downdip direction is estimated using the drilling data of Appendix B. If the two holes are drilled at different times, the possibility exists that one might have closed, due to salt creep, before the other is drilled. To account for this, the period of time for drilling was reduced to 10^3 years. This time period was based upon studies of rates of salt creep around drill holes in bedded salt formations (Cranwell, Campbell and Stuckwisch, 1982). At the mean drilling rate of 1.18×10^{-2} wells/ 1100 acres/year (Appendix B), this would amount to approximately 12 drill holes for the 10^3 year period. To determine the probability that at least two of these are located at a minimal distance of 3000 feet from each other in the direction of the gradient, we assumed, as in Appendix B, that wells are drilled according to a Poisson process. Here, however, we assume $\lambda t = 12$. Thus,

$$P(\text{at least two drill holes} \geq 3000 \text{ ft apart})$$

$$= \sum_{n=2}^{12} P_n(t) P(\text{at least two holes} \geq 3000 \text{ ft apart} | n \text{ holes})$$

$$= \sum_{n=2}^{12} \frac{(\lambda t)^n}{n!} e^{-\lambda t} \; P(\text{at least two holes} \geq 3000 \text{ ft apart} | n \text{ holes}).$$

To determine P(at least two holes $\geq$ 3000 ft apart|n holes), we assume n points to be located at random on line segment [0,8000]. Let $Y_1, Y_2, \ldots, Y_n$ be an ordering of these points from smallest to largest; i.e.,

$$0 \leq Y_1 \leq Y_2 \leq \ldots \leq Y_n \leq 8000.$$

Then

$$P(\text{at least two holes} \geq 3000 \text{ ft apart} | n \text{ holes})$$

$$= P(Y_n - Y_1 \geq 3000).$$

The joint density of $Y_1, Y_2, \ldots, Y_n$ is

$$f(y_1, y_2, \ldots, y_n) = \frac{n}{8000^n}.$$

Hence, the joint density for Y_1 and Y_n is

$$f(y_1, y_n) = \frac{n!}{8000^n}\int_{y_1}^{y_n}\int_{y_n}^{y_{n-1}} \cdots \int_{y_1}^{y_2} dy_2 \cdots dy_{n-2}\, dy_{n-1}$$

$$= \frac{n(n-1)}{8000^n}(y_n - y_1)^{n-2}.$$

Thus,

$$P(Y_n - Y_1 \geq 3000) = \frac{n(n-1)}{8000^n}\int_0^{8000}\int_0^{y_n-3000}(y_n - y_1)^{n-2}\, dy_1 dy_n$$

So,

P(at least two holes $\geq$ 3000 ft apart by time t)

$$= \sum_{n=2}^{12}\frac{(\lambda t)^n}{n!}e^{-\lambda t}[1 - n(3/8)^{n-1} + (n-1)(3/8)^n].$$

With $\lambda t = 12$, this probability is approximately equal to 0.6. Thus, the probability that the two vertical communications of the U-tube are formed by two drill holes a distance of at least 3000 feet apart will be taken as 0.6.

The probability that the two vertical communications are formed by a drill hole emplaced at some future date and a shaft or borehole emplaced at time of repository construction and in which the sealing material has failed is estimated using the drilling data of Appendix B and the probability of shaft seal failure. The shaft will assume to have been placed at one end of the repository. This leaves a region of area (8000 - 3000 ft) x 6000 ft = 691 acres for the drill hole to be placed. The parameter $\lambda t = 1180$ is therefore adjusted as follows:

$$
\begin{aligned}
\lambda t &= (\lambda t)\,\frac{691}{1100} \\
&= (1180)(.63) \\
&\approx 740
\end{aligned}
$$

The probability P that at least one drill hole is drilled at a distance greater than 3000 feet from the shaft is given by

$$
\begin{aligned}
P &= \sum_{n=1}^{740} \frac{(\lambda t)^n}{n!}\, e^{-\lambda t} \quad \text{P(at least one hole} \geq \text{3000 ft from shaft}|\text{n holes)} \\
&= \sum_{n=1}^{740} \frac{(\lambda t)^n}{n}\, e^{-\lambda t} \quad \text{[1-P(none of the n holes are >3000 ft from shaft)]} \\
&= \sum_{n=1}^{740} \frac{(\lambda t)^n}{n}\, e^{-\lambda t} \quad [1-(3/8)^n] \\
&\approx 1
\end{aligned}
$$

The probability of shaft seal failure is taken as 10^{-4}. Therefore, the probability that the vertical communictions of the U-tube resulted from a drill hole and and a shaft in which the sealing material has failed is taken as 10^{-4}.

The probability of the two vertical communications of the U-tube is found by summing the two probabilities of the previous paragraph. This sum is approximately equal to 6×10^{-1}. However, formation of the two vertical communications, even at a minimum distance of at least 3000 feet, does not necessarily imply formation of the U-tube. Flow connecting these two communications must still occur through the repository. Realistic estimates of this probability are felt to be impossible without the aid of near-field modeling. To account for this part of the U-tube formation, the probability of the two vertical communications is arbitrarily lowered by two orders of magnitude. Thus, the probability of Scenario R3 is given as:

Time (yr)	Probability
0-100	0
100- 10^5	6×10^{-3}

Scenario R4 - Scenario R4 postulates the existence of a massive dissolution cavity extending from the overlying aquifer to the repository. Formation of this cavity is assumed to have occurred by a disruption of the shale layer between the overlying aquifer and the salt followed by dissolution of the salt layers above the repository. The disruption of the shale layer above the repository might be caused by a number of events or processes such as thermal effects, impact fracturing, tectonics, subsidence, pressurization, drilling, etc. Estimation of probabilities for all possible initiating events and processes, at least on a generic basis, is unrealistic. Some have already been discussed (e.g., meteorite impacts, drilling, and tectonics). For purposes of this demonstration, a probability of 1 will be assigned to be the composite of initiating events for Scenario R4.

Salt dissolution rates following disruption of the overlying shale were analyzed using the DNET computer model (Cranwell, Campbell and Stuckwisch, 1982). One hundred sets of input values representing varying properties of the overlying aquifer, shale and salt units were analyzed with the DNET code to estimate a distribution of times for a dissolution cavity to reach the depth of the repository. Of these 100 sets of input values, only 49 resulted in a dissolution front reaching the depth of the repository in 10^5 years. Based on this, the probability that a dissolution cavity will reach the depth of the repository, given that a disruption of the overlying shale layer has occurred, will be estimated as 5×10^{-1}. Thus, the probability of Scenario R4 is estimated as 5×10^{-1}.

Scenario T2 - Without data from a specific site, the estimation of the probability that water wells are drilled downdip from the repository is difficult. Once such data were available, techniques similar to those used for arriving at probabilities for hydrocarbon exploration could be used (see Appendix B).

According to the 1970 publication of The Water Encyclopedia (1979), wells to obtain water were being drilled at the rate of approximately 420,000 per year. About 2% of these, or 8300, were deeper than 500 feet. If these were uniformly distributed over the land surface of the United States, this would amount to approximately 2×10^{-3} wells/mi^2/yr. The region at the hypothetical site located downdip from the repository consists of approximately 32 mi^2 (Campbell et al., 1978). This would amount to about 6.4×10^{-2} wells/yr, or 6400 wells in 10^5 years. Assuming wells are drilled in this region according to a Poisson process with $t = 6400$, the probability of at least one water well being drilled in this region during a period of 10^5 years after repository closure is, approximately, 1. Thus, a "rough" estimate of the probability of Scenario T2 is:

Time (yr)	Probability
0-100	0
$100-10^5$	1

Scenario T8 - Recall that Scenario T8 assumes the existence of a low-permeability fault or dike extending through the lower sandstone and shale downdip from the repository. The probability of this scenario can be estimated by assuming that the feature was formed by igneous intrusions into a fault zone. This, however, is an extremely crude estimate due to the hypothetical nature of the site. Site-specific faulting data and volcanic activity would be required to obtain realistic probability estimates.

The probability of this scenario can be estimated using the procedures discussed in Appendix D. Assuming that the area of the downdip region of concern in this scenario is 32 sq. mi., the probability of a pre-existing but undetected fault existing in this region is on the order of 10^{-2} to 10^{-1}, depending on the density of existing faults. For a new fault, this probability would be on the order of 10^{-5} for a 10^5 year period, assuming a formation rate of 1×10^{-8} faults/year.

Schneider and Platt (1974) estimate the probability of volcanic activity as 10^{-4} times that of faulting. This estimate was based on surface phenomena such as craters and calderas and, so, would probably be larger if underground phenomena were included. To account for underground phenomena, the above probability of 10^{-4} was arbitrarily increased by two orders of magnitude. Thus, the probability of Scenario T8 is estimated as 10^{-3} to 10^{-7} for a 10^5 year period.

The remaining scenarios involve combinations of the scenarios discussed above. Thus, their probabilities can be determined by multiplying the probabilities of the component parts. The scenarios and their corresponding probabilities are listed in Table 3.8.1. Note that these are the probabilities that the scenario occurs within 10^5 years after repository closure.

3.9 Final Screening of Scenarios

If one is fairly confident in the probabilities assigned to these scenarios in Table 3.8.1, Scenarios T8, (R2,T8), (R2,T10) and (R2,T1,T8) could be eliminated based on the cutoff imposed on this analysis (10^{-3} for 10^5 years). However, if there is a large degree of uncertainty in these estimates, some or all of these scenarios should be retained for additional consequence

Table 3.8.1

Scenario Probabilities

Scenario	Probability
BC	1
R1	2.5×10^{-3}
R2	2.5×10^{-1}
R3	1×10^{-2}
R4	5×10^{-1}
T2	1
T8	$1 \text{x} 10^{-3} - 1 \text{x} 10^{-7}$
R2, T2	2.5×10^{-1}
R2, T8	$2.5 \text{x} 10^{-4} - 2.5 \text{x} 10^{-8}$
R2, T10	$2.5 \text{x} 10^{-4} - 2.5 \text{x} 10^{-8}$*
R2, T1, T8	$2.5 \text{x} 10^{-4} - 2.5 \text{x} 10^{-8}$**
R3, T1	1×10^{-2}
R4, T1	5×10^{-1}

*The probability of T10 was assumed to be the same as T8.

**The probability of T1 was assumed to be the same as T2.

(transport) and health effects calculations. For purposes of demonstration, all of the above scenarios will be retained for further analysis. Furthermore, there are only 13 scenarios remaining at this point and so a great deal of time and effort are not required doing transport calculations on hundreds of scenarios. If several tens to hundreds of scenarios were still remaining at this point, some screening would have to be accomplished based on probabilistic arguments.

Transport calculations may not have to be performed on all the remaining scenarios if it is felt that certain ones will result in similar consequences. For example, transport calculations performed on the Base Case (BC) Scenario resulted in no discharges at River L for the 10^5 year period used in these analyses (Cranwell et al., 1982). Recall that, since a downward gradient exists in the undisturbed system, radionuclides released from the repository in the BC scenario would move to the lower aquifer and be transported along this aquifer and discharged to the surface environment at River L. Scenario T8 results in a change of the hydraulic gradient from downward to upward across the repository. Thus, radionuclides released from the repository under the conditions resulting from T8 would move to the middle sandstone aquifer and be transported along this aquifer with discharge to the surface environment at River L. Preliminary analyses showed that ground-water travel times from the repository to River L were not significantly different for the BC Scenario and T8. Thus, since Scenario BC resulted in no discharges, it was felt that detailed transport calculations need not be performed for Scenario T8.

The final set of scenarios on which radionuclide transport and health effects calculations were performed are listed in Table 3.9.1. The results of these transport and health effects calculations can be found in the project's final report (Cranwell et al., 1982). The scenarios listed in Table 3.9.1 are numbered according to the same numbering scheme used in the final report.

It should be emphasized once more that the scenarios selected depended, in part, on the characteristics of a hypothetical reference site. Thus, different scenarios would probably be selected for a site-specific analysis. Undoubtedly there will be disagreement on the scenarios selected for retention and on those eliminated. The reader should keep in mind that the scenarios selected were the result of a demonstration of a scenario selection procedure applied to a hypothetical site.

Table 3.9.1

Final Set of Scenarios

Scenario	Description
1 (BC)	Reference Site Without Disruptions
2 (T2)	Withdrawal Wells into Lower Sandstone Aquifer Downdip from Repository
3 (R2)	Borehole or Shaft Through Repository to Lower Sandstone Aquifer
4 (R2,T2)	Borehole or Shaft Through Repository to Lower Sandstone Aquifer with Withdrawal Wells into Lower Sandstone Downdip from Repository
5 (R2,T8)	Borehole or Shaft Through Repository to Lower Sandstone Aquifer with a Low Conductivity Fault or Dike in Lower Sandstone Downdip from Repository
6 (R2,T1, T8)	Borehole or Shaft Through Repository to Lower Sandstone Aquifer with Withdrawal Wells into Middle Sandstone Aquifer and a Low Conductivity Fault or Dike in Lower Sandstone Downdip from Repository
7 (R2,T10)	Borehole or Shaft Through Repository to Lower Sandstone Aquifer with a Low Conductivity Fault or Dike to Land Surface Downdip from Repository

Table 3.9.1 (cont'd)

Scenario	Description
8 (R1)	Borehole or Shaft to Repository Intersecting a Canister or Leached Waste from a Canister
9 (R3)	U-tube Connection Through Repository to Middle Sandstone Aquifer
10 (R3,T1)	U-tube Connection Through Repository to Middle Sandstone Aquifer with Withdrawal Wells into Middle Sandstone Downdip from Repository
11 (R4)	Massive Dissolution Cavity from Middle Sandstone Aquifer to Repository
12 (R4,T1)	Massive Dissolution Cavity from Middle Sandstone Aquifer to Repository with Withdrawal Wells into Middle Sandstone Downdip from Repository

4. SUMMARY AND CONCLUSION

This report has presented a procedure for selecting and screening scenarios for use in the analysis of a radioactive waste disposal site. This procedure was demonstrated by applying it to a hypothetical reference site containing a bedded salt formation as the host medium for the waste. All aspects of the scenario selection procedure were presented with the exception of those involving detailed radionuclide transport and health effects calculations. The results of these calculations can be found in the project's final report (Cranwell et al., 1982).

In the development and demonstration of the scenario selection procedure discussed in this report, several observations were made concerning the topic of selection and screening of scenarios for radioactive waste disposal in deep geologic formations. First, it is felt that no matter what criteria are used to select and screen scenarios for a real site analysis, the selection and screening should be done by means of an objective and consistent methodology involving several levels of analysis and screening. The factors affecting the long-term isolation of radioactive waste in deep geologic formations are too complex to involve simple selection procedures applied with just one level of screening. The evaluation of any site will generally be a sequential process involving several levels of analysis and evaluation. As the study of a site progresses and knowledge is gained with respect to what is known and unknown about the site, it will be necessary to appropriately modify the analysis of scenarios.

Second, the quantification of scenarios in terms of probabilities is undoubtedly one of the most difficult tasks in the scenario selection and screening procedure. As was pointed out earlier, use of these probabilities in estimates of risk (consequence times probability) should be avoided whenever possible. Furthermore, the development of generic probabilistic models and techniques for assigning probabilities to every possible scenario is unrealistic. Most scenario probabilities will have to be purely subjective due to lack of data, or will involve the analysis of extremely site-specific data by experts in the area associated with a scenario. An attempt to arrive at an estimate of a probability for a preliminary set of scenarios might be a worthwhile endeavor. However, it is unrealistic to expect accurate probabilistic values for all these scenarios.

Finally, one is always faced with the problem of "completeness". The procedure of classifying events, features and processes as was demonstrated in this report is felt to be a helpful aid in addressing the problem of completeness. The formation of scenarios by taking sequences of these phenomena aids in avoiding the possibility of overlooking potentially important scenarios. However, the importance of a scenario is, quite frequently, dependent upon the geologic and hydrologic properties assumed when analyzing that scenario. Thus, care also needs to be exercised when evaluating the importance of a scenario based on the physical properties assumed for the features comprising that scenario.

What has been presented in this report is "one" procedure for selecting and identifying important scenarios for geologic disposal of radioactive wastes. As was mentioned earlier, we do not claim that this procedure is the only one available for scenario selection. Furthermore, the scenarios selected in the demonstration analysis may not be those selected in a real site analysis. Nevertheless, it is felt that the procedure presented does provide a systematic means for selecting and screening scenarios and that this procedure can be applied to any geologic site being considered.

REFERENCES

Arnet, R. C., R. G. Baca, J. A. Caggiano, D. J. Carrell and S. E. Logan, Radionuclide Release Scenario Selection Process for a Possible Repository in Basalt, RHO-BWI-SA-83, Rockwell International, Richmond, WA (1980).

Arthur D. Little, Inc., Technical Support of Standards for High-Level Radioactive Waste Management, EPA 520/4-79-007D (1980).

Beckman, R. J., and M. E. Johnson, A Probabilistic Model for Estimating the Effects of Volcanism on Nuclear Waste Repositories, LA-UR-80-2166, Los Alamos Scientific Laboratory, Los Alamos, NM (to appear).

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

Bloom, A. L., The Surface of the Earth, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1969).

Bonilla, M. G., Historic Surface Faulting - Map Patterns, Relation to Subsurface Faulting, and Relation to Preexisting Faults, USGS-79-1239, Open-File Report, U.S. Geological Survey (1979).

Burkholder, H. C., Comments on the NRC Approach to Radioactive Waste Disposal Standards and the Technical Approach to Performance Assessment in the NWTS Program, NUREG/CP-0022, CONF-81-0372, Oak Ridge National Laboratory, Gatlinburg, TN (1981).

Campbell, J. E., R. L. Dillon, M. S. Tierney, H. L. Davis, P. E. McGrath, F. J. Pearson, H. R. Shaw, J. C. Helton and F. A. Donath, Risk Methodology for Geologic Disposal of Radioactive Waste: Interim Report, SAND78-0029, Sandia National Laboratories, Albuquerque, NM (1978).

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

Cranwell, R. M., J. E. Campbell and S. E. Stuckwisch, Risk Methodology for Geologic Disposal of Radioactive Waste: The DNET Computer Code User's Manual, SAND81-1663, Sandia National Laboratories, Albuquerque, NM (January 1982).

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

Crowe, B. M., Disruptive Event Analysis: Volcanism and Igneous Intrusion, LA-UR-78-2643, Los Alamos Scientific Laboratory, Los Alamos, NM (1978).

Dietz, R. S., Astroblems, Scientific American, v. 205 (1961).

Donath, F. A., and R. M. Cranwell, Probabilistic treatment of faulting in geologic media, Amer. Geophysical Union Monograph (1980).

Egan, D. and A. Golden, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste, 40CFR191, Draft No. 20, Environmental Protection Agency (1981).

Flint, R. F., Glacial and Quaternary Geology, John Wiley & Sons, Toronto (1971)

Franke O. L., and P. Cohen, Regional Rates of Groundwater Movement on Long Island, New York, U.S. Geological Survey, Prof. Paper 800-C (1972).

Gilluly, J., A. C. Waters and A. O. Woodford, Principles of Geology, 3rd edition, W. H. Freeman & Company, San Francisco (1968).

Glasstone, S., Effects of Nuclear Weapons, Revised Edition, U.S. Atomic Energy Commission (April 1962).

Griesmeyer, J. M., and D. Okrent, On the Development of Quantitative Risk Acceptance Criteria, ALO-130, UCLA-ENG-7969, UCLA School of Engineering and Applied Science, Los Angeles, CA (January 1981).

Halbouty, M. F., Salt Dome; Gulf Region, United States and Mexico (2nd Edition), Gulf Publishing Company, Houston (1979).

Halliday, I., The Variation in the Frequency of Meteorite Impact with Geographic Latitude, Meteorites, v. 2, No. 3 (1964).

Hartmann, W. K., Terrestrial and Lunar Flux of Large Meteorites in the Last Two Billion Years, ICARUS 4 (1965).

Hartmann, W. K., Long-Term Meteorite Hazards to Buried Nuclear Waste, PNL-2851, Pacific Northwest Laboratories, Richland, WA (1979).

Helton, J. C., and P. C. Kaestner, Risk Methodology for Geologic Disposal of Radioactive Waste: Model Description and User Manual for Pathways Model, SAND78-1711, Sandia National Laboratories, Albuquerque, NM (March 1981).

Johnson, K. S., Evaluation of the Permian Salt Beds in the Texas Panhandle and Western Oklahoma for Underground Storage of Radioactive Wastes, Office of Waste Isolation, Report Y/OWI/SUB-4494/1 (1976)

Johnson, K. S., and S. Gonzales, Salt Deposits of the United States and Regional Geologic Characteristics Important for Storage of Radioactive Waste, Office of Waste Isolation, Report Y/OWI/SUB-7414/1 (1978).

Jones, C. L., Salt Deposits of the Clovis-Portales Area, East-Central New Mexico, USGS-4339-9, Open-File Report, U.S. Geological Survey (1974).

Judson, S., and D. F. Ritter, Rates of Regional Denudation in the United States, Jour. Geophys. Res., v. 69 (1964).

Karnbranslesakerhet (KBS), Handling of Spent Nuclear Fuel and Final Storage of Vitrified High-Level Reprocessing Waste, Stockholm, Sweden (1978).

Koplik, C. M., M. F. Kaplan and B. Ross, "The Safety of Repositories for Highly Radioactive Wastes," Reviews of Modern Physics, Vol. 54, No. 1 (January 1982).

Logan, S. E., and M. C. Berbano, Development and Application of a Risk Assessment Method for Radioactive Waste Management, EPA 520/6-78-005 (1978).

Press, F., and R. Siever, Earth, W. H. Freeman Company, San Francisco (1974).

Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear power Plants, WASH-1400, NUREG-75/014, U.S. Nuclear Regulatory Commission (October 1975).

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

Ried, H. F., Studies of Muir Glacier, Alaska, Nat. Geogr. Mag., v. 4 (1982).

Santalo, L. A., Integral Geometry and Geometric Probability, Addison-Wesley, Reading, Mass. (1976).

Schneider, K. J., and A. M. Plath, High-Level Radioactive Waste Management Alternatives, BNWL-1900, Battelle Pacific Northwest Laboratories, Richland, WA (1974).

Stone & Webster, Subregional Characterization Report, Palo Duro and Dalhart Basins, Texas, ONWI Draft Report, Stone & Webster Engineering Corporation, Boston, MA (February 1981).

The panel members and their affiliations are: William S. Twenhofel, USGS, Denver, CO; William W. Dudley, USGS, Denver, CO; Randolph Stone, LLL, Livermore, CA; Frederick J. Pearson, USGS, Reston VA; Herbert R. Shaw, USGS, Menlo Park, CA; Donald Caldwell, USNRC, Wash., DC; Ben Ross, The Analytical Sciences Corp., Reading, MA; Edward Hawkins, USNRC, Wash., DC; and Martin Tierney, Sandia Laboratories, Albuquerque, NM. Working sessions of this panel were held on Dec. 7-8, 1976, at Grand Canyon, AZ; and again on April 13, 1977, in Carlsbad, NM.

REFERENCES (Cont'd)

Thurston, W., National Academy of Sciences, National Research Council, Division of Earth Sciences, Committee on Geologic Aspects of Radioactive Waste Advisory to the U.S. Atomic Energy Commission (1961).

U.S. Nuclear Regulatory Commission, Federal Regulations for Disposal of High-Level Radioactive Wastes in Geologic Repositories, 10CFR60 (1981).

WIPP (Waste Isolation Pilot Plant), U.S. Dept. of Energy Report, DOE/EIS-0026-D (1979).

APPENDIX A

Meteorite Impacts

The total depth of large meteorite impact craters has been determined to be about one-third of the diameter (Claiborne, 1974). Depth here means the distance from the top of the surrounding plane to the bottom of the "crushing zone" (Figure A.1). The crushing zone is formed by shattered rock fragments dispersed into the air at the time of impact and falling back into the crater after impact. Below the crushing zone is what is commonly referred to as the "fracture zone". This is the zone where underlying material was highly fractured but left in situ. Generally, the depth to the bottom of the fracture zone is determined to be one-half the diameter.

Figure A.1. Schematic Representation of Meteorite Crater

The impact of meteorites will be considered as a random process. There is evidence that this may not be entirely true since a slight latitude effect seems to exist (Halliday, 1964). To determine the probable number of craters of different diameter, a relationship between the number of craters and size observed for the moon will be used (Hartman, 1965); namely

$$N = KD^{-2.4} \tag{1}$$

where

N = the number of craters with diameter larger than D

K = empirical constant

On the basis of Canadian impact craters, the frequency of impacts producing craters larger than 1 km in diameter falls between 0.8×10^{-13} and 17×10^{-13} km^{-2} yr^{-1} (Hartman, 1965). The lower limit appears to be more consistent with geologic data and with Dietz's estimate of one every ten thousand years (Dietz, 1961). Therefore,

$$1 \times 10^{-13}\ km^{-2} yr^{-1} \tag{2}$$

will be taken as the best estimate of the frequency of impacts producing craters of 1 km or greater in diameter.

Using Equation 1, we have,

$$\frac{N_{Dkm}}{N_{1km}} = \frac{KD^{-2.4}}{K1^{-2.4}} = D^{-2.4}$$

Thus, the probability of formation of a crater D km in diameter or greater is $D^{-2.4}$ times that of the probability of a 1 km or greater crater. Let P_D be this probability. Then, using (2),

$$P_D = (1 \times 10^{-13})D^{-2.4}/\text{km}^2/\text{yr}$$

Set $F_D = 1-P_D$. Then

$$\frac{dF_D}{dD} = (2.4 \times 10^{-13})D^{-3.4} \qquad (3)$$

Now, consider a waste repository at a depth h below the land surface and with dimensions length = ℓ and width = w. Assuming the total depth of a meteorite crater to be approximately one-third the diameter, it would take a direct impact by a meteorite of crater diameter 3h to cause instantaneous release of radionuclides to the air or land surface. However, an impact by a meteorite of crater diameter larger than 3h could cause immediate release even if it were not a direct impact. Therefore, the plane region to consider concerning meteorite impacts should extend beyond that of the region of the repository (Figure A.2).

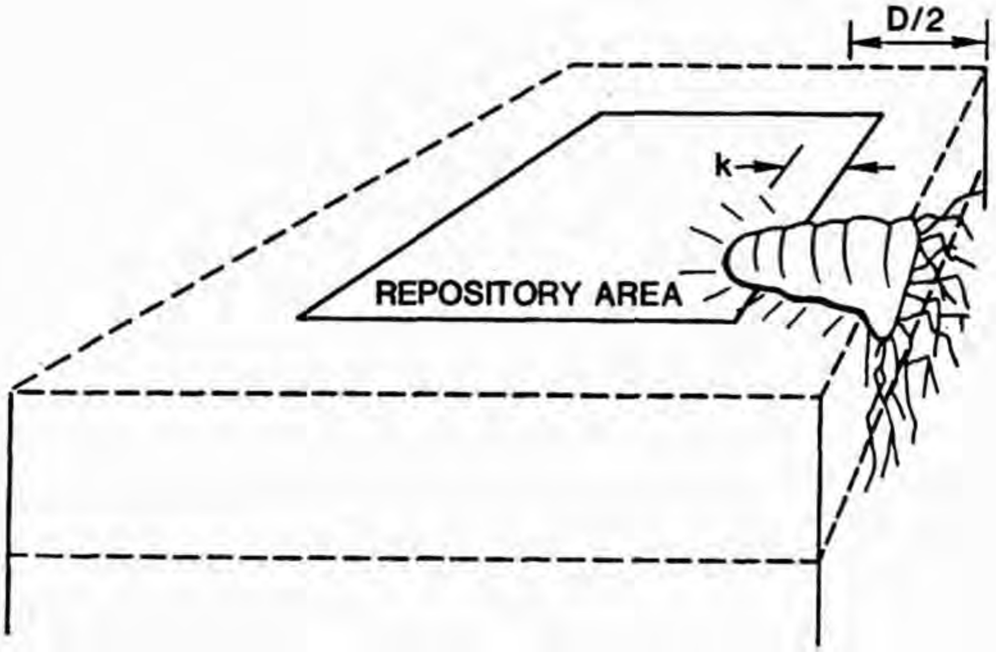

Figure A.2. Critical Region for Impact Craters

From this figure, the plane of interest should extend a distance of (D/2)-k beyond the repository boundary. That is, the plane of interest should be $(\ell+(D/2)-k)$ x $(w+(D/2)-k)$. To determine k, we use the general form of the equation of a parabola:

$$(x-u)^2 = 4p(y-v) \tag{4}$$

For our case, y=-h when x=0 and v=-h when u=0. Furthermore (since crater diameter is 3 times the depth), y=0 implies $x= \pm \frac{3h}{2}$. Thus,

$$k = 3/2\ [\sqrt{(D/3)h} - \sqrt{(D/3)h-h^2}] \tag{5}$$

Using this and Equation 3 we get that the probability of a crater intersecting the plane of interest is given by

$$\int_{3h}^{\infty} [\ell + (D/2)-k][w + (D/2) - k](2.4 \times 10^{-13})D^{-3.4}dD \tag{6}$$

For the Sandia reference repository we have

$$\ell \approx 4\text{km},\ w \approx 2\text{km},\quad h \approx 630\text{m}$$

Substituting these values into the integral in Equation 6, we get

$$7.82 \times 10^{-13}/\text{yr}$$

as the (yearly) probability of meteorite impact of sufficient force to cause instantaneous release.

For the fracture zone, the diameter of the crater is twice the fracture zone. In this case, k takes the form

$$k = \sqrt{(D/2)h} - \sqrt{(D/2)h-h^2} \tag{7}$$

and the integral in Equation (6) becomes

$$\int_{2h}^{\infty} [\ell + (D/2) - k][w + (D/2) - k](2.4 \times 10^{-13})D^{-3.4}dD \tag{8}$$

For the Sandia reference repository, the middle shale is about 400 meters below the surface. From Equation 8, the (yearly) probability of this being fractured by meteorite impact is

$$1.27 \times 10^{-12}/\mathrm{yr}$$

APPENDIX B

Inadvertent Intrusions (Drilling)

In determining the probability of radionuclide release resulting from drilling activity, both the probability of drilling into the 1100 acre parcel containing the repository and the probability of hitting a canister of waste material must be considered. Both of these determinations assume that drilling activity will continue in bedded salt regions into the future and that the waste material remains in the canisters.

Although one of the selection criteria for the proposed repository sites is low resource potential, the possibility of future drilling cannot be eliminated. Because of the unpredictability of the economic factors that control oil and gas exploration, exploratory drilling rates cannot be projected with any certainty into the future. To determine the probability of a random drill hole in a bedded salt region being in the 1100 acres containing the repository, an average drilling rate for bedded salt regions for approximately the years 1970 through 1979 was calculated. This range in years includes the recent national low in drilling activity in 1972 and a recent near-record high in 1979.

The areas from which drilling data were used are the New York portion of the Appalachian Basin, the Michigan Basin, the Permian Basin, the Northern Denver Basin, the Powder River Basin, and the Williston Basin (Figure B.1). Only those counties that are at least half underlain by bedded salt were included, and only exploratory drill holes were tabulated. The drilling data are compiled by state in Table B.1. Based on these drilling rates and the assumption that the repository area will be 1100 acres, the mean drilling rate at the hypothetical reference site is taken as 1.18×10^{-2}/yr. This would amount to 1180 exploratory holes drilled into the 1100 acre site over the 10^5 year period of our analysis. Assuming that exploratory holes are drilled into the site according to a Poisson process with $t = 1180$, the probability of at least one hole drilled into the repository over 10^5 years is given by

$$1 - e^{-\lambda t} = 1 - e^{-1180} \approx 1.$$

Given that drilling has occurred at the site, the probability that a canister is intersected is determined by examining extraction ratios for rooms and the use of geometric probabilities. For the hypothetical reference site, the extraction ratio is approximately 25%. Rooms are 560 ft. x 18 ft. x 18 ft. (see Campbell et al., 1978).

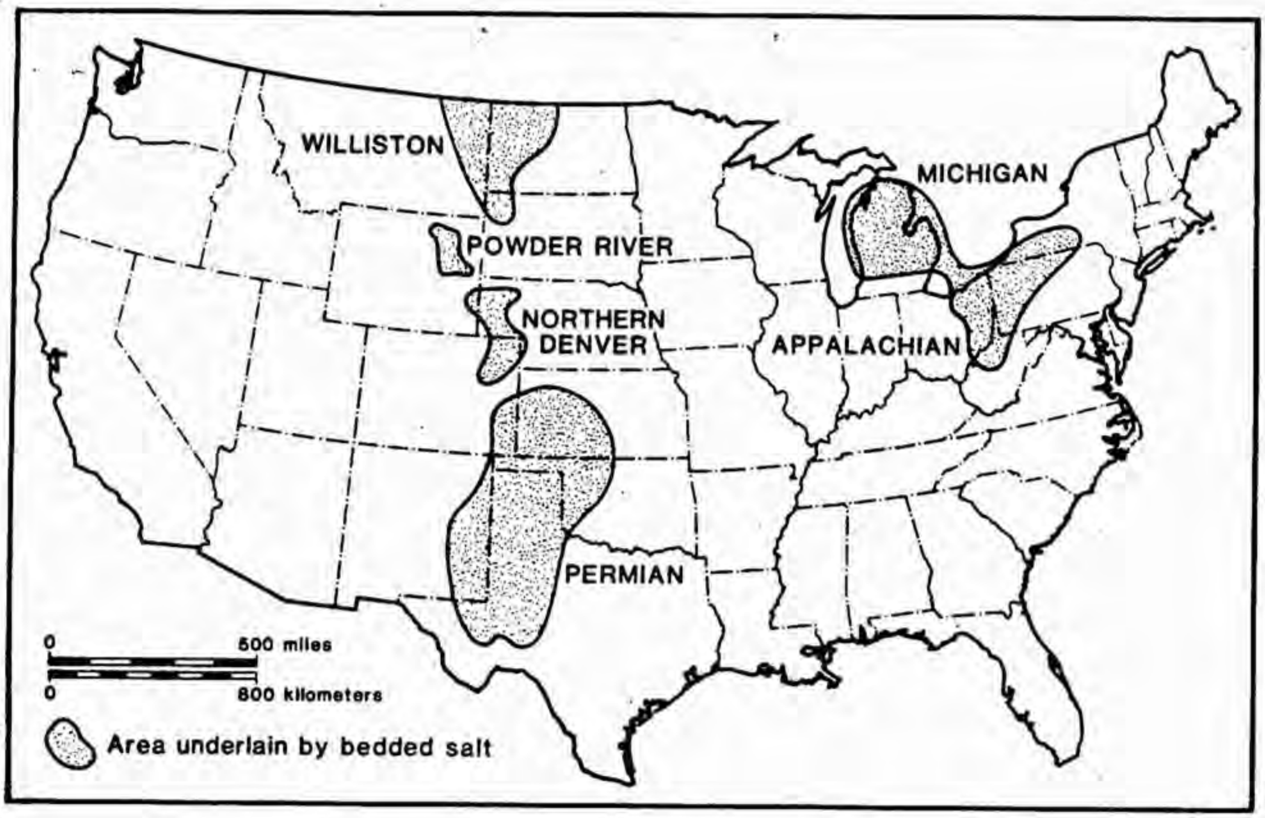

Figure B.1. Areas for Drilling Data

Each room is designed to contain 32 canisters of nuclear waste with each canister 10 feet long and 1 foot in diameter. The diameter of the drill bit is assumed to be 1 foot. A drill bit would only have to nick the edge of the canister to release some of the waste. Because the center of the drill bit must be within 1 foot of the center of the canister in order to hit the canister (Figure B.2), the effective target area of each canister is a circle with a radius of 1 foot.

Table B.1

Drilling Rates for Areas Underlain by Bedded Salt

State	Area Underlain by Salt[1] (mi^2)	Number of 1100 Acre Parcels	Number of Drill Holes[2] (wells/yr)	Mean Drilling Rate (wells/ 1100 acres/ yr)
Colorado	16,660.2	9,693.6	88.72	9.15×10^{-3}
Kansas	40,629.9	23,639.2	538.23	2.27×10^{-2}
Michigan	31,077.1	18,081.2	272.71	1.51×10^{-2}
Montana	12,454.7	7,246.4	33.62	4.64×10^{-3}
Nebraska	6,051.0	3,520.6	105.34	2.99×10^{-2}
New Mexico	23,656.9	13,764.0	123.29	8.96×10^{-3}
New York	12,238.4	7,120.5	27.86	3.91×10^{-3}
North Dakota	18,956.4	11,029.2	55.24	5.01×10^{-3}
Oklahoma	18,088.5	10,524.2	74.02	7.03×10^{-3}
South Dakota	2,673.7	1,555.6	8.29	5.33×10^{-3}
Texas	60,539.2	35,222.8	280.95	7.98×10^{-3}
Wyoming	4,740.1	2,757.9	92.94	3.37×10^{-2}
	247,766.1	144,155.2	1701.22	

Mean Drilling Rate for All States: 1.18×10^{-2} wells/1100 acres/yr

[1] Tabulated for each county at least 50 percent of which is underlain by bedded salt, excluding those counties where no drilling occurred in the time interval considered.

[2] Mean for
1970 - 1978 Michigan
1971 - 1978 New York
1970 - 1979 All other states

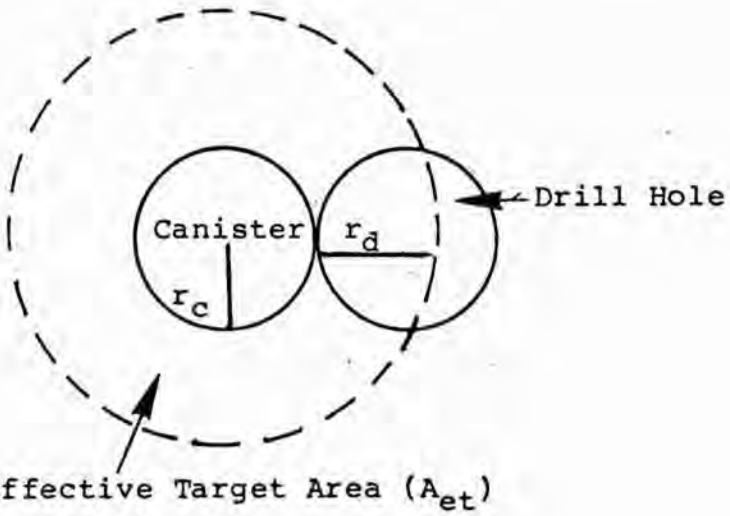

Figure B.2. Effective Target Area of a Canister

The probability of a random drill hole within the repository hitting a canister is determined as follows:

$P_{hc} = P_{hr} \cdot P_{cr}$

P_{hc} - probability of a random drill hole hitting a canister

P_{hr} - probability of hitting a room

P_{cr} - probability of hitting a canister within a room

$P_{hr} \approx$ extraction ratio (E_r)

$P_{cr} = A_{et}/A_r$

A_{et} - effective target area within a room

A_r - area of each room

$$A_{et} = n_c \pi \; (r_c + r_d)^2$$

n_c - number of canisters per room

r_c - radius of canister

r_d - radius drill bit

Therefore,

$$P_{hc} = \frac{E_r \; n_c \pi \; (r_c + r_d)^2}{A_r}$$

For the model repository described above, the probability of a random drill hole within the repository hitting a canister is approximately 2.5 x 10^{-3}.

The probability that a canister or leached waste from a canister is intersected over 10^5 years is found by multiplying the probability that the repository is penetrated by at least one drill hole and the probability that a canister or leached waste from a canister is intersected given that a hole is drilled. For the conditions of the hypothetical site, this probability is approximately 1 x (2.5 x 10^{-3}) = 2.5 x 10^{-3}.

APPENDIX C

Volcanic Activity

The probability that a volcano will disrupt the repository site is calculated using the probabilistic model described in Beckman and Johnson (to appear). This model yields the following equation.

$$P_r \text{ (disruptive event before time t)} = 1 - e^{-\left(\sum_{i=1}^{n} \lambda_i p_i\right) t}$$

where

λ_i= rate of occurence of volcanos at site i,

p_i = probability that a volcano at site i will disrupt the repository

and n is the number of sites in the vicinity of the repository where volcanic activity occurs.

Since this study is not site-specific, only one region for volcanic activity is considered; the entire western United States (Washington, Oregon, California, Idaho, Nevada, Montana, Utah, Arizona, Wyoming, Colorado and New Mexico). Furthermore, the repository is assumed to be located somewhere in this region. Thus, the model reduces to:

$$\text{Pr(disruptive event before time t)} = 1 - e^{-\lambda pt}$$

where

λ = rate of occurence of volcanos in western U.S.
= # of volcanos/#years

and

p = probability that a volcano will disrupt the repository

Now, the number of volcano vents that have shown activity within the last 10 million years in the western U.S. is approximately 1300, (Arthur D. Little, 1980). Thus;

$$\lambda = 1300/10^7 = 1.3 \times 10^{-4}$$

The dimensions of the waste repository are 1.8 by 2.4 km. Crowe (1978) states that the maximum zone of a volcanic disruption is 66 km^2 or a circle of radius 4.6 km. Thus, for a volcano to disrupt the repository, it must be within 4.6 km. of the boundary of the repository or within an area of 128 km^2 (11.0 x 11.6 km.). This yields;

$$p = \text{area of disturbance/total area of western U.S.} = 128/3 \times 10^6 = 4.3 \times 10^{-5}$$

and so

$$\Pr(\text{disruptive event within one year}) = 1 - e^{-5.6 \times 10^{-9}} \approx 5.6 \times 10^{-9}$$

This probability estimate is conservative in a number of ways. In the calculation, an equal distribution of volcanos is assumed. Actually, volcanos occur together in specific regions. The actual repository site would presumably be outside such regions. Some of the 1300 volcanos used in the calculation of λ occurred more than 10 million years ago. The actual value of λ should be somewhat smaller. The value of 66 km^2 is a maximum zone of disruption. Most zones will be much smaller and the estimate of p much smaller.

APPENDIX D

Faulting

We shall assume that at the time of repository closure the mean density of faults existing in a region R surrounding the repository site is λ_0 per unit area. We shall assume further that new faults appear in this region according to a nonstationary Poisson process with mean rate $\lambda_1(t)$ per unit area per year, where t indicates the time-dependent rate of formation of new faults. Then, the mean density of faults existing in the region R at some time t following closure of the repository site can be represented by

$$\lambda(t) = \lambda_0 + \int_0^t \lambda_1(t)dt \ . \qquad (1)$$

From Equation 1 the probability of exactly N faults existing in the region R by the time t is given by

$$P(N,t) = \frac{[\lambda(t)A]^N}{N!} \exp\,[-\lambda(t)A] \ , \qquad (2)$$

where A is the area of region R.

We will let p denote the conditional probability that, if a fault exists in the region R, it will intersect the repository site. Then, the probability that at least one fault intersects the repository site in the time interval (0,t) is given by

$$P = 1 - e^{-\lambda(t)pA}. \tag{3}$$

From Equation 3 we see that to determine a value of P, we need to know values of $\lambda(t)$ and p. The value of $\lambda(t)$ can be evaluated once a specific site for the waste repository has been selected. Geologic and historic records of tectonic and seismic activity, determination of ages of existing faults, and in situ measurements of local stresses can all be used to arrive at a representation of $\lambda(t)$.

The parameter p is calculated in terms of the spatial density of faults in the region R and the average length of these faults. The repository is considered to be a subregion, R_0, of R. Both R and R_0 are taken as rectangular regions and thus are convex (i.e., any line connecting two points on the perimeter of the region lies entirely within the region). Faults in R are taken as line segments of length ℓ, where ℓ is the mean length of the faults in R.

According to Santalo (1976), the probability that a line segment of length ℓ in R intersects R_0 is given by

$$p = \frac{2\pi A_0 + 2\ell P_0}{\pi ab - 2(a + b)\ell + \ell^2} \qquad (4)$$

where A_0 and P_0 are the area and perimeter, respectively, of R_0 and a and b are the lengths of the sides of region R.

To determine the probability that an existing but undetected fault in region R intersects the plane of the repository, we take $\lambda(t)$ in Equation 1 to be λ_0. For the hypothetical reference site, the repository has the dimensions of 1.42 miles x 1.52 miles. The valley containing the repository is assumed to have the dimensions of 57 miles x 152 miles (see Campbell et al., 1978). Mean fault lengths in this region will be taken as 2 miles. Thus, using Equation 4

$$p = \frac{2\pi\ (1.73) + 2(2)\ (5.32)}{\pi(57)(152) - 2(57 + 152)(2) + 2^2}$$

$$= 1.22 \times 10^{-3}$$

Thus,

$$P = 1 - e^{-\lambda_0(1.22 \times 10^{-3})}$$

Below are several values of P for different values of λ_0

$\lambda_0 = 1;\ P = 1.22 \times 10^{-3}$

$\lambda_0 = 2;\ P = 2.44 \times 10^{-3}$

$\lambda_0 = 3;\ P = 3.65 \times 10^{-3}$

$\lambda_0 = 4;\ P = 4.87 \times 10^{-3}$

$\lambda_0 = 5;\ P = 1 \times 10^{-2}$

$\lambda_0 = 6;\ P = 1 \times 10^{-2}$

For new faults, the probability that at least one intersects the plane of the repository is found by using the rate of formation of new faults, $\lambda_1(t)$, in Equation 3. Data from the Deleware and Palo Duro Basins indicate that rates of formation of faults in these regions is on the order of 10^{-8} faults/year. This rate is used for the hypothetical reference site. Thus, the probability that at least one of these intersects the plane of the repository is given by

$$P = 1-e^{-(10^{-8})(1.22 \times 10^{-3})}$$
$$= 1.22 \times 10^{-11}$$

DISTRIBUTION: SAND80-1429, NUREG/CR-1667

US NRC Distribution Contractor (CDSI)
7300 Pearl Street
Bethesda, MD 20014
375 copies for GF

Author selected distribution - 32 copies
(List available from author)

400	C. Winter	
1540	W. C. Luth	
1843	C. Northrup	
7223	R. L. Iman	
9400	A. W. Snyder	
9410	D. J. McCloskey	
	Attn:	D. C. Aldrich
		A. S. Benjamin
		L. D. Chapman
		J. W. Hickman
		G. B. Varnado
9413	N. R. Ortiz (5)	
9413	M. S. Y. Chu	
9413	R. M. Cranwell (25)	
9413	P. A. Davis	
9413	R. T. Dillon	
9413	L. E. Duda	
9413	N. C. Finley	
9413	J. C. Helton	
9413	A. B. Muller	
9413	G. E. Runkle	
9413	M. J. Shortencarier	
9413	M. D. Siegel	
9443	D. A. Dahlgren	
9730	W. D. Weart	
	Attn:	D. W. Powers
		T. O. Hunter
		M. L. Merritt
9756	D. Engi	
9760	R. W. Lynch	
	Attn:	L. W. Scully
		J. R. Tillerson
9762	L. D. Tyler	
8214	M. A. Pound	
3141	L. J. Erickson (5)	
3151	W. L. Garner (3)	
3154-3	C. H. Dalin (25) For DOE/TIC (Unlimited Distribution)	

Org.	Bldg.	Name	Rec'd by	Org.	Bldg.	Name	Rec'd by

Sandia National Laboratories