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Waste Isolation Safety Assessment Program

Scenario Analysis Methods for Use in Assessing the Safety of the Geologic Isolation of Nuclear Waste

November 1978

Prepared for
Office of Nuclear Waste Isolation
under its Contract with the
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Pacific Northwest Laboratory
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WASTE ISOLATION SAFETY ASSESSMENT PROGRAM SCENARIO ANALYSIS METHODS FOR USE IN ASSESSING THE SAFETY OF THE GEOLOGIC ISOLATION OF NUCLEAR WASTE

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EXECUTIVE SUMMARY

Assessing the safety of a nuclear waste repository system requires the identification and evaluation of potential disruptive phenomena that could compromise the repository system integrity. As part of the Department of Energy (DOE) sponsored Waste Isolation Safety Assessment Program (WISAP), a variety of safety assessment methods have been evaluated with respect to their potential utility in performing such evaluations.

The analysis of postulated events, sequences of events, and processes that can lead to system failure is called scenario analysis. System breach is defined as a condition of the repository in which the confinement features have been compromised resulting in a possible pathway for release of radioactive waste material to the biosphere. The relative utility of the various safety analysis methods to scenario analysis for a repository system was evaluated by judging the degree to which certain key characteristics (called criteria) are satisfied by use of the method. Six safety analysis methods were reviewed in this report for possible use in scenario analysis of nuclear waste repositories. These are: expert opinion, perspectives analysis, fault trees/event trees, Monte Carlo simulation, Markov chains, and classical systems analysis.

Four criteria have been selected based on consideration of the objectives and uses of scenario analysis (to a geologic repository). The criteria suggest that the methods: 1) be quantitative and scientifically based, 2) model the potential disruptive events and processes, 3) model the system before and after failure (sufficiently detailed to provide for subsequent consequence analysis), and 4) be compatible with the level of available system knowledge and data.

Expert opinion, fault trees/event trees, Monte Carlo simulation and classical systems analysis were judged to have the greatest potential application to the problem of scenario analysis. The methods were found to be constrained by limited data and by the knowledge of the processes governing the system--some more than others. It was determined that no single method

method is clearly superior to others when measured against all the criteria. Therefore, to get the best understanding of system behavior, a combination of the methods is recommended. Monte Carlo simulation was judged to be the most suitable matrix in which to incorporate a combination of methods.

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1.0 INTRODUCTION

A necessary part of commercial nuclear power production is safely managing potentially hazardous radioactive waste materials. To meet this need, many nations have established programs to develop repositories in deep geologic formations with sufficient isolation to prevent the possible release of radioactive materials. As in any complex endeavor involving potentially hazardous materials, such programs go through many stages of development before they become operational: the conceptual stage, a more detailed planning stage, a design stage and finally, the licensing and operation stage. Each stage has its own unique safety analysis needs. In the early stages, some perspective is needed on the relative safety considerations associated with the concept. However, in the licensing stage, detailed quantitative studies are needed to consider adequately all the factors that could affect the safety of the system. The National Waste Terminal Storage Program is now in the conceptual and planning stages, and will soon approach the licensing stage. Many safety analyses have been made of nuclear waste isolation repositories and to date have met the needs of each stage of the program. It must now be determined which safety analysis methods are best suited for performing the detailed safety analyses required for the licensing of a repository.

To conduct a comprehensive detailed safety analysis, it is necessary to identify and evaluate the ways that the system could potentially lose the integrity of its geologic confinement; that is, lead to a repository failure. To understand adequately the effect of potential loss of isolation, it is important to be able to predict the condition of a repository following the potential failure, as well as its likelihood of occurrence. Techniques for aiding in such an evaluation are called "Scenario Analysis Methods." The purpose of this document is to review existing safety analysis methods and evaluate their applicability to the needs defined for scenario analysis. However, scenario analysis by itself does not provide the total understanding of the safety of a repository. To achieve a safety assessment of the system, scenario analysis must be combined with the evaluation of the effect of potential loss-of-isolation events or combinations of such events. Assessment of the effect of such events is called "Consequence Analysis." Another document is being prepared as a part of this program which will analyze existing consequence analysis methods for applicability to the geologic isolation analysis.

Safety analysis methods which are examined in this report are: expert opinion (best typified by the Delphi method); perspectives analysis; fault tree/event tree; Monte Carlo simulation; Markov chains; and classical systems analysis. Each method is discussed and assessed individually with regard to its applicability to geologic isolation scenario analysis. The assessments were made by evaluating existing methods relative to a set of criteria developed considering the uses of a geologic isolation safety assessment and the characteristics of the problem.

It must be noted that the key to the quality of a safety assessment is the knowledge, insight and experience of the analyst. The various assessment methods discussed in this report serve only as tools to aid the analyst in satisfying the objectives of the assessment. However, an understanding of the principles, capabilities and limitations of the various tools available permits him to select those best able to perform the various parts of a particular assessment.

2.0 CHARACTERISTICS OF GEOLOGIC ISOLATION SAFETY ASSESSMENT PROBLEMS

Potentially disruptive phenomena that could affect the safety of the waste isolation repository during the time that the waste remains potentially hazardous are listed in Table 2.1. The scenario analysis method used in geologic isolation safety assessments must aid in identifying the processes and events that can individually, or in combination, defeat the isolation characteristics of the repository. The method should also be capable of estimating the likelihood of these events and the condition of the repository during and after such system disruptions. In addition to these key characteristics, other evaluators are the potential uses of a safety assessment; e.g., to aid in societal and regulatory decisions on the acceptability of geologic disposal of radioactive waste; to aid in decisions on the acceptability of particular sites for geologic disposal of radioactive waste; to aid in the inclusions of long-term safety considerations which affect repository design and waste form specification; and to identify research and development (R&D) required to improve the estimates of long-term safety, if desirable.

An examination of the events and processes in Table 2.1 illustrates that any scenario analysis is going to be limited by the availability of reliable data and also will be limited by the lack of understanding of some of the processes involved. Despite these limitations, the safety assessment methods should be founded, to the degree possible, on firm scientific and engineering data (objective rather than subjective) and should be capable of using input from recognized experts where the only source of data is subjective.

An evaluation of scenario analysis methods for all possible characteristics and criteria would be too voluminous to discuss adequately in this study. Therefore, we have reduced the criteria to consider only the most relevant requirements. The criteria selected for use in the methods evaluation follow in the next section.

TABLE 2.1. Potential Disruptive Phenomena for Waste Isolation Repositories

Natural Processes	Natural Events	Man-Caused Events	Repository-Caused Processes
• Climatic Fluctuations	• Flood Erosion	Improper Design/Operation	Thermal, Chemical Potential, Radiation, and Mechanical Force Gradients:
• Sea Level Fluctuations	• Seismically Induced Shaft Seal Failure	• Shaft Seal Failure	• Induced Local Fracturing
• Glaciation	• Meteorite	• Improper Waste Emplacement	• Chemical or Physical Changes in Local Geology
• River Erosion		Undetected Past Intrusion:	• Induced Groundwater Movement
• Sedimentation		• Undiscovered Boreholes or Mine Shafts	• Waste Container Movement
• Tectonic Forces		Inadvertent Future Intrusion:	• Increase in Internal Pressure
• Volcanic Extrusion		• Archeological Exhumation	• Shaft Seal Failure
• Igneous Intrusion		• Weapons Testing	
• Diapirism		• Nonnuclear Waste Disposal	
• Diagenesis		• Resource Mining (Mineral, Hydrocarbon, Geothermal, Salt)	
• New or Undetected Fault Rupture		• Storage of Hydrocarbons or Compressed Air	
• Hydraulic Fracturing		Intentional Intrusion:	
• Dissolution		• War	
• Aquifer Flux Variation		• Sabotage	
		• Waste Recovery	
		Perturbation of Groundwater System:	
		• Irrigation	
		• Reservoirs	
		• Intentional Artificial Recharge	
		• Establishment of Population Center	

3.0 SCENARIO ANALYSIS METHODS EVALUATION CRITERIA

Four criteria were selected for differentiating between existing scenario analysis methods. These four criteria (underlined below) contain many subset criteria; they are interactive, could be combined or altered in many ways to emphasize particular requirements, and could be given a variety of different names. However, in the present form they suit the purpose of this evaluation.

The first criterion follows from the degree of detailed safety evaluation that is required. Consequences of potential failures of the system, site acceptability, likelihood of system failure, and waste form adequacy all require evaluation. The method used for such evaluations must be quantitative and scientifically based. Furthermore, the method should attempt to provide a quantitative assessment of the uncertainty in the key system parameters (and subsequent uncertainty of the system safety) and it should be capable of quantitatively evaluating the effect of added engineered barriers and the site specific geologic features.

The disruptive geologic and man-caused phenomena are generally discrete events (e.g., volcanisms, meteorites and drilling) and/or slow continuous processes (e.g., plate tectonics and erosion). Most scenarios for repository breach, over the problem time frame, involve a combination of disruptive events and processes. Thus, the analysis method must model the disruptive events and processes and their combinations.

To evaluate the combined effect of events and processes, it is necessary to model the perturbations of the key system parameters prior to repository breach. To evaluate source terms, the repository system must also be evaluated at failure and thereafter in terms of the physical parameters which could effect a potential radionuclide release. Thus, it is necessary to model the system before and after disruptive events.

The method must be compatible with the system knowledge and data, yet be tractable. The method should not be data limited but should use physical geologic data to the maximum possible extent. The method should provide for controlled use of subjective opinion and inputs from qualified experts.

4.0 CATEGORIES OF SAFETY ASSESSMENT METHODS

To examine the suitability of the existing safety assessment methods to scenario analysis the methods were classified into six groups: expert opinion/ Delphi, perspectives analysis, fault/event trees, Monte Carlo simulation, Markov chains, and classical systems analysis. Assessment methods which do not address scenario analysis were not included. Each method is described in the following paragraphs with emphasis on input/output requirements, past and current application to geologic isolation, strengths and weaknesses, and a critique with respect to the selection criteria and their potential use in WISAP.

4.1 EXPERT OPINION

Expert opinion is an assessment technique in which a recognized body of experts provides scientific judgment or inputs. Expert opinion has been used extensively in waste management; an example is the National Academy of Sciences recommendation that nuclear wastes be stored in bedded salt formations (National Academy of Sciences 1957).

Delphi is a structured technique for obtaining expert opinion. The method can produce an estimate of the uncertainty of the conclusion. The classic Delphi consists of a series of questionnaires given individually to a group of experts in a manner which protects the autonomy of their responses. The first questionnaire elicits the opinions of the experts based only on their own knowledge and experience. Subsequent questionnaires contain feedback from the previous questionnaires, allowing the experts to comment on the group consensus. The process continues until there is a convergence of opinion or until it becomes obvious that additional results will not be generated. The Delphi method originated at the Rand Corporation in 1948 (Dalkey and Helmer 1963; Gordon and Helmer 1964; Helmer 1966). It has been used extensively for forecasting, long-range planning, urban and regional planning, and in defining a large variety of social goals.

4.1.1 Input/Output

Expert opinion can be solicited in three ways:

Workshops	-	A decision is reached by collective examination of the issues. A suitable group of experts must be convened.
Individual Interviews	-	Individual conclusions are obtained by individual examination of the issues.
Delphi Technique	-	A concensus decision can be obtained by individual examination of the issues with collective feedback. This approach combines the best features of workshops and individual interviews.

4.1.2 Application to Geologic Isolation

Historically, expert opinion has only been applied to the broad issues of geologic isolation. The "Conference on Public Policy Issues and Nuclear Waste Management" (Harrison Associates, 1977) attempted to seek expert opinion in the public policy context. The Enrivonmental Protection Agency has held two workshops (USEPA 1977a, and USEPA 1977b) in an attempt to obtain input to assist them in the development of criteria for waste management. Other examples of expert opinion used to evaluate the safety of geologic isolation are the independent evaluations by Willrich (Harrison Associates 1977), Lash (EPA 1977), Cohen (1977), Lapp (1977), Kubo and Rose (1973), Hamstra (1975), Cowen (1976), the Ford Foundations report (1977) on "Nuclear Power Issues and Choices", and the "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," (American Physical Society 1977).

Also in the past, while not related to waste isolation, the prediction of geologic processes has relied heavily on expert opinion. Site selection for tall buildings, bridges, dams, mines and water rights have traditionally required input from expert geologists. In this context, expert opinion methods must also be used to develop site specific and generic quantitative methods and data suitable for scenario analysis. Two workshops were conducted by WISAP (Jacobson 1978; Raymond 1978) in FY77 to explore the potential benefits and likelihood of success in obtaining expert opinion input on such matters.

It was determined that a cadre of 15 to 20 experts would be required to define the geologic (and other earth science) processes over the time frame of investigation (10^2 to 10^7 years). Additional experts would be required to apply the delphi technique.

4.1.3 Strengths and Weaknesses

The key strength of expert opinion is the ability to obtain information which could not be obtained by analytic methods, or which requires subjective judgment. Delphi can add further strength (Dalkey 1972; Turoff 1972a; Licklider et al. 1968; Turoff 1972b; Linestone and Turoff 1975; Sackman 1975; Welty 1973; Weaver 1972) because individual responses are anonymous, the participants need not meet face to face, and it provides a systematic and documented (auditable) approach to obtain a statistical distribution of expert opinion and/or group consensus.

There are many weaknesses in obtaining expert opinion (Mazur 1973; Benveniste 1972). Experts often have difference of opinion and difficulties can arise over credibility. Many experts are perceived to represent special interest groups. Disagreements will typically include the following elements: stepping beyond the bounds of real expertise, operating from different premises, differing personal values, selected use of technical knowledge, and the emotional desire to win the argument. In developing an opinion, experts usually rely on a few methods which simplify their assessment process but can lead to severe error. These methods are representativeness (the general relationship holds in most specific cases), availability (the frequency of an event is determined by the ease with which instances are brought to mind), adjustment (estimation by starting from an initial value from a known system and adjusting this value based on the differing characteristics of the new system), and anchoring (estimation by referral to a value from a known system without adjustment to the new conditions).

4.1.4 Critique and Recommendations

Expert opinion satisfies the method evaluation criteria as follows:

Criterion 1 - Quantitative and Scientifically Based

Expert opinion methods are usually qualitative, particularly when used to assess broad categories of interest. As such, expert opinion is unsuitable for use as a comprehensive safety evaluation tool in WISAP. However, submodel development for the geologic events and processes and related earth sciences can be assigned to experts or expert groups. These could develop scientifically based, quantitative, predictive submodels and related geophysical data. This input is required for scenario analysis and has been classified herein as expert opinion.

Criterion 2 - Model the Disruptive Events and Processes

Qualified experts can be found to develop the required submodels which characterize and predict the disruptive events and processes. This is seen as the only tractable approach to this problem. It is believed, however, that this application of expert opinion must be limited to submodel development, the interaction (of events and processes) problem can be better analyzed with a comprehensive logic model.

Criterion 3 - Model the System Before and After Disruptive Events

This criterion could be satisifed by an analytic system model which evaluates the key system parameters over the problem time frame. Elements of the system model could be based on expert opinion.

Criterion 4 - Compatible with System Knowledge and Data

This criterion is the primary incentive for incorporating expert opinion procedures into WISAP. Much of the data and subsystem knowledge available to WISAP will originate via the expert opinion method.

In view of the above evaluation, it is concluded that WISAP method must include some elements of expert opinion for those technologies where scientifically recognized relationships and data are not available. This approach can be strengthed by use of the Delphi technique in a peer review mode.

4.2 PERSPECTIVES ANALYSIS

Perspectives analysis is a qualitative technique for comparing one safety attribute of a given activity with a safety attribute of some other activity which is well understood or at least more familiar. The perspectives approach historically has been applied to overall safety evaluation and, it can be used as an evaluation tool in scenario analyses. Examples are the study of underground dissolution of a mineral or ore and of the risk of meteorite impact on population centers.

The earliest efforts to develop safety perspectives led to the development of the hazard indices. These indices attempt to combine the parameters which characterize waste isolation into an index on public health and safety. The indices use one or more of the following parameters: radioactive material quantity, specific activity, decay properties, chemical and physical form, packaging, toxicity, time behavior and pathways. The hazard indices are listed and defined in Table 4.1. They have been used extensively, both individually and in combination, to characterize the safety of geologic isolation. Examples of studies in which they have been used include: Comparison of the toxic content of high level waste to the toxic content of the uranium ore and tailings from which it came (Cohen 1977; Cohen 1976) and comparison of the toxic level of plutonium sent to high level waste (in year 2000) against the toxic level of lead sent to waste (in 1973) (Cohen 1975).

Examples of other studies which incorporate the comparative risk (or perspectives approach) are: The Reactor Safety Study (USNRC 1975) (risk of nuclear plant accidents compared to natural disasters), risk of plutonium shipments (Hall et. al., 1977), risk of antural and man-caused radioactivity (Turnage 1976), Oklo (Walton and Cowan 1975), underground testing of nuclear devices (Teller et. al., 1968), direct impact of disruptive events (Starr 1970), and risk comparisons to alternative energy resources (Grahn 1976; Straker and Grady 1977; Cottrell 1976; Blot et. al., 1977; Starr et. al., 1972; Petrikova 1970; McBride et. al., 1977).

4.2.1 Input/Output

Table 4.1 is a collected list of the hazard indices, their required inputs and an interpretation of their use (or output).

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4.2.2 Application to Geologic Isolation

The quantity of radioactive material, Q, present in isolation for various decay periods, compared to the natural occurring isotope quantities in the earth's crust, has been discussed by many authors (Winegardner and Jansen 1974; Smith 1975) in an attempt to place geologic isolation "in perspective." The various hazard indices extend this approach by incorporating additional considerations such as pathways.

TABLE 4.1 Hazard Indices[a]

Hazard Index	Definition and Inputs	Interpretation (for Nuclear Waste Isolation)[b]
Quantity of Radioactive Material (Q)	Waste Inventory (or waste released)	Comparison of waste inventories to natural radionuclides (or for use below).[c]
Maximum Permissible Concentration (MPC)	10 CFR 20[d]	Relative hazards of radioactive species (or for use below).
Maximum Permissible Intake (MPI)	$MPI_{air} = (7300\ m^3/yr)(MPC_{air})$ $MPI_{water} = (0.8\ m^3/yr)(MPC_{water})$	Same as MPC.
Hazard Measure (HM)	$HM = Q/MPC$	Volume of air or water to dilute Q radionuclides to one MPC.[c,e]
Modified Hazard Measure (HM1)[f]	$HM1 = D/D_2$ D = exposure D_2 = exposure limit	Ratio of anticipated exposure to allowable limit.
Modified Hazard Measure (HM2)[g]	$HM2 = Q(a/MPI_{H_2O} + b/MPI_{air})$ a,b = fractions of Q released to water and air.	
Modified Hazard Measure (HM3)[h]	$HM3 = \int_t^{t+d} (Q(t')/MPI)dt'$	Number of MPI in the environment versus time.
Potential Hazard Measure (PHM)[i]	$PHM = P \frac{Q}{MPI} \frac{1}{\lambda}$ P = probability of reaching man λ = decay constant	Risk of releasing Q versus time.
Hazard Index (HI)[j]	$HI = \frac{Q}{MPC(V)}$ V = entrained volume	Number of MPCs per unit volume.
Hazards Available Index (HA)[k]	$HA = \log_{10}HI + \log_{10}TF$ TF = transport factors	HI with pathway transport efficiency included.
Isolation Time (T)[l]	$T = -\frac{1}{\lambda} \ln \frac{MPC\ V_f\ D}{A\ L}$ V_f = ground water volume flow rate D = dilution factor A = waste leach area L = leach rate	Time which nuclides must be held to reduce concentrations to one MPC.
Relative Toxicity Index (RTI)[j,m]	$RTI = \frac{(Q/MPC)\ waste}{(Q/MPC)\ U_{ore}}$	Ratio, HI of the waste to HI of the uranium ore mined to generate the waste. This has been generalized to compare with substances other than uranium.

(a) A compilation from published studies.
(b) As defined by originator.
(c) Winegardner and Jansen 1974.
(d) USNRC 1974
(e) Smith 1975.
(f) Walsh et. al. 1977.
(g) McGrath 1974.
(h) Smith and Kastenberg 1976.
(i) Gera and Jacobs 1972
(j) Clarborne 1975; Hang 1977.
(k) Bruns 1976.
(l) Voss and Post 1976.
(m) Hamstra 1975; Haug 1976; Cohen and Tonnessen 1977; Rochlin 1977.

Hazard Measure, HM, has been used (Winegardner and Jansen 1974) to place in perspective releases from various portions of the reactor fuel cycle by specifying the required dilution volume to render the radionuclides safe (MPC levels). Walsh (1977) introduced the modified hazard measure, HM1, to evaluate the effect of environmental pathway on hazards from a variety of environmental pollutants, including nuclear. McGrath (1974) introduced the modified hazard measure, HM2, in an attempt to quantify the potential hazards of radioisotope releases to air and water. Smith (1975) introduced the modified hazard measure, HM3, as a method to assess the risk to future generations from future releases of radioisotopes. Gera (1972) introduced the potential hazard measure, PHM, in an attempt to assess the risk of radioactive isolation, that is to also include the probability of the radionuclides reaching man. Claiborne (1975) introduced the hazard index, HI, to assess the benefits of actinide removal from high level waste. Bruns (1976) introduced the hazards available index, HA, to compare the hazard from purex waste to the hazard from fallout. Voss (1976) has proposed the use of isolation time, T, to characterize the effectiveness of geologic isolation in restraining the transport of radionuclides via the groundwater transport path. J. Cohen (1977) and other authors (Haug 1977; Hamstra 1975; Haug 1976; Rochlin 1977) have introduced the relative toxicity index, RTI as an index by which the relative toxicity of nuclear waste is compared to the relative toxicity of other naturally occurring toxic elements. J. Cohen (1975) showed that the toxicity of the ^{239}Pu which goes to waste (projected for the year 2000) is comparable to the toxicity of lead sent to waste in 1973. He further argued that ^{239}Pu has a 24,000-year half life, while lead is stable and will persist indefinitely. B. Cohen (1977) compared the radionuclides in high level waste (aged to 1000 years) against the radionuclide inventories of the uranium mill tailings associated with creation of the nuclear waste. He concluded that the high level waste had a lower cancer potential.

4.2.3 Strengths and Weaknesses

While perspectives analysis can be used to characterize nuclear waste isolation in overall and seemingly logical arguments, the method has many shortcomings. The key weakness is that it does not model the actual system (waste form, site geology, etc.) and cannot calculate the actual hazards which could occur (such as the contamination of a ground and/or surface water system and the associated local population dose).

Perspectives analysis often ignores significant safety questions. For example, HM provides an index of safety for individuals exposed directly to a nuclide release, but it ignores integrated population dose (and attendant health effects) and the possibility of reconcentration. Furthermore, it ignores all detail of the release mode (which has a significant effect on potential dose).

Independent of the above considerations, perspective analysis applied to the analytical results of a comprehensive safety analysis can strengthen the analysis by making it more meaningful and communicable. The waste isolation safety assessment would benefit by comparing projected waste concentrations, toxicity, dose, and health effects with natural levels and the long term waste impacts of coal-fired generation.

4.2.4 Critique and Recommendations

Perspectives analysis was examined for possible use as an overall waste isolation release scenario analysis approach. The method was found to be weak in satisfying the WISAP criteria; specifically:

Criterion 1 - Quantitative and Scientifically Based

The method yields relative information only.

Criterion 2 - Model the Disruptive Events and Processes

As currently developed, the method ignores most time dependent processes except radioactive decay. It does not consider interaction of all events and processes or identify release sequences.

Criterion 3 - Model the System Before and After Disruptive Events

Perspectives analysis does not attempt to model the physical system.

Criterion 4 - Compatible with System Knowledge and Data

The method generally ignores system knowledge and data; however, in case more detailed methods are not tractable the method can be used in a communicable way to place perspective on maximum hazards.

A general conclusion regarding perspectives analysis is that this method is not applicable to the WISAP scenario analysis but can have limited application in WISAP consequence analyses. Possible perspectives analyses are:

- Comparison of calculated radionuclide concentration and dose to permissible and natural levels
- Comparison of estimated health effects with normal incidence
- Comparison of calculated potential toxicity against naturally occurring leached toxic ore concentrations
- Comparison of potential waste releases from natural disasters to the direct impact of the disasters, and
- Comparison of the long term impact of nuclear wastes with wastes from contemporary coal-fired power generation.

4.3 FAULT TREES/EVENT TREES

Fault trees and event trees are system failure logic modeling methods for system reliability and probabilistic safety analysis (Hammer 1972; Lambert and Yadigarolu 1977). These methods have been used extensively in the nuclear industry (e.g., The Reactor Safety Study, (USNRC 1975). In this approach, system failure logic is graphically displayed in tree-like structures. Computer-aided methods are available for analyzing these structures to determine both qualitative and quantitative aspects of the system reliability and/or safety performance.

The construction of the system failure logic model can be carried out as a complete analysis in either the fault tree method or the event tree method. The fault tree method utilizes deductive analysis (reasoning from the general to the particular); the event tree method uses inductive analysis (reasoning from the particular to the general). The fault tree approach begins with an event of interest and presents the logical development of this event to the level of basic systems component failures. The event tree approach starts with an initiating event and displays its propagation to an array of potential conseqences. These two methods can be melded to form cause-consequence analysis.

Fault trees are used in both qualitative and quantitative modes. Qualitative analysis includes the study of the fault tree to determine cut sets. A cut set is an event or a collection of component malfunctions (basic events) such that if the component malfunctions exist concurrently, the system event of interest will exist. A minimal cut set is such that if any event is removed, the cut set no longer exists. Quantitative evaluations involve determining probabilistic characteristics of the main events of interest (for example, release of radioactive material). These characteristics include reliability (the probability that an event has not occurred during a given time interval), failure (the probability that the event has occurred), the availabilty (the probability the event does not exist at a specified time), the expected number of events during a time interval, and the mean time to the event. Extensive computer-aided methods exist for this work (Fussell et al. 1974; Van Slyke and Griffing 1975; Vesely and Narum 1970; Burdick et al. 1976; Wagnen et al. 1977; Smith et al. 1976; Pelto and Purcell 1977; USNRC 1975).

A variety of system failure logic modeling methods in addition to fault trees/event trees have been developed (Hammer 1972). The more common of these methods is the preliminary hazards analysis (PHA), which is used when there is little information concerning the system design details or procedures, the fault hazards analysis (FHA), and failure modes and effects analysis (FMEA), which are used when details are available and when many components, assemblies, and subsystems are analyzed for failure causes and effects. These techniques are qualitative and their results are usually presented in tables.

4.3.1 Input/Output

Developing a system failure logic model requires system definition followed by logic model construction. System definition requires the evaluation of the system physical bounds, the initial state of all system components, occurrence probability of system events, and a detailed understanding of the system functions and interrelationships. Logic model construction then follows using the established fault tree or event tree procedures (Hassl 1965; Burdick and Fussell 1976; Hammond 1967; Newendorp 1976; Lambert 1975). Output of the fault tree analysis can be qualitative or quantitative to determine a variety of system reliabilty characteristics.

It is also possible to perform an uncertainty analysis concerned with establishing an interval estimate of the reliability characteristic of interest based on uncertainty in the input data for the basic events. No uncertainty is normally reflected in the analysis for errors and omissions in the logic model. Computer programs exist for uncertainty analysis (USNRC 1975).

4.3.2 Application to Geologic Isolation

We have identified four safety studies for geologic repositores (past and/or in progress) which incorporate fault trees. (We are unaware of the use of any other failure logic modeling technique in geologic isolation safety studies.) Schneider and Platt (1974) presented a preliminary top-level fault tree for geologic disposal. The tree was developed to 77 primary events. No quantitative estimates of probablistic and/or risk characteristics of the tree were performed. Logan (1977) has developed a geological repository risk assessment model and has applied it to a salt repository. The model incorporates fault trees to provide the relationships between various geologic and man-caused disruptive events. The fault trees include meteorite impact, volcanogenic transport, offset faulting and groundwater contact. The model includes consequence analysis and has been used to determine potential future population doses. Proske has described a risk analysis of a salt dome repository which included fault trees for three time phases: operational, 10^3 years, and 10^6 years. The operational and 10^3 years phase trees were evaluated. The consequence analysis has not been completed. Girardi et al. (1977) have calculated population dose based on a hypothetical salt bed repository failure. The analysis utilized fault trees which included 30 primary events with probabilities evaluated for the time period 10^3 to 10^6 years.

4.3.3 Strengths and Weaknesses

Fault trees have two strengths in application to scenario analysis. First, the method employs a deductive process (reasoning from the general to specific) to develop a system failure logic model. This process is essential for both collecting a set of potential accident release sequences and in fault tree construction. Secondly, fault trees are an established technique for system safety analysis and have gained wide acceptance in the nuclear industry. Extensive methodology exists for analyzing these models and the models are generally effective communication tools.

Geologic isolation scenario analysis requires the simultaneous analysis of continuous perturbing geologic processes and disrupting events. This requirement is not readily satisfied by fault tree analyses; their key weakness is the assumption of only two states, failed and nonfailed. This binary assumption is not required on a theoretical basis; however, at present the multistate case has been considered too tedious even for computer solution. Geologic isolation safety assessment clearly needs techniques that permit partial failure plus simultaneous consideration of numerous initiating events.

4.3.4 Critique and Recommendations

With regard to satisfying the WISAP method evaluation criteria, fault trees/event trees have the following qualifications:

Criterion 1 - Quantitative and Scientifically Based

The method can be used in a quantitative mode to identify release scenarios and evaluate their probabilistic characteristics. Subsequent determination of the source term would not be considered part of the fault tree analysis.

Criterion 2 - Model the Disruptive Events and Processes

Fault trees will model discrete events and will also model continuous processes (and their interaction) if a time step approximation (to continuum) is used and the fault trees are reevaluated for each time step. An extension of the fault tree analysis would be required in the form of a systems model which is continuously updated over the problem time frame so that current failure probabilities are readily available. The modeling approach for the continuous processes would become exceedingly complex.

Criterion 3 - Model the System Before and After Disruptive Events

The system logic model addresses probabilistic considerations only. The WISAP method, however, must continually update the repository characteristics (e.g., pore pressures, state of stress, intergranular and incremental fracture permeabilities) for purposes of evaluating system failure probability and failure source terms (groundwater transport phenomena). Fault trees must be coupled to a suitable system model to satisfy this criteria.

Criterion 4 - Compatible with System Knowledge and Data

Fault trees are compatible with waste repository systems with the exception of the difficulties identified above. The method is also communicable; the fault tree/event tree diagrams simplify this task. As with all logical and/or analytic approaches to geologic isolation scenario analysis, the method is complex and adequate treatment of this problem by this method is difficult within the cost and time limits of the industry.

The deductive system logic modeling approach of fault tree analysis has strength and application to geologic isolation safety assessment. Specifically, the WISAP method must have a logic model to describe the interaction of the geologic and man-caused disruptive events and processes. The fault tree model fits this need. The key weaknesses of the fault tree analyses are the limitations on the time dependent processes imposed by binary logic, and that the method is very cumbersome in dealing with a multi-state case. Furthermore, an accurate, continuously updated system state is necessary to allow evaluation of source terms and/or consequence analysis for the geosphere transport pathway.

Several aspects of the fault tree approach are applicable to the WISAP method, specifically:

- A deductive logic model in fault tree format which shows the interrelationships of the disruptive events and processes.
- A fault tree logic model coupled to a system state model which is updated by a more suitable method (e.g., Monte Carlo simulation).
- Fault trees used as direct input in a scoping mode, to consequence analysis, i.e., a parametric study to determine the potential range of accidents and their consequences.

4.4 MONTE CARLO SIMULATION

The term "Monte Carlo" originates from von Neuman and Ulan (International Business Machine Corp.) exemplified by their use of "Monte Carlo analysis" to solve nuclear shielding problems that were too expensive for experimental evaluation and too complicated for analytical solution. Monte Carlo analysis involves the solution of a mathematical problem by simulating a stochastic process that has probability distributions satisfying the mathematical problem. With introduction of computers, Monte Carlo simulation took on additional meaning because it was possible to build the required elaborate mathematical models (describing a system of interest) on a computer. In recent years, the term "simulation" has been used to describe the science of analytical model building. For geologic isolation, simulation would be defined as a numerical technique for conducting experiments on a digital computer which involve mathematical models that describe the geophysical states, processes and events associated with the repository. Monte Carlo (Hammersley and Handscomb 1964) may be used to solve complex systems without determination of the analytical representations of the system (although the principal system parameters and potential state changes must be described in mathematical form), to solve systems which are characterized by complicated probability equations, to solve integral-differential equations, and to solve systems of linear equations.

Monte Carlo is a "game of chance" technique. Random sampling is used to determine a solution rather than analytical procedures. Monte Carlo is illustrated by the following evaluation of the definite integral:

$$A = \int_0^1 x \, dx = \frac{x^2}{2} \Big|_0^1 = 1/2$$

Normally, this integral is solved by one of three methods; analytically to obtain an exact solution, numerically, by an approximation method such as Simpson's rule, or graphically to measure the area under the curve.

Monte Carlo would be applied to the problem as follows: Select n pairs of random numbers in which there is an equal chance of any value between 0 and 1. Let each of the pairs of numbers represent a point in the XY plane. Then find the percentage of points in the n samples which fall under the curve of the function and within the boundaries 0, 0; 1, 0; 1, 1; 0, 1. This percentage gives the approximate value of the definite integral. Using a uniform random number table and arbitrarily selecting a sample size of 80 points, if 41 out of 80 might fall under the curve of the function, the estimated value of the integral by Monte Carlo then would be 0.5125 as compared to the exact value determined analytically to be 0.5.

A number of "simulation languages," GPSS, SIMSCRIPT (Markowitz et al. 1962), GASP (Kiviat 1963), SIMPAC (1962), DYNAMO (Pugh 1963), and SIMULATE (Holt et al. 1964) are available which simplify the task of writing computer simulation programs. These languages provide a generalized structure for designing simulation models and provide flexibility in the output formats.

4.4.1 Input/Output

A Monte Carlo simulation of a waste repository would require the following inputs:

> A list of potentially disruptive natural and man-caused events and processes with the interdependencies of the processes deterministically identified within the framework of a logic tree.[a] (An example of a chain of interdependent processes could be the following scenario: a worldwide warming trend, mean sea level increase, inundation of the land over the repository, renewed sedimentation and compaction, salt dome growth, stress induced overburden fracturing, groundwater penetration, and salt dissolution.) Deterministic characterization of these processes and their dependencies is likely to require the expert analysis of geologists and geophysicists.[b] Deterministic characterization at a minimum consists of defining limits on their probabilities, rates, durations, lifetimes, affected areas and volumes. A stratified model of the site-specific geology would be constructed by using site exploration data. The system output parameters of interest must be identified.

Monte Carlo simulation of a geologic respository could be programmed to yield the following output:

> Potential breach types.
>
> Failure times.
>
> Repository response curves. That is, the parameters which describe the state of the repository are defined as a function of time (e.g., pore pressures, intergranular and incremental fracture permeabilities, and thicknesses of all the layers).

(a) See fault/event trees, Section 4.3.
(b) See expert opinion/Delphi, Section 4.1.

The containment breaches, failure times, and repository response curves provided by the Monte Carlo simulation would be combined to determine the boundary conditions for a subsequent consequence evaluation.

As suggested above, Monte Carlo simulation of a geologic repository would step through time assuming random occurrence of the disruptive events (at the estimated probabilities and distribution functions) and continuous occurrence of the slow processes at their estimated rates, variations, and lifetimes. This procedure would simulate repository behavior and, if applied until one of the postulated breach types occurs, would produce an estimate of the time and conditions of this type of repository breach. By performing this repository simulation a large number of time (the Monte Carlo process), a distribution of breach types, times, and conditions would be produced. From this distribution, the probabilities of a given breach type in any given time interval would be calculated.

4.4.2 Application to Geologic Isolation

A first-generation computer code to implement a "Monte Carlo simulation/fault tree disruptive events/layered earth model" has been completed for WISAP evaluation. While this first-generation computer model illustrates that Monte Carlo simulation can be applied to geologic isolation, the geophysical models in this first generation computer code are too limiting to warrant publication of its output.

4.4.3 Strengths and Weaknesses

Simulation's key strength is its potential ability to predict system performance. Simulation is usually used when: it is impossible or extremely costly to observe certain processes, the system is too complex to be described in closed form mathematical equations, it is not possible to obtain a solution to the system equations by analytical techniques, and/or it may be impossible or very costly to perform validating experiments on the models describing the system. The geologic processes generally fit these criteria.

4.4.4 Critique and Recommendations

Monte Carlo simulation has some key strengths when compared against the WISAP risk scenario analysis methods criteria:

Criterion 1 - Quantitative and Scientifically Based

Monte Carlo can provide numerical assessments of deterministic and stochastic system models using the random sampling method. The method is scientifically sound and is only limited by the model detail.

Criterion 2 - Model the Disruptive Events and Processes

The Monte Carlo method could be used to evaluate a release sequence logic model (for example, a fault tree model which is updated at each time step). There are no limitations in modeling the problem time frame and considering interaction of all events and processes. However, there may be limitations imposed by the large number of simulations required for developing an adequate failure distribution.

Criterion 3 - Model the System Before and After Disruptive Events

The system model is the key strength of the Monte Carlo method. The method will solve any model. A time dependent repository system model can be developed.

Criterion 4 - Compatible with System Knowledge and Data

The method is compatible with system knowledge and data, although extensive peer review would be appropriate to judge the validity of the model and its elements.

The above evaluation suggests that the Monte Carlo simulation method is suitable for several uses in scenario analysis, specifically; evaluation of the disruptive events/processes logic model, continuous updating of the layered earth repository model and statistical evaluation of the breach/release/time relationships.

4.5 MARKOV CHAINS

The Markov process (Parzen 1972) is a set of analytical procedures which can reduce a system of many stochastic processes, effects, and paths into a single stochastic relationship. Such a system can be described as a series of Markov chains. A Markov chain is a model of a random variable X_i in a stochastic process which has the property that the value of X_i depends only upon the previous random value of this variable, X_{i-1}, and affects only the subsequent value of this random variable, X_{i+1}. The term "chain derives from the linking of the random variables to their immediately adjacent neighbors in the sequence.

A Markov chain step could be set up as follows: Let X_0 represent the present status of a physical system. We are interested in X_1, the next status of the system. A probability distribution must be formulated for the possible values of X_1. For example, if the next state can consist of three alternatives, rest, moderate reaction, or eruption, probability distributions must be formulated for each of these transitions under the assumption that this system is initially at rest.

The largest application of Markov chains (Parzen 1972) has been in the area of decision modeling for equipment replacement and inventory control.

4.5.1 Input/Output

To model a system in Markov chains: 1) one must be able to specify all states of the system, 2) the system states and associated probabilities must conform to the definitions of stochastic processes and Markov chains, 3) probability models must be discrete in time, 4) rates of system transition among possible states must be constant, and 5) all transition matrix probabilities must be available. Complex systems usually do not comply with all of these requirements. In general, the system must be very well understood.

4.5.2 Application to Geologic Isolation

For geologic isolation, the Markov chain method would require the specification of a finite number of states for the repository. Each state would describe a different level of degradation. Probabilities for transition from one state to the next would be specified. Subsystems would be described by a set of differential equations which would be solved numerically.

4.5.3 Strengths and Weaknesses

See Critique below.

4.5.4 Critique and Recommendations

Markov chains were examined for their application to the WISAP method with the following results:

Criterion 1 - Quantitative and Scientifically Based

The method does provide a quantitative assessment for stochastic system models. It is scientific and theoretically sound.

Criterion 2 - Model the Disruptive Events and Processes

The method will only model discrete random processes that are independent of previous states. It is not easily suited to continuous processes and would be difficult to apply to interacting continuous processes. The method would model the problem time frame and could identify release sequences.

Criterion 3 - Model the System Before and After Disruptive Events

Markov chains, like fault trees, only address probabilistic considerations. An additional system model coupled to the Markov chain analysis would be needed to allow evaluation of source terms and boundaries for the consequence analysis.

Criterion 4 - Compatible with System Knowledge and Data

The method is limited to discrete random processes only. Application to interactive continuous processes would require development of a suitable approximation to convert continuous processes to discrete events. Furthermore, the method requires well defined system transition probabilities. These definitions may not be available in sufficient rigor to provide successful application of the method. More sophisticated Markov approaches have been proposed to circumvent these problems.

Markov chains also present a communication problem; the approach is technical, formal and very difficult to describe. The current WISAP time/ limits do not appear compatible with the Markov chain approach.

4.6 CLASSICAL SYSTEMS ANALYSIS

Classical systems analysis is the completely deterministic prediction of system behavior using the laws of science and engineering. This technique requires that explicit relationships exist between all processes at work on and within the system. This kind of analysis has two parts, the determination of whether certain occurrences are possible and the prediction of the resulting conditions when those occurrences which are possible happen. The usual method of accomplishing the first part is stability analysis; the method for accomplishing the latter is perhaps best named science and engineering analysis.

Stability analysis is a deterministic technique for analyzing whether important properties of the system of interest remain unchanged if the system is disturbed. Applications of the technique, which began appearing in the middle of the nineteenth century, span the entire range of science and engineering disciplines (Rayleigh 1878; Lin 1955; Cheng 1959; Hetrick 1971; Rocard 1957).

The analysis procedure begins by developing an idealized conceptual model of the system and specifying the system property whose stability is to be analyzed. Mathematical models are then made of the important processes at work within the model system. This modeling activity produces a set of coupled differential equations (along with mathematical expressions for the appropriate boundary conditions) which describes not only the individual processes but also their interaction. Linear and nonlinear stability analyses are then performed on the model system. The linear analysis determines the system's response to mathematically imposed small arbitrary disturbances. Such small disturbances are ever present in all real systems. In linear analysis the descriptive equations and the boundary conditions are linearized if they were initially nonlinear. Thus an analytical solution to the descriptive equations is often possible. The nonlinear analysis determines the system's response to large arbitrary disturbances. Such large disturbances are occasionally present in real systems as a result of rapidly occurring events. A numerical solution to the nonlinear equations is normally required. If the model system damps the imposed disturbances and the property of interest returns to its predisturbance state, the system is said to be stable; if the system allows the disturbance to grow in amplitude, the system is said to be unstable, and the analysis proceeds to determining the rate of approach to system breakdown. Breakdown occurs when the unstable property has changed to such an extent that the modeled system can no longer be described by the original set of descriptive equations.

Science and engineering analysis investigates the instability scenarios identified in the first part of the analysis to determine the effect of their occurrence on the system (e.g., determine the effect of canister movement on the repository). The analysis uses the same system model developed for the stability analysis and simultaneously solves the resulting set of differential equations without introducing a mathematical disturbance into the system.

4.6.1 Input/Output

To apply systems analysis techniques, the processes of the system must be expressed in quantitative mathematical form and the data must exist to evaluate the physical constants and boundary conditions. This requires that the system of interest be well characterized. The analysis output is either a conclusion that the system is stable or the system is unstable, approaching disintegration at a predicted rate, and a system state description after failure. By varying the range of the input parameters, the region of instability can be bounded, and this is useful in system design.

4.6.2 Application to Geologic Isolation

To date, there have been no applications of classical systems analysis to the assessment of geologic isolation safety although the use of this technique has been proposed (Burkholder et al., 1977). Stability analysis may be useful in determining whether the combination of natural and waste induced processes could cause instability such as local fracturing, metamorphosis of the local geology repository movement, or movement of individual canisters. Both the linear and the nonlinear analysis techniques may be useful; in particular, nonlinear analysis could be used to evaluate whether the occurrence of large disturbances such as earthquakes could initiate instability in the system.

4.6.3 Strengths and Weaknesses

See critique below.

4.6.4 Critique and Recommendations

Evaluation of classical systems analysis for use as a comprehensive WISAP release scenario method yielded the following conclusions:

Criterion 1 - Quantitative and Scientifically Based

Classical systems analysis is quantitative and scientifically based.

Criterion 2 - Model the Disruptive Events and Processes

Classical systems analysis can model any process which can be described in a deterministic mathematical form. However, its use in modeling the interaction of these processes would be difficult due to the difficulty of deriving a closed set of equations which describe the total system over the problem time frame.

Criterion 3 - Model the System Before and After Disruptive Events

Classical systems analysis would provide this information if an adequate deterministic system model were available.

Criterion 4 - Compatible with System Knowledge and Data

There is insufficient knowledge of geosphere processes to model them by deterministic equations. An unrealistic effort in geosphere study would be required to gather sufficient data to apply this method as a comprehensive scenario analysis method.

Classical systems analysis appears to be limited to specific problem areas of geologic isolation safety assessment; the characterization of near-field effects (heat dissipation, rock mechanics, and soil chemistry). The technique is not well suited to analyzing geologic events which are difficult to model by continuum mathematics. Thus, classical systems analysis is not a comprehensive technique for predicting repository release scenarios but rather is a specialized method for analyzing only a portion of the assessment problem.

5.0 SUMMARY AND CONCLUSIONS

In order to analyze the potential modes for breach of a nuclear waste repository, an appropriate methodology for analysis must be chosen. The authors of this report selected several possible approaches for analysis and evaluated these on the basis of the following criteria; the method should:

- be quantitative and scientifically based,
- model the potential disruptive events and processes,
- model the system through time to the failure event in sufficient detail to provide input to a subsequent consequence analysis,
- be compatible with the currently foreseeable level-of-knowledge of system data and understanding of the operative events and processes.

These criteria were applied to the following methodologies: expert opinion, perspectives analysis, fault trees and/or event trees, classical systems analysis, Markov chains and Monte Carlo simulation. These methods were selected for study because we believe that these were the most suitable for the needs of the WISAP Program for breach scenario analysis.

Expert opinion is an assessment technique in which a body of recognized experts perform the analysis based on their professional judgment. As such, there are elements of subjectivity associated with the use of the method of expert opinion. Nevertheless, it was concluded that the WISAP scenario analysis can profit by incorporating expert opinion where scientifically recognized theories and data sources are unavailable.

Perspectives analysis is the qualitative method of comparing a poorly understood attribute of a given activity with a similar, better understood, attribute of some other activity. Inherently, this approach is nonquantitative but it can be made semi-quantitative by developing a set of indices against which various understood activities, which bracket the poorly understood activity, may be compared. The general conclusion regarding perspectives analysis was that this methods would be ill-suited for WISAP scenario breach analysis but might have limited application within the overall WISAP analyses.

Fault trees and event tress are mathematical logic modeling systems for analyzing the failure modes or probable fate of a system. The strength of this approach is the logical reasoning on which it is based; the weaknesses in application to WISAP are its limited ability for dealing with time-dependent processes and multi-state situations. The conclusion was that, for WISAP repository breach scenario analyses, the fault tree/event tree approach would be appropriate in defining the disruptive event and process failure sequences.

Classical systems analysis is the deterministic prediction of system behavior according to solution of governing equations based on the appropriate laws of nature. Suitable approximation to the exact equations can often lead to sensible analyses of very complicated systems. However, the equations governing most geologic processes and events are not known. Therefore, classical systems analysis was not judged to be suitable for overall analysis of repository breach.

Markov analysis is a set of stepwise analytic procedures which can reduce a system of many random processes and effects into a single stochastic relationship. The Markov method, in its simplest form, is not well-suited to analysis of continuous processes nor to interacting processes and events. More sophisticated Markov approaches have and could be developed but, because of the complicated structure of Markov analyses, the difficulty of communicating between disciplines was judged to render this technique unsuitable for WISAP.

Monte Carlo analysis replaces the analytic approach to the solution of complicated mathematical problems by a probabilistic approach. As such, it is particularly well-suited for use when analytic relationships are unavailable. Geological events and processes generally fall into that category. Monte Carlo analysis was, therefore, chosen to develop a pilot model which can be studied to determine the suitability of this approach.

It should be noted, in selecting the methods considered, the technique of consequence analysis was defined in a very specific sense, and consideration of this approach was referred to a second study. However, consequence analysis also has a broader definition wherein consequence analysis is used as a form of safety analysis in which scenarios (e.g., maximum credible accident) are postulated and the entire accident sequences from disruptive events and processes leading to breach and the acquisition of the dose by man are assessed as a unit. Because of the detailed assessment goals of WISAP, this approach was excluded.

In summary, the integrated approach chosen for the WISAP breach scenario analysis involves expert opinion in selecting the events and processes to be considered; in this process, fault trees and/or event trees play an important intermediate role.

Expert opinion will continue to be used throughout the analysis to provide predictive disruptive factor input, data, analysis of the results, and to recommend improvements. All the events and processes judged to be important are being incorporated into a unified model using Monte Carlo and simulation techniques. Those elements which can be analyzed deterministically will be; those which cannot will be analyzed stochastically.

The purpose of this document was to discuss the various methods of analysis that could be used to analyze the geologic meteorological and man-caused interactions which could cause a breach of the repository and provide a possible pathway to the biosphere.

It is important to note that this document outlines the basic methodology that was assessed for use in a first generation computer simulation model. The methodology utilized in the first generation model is not fixed. As the quantification of geological processes to the overall WISAP safety analysis is outlined better, the simulation model will evolve. While doing so, it may assume a character quite different from the initial concept and will utilize different and/or additional analysis methods.

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