Assessment of Effectiveness of Geologic Isolation Systems

A Conceptual Simulation Model for Release Scenario Analysis of a Hypothetical Site in Columbia Plateau Basalts

January 1981

Prepared for the Office of Nuclear Waste Isolation
under its contract with the U.S. Department of Energy

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$_____*; Microfiche \$3.00

*Pages	NTIS
	Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

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A CONCEPTUAL SIMULATION MODEL FOR RELEASE
SCENARIO ANALYSIS OF A HYPOTHETICAL SITE IN
COLUMBIA PLATEAU BASALTS

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Under its Contract with the
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PREFACE

This report is a status report for an evolving methodology for release scenario development for underground nuclear waste repositories. As such, it is intended for use as a reference point and a preliminary description of an evolving geoscience methodology. When completed this methodology will be used as a tool in developing disruptive release scenarios for analyzing the long-term safety of geological nuclear waste repositories.

As a draft, this report was used as a focal point for discussion at a Release Scenario Analysis Workshop held in August, 1979, by the Waste Isolation Safety Assessment Program (WISAP) in Seattle, Washington. With the exception of numerous editing and typographical corrections, this report contains the same information as the earlier circulated draft and serves to document the state of the methodology at that time (August 1979). A new status report on the Release Scenario methodology is currently scheduled for release the end of 1980. This next version will contain a new, updated version of the release scenario methodology and describes the many changes implemented as a result of comments by the participants of the FY-1979 workshop following discussions of this report.

While a basalt environment is used as an example, this report is not intended to reflect an actual site safety assessment for a repository in a media. It is rather intended to present a methodology system framework and to provide discussions of the geological phenomena and parameters that must be addressed in order to develop a methodology for potential release scenarios. It is also important to note that the phenomena, their interrelationships, and their relative importance along with the overall current structure of the model will change as new geological information is gathered through additional peer review, geotechnical input, site specific field work, and related research efforts.

ACKNOWLEDGMENT

This research was supported by the Waste Isolation Safety Assessment Program being conducted by Pacific Northwest Laboratory. This program was sponsored by the Office of Nuclear Waste Isolation, which is managed by Battelle Memorial Institute under contract EY-76-C-06-1830 with the Department of Energy. On October 1, 1979, WISAP became the Assessment of Geologic Effectiveness of Geologic Isolation Systems (AEGIS) Program and the Waste/Rock Interactions Technology (WRIT) Program. This report was issued by AEGIS.

The contents of this report represent the efforts of a relatively large group of individuals. In the body of the report, reference is made to: 1) the WISAP Task 1 Research Team, and 2) the Consulting Team. Individual members of these groups are listed below. To keep the document a manageable size, many of the details associated with the topics presented herein are deferred to a set of topical reports contained in the reference list. Most of the discussions in this report are based on the inputs of the consulting team.

WISAP Task 1 Participants

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CONTENTS

PREFACE	iii
ACKNOWLEDGMENT	iv
WISAP TASK 1 PARTICIPANTS	v
INTRODUCTION	1
REPOSITORY SIMULATION	8
EXAMPLE SUBMODELS	21
CLIMATE	26
Milankovitch Theory	30
Dust Loading of the Atmosphere.	34
Summary	36
PRECIPITATION, RUNOFF, AND INFILTRATION	37
Precipitation	40
Summary	47
CONTINENTAL GLACIATION	47
Ice Sheet Advancement and/or Accumulation Rates	49
Maximum Southerly Extent of Continental Ice Sheets.	50
Isostatic Subsidence and Rebound	52
Induced Stress and Crustal Fracturing	52
Incremental Permeability Associated with Ice Induced Fracturing.	55
Ice Scouring	55
Pressurized Recharge.	55
Drainage of Meltwater	58
Summary	59

ALPINE GLACIATION	60
Summary	65
SEA LEVEL FLUCTUATIONS	66
GEOMORPHIC EVENTS	71
River Flows	73
Inundation of the Basin	77
Recharge	79
Sedimentation	80
River Course Alteration	80
General Denudation	82
Stream Erosion	82
Flood Erosion	86
Wind Erosion	86
Summary	87
DEFORMATION	87
Undetected and/or Accelerated Deformation of the Basalts	91
Probability of an Undetected Anticline	94
Strain Rate	95
Probability of a Fault Associated with the Folding.	96
Probability of Shear Displacement on Pre-Existing Joints	96
Associated Permeability Increases	97
Faulting in the Sub-basalt Basement.	101
Vibratory Excitation and Backfill Material Response	102
Impact Fracturing	104
Hydraulic Fracturing.	105

Summary	108
METEORITES.	110
Argument to Eliminate Future Meteorite Analyses.	110
Preliminary Analysis.	118
Summary	118
MAGMATIC ACTIVITY	123
Summary	129
UNDETECTED FEATURES	129
Undetected Boreholes.	132
Basaltic Ring Structures	132
Remnant Stream Beds	134
Lava Tubes.	137
Summary	137
REPORT SUMMARY	141
Interface Between Release Scenario and Release Consequence Studies	141
Site Specific Nature of the Problem.	142
Columbia Plateau Submodels	142
Incorporation of Near Field Results.	143
Interactive Utilization of the Tool.	143
REFERENCES.	145
APPENDIX - GLOSSARY OF TERMS	A.1

FIGURES

1	Waste Isolation Safety Assessment Program	3
2	Logic Flow Diagram	9
3	Example of Phenomena Interrelationships	11
4	Example Layer Earth Model.	12
5a	Initial System State Time = 0 Years.	15
5b	System Perturbation Time = 10^N Years	15
5c	Breach (Potential Failure) Time = 10^{N+M} Years	16
5d	Failure Time = 10^{N+M+L} Years	16
6	Submodel Block Diagrams	23
7	The Columbia Plateau (RH0-BWI-78-100)	26
8	Major Topographic Features (RH0-BWI-78-100)	27
9	Simplified Cross-Section of Study Area	28
10	Astronomical Climatic Index (ACLIN) as a Function of Time	32
11	ACLIN for 122,000 B.P. (Before Present) to 60,000 A.P. (After Present)	34
12	Future Natural Climate vs. Time as Predicted From ACLIN Without Ash Load Perturbations	35
13	Atmospheric Dust Load	36
14	Climate, Submodel	37
15	Calculation of Difference of Summer Precipitation in mm. Day ⁻¹ Between 18,000 Years BP and Present Day, by Members of CLIMAP Group	43
16	Test Density Curves Relating Precipitation to the Climatic Index	44
17	Possible Relationships Among Rainfall, Recharge, and Regional Hydraulic Gradients	46

18	Glacial Areas of the Conterminous United States	51
19	Example Stress Conditions Beyond the Edge of an Ice Sheet . .	54
20	Conceptualization of Glacial Recharge of Ground Water . . .	56
21	Estimated Annual Average Columbia River Flows.	59
22	Continental Glaciation Logic Flow Chart	61
23	Areas Affected by Mountain Glaciers in the U.S.A.	64
24	Probability of Alpine Glaciation in the Great Basin as a Function of Distance from a Dominant Peak	66
25	Alpine Glaciation Flow Chart	67
26	Logic Flow for Sea Level Fluctuations	72
27	Assumed Extent of Glacial Advance at 18,000 Years B.P. . .	74
28	Extent of Missoula Flooding	76
29	Development of a Hydraulic Constriction at Wallula Gap . .	78
30	Approximate Area of Hanford Reservation Inundated by a Flow of $2.97 \times 10^6 \text{ m}^3\text{s}^{-1}$	79
31	Climate and Sediment Yield	81
32	Suspended Solids Denudation Rate as a Function of Elevation .	83
33	Rates of Denudation	85
34	Logic Flow Diagram for Geomorphic Events Submodel	88
35	Earthquake Epicenters for the West and Eastern Washington Data Files	93
36	Stress Orientation, Pacific Northwest, and Basin Range Provinces	95
37	Fault Intersection Probabilities	98
38	Parallel Plate Fracture Model	99
39	Conductivity vs. Fracture Width for Various Joint Spacing . .	100
40	Assumed Crack Geometry Around Shaft Seal	105

41	Calculated Peak Acceleration at the Surface and Associated Tunnel Damage	106
42	Logic Flow Diagram for Deformation	111
43	Flow Logic for Faulting in the Sub-Basalt Basement	112
44	Logic Flow for Shaft Seal Failure Submodel	113
45	Critical and Sensitive Damage Zones for Meteorite Impacts	119
46	Relationship Between Crater Diameter (D), Depth of Excavation (d) and Depth of Fracturing (df)	119
47	Relationship Between Crater Diameter and Total Impact Kinetic Energy	120
48	Logic Flow Diagram for Meteorite Submodel	121
49	Block Diagram of Plutonic and Volcanic Structures	124
50	Map Showing the Columbia and Snake River Basalts of Northwestern United States	126
51	Schematic Diagram of Multiple Flows From Linear Fissures	126
52	Logic Flow for Magmatic Submodel	130
53	Potential Consequences Associated with Undetected Features	133
54	Sequence of Events Postulated to Explain the Basaltic Ring Structures	135
55	Remnant Stream Beds: a) Pre-Flow Conditions, b) During Flow Advance, c) Post-Flow Conditions	136
56	Logic Flow for Undetected Features	138

TABLES

1	Potentially Disruptive Phenomena	4
2	Example LEM Categories	13
3	Example Components	13
4	Primary Output at Each Time Step for Each Stratigraphic Unit.	18

5	Secondary Output at Each Time Step.	18
6	Multiple Simulation Output Format	20
7	Submodels	21
8	Submodel Interaction	29
9	Climate Submodel Data	39
10	Late Pleistocene Climate Reconstructions Overview of Published Data	41
11	Age of Glacial Terminations - Summary of Published Estimates	48
12	Crustal Stresses Associated with Large Ice Sheets	53
13	Continental Glaciation Submodel Data	63
14	Required and Available Data for the Alpine Glaciation Submodel	70
15	Potential Ocean Level Variations	71
16	Sea Level Fluctuation Submodel Data.	73
17	Ranges of Average Annual Columbia River Flow	75
18	Rates of Regional Erosion in the United States	84
19	Geomorphic Events Submodel Data	90
20	Example Bulk Permeabilities for a Joint Rock Calculated From Parallel Plate Theory	100
21	Reported Seismic Events ($M \geq 5.5$) Near Hanford Since 1872	103
22	Predicted Future Earthquakes for Hanford Area Over the Next Few Hundred Years	104
23	Summary of Damage Levels	107
24	Deformation Submodel Data	114
25	Sub-Basalt Basement Fault Data	115
26	Shaft Seal Failure Submodel Data	117
27	Example Parameter Magnitudes for Meteorite Impact	120

28	Data Requirements and Availability of Meteorite Submodel . . .	122
29	Generalized Classification of Volcanic Activity Based on Approximate Magmatic Compositions	125
30	Transport Distances and Eruption Types of Volcanic Events . . .	127
31	Magmatic Activity Submodel Data	131
32	Undetected Features Submodel Data	139

INTRODUCTION

The management of potentially hazardous radioactive waste products and spent fuels is an integral part of the commercial nuclear energy policy in the United States. Based on this policy, the U.S. Department of Energy (DOE) implemented the National Waste Terminal Storage (NWTS) Program to evaluate alternatives for the safe long-term storage of nuclear wastes. As part of this program, Battelle, Pacific Northwest Laboratory conducted the Waste Isolation Safety Assessment Program (WISAP) under the sponsorship of the Office of Nuclear Waste Isolation (ONWI).

The objectives of the Waste Isolation Safety Assessment Program (WISAP) were to: 1) develop the capabilities needed to assess the post-closure safety of geologic repositories, 2) obtain scientifically defensible generic and site-specific data necessary for safety assessments, 3) provide, as needed, studies to further support these data and analyses, 4) demonstrate the assessment capabilities by performing analyses of reference sites, 5) apply the assessment methodology to assist the National Waste Terminal Storage Program in site selection, and 6) perform repository site analyses responsive to the time schedule and to the level of sophistication required to meet the licensing needs of the National Waste Terminal Storage Program.

There are two basic components of repository post-closure safety assessments:

- identification and analyses of breach scenarios and the pattern of events and processes causing each breach
- identification and analyses of the environmental consequences of radionuclide transport and interactions subsequent to a repository breach.

The Waste Isolation Safety Assessment Program addressed only the far-field, long-term safety of an underground nuclear waste repository. The operational, near-field, and waste-induced portion of the overall safety assessment is being developed for DOE by other contractors through ONWI.

WISAP was divided into four technical tasks. These tasks were:

- Task 1 - Release Scenario Analysis
- Task 2 - Waste Form Release Rate Analysis
- Task 3 - Release Consequence Analysis
- Task 4 - Sorption/Desorption Analysis

The tasks combine to form the overall safety assessment methodology. The integration of these individual tasks is outlined in Figure 1.

This report is a product of the Task 1 - Release Scenario Analysis research effort. The primary objectives of the task are: 1) analyze the full spectrum of geologic and man-caused phenomena which, alone or in concert, could conceivably lead to the release of radioactive contaminants from the immediate repository boundaries, 2) estimate the probabilities associated with any potential "breach" scenarios, and 3) quantitatively bound the initial conditions necessary for a parametric consequence analysis with geosphere and biosphere transport codes. Example phenomena are listed in Table 1.

It is suggested that any safety assessment tool devised to meet these objectives be stochastic in nature and flexible enough to incorporate objective and subjective input from a variety of geoscience disciplines. This conclusion reflects man's limited understanding of natural geologic and hydrologic systems, and the limited data availability.

This report is a conceptual presentation of a methodology entitled Repository Simulation. This simulation approach is a composite of qualitative fault trees, Delphi-like techniques, and Monte Carlo simulation. The user-interactive computer tool is designed to assist geoscientists in identifying and quantifying the various potential geological and hydrological system states in which future repository site might exist.

Although necessarily simple relative to any real geosystem, this computer model reduces a complex, multivariate problem to a set of interrelated but concise components that can be more easily addressed by geoscientists. The key is to focus the efforts of the experts on one segment of the problem at a time within a framework whereby integration of all the components can be achieved.

FIGURE 1. Waste Isolation Safety Assessment Program

Reasons for a computer-enhanced methodology include:

- 1) Significant interaction among disruptive phenomena exists. For example, climate, precipitation, continental and alpine glaciation, erosion, sedimentation, and groundwater recharge are all synergistic in nature.

- 2) Most of the disruptive phenomena listed in Table 1 are time dependent and therefore initiation and consequences cannot always be considered simultaneously.
- 3) Data uncertainties dictate reliance on probability distributions rather than discrete numbers.
- 4) The sensitivity of the output to variations in the input must be analyzed to help optimize subsequent time and money expenditures.
- 5) The output of the methodology must be tailored to provide input to the consequence (nuclide transport) analyses. The release scenario

TABLE 1. Example Potentially Disruptive Phenomena

<u>Natural Phenomena</u>	<u>Man-Induced Phenomena</u>
Climatic Fluctuations	Improper Design/Operation:
Glaciation	- Shaft Seal Failure
Denudation and Stream Erosion	- Improper Waste Emplacement
Magmatic Activity	Undetected Past Intrusion:
- Extrusive	- Undiscovered Boreholes or
- Intrusive	- Mineshafts
Epeirogenic Displacement	Inadvertent Future Intrusion:
- Igneous Emplacement	- Archeological Exhumation
- Isostasy	- Weapons Testing
Orogenic Diastrophism	- Non-Nuclear Waste Disposal
- Near Field Faulting	- Resource Mining (Mineral,
- Far Field Faulting	Hydrocarbon, Geothermal,
- Diapirism	Salt, Water)
Static Fracturing	- Storage of Hydrocarbons or
- Surficial Fissuring	Compressed Air
- Impact Fracturing	Perturbation of Groundwater
- Hydraulic Fracturing	System:
Meteorites	- Irrigation
Dissolutioning	- Reservoirs
Sedimentation	- Intentional Artificial
Flooding	Recharge
Undetected Features	- Establishment of Population
- Faults	Center
- Breccia Pipes	
- Lava Tubes	
- Gas or Brine Pockets	
- Shear Zones	

task must estimate the input variable ranges for the release consequence task, to provide a basis for parametric consequence studies.

- 6) The methodology must explicitly reveal the conceptual model of the geoscience users and provide a degree of auditability to the study.

The Release Scenario Analysis Task is designed to address the potential long-term geologic and hydrologic changes that might occur in the vicinity of a high-level waste or spent fuel repository. Although the simulation methodology being proposed is applicable to any desired time frame, emphasis has been placed on the 10^3 to 10^6 years following final closure of the repository. Other studies outside of WISAP will address the operational phase of the facility and the changes in the geohydraulic system that might be induced by the presence of the waste, e.g., fracturing of the host rock due to thermal loading and unloading. It is anticipated that the output of these studies will be used as input to any long-term release scenario analysis.

With respect to long-term studies, it is recognized that approximately 99% of the projected radioactivity in reprocessed waste will be represented by ^{90}Sr and ^{137}Cs , and that these isotopes will decay to innocuous levels after 600 years, or roughly 20 half-lives (Gera and Jacobs 1972). However, certain fission products and selected actinide elements can remain toxic for hundreds of thousands of years if in sufficient concentrations.

The primary output of such a Release Scenario analysis is conceived to be a set of potential future geological and hydrological state descriptions with some estimates of occurrence probabilities. Such system descriptions (hydraulic conductivities, fluid potentials, pathlengths, etc.,) can be used by geosphere/biosphere transport modelers for the purpose of conducting consequence analyses on the predicted breach, if any. For the purpose of this study, a breach is defined as a specific volumetric flux of a potential transport medium through the immediate boundaries of the repository cavity.

To facilitate understanding of the proposed Repository Simulation modeling approach, the Columbia Plateau in the state of Washington is used as a

hypothetical repository region. However, this report does not represent a preliminary release scenario analysis for this area. As is pointed out in the text, a great deal of additional information is necessary to support such an undertaking. The site-specific nature of the release scenario analysis and release consequence analysis is such that generic applications of the computer codes, although possible, will not be particularly satisfying or enlightening. Site-specific adaptation and use are essential; in this report the Columbia Plateau serves as an expedient example.

The primary motivation for the computer methodology is to analyze and present information in a logical and auditable format, to facilitate future discussion, to focus thinking on manageable size segments of the problem, and to provide a flexible framework for incorporating constructive suggestions and criticisms from individuals representing a broad spectrum of backgrounds.

This report is devoted to a description of the Repository Simulation methodology as conceptualized for a hypothetical site in the Columbia Plateau basalts. The information is presented in the form of: 1) theory and diagrammatic flow charts, 2) required input and output tables, and 3) example data distributions.

It must be emphasized that this is not a preliminary safety assessment but, rather, is a conceptual example of how such a Release Scenario study might be conducted. Furthermore, the report is designed as a working document upon which the geoscience community can focus its thinking, direct its criticisms, and channel its suggestions for future evolution of the model and associated data. As such, the framework of the model will necessarily change as a better understanding of the phenomena and their interactions are described by the geoscience community. In this sense, the overall conceptualization of the geologic and hydrologic system represented in this model will evolve as our understanding and knowledge of the local geosystem expands. Hence, the model and submodels discussed within this report should not be considered unalterable and final.

The influence of man and his developing technology is not addressed within the current framework of the conceptualized model described in this report.

While it is recognized that man could have a significant influence on the geological system, it is extremely difficult to describe the potential system perturbations within the confines of a quantified computer logic. This results from the uncertainty inherent in attempting to describe future courses of man's technological ability. The exact manner of how potential human intervention will be addressed and incorporated in the final safety analysis is still under study.

A description of the overall Repository Simulation methodology is given in the next section. The report then includes discussions on the following topics: 1) climate, 2) precipitation, runoff, and aquifer recharge, 3) glaciation, 4) sea level fluctuations, 5) flooding, sedimentation, and erosion, 6) folding, faulting, jointing, and fracturing, 7) shaft seal integrity, 8) undetected basement faulting, 9) other undetected features, 10) meteorites, and 11) magmatic activity.

REPOSITORY SIMULATION

Figure 2 reveals the general logic flow of the Repository Simulation methodology. Basically, it is a brute-force approach with the following five fundamental components: 1) characterization of individual disruptive phenomena, 2) identification of potential interactions, 3) development of a simplified layered earth model, 4) establishment of system response rules, and 5) individual or multiple simulations of the geological and hydrological system. Figure 3 illustrates an example of interrelationships among phenomena and potential synergisms. The bookkeeping component of the Repository Simulation methodology is the Layered Earth Model (LEM) shown conceptually in Figure 4. Tables 2 and 3 present details of the LEM and some illustrative system response rules.

Multiple simulations are necessary to outline the numerous potential geological and hydrological states of the system and to rank them with respect to estimated probabilities. At the end of any given simulation, the system is reinitialized to the state in which the repository resided at time of final backfill and closure.

A breach of the system is defined by a specific volumetric flux of a contaminant transport medium, such as nuclide-bearing water, through the immediate repository boundaries. Note that this requires 1) a pathway, and 2) a difference in hydraulic potential along the path. The model monitors for a breach at the conclusion of each time step during each simulation run. If, during the time step under consideration, either condition is insufficient to support a volumetric flux exceeding a predetermined value, a breach does not occur. This is not to say that both conditions will not be met during subsequent time steps in a simulation run.

At the beginning of any given simulation run, the LEM is initialized to reflect the state of the geologic and hydrologic system at the time of repository backfill. An analogy for the LEM in the one-dimensional model might be a borehole from the land surface down through the repository and all layers above

FIGURE 2. Logic Flow Diagram

FIGURE 2. (contd)

FIGURE 3. Example of Phenomena Interrelationships

GENERAL LITHOLOGY	UNIT NUMBER	LAYER THICKNESS (METERS)	HORIZONTAL PERMEABILITY (MILLIDARCIES)	VERTICAL PERMEABILITY (MILLIDARCIES)	GROUNDWATER HEADS (METERS BELOW SURFACE)
LOOSE SILT SAND AND GRAVEL	1	125	2000.0	200.0	40.0
CEMENTED SAND AND GRAVEL	2	200	1000.0	100.0	40.0
BASALT	3	300	0.13	0.13	52.0
SEDIMENTARY INTERBED	4	25	300.0	30.0	43.0
BASALT	5	250	0.013	0.013	55.0
SEDIMENTARY INTERBED	6	25	1330.0	133.0	43.0
BASALT (REPOSITORY)	7	100	0.013	0.013	52.0
SEDIMENTARY INTERBED	8	25	1330.0	133.0	44.0
BASEMENT	9	∞	0.013	0.013	61.0

FIGURE 4. Example Layer Earth Model

and below it. Vertical averaging of a real geosystem should reduce the number of layers to ten or less, with biasing toward those layers closest to the repository.

Each stratigraphic unit represents a spatially uniform cell to which a variety of geological, hydrological, and chemical data can be associated. Of primary interest are: 1) the thickness of the layer; 2) vertical and horizontal hydraulic conductivities; 3) vertical and horizontal hydraulic gradients; 4) effective stresses; 5) the lateral distance down any given layer to a discharge point to the biosphere (e.g., lake, river, aquifer), and 6) a "short-circuit" (fault zone, breccia pipe, or ring structure) to another layer.

At the end of each time step in the simulation, these characteristics of the LEM are updated based on how the ongoing scenario processes (erosion, glaciation, faulting, etc.) perturb the system. A fundamental assumption is that the order of updating within a single time step is not significant. In other words, the LEM characteristic may lag the ongoing processes or disruptive events by as much as one time step. If these steps are relatively small, e.g., 10^2 or 10^3 years, this necessary assumption should have no significant effect.

TABLE 2. Example LEM Categories

Dimensional Characterization
 Number of layers
 Relative height and thickness
 Spatial coordinates

Anomalies
 Faults
 Shear zones
 Breccia pipes
 Lava tubes
 Wells and boreholes

General Hydrologic Parameters
 Topography and drainage
 Hydraulic potentials
 Hydraulic conductivities
 Recharge and discharge

1. Natural
2. Man-caused
3. Areal extent
4. Elevation

State of Effective Stress

Rock Properties

- Porosities and permeabilities
- Strength characteristics

 Elastic properties
 Inelastic properties
 Thermal properties
 Inhomogeneity and Anisotropy

Valuable Resources

- Minerals
- Oil, gas
- Water

Back-fill Material Characteristics
 Relative to Host Rock Formation
 Density
 Compressibility
 Acoustic Impedance

TABLE 3. Example Components

Disruptive Phenomena Data
 Occurrence probabilities
 Rate
 Magnitudes
 Phase data (lag time)

Layered Earth Model
 Number of layers
 Thickness of the layers
 Mechanical and chemical properties
 Hydraulic conductivities
 Hydraulic potentials
 State of effective stress

Example System Response Rules
 North American climate related
 to orbital parameters and atmospheric dust load
 Denudation is related to climate, elevation differences, and rock properties
 Glaciation may result in erosion, fracturing, and recharge
 Fault rupture effects hydraulic conductivities and potentials
 Overburden accumulation may change the state of effective stress, porosities, and permeabilities.
 Increased precipitation may affect aquifer recharge, water table elevation, and erosion

Breach Interrogation and Input to Consequence Analysis
 Breach is defined by a specified volumetric flux of a fluid through the immediate cavity boundaries
 Input to consequence analysis includes: scenario probability simulated time, and layered earth model description

Figures 5a through 5d present the concept of system perturbation, breach, and failure through a hypothetical scenario. The first diagram shows the repository at time zero (backfill). At year 10^N the system has been perturbed by erosion, possible pressurized glacial recharge of the deep aquifers, and river course alteration. However, the low permeability of the host basalt maintains the isolation integrity of the system. Thus we have only a perturbation, i.e., some system characteristics have changed but no breach has occurred. At year 10^{N+M} , faulting in the basement strata or anticlinal deformation near the site has induced shear displacement on the joints in the host basalt layer. Associated enhancement of the vertical permeability results in creation of a continuous path from an underlying aquifer through the repository to an overlying aquifer. The fluid potentials or hydraulic heads are such that a small flow is created in a downward direction. Thus a breach has occurred and transport codes can be used for the consequence analysis. Data such as time of the breach, hydraulic conductivities, hydraulic gradients, and distance to the irrigation wells and the river are given to the transport modelers as input conditions. A failure occurs only if the output of the consequence models show unacceptable contamination of the biosphere. In other words, the "breach" need not lead to a "failure." Note, however, that in year 10^{N+M+L} , renewed glaciation has perturbed the flow conditions by increasing the head in the aquifer below the repository (layer G in Figure 5d) by wet based ice loading of the distant recharge areas. The upper aquifer is not so affected. Alternatively, increased pumping from the upper aquifer (layer E in Figure 5d) has reduced the head and, therefore, flow is now going from the lower aquifer through the fractured repository zone to the upper aquifer and toward another discharge point along a different path. Once again the transport codes would be exercised to address the potential consequences to the biosphere. Note, however, that the original fracture zone may have "healed" or closed due to secondary mineralization or creep closure, and thus no breach would exist.

One can envision the large number of potential scenarios that can be generated by such speculation. Thus, two modes of computer operation will be available: 1) the user-oriented, interactive-graphical mode where the geoscientist selects his own disruption phenomena combinations and associated magnitude, rate, and delay time data; and 2) a Monte Carlo mode.

FIGURE 5a. Initial System State Time = 0 Years

FIGURE 5b. System Perturbation Time = 10^N Years

FIGURE 5c. Breach (Potential Failure) Time = 10^{N+M} Years

FIGURE 5d. Failure Time = 10^{N+M+L} Years

In the interactive mode, users select their own scenarios and data from the supplied distributions. In this manner, they can conduct parametric analysis rapidly and efficiently and examine coupling phenomena in increasing levels of detail. The variations in the system with time and the chosen phenomena can be observed by following the characteristics of the layered earth model. These characteristics are updated at the end of each time step, e.g., 100 or 1000 years.

In the Monte Carlo mode, the computer will automatically combine disruptive phenomena into scenarios based on relative occurrence probabilities, select data from the supplied distributions, and scan for a breach at the end of each time step. If a breach is manifested, description of the breach and the geohydrological system at that time step is then fed to the hydrological and nuclide transport models so that the consequences for the biosphere can be quantified. Tables 4 and 5 list the output parameters which are indexed according to stratigraphic unit and simulated time. At the end of any given time step or subsequent to the completion of any scenario (case history), the operator can interrogate the data files for a partial or complete description of the layered earth model. Additionally the operator can examine a history file which contains information on any significant features, e.g., faults, which occurred during the time step. Table 6 shows conceptually how multiple simulations from a Monte Carlo run can be presented. In this example, the operator is interested in only the first 10^4 years in multiple 10^6 year simulations. Such a table would represent the various states in which the repository might exist by year 10,000. The breach column of Table 6 indicates whether or not the particular state characteristics have resulted in a specific volumetric flow of a transport fluid through the immediate repository boundaries.

It is possible to arbitrarily select a breach at some specific point in time and conduct hydrologic and nuclide transport calculations based on existing geological or hydrological conditions. The input to the consequence analysis (e.g., pathlengths, hydraulic conductivities, hydraulic gradients, and sorption coefficients) must be altered to observe the variations in the output.

TABLE 4. Primary Output at Each Time Step for Each Stratigraphic Unit

- Hydraulic conductivity (vertical and horizontal)
- Fluid Potentials (vertical and horizontal)
- Effective Stresses (vertical and horizontal)
- Layer Thickness
- Elevation of Surface
- Breach Status
- Breach Description, if any
 - Pathlengths along discrete vertical and horizontal legs
 - Conductivities along the flow paths
 - Potential gradients along the part
 - All associated probability information

TABLE 5. Secondary Output at Each Time Step

<u>Submodel</u>	<u>Output</u>
Climate	Climatic State Recharge Precipitation Major Stream Flows
Continental Glaciation	Status Ice Scouring Incremental River Flow Pressurized Recharge Incremental Fracture Permeability Incremental Sub-basal Groundwater Flow Isostatic Effects Ablation Melt Water
Alpine Glaciation	(similar to Continental)
Geomorphic Events	Stream Erosion Denudation Sedimentation Coordinate Variations in Recharge and Discharge Points "Missoula" Type Flooding

Table 5. (contd)

<u>Submodel</u>	<u>Output</u>
Sea Level Fluctuations	Elevation Relative to Site Incremental Changes in Hydraulic Gradients Erosion or Sedimentation Vertical Recharge Groundwater Table Elevation
Deformation	Distance from Undetected Feature Incremental Permeability due to Lateral Fault Extension Degradation of Permeability due to Healing Incremental Permeability due to Shear Displacement on Joints
Sub-Basalt Faulting	Incremental Permeability Type (Normal, Reverse, Strike slip) Width, Length, Displacement Peak Acceleration, Velocities, Frequencies, Duration, and Attenuation Stress Change
Shaft Seal Failure	Incremental Permeability Dimensions
Undetected Features	Type Location Incremental Permeability
Meteorites	Crater Depth Fracture Depth Incremental Permeability Seismic Energy Release
Magmatic Activity	Distance from Site Material Dispersed to Air Material Dispersed to Surface Water Material Exposed to Ground Water

TABLE 6. Multiple Simulation Output Format

PRIMARY OUTPUT
FOR MULTIPLE SIMULATIONS

Time = 10^4 years in a 10^6 year simulation
Layer = 8 (contains repository)

Simulation	Hydraulic Conductivities		Hydraulic Gradients		Effective Stress		Elev	Breach Status
	Horizontal	Vertical	Horizontal	Vertical	Max	Min		
1	x_{11}^H							x_{91}
2	.	.					.	
.	.	.					.	
.	.	.					.	
.								
N	x_{1N}^H							x_{9N}

Mean $\bar{x}$ ← ————— →

$$\text{Variance} = \sum_{j=1}^N \frac{(x_{ij} - \bar{x})^2}{N}$$

The Repository Simulation methodology is designed to assist in this parametric consequence study by bounding the perturbations one must place on the input parameters used in the numerical transport models.

EXAMPLE SUBMODELS

Table 7 lists the various submodels discussed in this report. These models are presented in the following format:

- block diagrams revealing submodel interactions and anticipated effect on the four fundamental LEM variables (pathlengths, hydraulic conductivities, fluid potentials, and effective stress)
- logic diagrams detailing the components of each submodel
- data requirements
- desired output.

Figures 6a through 6e are block-tree diagrams that illustrate submodel interaction. A tabular listing of the submodel interactions is shown in Table 8. The components of each submodel will be highlighted in the remainder of this report.

The information presented is based upon a hypothetical site in the Columbia Plateau Basalt region of Washington State. Figure 7 shows the geographic characteristics of this Pacific Northwest region. Figures 8 and 9 present the general geomorphology and cross sectional characterization of the hypothetical site. It is assumed that the repository site encompasses 10 km^2 and is surrounded by a 100 km^2 sensitivity zone. For the purpose of this report, the hypothetical site is assumed to be beneath Battelle, Pacific Northwest Laboratories. This hypothetical site was chosen because of the relative amount of data available and currently being generated by the Basalt Waste Isolation Program, and also because of the research staff's proximity.

TABLE 7. Submodels

Climate	Sub-basalt basement faulting
Continental glaciation	Shaft seal failure
Alpine glaciation	Undetected features
Sea level fluctuations	Magmatic activity
Geomorphic events	Meteorites
Deformation

FIGURE 6a. Submodel Block Diagrams

FRACTURING

FIGURE 6b. (contd)

MAGMATIC ACTIVITY

FIGURE 6c. (contd)

METEORITES

FIGURE 6d. (contd)

EXAMPLE UNDETECTED FEATURES

FIGURE 6e. (contd)

FIGURE 7. The Columbia Plateau (RHO-BWI-78-100)

CLIMATE

The prediction of the potential future climatic states for the North American Continent is based on the Milankovitch Theory of the earth's orbital perturbations and the random, superimposed ash loading of the atmosphere. Other factors may also affect climatic conditions. However, for the purpose of this model, it is assumed that these factors will either effectively remain constant during the next 10^6 years (e.g., land-sea distribution), or are included as a random "noise" factor (e.g., sunspot activity or a CO_2 -induced "greenhouse effect") in the model.

FIGURE 8. Major Topographic Features (RHO-BWI-78-100)

FIGURE 9. Simplified Cross-Section of Study Area

TABLE 8. Submodel Interaction

PATH LENGTH# 1	CONT. GL	FAULT	FOLD	EROSION	MAGMA	ALP. GL.	UNDETECT	SEA	CLIMATE	METEOR	SHAFT
CONT. GL	0	0	1	1	1	1	0	1	0	0	1
FAULT	0	0	1	0	0	0	0	1	0	0	1
FOLD	0	0	0	0	0	0	0	1	0	0	1
EROSION	0	0	0	0	1	0	0	1	0	0	0
MAGMA	0	0	0	1	0	0	0	1	0	0	0
ALP. GL.	0	0	0	1	1	0	0	1	0	0	0
UNDETECT	0	1	1	0	0	0	0	0	0	0	1
SEA	0	0	0	1	1	0	0	0	0	0	0
CLIMATE	1	0	0	1	0	1	0	0	0	0	0
METEOR	0	0	0	0	1	0	0	1	0	0	1
SHAFT	0	0	0	0	0	0	0	0	0	0	0

Four climatic states are considered:

- 1) Interglacial: global climates not significantly different from the present, or possibly warmer.
- 2) Temperate Interstadial: global climates cooler than at present, but generally mild.
- 3) Interstadial: global climates significantly cooler than at present; northern mid-latitudes close to glacial mode.
- 4) Stadial (Full Glacial): global climates harsh and cold; northern midlatitudes largely glaciated.

Interglacial climatic states will not initiate or support ice sheets of continental magnitude in the present temperate regions. Temperate interstadial and interstadial states will support an already established ice sheet, but will not initiate one unless some external triggering phenomena, such as particulate loading of the atmosphere by volcanic eruption, occurs. Stadial climatic states will initiate glaciation.

Climate affects regional precipitation, evapo-transpiration, infiltration, river runoff, glaciation, and hence, such things as sea level, erosion and sedimentation rates. The requirements for this submodel mainly focus on volcanic dust loading of the atmosphere and the earth's orbital parameters. On the time scale of 10^4 - 10^5 years, the pattern of solar radiation reaching the earth's surface is assumed to be dominant over other natural variables driving the temporal variations in the North American climate.

Milankovitch Theory

The difference between the present average annual surface air temperatures and that consistent with the most recent glacial episode (18,000 years before the present) is estimated to be 5 to 6°C (Kukla).^(a) On the time scale of 10^0 - 10^2 years, climate is modified by the changes in atmospheric turbidity. Such increase was observed to cause a decrease in the insolation reaching the

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

ground and, consequently, in the air surface temperatures. Natural fluctuations of atmospheric turbidity are related to volcanic activity (which is in principle random), to the changing areas of deserts and semideserts, and to the varying vigor of atmospheric circulation. On the longer time scales (10^4 - 10^5 years), the variation in the three principle elements of the earth's orbit around the sun are considered responsible for a considerable part of natural climatic variance. Future magnitudes of surface temperatures may be estimated by combining the three conventional measures of the earth-sun orbital elements in an equation whose solution closely correlates with the available paleoclimate (historical) evidence of the last 250,000 years.

The three variables are: 1) the obliquity, or tilt of the earth's rotational axis relative to the plane of the ecliptic (E), 2) the eccentricity or the measure of the sun's departure from the geometric center of the ecliptic (e), and 3) the longitude of the perihelion or the angular distance to the point of the Earth's closest approach to the sun from the autumnal equinox (W).

The periodicities of these three variables are: $E = 40,000$ years, $e = 92,000$ years, and $W = 21,000$ years. With the proper phase relationships, the maximums associated with the various harmonics will result in a dominant 100,000 year periodicity. The major feature of the ice ages for the last 600,000 years is this 100,000 year periodicity .

With harmonic analysis, it is possible to compute a relative Astronomic Climatic Index (ACLIN). The values of ACLIN over the last 10^6 years and the projected values over the next 10^6 years are shown in Figure 10. Correspondence of ACLIN with radiometric data on coral reefs is shown in Figure 11. The calibration of the ACLIN index with such radiometric data and with the deep sea record resulted in the following relationships:

- A full interglacial climate lasted for about 10,000 years and was centered at ACLIN peaks of 4.3. Global climates were not significantly different from present or were warmer.
- Temperate interstadial climates lasted for about 8000 years and were centered at ACLIN peaks of 3.6. Global climates were cooler than at present but generally mild.

FIGURE 10. Astronomical Climatic Index (ACLIN) as a Function of Time (modified by Kukla). (a) (Outlined area detailed in Figure 11. Present time at year = 0, past = negative numbers, future = positive numbers.)

(a) This figure is based on research done by Kukla, which is reported on in part in this document

FIGURE 11. ACLIN for 122,000 B.P. (Before Present) to 60,000 A.P. (After Present). (a) (Correlated with past sea levels based on radiometrically-dated coral reefs in Barbados and New Guinea. Detailed from Figure 10.)

(a) This figure is based on research done by Kukla, which is reported on in part in this document.

- Moderate or cold interstadial climates lasted for about 4000 years and were centered at ACLIN highs of 2.5. Global climates were significantly cooler than at present. Northern mid-latitudes are in or close to a glacial mode.
- Stadial climate for all other time, with global climates harsh and cold, northern mid-altitudes largely glaciated (Kukla).^(a)

Figure 12 presents the future gross climatic states as predicted by the Milankovitch theory on the assumption that there are no outside perturbations. The next section discusses external triggering phenomena, such as major volcanic eruptions, which can significantly affect this curve.

Dust Loading of the Atmosphere

Research has suggested that large amounts of ash introduced into the atmosphere during periods of increased volcanic activity may have lowered the average temperature of the earth's surface enough to induce a glacial episode if the existing climatic conditions were such that an unstable or sensitive climatic state already existed. Budyko (1968) estimates that 50-100 great explosive eruptions during a single century could individually reduce the direct solar radiation to the surface by 10 to 20% for a few years lowering the average air temperature 1 to 3°C. Using geologic evidence, Lamb (1970) suggests that the frequency of great eruptions during the last few centuries is a conservative estimate of the average frequency during the entire Quaternary period (about 2 million years). For the purpose of this study, it is assumed that the frequency of major volcanic eruptions during the last four or five centuries will continue for the next 10^6 years. Figure 13 shows the stratospheric dust loading curve for the last 120 years.

Lamb's (1970) study of the chronology of volcanic eruptions from 1500 to 1968 reveals that 25 individual eruptions were greater than or equal to the 1883 eruption of Krakatoa. Over this time span, 50 additional eruptions occurred ranging individually in size from 10 to 80% of the level of Krakatoa. Lamb

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

FIGURE 12. Future Natural Climate vs. Time as Predicted From ACLIN Without Ash Load Perturbations

considers these 75 individual eruptions to be large enough to have significant effects on the climate. Although a probability density function might be generated that would reveal the probability of an eruption as a function of its atmospheric dust loading potential, the following will be assumed initially: 1) the frequency of eruptions equal to or greater than Krakatoa will be estimated at 5 per 1000 years, 2) ten percent or less of these eruptions will be sufficient to switch the gross climate state to a lower grade, that is, for example, interglacial to temperate interstadial or interstadial to stadial, 3) once in the stadial state, glacial growth will be self-perpetuating until the climate returns to interstadial, and 4) the probability estimate of $5 \times 10^{-3} \text{ yr}^{-1}$ for a volcanic dust-induced glaciation will be constant for the next 10^6 years. This analysis assumes "worst case" conditions and recognizes that an individual Krakatoa-sized eruption may not be sufficiently large to trigger a glaciation.

It is of some interest to note the manner in which dust in the atmosphere results in lower temperatures. Dust particles in the atmosphere absorb both incoming solar and outgoing terrestrial radiation, thus resulting in the warming of the dust-polluted level. However, reflection and scattering which have an opposite effect tend to be dominant over absorption. The amount of reflection and scattering depends on the wavelength of the radiation and on the size of the dust particles. If the ratio of wavelength to the size of the particles is low, reflection and scattering is high. The average diameter of the dust particles in the troposphere is 1.85 microns, which is greater than the wavelength of the largest incoming portion of solar radiation, but less than that of reradiated terrestrial energy by a factor of six or seven (Humphreys 1940). Thus, in effect, the dust particles screen out the incoming solar radiation but allow the terrestrial radiation to pass through out into space. The net result is a general cooling trend. Such a worldwide impact is believed to have followed the Krakatoa eruption in 1883 for a period of a few years (Lamb 1970).

Summary

Gross future climate conditions in North America are being predicted by a model based on the Milankovitch theory of orbital perturbations. Following common paleoclimatic usage, four levels of severity are arbitrarily recognized.

FIGURE 13. Atmospheric Dust Load (Bullard 1976)

When the orbital parameters are in transitional mode, terrestrial factors, such as exceptionally frequent volcanic eruptions and/or man-made particulate pollution, could induce a shift into the cooler climatic state and thereby initiate major alpine and/or continental glaciations. In addition to glacial activity, climate is largely the driving force for precipitation, groundwater, recharge, runoff, and sea level fluctuations. The general logic flow for the climate submodel is presented in Figure 14. Variable definitions are given in Table 8, and the input requirements and available data are presented in Table 9.

PRECIPITATION, RUNOFF, AND INFILTRATION

Precipitation, infiltration, evapotranspiration, base level flow, and surface water flow are determined to a major extent by climate, distance from large water bodies, and the general topography. Precipitation can be shown to affect erosion, flooding and sedimentation, groundwater flows, and water table elevations.

FIGURE 14. Climate, Submodel 1

TABLE 9. Climate Submodel Data(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
CLIMATE STATE 1 AS A FUNCTION OF TIME	CLIMATIC STATE 1	BASED ON ORBITAL PARAMETERS
PROBABILITY OF RANDOM PERTURBATION CHANGING CLIMATIC STATE	$5 \times 10^{-3} \text{ YR}^{-1}$	PROBABILITY OF A MAJOR VOLCANIC ERUPTION CAPABLE OF PERTURBING THE CLIMATE
DENSITY CURVE GIVING FRACTION OF PRECIPITATION FOR EACH CLIMATIC STATE	DENSITY	cm Yr^{-1}
DENSITY CURVE GIVING FRACTION OF PRECIPITATION RETURNED BY EVAPORATION FOR EACH CLIMATE STATE ¹	DENSITY
PERCENTAGE OF RAIN FALL GOING TO RECHARGE FOR EACH THE CLIMATIC STATE ¹		
FACTOR TO CHANGE PRECIPITATION TO RIVER FLOW M^3S^{-1}		
CHANCE FOR UPLIFT TO WEST		
CHANCE FOR LOCAL UPLIFT		
CHANCE FOR UPLIFT TO EAST		
FACTOR USED TO CHANGE PRECIPITATION DUE TO UPLIFT IN EAST		
FACTOR USED TO CHANGE PRECIPITATION DUE TO UPLIFT IN WEST		
FACTOR USED TO CHANGE PRECIPITATION DUE TO LOCAL UPLIFT		

1) INTERGLACIAL, 2) TEMPERATE STADIAL, 3) INTERSTADIAL, 4) STADIAL

(a) Data is under development and not available at this time.

Precipitation

The probability of the average annual precipitation, I , changing by a factor over its present level is defined as:

$$I = F(c, d_m, r)$$

where I is a function of:

c = climatic state

d_m = downwind distance from a large body of water

r = regional topographic factor (Kukla 1979).

The relationship between climatic state and precipitation was obtained from published data dealing with the climatic interpretations of Pleistocene (past 1 million yr) snowlines and lake levels. In addition, past precipitation has been estimated indirectly from paleoecological vegetation analyses based on the pollen record. The reconstructed departures of Pleistocene annual temperature and precipitation from present local equivalents are presented in Table 10 and Figure 15. From these data, curves can be generated relating precipitation levels to the Astronomic Climate Index (ACLIN). However, as shown in Figure 16 these curves, which were generated with test data, are valid only for fixed d_m and r factors. It may be possible to estimate the incremental precipitation that might be expected either by decreasing the distance to a large water body or changing the topographic factor.

Kukla's data^(a) show that the estimated difference between the present and the full glacial precipitation is, generally, within the ranges of recent year-to-year variability as recorded in the western United States during the last 90 years. Thus, he concludes that even the expected extremes do not significantly differ from the recently observed short term variations. In other words, if the topography and distance to large water bodies remain relatively constant, the available precipitation data indicate that a two- to four-fold increase in precipitation should be considered conservative.

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

TABLE 10. Late Pleistocene Climate Reconstructions Overview of Published Data

Site	Author & Reference	Present Annual Mean		Reconstructed Pleistocene (Annual)				Difference	
		Precip (mm)	Temp (C)	Precip (mm)	Temp (C)	Evap (mm)	Runoff (mm)	Precip (mm)	Temp (C)
Lake Lahontan	Broecker et al. (21)	200		460		960		+260	-5
Lake Lahontan	Galloway (rt)	180		160				-20	-(10-11)
Lake Lahontan	Mifflin et al. (47)	155		280 ^a		940 ^a	170	+125 ^a	-2.75
Lake Lahontan	Benson (re)	155		185-		150-		+(30-230)	-(10-15)
Extreme N.W. Nev.	Mifflin et al.	295		535				+240	-2.75
Lake Bonneville	Galloway (rt)	200		185				-15	-(10-11)
Spring Valley Lake, Nev.	Snyder et al. (te)	300		510		790		+210	-(4.5-5)
Spring Valley Lake, Nev.	Galloway (rt)	230		185				-45	-(10-11)
Spring Valley Lake, Nev.	Mifflin et al. (47)	150		370 ^a 425 ^b		-13%		+220 ^a +275 ^b	
Basin, Nev.	Mifflin et al. (47)	200		370		10%		+170	-2.75
	Leopold (10)	360		510		740	125	+150	-(6-7)
	Galloway (45)	320		275		620		-45	-(10-11)

TABLE 10. (contd)

Site	Author & Reference	Present Annual Mean		Reconstructed Pleistocene (Annual)				Difference	
		Precip (mm)	Temp (C)	Precip (mm)	Temp (C)	Evap (mm)	Runoff (mm)	Precip (mm)	Temp (C)
San Augustin, N.M.	Galloway (45)	290		265				-25	-(10-11)
Lake Cochise, Ariz.	Galloway (45)	280		260				-20	-(10-11)
ano Estacado Lakes, N. Texas	Reeves (51)	480		480		1100		0	-5
ano Estacado Lakes, N. Texas	Reeves (52)	480		870		1080		+390	-5
High Plains Lake Region, W. Texas	Reeves (44)	365		740			760	+375	-10
American S.W.	Brakenridge (48)					REDUCED	INCREASED	0	-(7-8)
arles Valley, Calif.	Smith (9)	95		95-290		175	+300-600%	0-+195	
ner Pass Sierra Nev. Mtns	Curry (46)	1020 ^c		1200-2700 ^c		100 ^d		+180-1680 ^c	

KEY: * value used by author
 a Lake Basin
 b Drainage Basin
 c Snowfall water equivalent only
 d Snowmelt water equivalent only

All Values Are Rounded

FIGURE 15. Calculation of Difference of Summer Precipitation in mm. Day⁻¹ Between 18,000 Years BP to Present Day, by Members of CLIMAP Group. (map of North America supplied by T. Hughes)

FIGURE 16. Test Density Curves Relating Precipitation to the Climatic Index

Unfortunately, the validity of the reconstructed data is limited and the possibility of larger increments can not be totally dismissed. For example, in his discussion on glaciation, Bull^(a) concludes that the ablation or melting of ice during the retreat phase of the Laurentide ice sheet apparently cannot alone account for the inferred flow rates in the Mississippi River. Ice sheet ablation might result in an annual river flow on the order of ten times the present volume, but measurements on the changes in the stable oxygen isotope ratio of cores from the Gulf of Mexico allude to substantially higher river discharges to account for the four to eight percent dilution of the Gulf waters. Bull asks the question: Was the rainfall in the drainage basin much greater during the ice ablation period than now, even though it appears the climate was drier during the full stadial climate periods? Paleoclimatic evidence indicates that this indeed might have been the case in the Midwest. For example, spruce forests flourished over the Nebraskan sand dunes during

(a) Bull's work is reported in part in this report. A summary of his research has been published (Bull 1979).

deglaciation times. The area was arid during full glacials and is also arid today. A similar situation may have occurred in the Columbia Plateau. Regardless of the uncertainty, until more evidence can be gathered on paleodrainage systems, precipitation, and runoff, the two- to four-fold increase in precipitation will be assumed for the areas draining the area of the Columbia Plateau.

Before expending additional effort characterizing probability density curves for precipitation, it is prudent to consider how a four-fold or even a ten-fold increase in precipitation might affect the aquifers and surface drainage systems in the vicinity of the repository. Qualitative relationships between rainfall and recharge, and recharge and hydraulic gradients are shown in Figure 17. The percentage of the precipitation occurring as base flow (groundwater) and that occurring as surface runoff must be estimated. To lend perspective, the average annual recorded Columbia River flow just north of Hanford is $3.43 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ with maximum possible flows of $3.96 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ (Corps of Engineers 1950). If precipitation increased by a factor of four with no change in runoff ratio, then the average flow might be about $1.36 \times 10^4 \text{ m}^3 \text{ s}^{-1}$. Results of hydrograph examinations indicate that the mean annual flow ranges from 25 to 40% of the peak flow (Leopold, et al. 1964). Thus for a four fold increase in precipitation, a peak flow of $(1.36 \times 10^4 / 0.25)$ or $5.66 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ might be possible for the Columbia River. This estimate is independent of glacial activity and does not take account of changes in factors such as evapotranspiration, or ground water recharge rates. Additionally, during stadial conditions river flow and ground water recharge may be limited to three months a year with consequent increases in flow during peak conditions. The potential consequences associated with such a flow are discussed in the section on flooding, erosion, and sedimentation.

Obviously such factors as surface retention, vegetation cover, evapotranspiration, and infiltration capacity of the soil are important with respect to high resolution studies and real world conditions, but for this generic study the following assumptions are made:

- 1) increased precipitation will not increase deep aquifer flow conditions in the vicinity of the site to any significant degree, unless the water is under pressure caused by the formation of a lake or glacial ice over a large portion of the recharge area

FIGURE 17. Possible Relationships Among Rainfall, Recharge, and Regional Hydraulic Gradients (Davis 1979)

- 2) nearly all precipitation (80% will be available for surface flow and associated river erosion, flooding, and sedimentation effects. The assumptions are based on the evaluation of paleoclimatic indicators from the Columbia Plateau.

There is no evidence of a significantly denser vegetational cover in the area during Late Pleistocene. On the contrary: migrating loess and sand dunes point to a rather bare surface. In such conditions the extra precipitation has to come either as torrential rains during the growing season or as snow or rain during winter. In both cases the surface permeability had to be low: in summer the soil was dry and in winter frozen. It is probable that an

impermeable permanently frozen ground (permafrost) existed during peak stadials over much of the Columbia Plateau.^(a)

Summary

Existing data indicate a two to four fold maximum increase in precipitation for the area in question. Eighty percent of this water will be assumed to augment surface drainage systems. Recharge to the unconfined aquifer at the site will be increased by a factor of three to five or more since evapotranspiration rates will be subdued during the cooler, wetter climate. This may affect the water table elevation but should have no significant effect on a hydraulically isolated 300-1000 m deep repository. The deeper aquifer will be unaffected by an increase in precipitation unless a lake or ice sheet is superimposed over the major part of a recharge area. The model will vary the precipitation in response to temporal changes in the Astronomic Climatic Index (ACLIN), major topographic changes, and changes in the distance to the ocean. Maximum increases in precipitation will increase the volumetric flow in the Columbia to approximately $1.42 \times 10^4 \text{ m}^3 \text{ s}^{-1}$. Peak flows of short duration, however, will be assumed to reach $5.66 \times 10^4 \text{ m}^3 \text{ s}^{-1}$. Precipitation, runoff, and infiltration are a part of the climate submodel shown in Figure 15. Table 11 summarizes input requirements and current data availability.

There is the possibility that future climatic conditions may cause the onset of renewed worldwide continental and/or alpine glaciation. It is therefore necessary to anticipate the consequences of such events. These consequences are addressed in the continental and alpine glaciation submodels.

CONTINENTAL GLACIATION

Analysis of the effects of continental glaciation in the Columbia Plateau region is somewhat complicated, largely because there is no direct evidence supporting the existence of an ice sheet ever covering the plateau. Some observations of the climatic history of the last million years indicate that for only about 10% of the time was the climate as warm or warmer than the

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

TABLE 11. Age of Glacial Terminations - Summary of Published Estimates^(a)

Termination	Broecker and Van Donk 1970	Kukla 1970	Shackleton and Opdyke 1973	Kukla 1975	Ruddiman and McIntyre 1976	Hays, Imbrie and Shackleton 1976	Average (10 ³)
I	11,000	10,500	13,000	11,000	13,500	10,000	11.5 -1 +2
II	127,000	128,000	128,000	128,000	127,000	127,000	128.0 -1 +0
III	225,000	243,000	251,000	245,000	220,000	247,000	240.0 -20 +10
IV	300,000	333,000	347,000	335,000	315,000	336,000	330.0 -30 +20
V	380,000	370,000	440,000	415,000	380,000	425,000	400.0 -30 +40
VI		485,000	502,000	480,000	455,000		480.0 -25 +20
VII		600,000	592,000	575,000	515,000		570.0 -55 +30
VIII			647,000	635,000	605,000		630.0 -25 +20
IX		726,000	706,000	700,000			710.0 -10 +15
X		845,000	782,000				810.0 -30 +35

(a) This information was compiled by Kukla, and reported in this document.

present. Also, the past record shows that no interval of global climate with temperatures as warm or warmer than present lasted uninterruptedly for more than about 1.1×10^4 years. Paleoclimatic studies suggest that up to ten full glacial cycles might be expected in the next 10^6 years.

The separation between the repository site and the edge of an ice sheet at its maximum extent is an important variable. Past advances will be used to estimate future advances, with the one important exception discussed below. Similarly, the separation between the major aquifer recharge areas and the ice sheets must be estimated. If the ice should overrun the repository site and/or the recharge areas, pressurized vertical recharge to unconfined and/or confined systems should be assumed. The anomalous pressure will depend on the estimated ice thickness. If the ice sheet comes within approximately 200 km of the site, flexural stresses at and beyond the edge of the ice should be estimated. The current computer code relies on a straightforward mechanical loading model. The probability of fracturing and/or shearing of pre-existing joints beyond the immediate edge of a sheet is calculated as a function of the computed radial and tangential flexural stresses. If fracturing is assumed, fracture spacing, length, and depth are selected from supplied probability density distributions. Associated permeability increases are computed based on an idealistic parallel plate model, described later in a section on deformation.

The rate and amount of ice scouring is selected from a similar distribution. Subsidence will depend primarily on the ice thickness, since it will be assumed that the mantle will isostatically accommodate adjustments immediately and completely. Potential major river flows will be estimated based on ice sheet ablation rates, ice dam failure frequency and magnitudes, and normal flow as determined by the climate submodel. These values will in turn input into the geomorphic events submodel. The following paragraphs elaborate on many of the components of the continental glaciation submodel.

Ice Sheet Advancement and/or Accumulation Rates

The climate model specifies several glacial episodes occurring at frequencies similar to those shown in Table 11. However, the delay or lag time between the onset of continental ice accumulation in Canada and the possible

arrival or buildup of ice at or near the Columbia Plateau must still be estimated. The time history of ice accumulation in any given area is a complicated function of glacial velocity and net snow accumulation along the length of the glacier.

With respect to vertical accumulation of ice an estimated rate of 0.6 m yr^{-1} seems to be the upper limit (Weertman 1964, 1976). However, he concludes that this is somewhat high, especially near the outer margins of the ice sheet. He suggests that the vertical accumulation rate ranges from 0.03 to 0.6 m yr^{-1} , once a permanent base has been established.

Very little information is available on ice advancement and retreat. In general, advancement rates are considered to be slower than recession rates. Some estimates on ablation of ice during the retreat phase of the Laurentide ice sheet are available. The southern limit of the large Erie Lobe was estimated to retreat across Ohio from its southernmost extent near Chillicothe to the position of Lake Erie, a distance of about 450 km, in about 3×10^3 years. This involves a recession rate of 0.15 km yr^{-1} (Goldthwait et al. 1965). An estimate for the later stages of ablation is 0.24 km yr^{-1} (Brotchie and Silvester 1969). Rates from 0.1 to 0.4 km yr^{-1} will be used in the simulation model for the retreat phase. Average advancement rates are likely to be considerably lower, but to be conservative, the similar rates will be used.

Maximum Southerly Extent of Continental Ice Sheets

The maximum volume and hence extent of continental glaciations may be approximately determined from sea-core records of oxygen isotope records, which may be interpreted in terms of ice volumes. The ice-volume record over the last 6×10^5 years shows a general trend towards increased extent of continental ice sheets with time (Shackelton and Opdyke 1964). Thus the argument can be made that future glacial advances may extend beyond the southern border defined by the Kansan advance, which is generally considered to be the maximum Pleistocene advance. The extent of this advance is shown in Figure 18.

The team of consulting glaciologists for WISAP suggests that areas likely to be affected by ice sheets in the future are the same areas that have been glaciated in the past. However, they state that there is a possibility of an

FIGURE 18. Glaciated Areas of the Coterminous United States (After U.S. Geological Survey)

additional 400-600 km southerly advance beyond that of the Kansan stage in areas where glaciation was not predominantly controlled by topographic features.

The above estimate of an additional 400-600 km of glacial advance is based on the present understanding of glaciation in the midcontinent region of the United States. There may, however, be differences in glaciation between the midcontinent and Pacific Northwest. Because of this possibility, the estimate should be viewed with a degree of caution. Also, there is no evidence to indicate that the Pasco Basin has ever been glaciated in the Past.

The increasing severity hypothesis (additional 400-600 kilometer advance) discussed previously results in a 10^{-7} yr^{-1} probability of ice loading in the Basin during any future glacial episodes. It is estimated that there is a 10^{-7} yr^{-1} probability for ice loading directly over the site, and a 10^{-5} yr^{-1} probability for ice loading on some of the major recharge areas servicing the aquifers of the Pasco Basin.

Isostatic Subsidence and Rebound

As a region becomes loaded with ice, isostatic adjustments in the upper mantle result in a subsidence of the land surface. When the load is removed, rebound occurs similar to that being experienced in Canada and Scandinavia today. For an ice to mantle rock density ratio of 1:4, an ellipsoidal ice sheet profile (4.5 km thick, 1500 km radius), and a viscous flow model for mantle materials, computations indicate that between 1000 and 1500 meters of subsidence would be possible under the center of an ice sheet (Brotchie and Silvester 1969). However, crustal subsidence and rebound are expected to have no significant effect on subsurface permeabilities, even though shallow surficial cracking (10-15 m deep) may develop. This is because more pressure effects should result in an essentially constant effective stress at depth. Even isostatic rebound with uplift rates of 2 cm yr^{-1} in some case (Walcott 1972) should have no serious effect on the subsurface geohydrological properties.

Induced Stress and Crustal Fracturing

Some concern is being expressed concerning the flexural stresses induced just beyond the edge of large ice sheets in areas that are not being depressed

but may be experiencing minor uplift (bulging). Table 12 and Figure 19 illustrate the deflections and stresses in the crust associated with an ice sheet of parabolic profile, of central thickness 3,000 meters and radius of 1450 kilometers. The variation of the radial flexural stresses, the tangential flexural stresses, and the shear stresses are given as a function of distance from the center of the ice sheet. Of particular interest is the transition from compressive to tensional stresses and then back again to compressive stresses as one moves out radially from the periphery of the ice sheet.

The radial stresses, on the order of 10 bars, may be sufficient to fracture crustal material, especially if pre-existing zones of weakness, e.g., joints, fissures, and faults are present. Peltier and Andrews (1976) and Weertman (1976) conclude in similar studies that the induced stresses may be in the range of 10-250 bars, and fracturing, if it occurred, would be most intense near the periphery of the ice. Weertman suggests that fracturing might be the result of creep rupture instead of brittle failure. Displacement on faults along the coast of Maine, the Finger Lakes in New York, and areas associated with the Great Lakes are cited as examples of this phenomenon. Preferential erosion might occur subsequent to such fracturing. No such ice induced fracturing has been reported in the Columbia Plateau region. The possibility and effects of ice-induced fracturing are currently being investigated by a WISAP consultant.

TABLE 12. Crustal Stresses Associated with Large Ice Sheets (Bull 1978)

Distance from center, km	0	290	580	870	1160	1450	1500	1600	1700	1800
Deflection (m)	802	769	673	513	288	23	4	4	-1	0
Flexural stress, radial (MPa)	-1.6	-1.5	-1.5	-1.4	-1.1	10.3	7.9	1.2	-0.4	-0.2
Flexural stress, tangential (MPa)	-1.6	-1.5	-1.5	-1.5	-1.6	-1.5	1.3	0.3	-0.1	-0.1
Shear stress (MPa)	0.0	0.0	0.0	0.0	0.0	0.1	-0.7	-0.4	-0.0	-0.0

FIGURE 19. Example of Stress Conditions Beyond the Edge of an Ice Sheet

The radial stresses, on the order of 10 bars, may be sufficient to fracture crustal material, especially if pre-existing zones of weakness, eg, joints, fissures, and faults are present. Peltier and Andrews (1976) and Weertman (1976) conclude in similar studies that the induced stresses may be in the range of 10-250 bars, and fracturing, if it occurred, would be most intense near the periphery of the ice. Weertman suggests that fracturing might be the result of creep rupture instead of brittle failure. Displacement on faults along the coast of Maine, the Finger Lakes in New York, and areas associated with the Great Lakes are cited as examples of this phenomenon. Preferential erosion might occur subsequent to such fracturing. No such ice induced fracturing has been reported in the Columbia Plateau region. The possibility and effects of ice-induced fracturing are currently being investigated by a WISAP consultant.

The region considered susceptible to fracturing is within 200 km of the edge of any large ice sheet. This zone appears to be relatively independent of the ice sheet radius. The prior geologic setting is of paramount importance. In the Columbia Plateau area, the perceived lack of such features must

carry considerable weight. However, the possibility of the ice advancing further in the future than in the past cannot be dismissed. In addition, stress relaxation may be manifested as small scale shear deformation on zones of weakness (eg, joints) rather than as massive fractures.

Incremental Permeability Associated with Ice Induced Fracturing

The research team has not made an estimate of associated fracture permeabilities. This is a very important variable and will require careful consideration. A discussion of general fracture permeability is given in a subsequent section on deformation.

Ice Scouring

A large number of ice scouring rate estimates are available in the literature (White 1972, Matthews 1975, Ruddiman 1977). The estimates span the range of 5 to 150 m per million years. The WISAP consulting team suggests a generic range of 30 to 300 m per million years during glacial stadials, although the higher end of the scale may be more pertinent to regolith (brecciated, weathered) material than to bedrock.

Sugden (1976) concludes that deep selective linear erosion can occur near the ice sheet margin by ice streams where the ice base is locally thawed and suggests that the Finger Lakes were formed in this manner. It should be noted that ice scouring occurs mainly during the advancement stage of glacial activity. During recession, the zone around the periphery of the ice should be depositional in nature although erosion, which is largely related to basal ice velocity, will still continue at interior points of the ice sheet base. Selective linear erosion, erosion by glacial-fed streams and massive flooding associated with ice dam failures may be the exception to this rule. Some suggested rates are presented in subsequent discussion of the geomorphic events submodel.

Pressurized Recharge

Figure 20 illustrates a mass of ice superimposed on a repository sited in a basin and/or ice superimposed on a major recharge area of a deep aquifer underlying the basin. The recharge areas are presumed to be closer to major topographic highs and therefore more susceptible to alpine glaciation. As mentioned previously, the estimated probabilities for loading of the basin and

WET-BASED GLACIAL RECHARGE

FIGURE 20. Conceptualization of Glacial Recharge of Ground Water

recharge areas are 10^{-7} per year and 10^{-5} per year respectively. Calculating the expected time ratio of continental ice loading to ice free conditions, the cumulative probability values for 10^6 years are estimated as 0.10 and 0.90, respectively.

A possible point of concern is how such ice accumulation might perturb the subsurface hydrologic regime. If the ground beneath the glacial ice is frozen, recharge to the aquifers will effectively cease. If, on the other hand, the geothermal heat flow and/or frictional heating are such that wet-based glacial conditions are supported, then between 2 and 5 centimeters per year of water will be available for recharge on a continual basis.^(a) This water will be under considerable pressure because of the weight of the ice column above it. In general, this factor will be 0.09 bars per meter of ice. The most significant unknowns are the variations in the geothermal heat flow and frictional heating and their relationship to the thawing of the glacier base.

Bull^(a) reports that the average geothermal heat flow is 1.2×10^{-6} cal/cm² sec⁻¹ but suggests that this value be doubled because much of the Cordilleran ice sheet was over a relatively active tectonic area. Frictional heating might result in an additional factor of two increase in heat available to basal melting. The research team concludes that at some point in its life, every area of the ice sheet will be wet based, and therefore pressurized recharge is a near certainty at some point in time if an area is ice covered. At the repository site, this would be manifested as recharge to the unconfined aquifer and also as a change in the elevation of the water table relative to the land surface.

At the recharge areas of the shallow and deep confined aquifers, pressurized recharge might occur if the area was totally ice covered and if ice toe drainage was not exceptionally high. For example, if the ice were 500 meters in thickness, the pressurization would be approximately 45 bars, or 45 times as great as it is presently. This might have an effect on the flow conditions

(a) Bull's work is reported in part in this report. A summary of his research has been published (Bull 1979).

in the aquifers associated with the repository. The increased head, however, will not necessarily increase the hydraulic gradients in the aquifers. The extent, magnitude, and direction of these gradients are difficult to predict, but are critical to the model. It is interesting to speculate on the potential consequences associated with spatially differing recharge areas for the different aquifers. It may be possible to enhance the fluid potentials and flow velocities in one aquifer and not affect a deeper or shallower aquifer.

One of the strongest arguments for such pressurized recharge and total saturation of the ground is glacial sliding, which can only occur under wet-based and saturated conditions.^(a) Since considerable evidence for sliding is available, recharge and saturation appear to be a near certainty for at least a part of the time an area is ice loaded. Similar recharge and saturation would occur if an area were flooded by a lake. The primary difference between the respective recharge pressures would be due to the density difference between ice and water. Beneath the lake, the pressure for recharge would be about 0.11 bars per meter of water depth and 0.09 bars per meter of ice thickness for wet-based glaciers.

Drainage of Meltwater

The dramatic effects of large and even catastrophic discharges of glacial meltwater is in no place better demonstrated than in the scablands region of the Pacific Northwest. A subsequent section is devoted to a discussion of Columbia River flows from current levels, up to levels associated with Missoula-type flooding which resulted from the failure of ice dams impounding up to $2 \times 10^3 \text{ km}^3$ of water. Baker (1973) estimates that Missoula flood waters passed through Wallula Gap at a rate of approximately $9.06 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. Erosion, sedimentation, lake impoundment and potential river course alterations will be covered in this later section. To lend perspective, Figure 21 presents some estimated annual average Columbia River flows for the case of:

(a) Bull's work is reported in part in this report. A summary of his research has been published (Bull 1979).

*RATIO OF ESTIMATE FLOW TO THE MEASURED 1978 ANNUAL AVERAGE ($2.32 \times 10^3 \text{ m}^3 \text{s}^{-1}$)

FIGURE 21. Estimated Annual Average Columbia River Flows

1) ice ablation (melting) with today's precipitation, 2) ice ablation with a four- to five-fold increase in precipitation, and 3) various levels of ice dam failures.

Summary

In summary, should continental glaciation occur in the future, it could potentially affect: subsidence, crustal fracturing, material scouring, pressurized recharge of aquifers, surface water flow, selective stream erosion, and sedimentation. In this model, the frequency of continental glaciers is determined by the temporal variations in climate. Future southerly advance of large ice sheets will be based on past advances, but may potentially exceed

the Kansan advance by 400 to 600 km. The Columbia Plateau in eastern Washington has not been significantly glaciated in the past. However, there is a probability of 10^{-7} yr^{-1} that the Pasco Basin will be ice loaded and a 10^{-5} yr^{-1} probability that a major aquifer recharge area will become ice loaded during the next 10^6 years.

Subsidence and isostatic rebound effects are not considered to be significant. However, some potential exists for flexural stress-induced fracturing within a 200 km zone of the edge of a large ice sheet. Such fracturing has apparently been observed in the midwest and the eastern United States; however, no such phenomenon has been reported for the Columbia Plateau. Ice scouring rates are in the range of 30-300 m per million years. Pressurized recharge would be at 0.09 bars m^{-1} for ice and 0.11 bars m^{-1} of depth for water. Approximately 2-5 cm yr^{-1} of water would potentially be available for pressurized recharge beneath a wet-based glacier on a continual basis.

The drainage of meltwater from glaciers and/or ice dam failures can occur in the Columbia River as any volumetric flow up to $9.06 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. This maximum is associated with Missoula-type flooding. The breach of a repository within a basalt layer requires the creation of a sufficiently high permeability pathway and sufficiently high fluid potential differences along the path. Figure 22 presents the logic flow for the submodel. Table 13 presents data requirements and availability.

ALPINE GLACIATION

Several of the potential consequences of alpine glaciation are similar to those associated with continental glaciation. A differentiation has been made in this report because mountain glaciers from eastern and western topographic highs have approached the Columbia Plateau to within a few tens of kilometers (Bull 1979). Furthermore, aquifer recharge areas are more likely to be affected by such glacial advances. Figure 23 shows the extent of these ice masses during a glacial period some 18,000 years ago. The research team suggests that future advances may be more extensive than those of the past.

FIGURE 22. Continental Glaciation Logic Flow Chart

FIGURE 22. (cont)

TABLE 13. Continental Glaciation Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
ICE ADVANCEMENT/DECAY RATES FOR EACH CLIMATIC STATE (1)
ABLATION MELT FLOW		DRAWS WHEN GLACIER IS IN DECAY
CHANGE IN VERTICAL PERMEABILITY DUE TO GLACIER STRESS FIELD		IN BASALT ONLY
CHANGE IN LATERAL PERMEABILITY DUE TO GLACIER STRESS FIELD		IN BASALT ONLY
ICE EROSION RATES
GLACIER STRESS FUNCTION
LIFE OF GLACIER MADE LAKE		FIRST HUMP REPRESENTS LIFE TIME OF LAKE DUE TO TILL DAM, 2nd HUMP REPRESENTS LIFE TIME OF LAKE DUE TO DEEP ICE SCOUR
CHANCE OF LAKE FORMATION AFTER CONTINENTAL GLACIER LEAVES SITE		
GROUND WATER RECHARGE FACTOR	0.09 BARS M ⁻¹ OF ICE THICKNESS	WET BASED GLACIERS ONLY, TOTAL SEDIMENT SATURATION
CHANCE FOR CONTINENTAL GLACIER RECHARGE THIS TIME STEP		ALL CONDITIONS NECESSARY FOR FAR RECHARGE TO AQUIFER SYSTEM

(a) Data is under development and is not available at this time.

FIGURE 23. Areas Affected by Mountain Glaciers in the U.S.A.

Alpine glaciation depends on: 1) climatic state, 2) elevation of the late Pleistocene snowline, 3) the distance from a dominant peak, 4) the elevation of the present regional orographic snowline, 5) the elevation of the past glacier terminal, 6) the elevation of the regional dominant peak, 7) the site surface elevation 8) the amount of future uplift or subsidence of the site, 9) a slope exposure parameter, and 10) the downwind distance from a major water body^(a).

Kukla^(a) shows that the lowest future elevation of alpine glaciers, expected in the next 10^6 years might be predicted from:

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

$$Z_{g_{min}} = Z_s - 1.25 (Z_s - Z_p) - h_u - (Z_p 1 - Z_g) \text{ with } P_{min}$$

where

$Z_{g_{min}}$ = lowest future elevation of mountain galciers

Z_s = present regional snowline elevation

Z_p = a recorded late Pleistocene snowline elevation

h_u = an anticipated uplift

$Z_p 1 - Z_g$ = a cumulative probability distribution

P_{min} = ALCLIN values

The maximum uplift for mountains and valleys are estimated to be 1000 m and 500 m respectively over a 10^6 year period. The probability distribution of a site being alpine glaciated as a function of the distance from a dominant peak is given in Figure 24.

Several of the potential consequences associated with alpine glaciation are quite similar to those of continental glaciation and will not be repeated. Major difference is that continental glaciers generally occupy the lower elevations first, e.g., below 2500 m in Canada during the last epoch. Their effects on crustal loading are less, and because they occupy mountainous bedrock areas which tend to have relatively low permeabilities, direct recharge from their bases is of less importance. Alpine glaciers, as the name implies, are initiated at significant elevations and descend down the slopes of the topographic highs.

Summary

Alpine glaciation estimates are based on the climatic state, the elevation of the late Pleistocene snowline, the distance from a dominant peak and the elevation of the peak, the site surface elevation, and the downwind distance form a large body of water. Figure 25 presents the logic flow diagram for alpine glaciation. Data requirements and availability are illustrated in Table 14.

FIGURE 24. Probability of Alpine Glaciation in the Great Basin as a Function of Distance from a Dominant Peak^(a)

SEA LEVEL FLUCTUATIONS

This section briefly discusses how the ocean level might change during the next 10^6 years, and how such changes might affect the Columbia Plateau. Numerous variables influence sea level fluctuations. These include: 1) the galactic cycle, which is on the order of 200 to 250 million years; 2) paleogeography or continental drift; 3) earth orbital physics, with a 41,000 year cycle of axial tilt, a 21,000 year cycle of precession, and a 95,000 year cycle of orbital eccentricity; and 4) the solar cycle, with its variable sun spot density (Schwartz 1979).

(a) This information was based on work done by Kukla, which is reported in part in this document. A summary of Kukla's research has been published (Kukla 1979).

FIGURE 25. Alpine Glaciation Flow Chart

FIGURE 25. (contd)

FIGURE 25. (contd)

TABLE 14. Required and Available Data for the Alpine Glaciation Submodel^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
RATE OF GLACIER GROWTH AT FAR RECHARGE AREA		BUILDUP OF ICE THICKNESS
RATE OF GLACIER GROWTH AT THE SITE		BUILDUP OF ICE THICKNESS
EROSION OR DEPOSITION BY ALPINE GLACIER AT THE SITE
MINIMUM AMOUNT OF TIME BETWEEN APPEARANCE OF THE GLACIER ON THE FAR RECHARGE AREA AND APPEARANCE ON THE SITE		"LAG" TIME
PRESURIZED RECHARGE FACTOR	0.09 BARS M ⁻¹ OF ICE THICKNESS	
CHANCE FOR FAR GLACIER RECHARGE TO AQUIFER SYSTEM		ALL CONDITIONS NECESSARY FOR FAR RECHARGE BY ALPINE GLACIER ACTIVE
CHANCE FOR ALPINE GLACIER ON FAR RECHARGE AREA		GIVEN STADIAL CLIMATE
CHANCE FOR ALPINE GLACIER AT THE SITE		GIVEN: 1) CONTINENTAL GLACIAL NOT THERE ALREADY 2) CASCADES HAVE UP LIFTED 3) GLACIER ON FAR RECHARGE AREA 4) PAST "LAG" TIME

(a) Data is under development and is not available at this time

All of these factors affect the state of world eustasy which is subdivided into glacio-eustasy, a change in the quantity of water, and tectono-eustasy, a change in the shape and volume of the container or ocean basin (Schwartz 1979). Table 15 lists the magnitude and rate of change associated with both glacio- and tectono-eustatic changes of sea level for periods of 10^5 and 10^6 years, respectively. Like glaciers, ocean levels may go through several cycles in a 10^6 year time frame.

At present, the sea level is rising at $3-4 \text{ mm yr}^{-1}$ ($1-2 \text{ mm yr}^{-1}$ glacio-eustatic and 2 mm yr^{-1} subsidence). A short term maximum rate of ocean level increase is estimated to be $20-40 \text{ mm yr}^{-1}$. Hollin (1977), however, suggests that very rapid increases of up to 140 mm yr^{-1} may occur due to surging of major parts of the Antarctic ice sheet.

The land surface near the center of the Pasco Basin is about 120 meters above sea level. The upper surface of the underlying basalt is as much as 80 meters below sea level. Inundation by the ocean or backup of the Columbia and Snake Rivers is conceivable, especially if additional erosion and/or subsidence of the area occur. If such inundation were to occur it would probably result in: 1) sedimentation, 2) total saturation of the sediments, and 3) substantial lowering of shallow aquifer gradients.

Ocean level fluctuations, coastal erosion, sedimentation, and sediment saturation are not particularly significant with respect to a repository buried at a depth of 300 meters or more in basalt. However, such perturbations to the topography and subsurface hydraulic gradients should be included for completeness. Figure 26 presents the general logic flow diagram for this submodel. The data requirements and availability are shown in Table 16.

GEOMORPHIC EVENTS

This submodel examines the following topics: 1) Columbia River and tributary flow as a function of precipitation and glacial meltwater runoff,

TABLE 15. Potential Ocean Level Variations

<u>Type</u>	<u>Amount</u>	<u>Range</u>	<u>Rate</u>
Glacio-eustatic	100 m	200 m	10^5 yrs per cycle
Tectono-eustatic	250 m	500 m	10^6 yrs per cycle

FIGURE 26. Logic Flow for Sea Level Fluctuations

TABLE 16. Sea Level Fluctuation Sub Model Data

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
DENSITY FUNCTION FOR DEPOSITION IF SITE FLOODED BY SEA

2) flooding of the basin as a function of river flow and the relative elevation difference between Wallula gap (a likely location of hydraulic damming during catastrophic flooding, Figure 17) and the ground surface above the repository, 3) sedimentation in a low energy lake environment, 4) recharge to the unconfined aquifer zone, 5) potential river course alterations caused by sediment infilling, and 6) stream erosion during initial and final stages of flooding and stream erosion and deposition in general.

River Flows

River flow in the Columbia is considered to be a superposition of surface runoff from: 1) precipitation over the watershed, 2) average ice ablation, and 3) catastrophic ice dam collapse. The values assigned to these variables come from the submodels on climate and continental glaciation. Figure 27 shows the extent of glacial ice 18,000 years ago.

Table 17 shows the ranges of annual average Columbia River flows based precipitation, ice melting, and ice dam collapse. Past experience with river hydrographs has shown that the mean annual flow ranges from 25 to 40% of the peak flow (Leopold et al. 1964). This relationship is considered in the submodel.

FIGURE 27. Assumed Extent of Glacial Advance 18,000 B.P.

TABLE 17. Ranges of Average Annual Columbia River Flow

Estimated Flow	Discharge at Hanford m ³ sec ⁻¹	Ratio to Columbia River Mean Annual Flow
Columbia River Average Annual Flow	3.43×10^3	1
Glacial Melt (annual average)	2.38×10^4	7
Glacial Melt with a Factor of 4 Increase Increase in Precipitation (annual average)	9.63×10^4	28
Maximum Flood Associated with Ice Dam Collapse (weekly average)	9.06×10^6	2645

Catastrophic river flows caused by rapid drainage of large ice-dammed lakes occurred at a rate of $5 \times 10^{-5} \text{ yr}^{-1}$ (Bretz 1969) during previous glacial episodes. A classic example is the series of Missoula or scabland floods that have occurred in eastern Washington from the repeated collapse of large ice dams in western Montana. Figure 28 shows the extent of a major Missoula ice dam flood. Missoula-like floods have in the past and will almost certainly inundate the Pasco Basin again. Such flooding occurred not only at the end of the glacial episodes, but also occurred as a result of ice-front fluctuations during glacial episodes. Extensive lobes of ice caused perhaps by changes in the basal thermal conditions formed around the periphery of the ice sheet. Some of the ice lobes dammed streams draining the upland areas and formed ice marginal lakes that trapped seasonal meltwater. The probability of such a flood occurring in the Columbia Plateau area during any 100-year period during or immediately following a glacial episode appears to be approximately 10^{-2} (Tubbs 1979).

Tubbs concludes that 7 to 9 major Missoula-type flooding episodes might occur in the Pasco Basin in the next 10^6 years. However, many smaller floods from other impounded lakes are also likely.

FIGURE 28. Extent of Missoula Flooding (after Thornbury, 1969)

Inundation of the Basin

Flood waters associated with ice-dam failures have often been impounded in the Pasco Basin because of a hydraulic constriction of Wallula Gap. Given similar flood conditions it is probable that such impoundment will occur in the future. Wallula Gap is a deep cut through a basalt anticline, as is shown in Figure 29, which forms an effective hydraulic dam for the elevated flow rates associated with ice-dam failures. The maximum lake elevation resulting from such impoundment is 350 m. This represents a volume of 730 km^3 of water within the Pasco Basin alone. Estimates of the persistence of such lakes range from one day to two weeks with a few days to a week probably being the most reasonable figures (Tubbs 1979). Smaller lakes might be associated with smaller ice-dam failures.

An estimate of the discharge capacity of Wallula Gap is necessary to determine the critical flow below which high energy river flow and associated erosion are possible, and above which a lower energy lake environment with associated sedimentation will exist.

This submodel checks the calculated inflow into the Pasco Basin. If the inflow exceeds the maximum possible outflow at Wallula Gap ($9.06 \times 10^6 \text{ m}^3 \text{ s}^{-1}$) a temporary lake forms in the basin due to hydraulic damming of Wallula Gap. Peak flows are used to compute erosion associated with the initial phase of such a flood.

Erosion and sedimentation therefore are functions of the river flow coming into the basin, the elevation of the ground surface above the repository, the lake elevation, and the flow at the Wallula Gap discharge point. If sedimentation and erosion are such that the general topography of the Pasco Basin is not changed significantly, then Figure 30 would be applicable. This figure shows the approximate area of the Hanford Reservation inundated by flow of $2.97 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ or about 33% of the maximum Missoula flood level.

Because of the buildup of ice during a glacial period, the sea level would be progressively lowered by as much as 100 m, which in turn would lower the base level of the Columbia River. Thus, channel bed erosion would be initiated at the mouth of the river and continuously work its way back towards Wallula

FIGURE 29. Development of a Hydraulic Constriction at Wallula Gap (Erosion May Require 10^6 or More Years)

Gap. Side wall erosion as well as bed scouring may result in the elimination of the gap as a hydraulic dam. This would result in higher energy flows through the Pasco Basin and consequently enhanced erosion. Therefore, the potential for and magnitude of erosion of Wallula Gap is included in the model.

FIGURE 30. Approximate Area of Hanford Reservation Inundated by a Flow of $2.97 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (water surface elevation at 220 m present MSL)

Recharge

If a lake is created over the repository site, water at the bottom of the lake will be forced into the ground under a pressure of about 0.11 bars/meter of lake depth. As a result, the elevation of the water table may increase and the horizontal hydraulic gradients in the shallow unconfined aquifers may be reduced substantially. These effects may be negligible, however, due to the short duration of floodwater impoundment.

Sedimentation

As the flood waters enter the Pasco Basin and the low energy lake environment, they lose their sediment transporting capability. Figure 31 shows the relationship between mean annual precipitation and maximum sediment load. Attempts are being made to generate similar curves relating Columbia River and tributary sediment loads as a function of volumetric flow or stream potential. The largest sediment load should be associated with the large Missoula-like floods. Flood waters are assumed to be at maximum sediment transport efficiency even though scouring of the scablands may become progressively more difficult with successive floods.

Flood deposition in the Pasco Basin, is greatest at the canyon and coulee mouths on the north and east sides of the basin, since these are the directions from which the dominant flows come. Such sediment buildup can affect the state of stress of the system and the vertical distance from the repository to the ground surface. It may also result in alteration of the course of the Columbia River. This could reduce contaminant transport distances and potentially cause selective stream erosion over the repository.

River Course Alteration

The Columbia River, because of far greater runoffs during the Ice Age (Pleistocene Epoch) than now, is a markedly underfit stream. It occupies a well established and adjusted course so that it can handle at least several times its present flow rate without appreciable changes in its course.

Recognizable, systematic changes have occurred in the course of the Columbia River as it downcut its channel. The shifts that have occurred were influenced in part by the geologic structures, so that the new river occupies a relatively stable course and channel through the synclinal parts of the Pasco Basin.

Glacial floods could alter this course by lateral river erosion and/or sediment infilling of the channel by tributary streams during major ice dam flooding. A certain probability exists that the river could be superimposed over the repository site. Subsequent local stream erosion could be substantially greater than general denudation especially if folding was occurring.

FIGURE 31. Climate and Sediment Yield
(adapted from Schumm, 1965)

It is conceivable for the main stream of the Columbia River to be temporarily blocked by a landslide, glacial ice lobe, or volcanic material (e.g. lava flow). With the main stream temporarily blocked, flow down the coulees, the lower Snake River, and conceivably the Yakima River, could rapidly deposit sediments in the Columbia River channel. Such sediment buildup would reduce the channel gradient. The Columbia River would thus tend to dump its own sediment load once it encountered the reduced gradient. This could further enhance the channel infilling.

Similar infilling might result from the deposition of sediment during a Missoula-like flood. As the flood waters receded, the river might select a new course, probably in a more direct line from Sentinel Gap to Wallula Gap over a local floodplain. A presumed steep gradient over the basin fill materials might result in rapid headward erosion. The Columbia would then be

incised into a new channel, possibly over the buried repository. Major erosion would be stream downcutting as opposed to general denudation. The possibility of river channel alteration from blockage caused by landslides, volcanic extrusions and/or ice effects must be considered as well.

General Denudation

Denudation refers to a general lowering of the land surface from erosional processes and must be distinguished from stream or glacial downcutting. Exhumation of a repository is unlikely to result from denudation. However, the removal of tens of meters of surficial material is certainly possible. This could change the potential pathlength for nuclide migration by the removal of a relatively impermeable layer or by affecting recharge to the ground water system. Stream erosion rates may also be affected.

Using this present mean annual precipitation and temperature, the total denudation rate for the Pasco Basin is estimated to be 50 m per 10^6 years (Tubbs 1979). However, some of the smaller drainage basins tributary to the Columbia River support higher relief ratios, consequently higher denudation rates are probable in these areas. A temperature decrease of 4-5°C accompanying a slight precipitation increase, might result in a denudation rate of 100 m per 10^6 years (Tubbs 1979).

The rate of denudation is site dependent. Among other factors, it depends on climate, topography, material lithology, and to a major extent, human activity. Erosion rates can be increased by as much as an order of magnitude by injudicious farming (Judson 1968). Figure 32 and Table 18 indicate the effects of relief and runoff on general denudation. Figure 33 shows the current denudation rates in the Columbia River system relative to several other areas in the United States.

Stream Erosion

Average or general denudation rates do not reflect the much greater rates that are possible for local stream erosion. Gera and Jacobs (1972) used the Grand Canyon to illustrate this point. They conclude that the Grand Canyon, 350 km long and 1600 m maximum depth, was formed in 1.5 to 2 million years during the period the region was being uplifted to a height of 1800 to 2400 m

1. LO (CHINA)	15. RED (U.S.A.)
2. YELLOW OR HWANG (CHINA)	16. MISSISSIPPI (U.S.A.)
3. KOSI (INDIA AND NEPAL)	17. CHEYENNE (U.S.A.)
4. GANGES (INDIA)	18. TENNESSEE (U.S.A.)
5. RED OR YUAN (NORTH VIETNAM AND CHINA)	19. SMALL BASINS IN OKLAHOMA AND TEXAS (U.S.A.)
6. BRAHMAPUTRA (EAST PAKISTAN AND TIBET)	20. ROANOKE, VIRGINIA (U.S.A.)
7. INDUS (WEST PAKISTAN)	21. SANTEE, NORTH CAROLINA (U.S.A.)
8. YANGTSE (CHINA)	22. SAVANNAH, GEORGIA (U.S.A.)
9. COLORADO (U.S.A.)	23. AMAZON (SOUTH AMERICA)
10. MEKONG (SOUTH-EAST ASIA AND CHINA)	24. NILE (NORTH-EAST AFRICA)
11. RIO GRANDE (U.S.A. AND MEXICO)	25. SUSQUEHANNA, PENNSYLVANIA (U.S.A.)
12. MISSOURI (U.S.A.)	26. BRAZOS, TEXAS (U.S.A.)
13. SMALL BASINS IN EAST WYOMING (U.S.A.)	27. PEARL, MISSISSIPPI (U.S.A.)
14. SALT (U.S.A.)	28. POTOMAC, VIRGINIA AND MARYLAND (U.S.A.)

FIGURE 32. Suspended Solids Denudation Rate as a Function of Elevation (adapted from Carson and Kirkby 1972)

TABLE 18. Rates of Regional Erosion in the United States (modified from Judson and Ritter 1964, Gera and Jacobs 1972)

Drainage Region	Drainage Area ^(a) (10 ³ km ²)	Runoff (10 ³ m ³ /sec)	Load (tons/km ² /yr)			Denudation (cm/1000 yr)	% Area Sampled	Average Years of Record
			Dissolved	Solid	Total			
Colorado	629	0.6	23	417	440	17	56	32
Pacific Slope California	303	2.3	36	209	245	9	44	4
Western Gulf	829	1.6	41	101	142	5	9	9
Mississippi	3238	17.5	39	94	133	5	99	12
South Atlantic and Eastern Gulf	736	9.2	61	48	109	4	19	7
North Atlantic	383	5.9	47	69	126	5	10	5
Columbia	679	9.8	47	44	101	4	39	2
TOTAL	6797	46.9	43	119	162	6		

(a) Great Basin, St. Lawrence, and Hudson Bay drainage not considered.

FIGURE 33. Rates of Denudation

above sea level. These estimates result in a stream erosion rate of $800 \text{ m } 10^6 \text{ years}$, 5 times higher than the regional denudation rate ($160 \text{ m } 10^6 \text{ years}$). This is not a unique case. Many valleys show evidence of changes in flood level in Quaternary times of tens to hundreds of meters (Fournier 1960, Holeman 1968).

For the Pasco Basin, average stream erosion rates do not vary significantly from the general denudation rates. One exception is that greater stream erosion rates can be expected if the area in question is a growing anticline cut by the Columbia River or one of its tributaries. If the river were to alter its course such that it was superimposed over a growing anticline, the erosion rates might be in the range of $300 \text{ to } 500 \text{ m per } 10^6 \text{ year}$ (Tubbs 1979).

Flood Erosion

Presently, no estimate has been made of erosion associated with repeated ice-dam flooding. However, volumetric flows of up to $9.06 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ are believed to be possible in the Pasco Basin for periods of a few days. Other flows up to this magnitude are also possible due to the release of ice margin lakes by ice dam failure. It is important to emphasize that erosion is extremely sensitive to flow rate. Therefore estimates of erosion should consider peak flows and as well as hydraulic damming at Wallula Gap.

Some attempt is being made at correlating the erosion potential of the Columbia River with its competent velocity during any given flood event. The competent velocity is considered to be 0.7 time the mean cross sectional velocity. The peak mean cross sectional velocity is estimated at four times the annual average mean cross sectional velocity. Thus far, estimates of erosion rates have been restricted to gravelly soils only, and no estimate for basalt is available. Therefore, the range of erosion rates given by Tubbs will be used initially. These rates suggest that uplift of an area has an order of magnitude greater effect on erosion rates than variations of the local climate. A similar finding has been reported for a larger class average of erosion rates (Gera and Jacobs 1972).

It is important to select a repository site where excessive erosion in the future is highly unlikely. The consequences associated with denudation or stream erosion are not limited to a reduction of overburden thickness and thus transport pathlength. Quite possibly the removal of a relatively impermeable layer could permit vertical recharge and new groundwater circulation pattern development which may have an adverse affect on the hydrologic conditions of a repository site.

Wind Erosion

Although under present conditions surficial wind erosion on the Columbia Plateau can be on the order of 1.0 cm yr^{-1} locally, armoring and depression refilling is such that this erosion mechanism can only be sustained locally for an extremely short time.

Summary

In summary, river flow is modeled as a superposition of variables such as precipitation over the watershed, average ice melt runoff, and catastrophic dam collapse. Flow through the hydraulic constriction at Wallula Gap and the inlet flow to the basin determine the river/lake conditions within the Pasco-Basin. Erosion is associated with a high energy river environment. The lake environment affects sedimentation and vertical recharge to the unconfined zone. River course alteration is a possibility, especially if the main stream of the Columbia River were to be blocked temporarily upstream from the basin. Denudation and selective stream erosion rates are given as averages. However, some attempt is being made to correlate erosion with peak river flows and material properties. The fundamental variables affected by this submodel are path-length, effective stress, and shallow aquifer potentials. Figure 34 presents a logic flow for this submodel. Table 19 lists data requirements and data availability.

DEFORMATION

In this report, a fracture system is defined as a series of interconnected cracks that may support a permeability differing from that of intact rock. Dilational and/or shear displacements are considered. The following categories are covered: 1) undetected and/or accelerated deformation of the basalts, 2) faulting in the sub-basalt basement, 3) surficial fissuring caused by material loading or unloading, 4) impact fracturing, and 5) hydraulic fracturing. Deformation can affect all of the fundamental variables (pathlengths, conductivities, fluid potentials, and effective stresses) and, therefore, this is considered an extremely important submodel. However, the following paragraphs are to serve only as an example of how a submodel on deformation might be ultimately constructed. It must be recognized that as new theories are proposed and the geological and geophysical characteristics of an area such as the Columbia Plateau are better identified, the components of the various submodels presented herein must be similarly updated.

FIGURE 34. Logic Flow Diagram for Geomorphic Events Submodel 1

FIGURE 34. (contd)

TABLE 19. Geomorphic Events Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHIC REPRESENTATION OR DATA	COMMENTS
DENSITY FUNCTION FOR TRANSLATING AVERAGE RIVER FLOW TO PEAK FLOW FOR EACH CLIMATIC STATE		MULTIPLY AVERAGE FLOW BY NUMBER DRAWN TO GET PEAK FLOW
AVERAGE NUMBER OF 'MISSOULA' FLOODING		FOR POISSON DISTRIBUTION
DENSITY FUNCTION FOR 'NORMAL' EROSION FOR 'MISSOULA' FLOODING
DENSITY FUNCTION FOR INCREASED 'MISSOULA' FLOOD EROSION DUE TO FOLD GEOMETRY		MULTIPLY NORMAL EROSION TO GET TOTAL EROSION
DENSITY FUNCTION FOR DEPO- SITION DURING LAKE FORMATION OF MISSOULA FLOOD
DENSITY FUNCTION FOR REGIONAL UPLIFT
DENSITY FUNCTION FOR FOLD GROWTH RATES
DENSITY FUNCTION FOR 'NORMAL' DENUDATION RATE
DENSITY FUNCTION FOR 'NORMAL' STREAM EROSION RATE
CHANCE FOR RIVER FALLING ON THE SITE WHEN RIVER MOVES		
UPPER LATITUDE OF 'SENSITIVE' AREA FOR GLACIER FLOODING		
LOWER LATITUDE OF 'SENSITIVE' AREA FOR GLACIAL FLOODING		

CONTINUED ON NEXT PAGE

(a) Data is under development and is not available at this time

TABLE 19. (contd)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
MAXIMUM FLOW AT WALLULA GAP WITHOUT HYDRAULIC DAM FORMING		
CORRECTION FACTOR FOR 'NORMAL' STREAM EROSION FOR EACH ROCK TYPE		
CORRECTION FACTORS FOR 'NORMAL' STREAM EROSION FOR EACH CLIMATE STATE		
CORRECTION FACTOR FOR 'NORMAL' DENUDATION EROSION FOR EACH ROCK TYPE		
CORRECTION FACTORS FOR 'NORMAL' DENUDATION EROSION FOR EACH CLIMATE STATE		

Undetected and/or Accelerated Deformation of the Basalts

The possibility of an undetected deformational feature existing at some distance from the repository, must be considered in a release scenario analysis. The cumulative probability of such a feature probably increases and the consequences decrease as a function of distance from the repository. Therefore, an estimation of the probability of undetected features occurring within an appropriate distance from the repository site is recommended. Such features might be: 1) anticlines with or without associated faults, 2) synclines, and 3) faults in the sub-basalt basement.

One example approach to undetected feature probability estimation is to infer a geologic slip rate and cumulative deformation in an area from recorded microseismic data. It is assumed that the state of stress and the average strain rate for the region in question have remained relatively constant during the last few million years (Coombs 1979). Thus the amount of inferred deformation might be compared to the amount of observable deformation. The difference would be a gross estimate of undetected deformation. Such analysis

is based on the percentage of recorded seismicity that can be attributed to known features. The remainder is considered to be associated with undetected features.

Regional compressive stresses in the Columbia Plateau region have resulted in the anticlinal deformation of the basalt flows in many locations. Most of the major visible anticlines vary from 75 to 150 km in length, average about 2 km in width, and generally trend N 55 W to east-west. It has been suggested that for a layered system (e.g., the Columbia Plateau basalt flows) the wavelength of folding might be inversely proportional to the thickness of the layered sequence in the given area (Biot 1965). Beyond some magnitude of deformation, stresses may no longer be effectively relieved by folding. In the Columbia Plateau the subsequent result might be thrust or reverse dip-slip faulting, often along east-west oriented zones or planes of weakness. Some or all of the fault displacement may possibly be accommodated within pre-existing jointing or other planes of weakness associated with the basalt flows. Such shearing within the joints may account in part for the temporal and spatial clustering of microearthquakes observed in the area (Rothe 1978). It may be conceivable, therefore, to correlate microseismicity with folding and faulting in the Columbia Plateau Region. If so, such correlations might assist other geological and geophysical studies in the identification of undetected folds and faults which are masked by the upper stratigraphic units.

Many examples can be found of large discrepancies between geological reconnaissance and microseismic data, especially in areas of low to moderate seismic activity. Wight (1979) cites the Flathead Lake area of Montana, where less than 20% of the activity could be attributed to mapped faults, and the state of Washington, where perhaps less than 10% of the recorded seismicity can be associated with known features. A plot of seismicity in Washington is shown in Figure 35. Naturally the data reflects a certain bias towards areas that have been instrumented for seismicity in the recent past.

For a central eastern Washington area of 10^5 km^2 , Wight generated a recurrence relationship between seismicity and geologic slip rate and compared the result with the average strain rate for the region. The regional strain

FIGURE 35. Earthquake Epicenters from the West (circle) and Eastern (triangles)
Washington Data Files (Bishop 1978)

rate estimated from anticlinal deformation is approximately 3 km per 4×10^6 years (Coombs 1979). Wight (1979) concludes that in this region the probability of a strain energy release comparable to a moderately-sized earthquake occurring in any 10^2 km^2 area during in the next 10^6 years (Wight 1979) is 10^{-6} yr^{-1} or less.

The following points should be considered: 1) Ongoing geological and geophysical studies on the Columbia Plateau should result in more of the deformational features being discovered and mapped, 2) Probability of not detecting the feature should approach zero as the distance from the repository cavity approaches zero, 3) Deformation (strain energy release) may be manifested as folding, faulting, or small scale shear displacements of pre-existing joint features. Furthermore, a distinction must be made between deformation of the basalt layers and deformation of the sub-basalt basement. Seismicity below 8-10 km in the central basin area is probably due solely to deep seated basement features.

Another approach to the undetected feature problem is to examine the record of site investigations for nuclear power plants, dams, and mines. Some statistics can be compiled on the number of features discovered during or subsequent to construction. This work which is being spearheaded by Professor Baecher of MIT is not currently incorporated into the Repository Simulation model.

Probability of an Undetected Anticline

The probability of locating the repository within a given distance of an undetected anticline must be supplied to the model. Presumably this will come from refined geophysical, geological, and seismological investigations. Changing tectonic stresses in the region and/or perturbation of the average strain rate would affect the probability numbers. However, Coombs (1979) suggests that the direction and magnitude of the tectonic stresses on the Columbia Plateau should remain constant for at least the next 10^6 years. The area should continue to support a maximum compressive stress oriented roughly north-south, as is shown in Figure 36 (Coombs 1979). The minimum compressive axis is generally considered to be within 45 degrees of vertical.

FIGURE 36. Stress Orientation for Pacific Northwest and Basin Range Provinces (Coombs 1979)

Strain Rate

Conceivably the strain rate could change even if the tectonic stress state remained constant. Therefore, a range of possible changes along with estimated probabilities must be supplied to the model. As yet, no such data have been generated so a normal Poisson distribution centered on 0.75 mm/yr^{-1} is being assumed for the region.

Probability of a Fault Associated with the Folding

Apparently after a certain magnitude of anticlinal deformation, stresses can no longer be relieved by folding. The result in the Columbia Plateau is reverse dip-slip or thrust faulting on approximately east-west oriented planes (Rothe 1978). Such displacement may give rise to the asymmetrical configuration of the anticlines. The observed faults might also be explained as gravity sliding along the steep slope of a tight fold.^(a) Micro-earthquake activity, possibly of the swarm type, might be associated with such faulting and gravity sliding. Although some swarm areas have been active more than once, a tendency exists for lateral migration of the activity, presumably along the axis of the fold (Malone et al. 1976). If lateral fault growth or fracture extension is a real phenomenon, then the model must be supplied with the probability that the repository will be intersected by such a fault. Because the microseismic swarm activity is located from near the ground surface down to about 4 to 6 km, depth is not a significant factor in this probability estimation.

Probability of Shear Displacement on Pre-Existing Joints

Rather than a major fault, shear displacement on a set of pre-existing joints might account for the deformation and associated seismic energy releases. In this case, the blocks between joints would remain relatively unaltered, but the hydraulic flow characteristics of the joints might change. The closer the site is to a known anticlinal feature, the greater the probability of joint displacement.

Rothe (1978) shows that on the average, earthquakes swarms exhibit a 4-5 km² spatial extent, but a 10 km² sensitivity zone is more conservative. Based on these data, and the fact that the observable anticlines are 2 km wide on the average and range from about 5 to 20 km apart, it may be possible to estimate probabilities of shear displacement on pre-existing joints based on the distance from the undetected feature.

(a) This information is based on work done by Davis which is reported in part in this document. A summary of Davis' research has been published (Davis 1979).

Associated Permeability Increases

The probability of a fault intersecting the repository is related to the distance from a known anticline, the estimated distance for a hypothesized undetected anticline, and the density of known faults in the area, as shown in Figure 37. Regardless of whether a fault or a zone of shear planes is being hypothesized as a release scenario, the result is characterized as: 1) alterations in hydraulic conductivity, and 2) alterations in fluid potentials along the path.

In many areas where the basalts have undergone anticlinal deformation, the joints were found to be altered by ground water and in some cases slicken-sided (Rothe 1978). This implies that for at least a period of time following the opening of the joints, water may be vertically mobile through all or part of a basalt flow, and horizontally mobile in the vesicular flow tops. Such vertical water mobility might in part explain the lateral and vertical migration of seismic activity associated with earthquake swarms. The presence of water might reduce the effective stress on any potential shear plane and hence allow further displacement at a lower level of shear stress.

The probability and hydrogeologic effect of faulting varies with the nature of the faulting process. The fault type depends on the state of effective stress and the mechanical characteristics of the material being faulted. Effective stress depends on the tectonic stresses, lithostatic or overburden stresses, and interstitial fluid pressures.

Faulting in alluvial aquifers commonly reduces the horizontal permeability of aquifers by producing gouge, localizing cementation by secondary minerals, reorienting flat clasts with their long axis parallel with the fault plane, and probably most important, by offsetting permeable beds so that they are set against nonpermeable zones.(a)

Faulting in brittle rocks may increase local permeabilities by several orders of magnitude. Inflows of large volumes of water into mines and tunnels

(a) This information is based on work done by Davis which is reported in part in this document. A summary of Davis' research has been published (Davis 1979).

FIGURE 37. Fault Intersection Probabilities (Little 1978)

along fault zones are widely reported in the literature. However, unless these fracture pathways are connected to aquifer, continued water flow is unlikely. The water storage capacity of the low porosity rocks is usually less than 5% of their total volume.^(a)

Existing faults in the Columbia Plateau region need to be investigated, and groundwater flow characteristics determined. A distribution of known or inferred fault lengths and widths would also be beneficial. For example, Bond (1978) reports that a fault zone associated with Rattlesnake Mountain may be less than 100 m wide. Faults lengths on the Columbia Plateau on the order of 40-50 km have been observed or inferred (Brown 1978).

Estimating the limits of bulk permeabilities for a fault or joint deformation scenario is a difficult task, at best. One example approach is to use a parallel plate model similar to that described by Brace (1978). Figure 38 presents the model. For basalt, the principal joints or fractures are presumably

(a) This information is based on work done by Davis which is reported in part in this document. A summary of Davis' research has been published (Davis 1979).

S = JOINT SPACING = 1 m

W = APERTURE WIDTH = 100×10^{-6} m

K = PERMEABILITY $\frac{W^3}{12S}$ 10^{-13} m² 100 md

FIGURE 38. Parallel Plate Fracture Model (Brace 1978)

oriented vertically in the colonnade and entablature, and random throughout the remainder of the flow. The primary parameters are then joint spacing and aperture width. The empirically derived relationship presented by Brace is as follows:

$$k = \frac{w^3}{12s}$$

where:

k = permeability (m²)

w = aperture width (m)

s = joint spacing (m)

Table 20 and Figure 39 present some estimated permeabilities based on this relationship and some illustrative parameter values.

Rothe (1978) speculates that at depth the thinner basalt flows (≤ 30 m) apparently have, on the average, joint spacings of 1.0 m. Thicker flows (50-100 m) tend to spacings of about 10.0 m. Outcrops reveal a much greater density of smaller fractures; however, these features may be due to the relaxation of confining stresses by unloading or deformation. Characterization of the fracture densities, aperture widths, secondary mineral deposits, and bulk hydraulic conductivities should be given high priority in future field investigations. Data are especially required for temperature and stress conditions

TABLE 20. Example Bulk Permeabilities for a Joint Rock Calculated From Parallel Plate Theory

Joint Spacing (m)	Aperture Width (mm)	Permeability (m ²)	Permeability (md)	Hydraulic Conductivity (cm sec ⁻¹)
0.1	10 ⁻¹	10 ⁻¹²	10 ²	10 ⁻⁴
0.1	10 ⁻²	10 ⁻¹⁵	10 ⁻¹	10 ⁻⁷
1.0	10 ⁻¹	10 ⁻¹³	10 ¹	10 ⁻⁵
1.0	10 ⁻²	10 ⁻¹⁶	10 ⁻²	10 ⁻⁸
10.0	10 ⁻¹	10 ⁻¹⁴	10	10 ⁻⁶
10.0	10 ⁻²	10 ⁻¹⁷	10 ⁻³	10 ⁻⁹
10.0	10	10 ⁻¹¹	10 ³	10 ⁻³

FIGURE 39. Conductivity vs. Fracture Width for Various Joint Spacing

that might be expected at the depth of the repository. Joints and fractures are not always parallel and continuous features, and therefore water flow, if any, may be along a very tortuous path. Consequently bulk hydraulic conductivities should be determined from field data if possible rather than by Brace's (1978) empirical relationship.

Note that in this Repository Simulation model, a breach of the repository requires creation of a continuous path that connects fluid sources with different fluid potentials or dynamic heads. Both a pathway and a fluid potential difference must be present for water flow through the repository. Also of importance is the effect differential fluid potentials may have on the lateral flow in interconnected but separate flow zones.

Development of the pathway and changes in the head differential need not occur simultaneously. Pressurized recharge of an aquifer from glacial loading may change the fluid potentials tens of thousands of years after the interconnecting path has been created by shear deformation of the joints. Therefore, a distribution of possible fracture healing rates may need to be supplied. Such healing or permeability degradation might be caused by secondary mineralization and/or creep closure in response to the confining stress at depth. Bookkeeping of such time dependent information is the primary mission of the layered earth model (LEM) part of the Repository Simulation model.

Faulting in the Sub-basalt Basement

Although the thick sequence of basalts obscures the basement, the type and magnitude of basalt deformation indicates the possibility of glide motion at depth (McKee 1972). Until the distribution of deep faults (if any) can be mapped, a random distribution of basement faulting must be assumed. Geologic slip rate may possibly be inferred from deep seismicity. In this manner the probability of an rupture on undetected basement fault within a 100 km^2 area around the repository may be estimated.

It is unlikely that a fault in the sub-basalt basement, which has not moved since the basalt layer hosting the repository was formed (8 to 14 million years ago), will rupture through the repository in the next 10^6 years. Therefore, the assumption has been made that if no fault is detected during the

construction of the repository, no fault exists at depth directly below the repository. Angular or lateral extension of a neighboring deep fault intersecting the repository area is also considered unlikely.

It is possible, however, that an undetected fault runs adjacent to the repository but not through it. Subsequent displacement on the fault might then trigger displacement on the joint features intersecting the repository. Thus, the deep seated undetected fault might replace the basalt anticline as the mechanism for inducing shear displacement of joints.

Wight indicates that offset displacement associated with a single earthquake in the Pasco Basin might be in the range of 0.1 to 1.0 meters. Offset on the secondary path (joints) is assumed to be about a few centimeters at most. Once shearing along a joint has occurred, subsequent offset may be possible at lower stress levels. As a consequence, deep-seated fault rupture may facilitate future deformation or strain release in the affected basalt layers.

Vibratory Excitation and Backfill Material Response

The effect of seismic energy propagation (earthquakes) and the potential impact on a repository buried 300 meters or deeper in the basalt must also be analyzed. Vibratory excitation apparently represents a negligible hazard to a backfilled repository, provided the backfill has been properly designed and engineered (Wight 1979). A recent study for underground reactors suggests that the ground motion at depth in an undisturbed medium can be one-half to two-thirds of the ground motion experienced at the ground surface (Wight 1979). Therefore, the backfill must be engineered in such a way that the material acoustic impedances are closely matched. To do this, seismic design criteria for the backfill are required.

Depending principally on the distance and magnitude of the earthquake, ground motion excitation in the Columbia Plateau region might be expected to encompass accelerations in excess of 1 g, velocities greater than 20 cm sec^{-1} , frequencies up to at least 50 Hz, and total duration of the excitation exceeding 40 seconds sometime in the next 10^6 years (Wight 1979). Table 21 shows

TABLE 21. Reported Seismic Events ($M \geq 5.5$) Near Hanford Since 1872

Location	Date	M	$I_{\max}$	Distance from 200 Area	Intensity at 200 Area
US-Canada	12/14/1872	7.5	9	304 km	V
Puget Sound	4/13/49	7.1	8	232	I - IV
Puget Sound	4/29/65	6.9	8	223	IV
Milton-Freewater	7/16/36	5.8	7	122	IV
Puget Sound	11/13/39	5.8	7	267	III
Puget Sound	4/29/45	5.5	7	182	I - IV
Corfu	11/1/18	-	6(?) Prob. 4	14	III - IV
Cascades	12/30/26	-	6	54	I -III

some of the historical seismicity reported for the Pasco Basin areas. The only large historical earthquakes that have occurred in the region were at distances greater than 200 kilometers from the Pasco Basin. The geologic evidence suggests that a few moderate to strong earthquakes have occurred in the Pasco Basin. Using a fault-surface area relationship ($M = 4.2 + \log A$) from Wight (1979), where M is the Richter magnitude and A is the rupture surface area of the fault, the potential earthquakes shown in Table 22 are predicted.

Depths of the faults are estimated from depths of microseismic events in the area. Fault length is measured at the surface. The product of fault length and fault depth (measured along the dip of the fault) is the fault surface area. Using Wight's (1979) empirical relationship:

$$A_g = \frac{472 \times 10^{0.28M}}{(R + 25)^{1.3}}$$

where:

TABLE 22. Predicted Future Earthquakes for Hanford Area Over the Next Few Hundred Years

<u>Fault</u>	<u>Length</u>	<u>Depth</u>	<u>Area</u>	<u>M</u>	<u>Distance from 200 Area</u>
Saddle Mountain	25 km	10 km	250 km ²	6.6	20 km
Untanum	20 km	10 km	200 km ²	6.5	10 km
Walla Walla	20 km	10 km	200 km ²	6.5	100 km
Wallula Gap	5 km	5 km	25 km ²	5.6	50 km

A_g = peak ground acceleration (cm/s²)

R = distance (km)

M = local Richter magnitude.

values of 0.24, 0.32, 0.06, and 0.07 cm/sec² respectively, are obtained for peak accelerations of the four potential earthquakes shown in Table 22. Blume and Associates (1971), in work done for seismic design of nuclear reactors at Hanford, conservatively estimated that the maximum credible earthquake over the next 50 years is Richter magnitude 6.7 (modified Mercalli Intensity = VIII) located at the northwest end of the Rattlesnake-Wallula fault zone and resulting in 0.25 g acceleration on the Hanford Reservation. Wight (1979) has calculated that an annual probability of the maximum ground acceleration of exceeding 0.20 g in the area is 10^{-4} .

Wight concludes that with careful attention to matching acoustic impedances between country rock and backfill material, vibratory effects should be minimized and shaft seal failures caused by large earthquakes may be avoided. A hypothetical seal failure is shown in Figure 40. Some data on tunnel damage are presented in Figure 41 and Table 23.

Impact Fracturing

Impact fracturing is related to phenomena such as meteorite impact. The suggestion has been made that below a crater a fracture zone exists that is about four times the depth of the crater (Hartman 1979). Thus, a meteorite

FIGURE 40. Assumed Crack Geometry Around Shaft Seal (Little 1978)

about four times the depth of the crater (Hartman 1979). Thus, a meteorite might breach the repository without excavating it. This will be further discussed in the section on meteorites.

Hydraulic Fracturing

The final potential fracture mechanism considered in this study hydraulic fracturing. Extension fractures associated with hydraulic fracturing are found in a wide variety of geologic settings. Typically these cracks are filled with fluid (e.g., water, oil, gas, air) and it appears that fluid pressure and pressure gradients have played an important role in dilation and propagation of the fractures (Pollard 1978).

An example of extensional fracturing is hydro-fracturing. The assumption is that material overlying the basement rock has relatively low tensile

FIGURE 41. Calculated Peak Acceleration at the Surface and Associated Tunnel Damage (Pratt et al. 1978)

strength. If the interstitial or pore fluid pressure is increased to the magnitude of the minimum principal stress, the material is fractured in a dilational mode with the fracture plane orientation being basically perpendicular to the minimum principal stress.

TABLE 23. Summary of Damage Levels (Pratt et al. 1978)

	DISTANCE, km	MAGNITUDE	
STRONG, TENSILE, AND SOME RADIAL CRACKING (BAUER, CALDER)	5	6.5	DAMAGE TO STEEP, WEATHERED ROCK (ORIARD)
	10	6.5	NO DAMAGE TO COMPETENT ROCK (ORIARD)
FORMATION OF NEW CRACKS IN ROCK (LANGEFORS, LINDSTROM)	5	6.0	
	10	6.0	DAMAGE TO UNSOUND ROCK
FALL OF STONES IN UNLINED ROCK TUNNELS (LANGEFORS, LINDSTROM)	5	5.0	
	10	5.0	FALLING OF PARTIALLY LOOSENEED ROCK OCCASIONAL FALLING OF LOOSE STONES SAFE (ORIARD)

Natural phenomena may result in perturbation to the hydraulic system that could result in abrupt increases in hydraulic potentials, repository flooding, and possibly hydraulic fracturing. Such changes could be produced by a variety of causes, including local ponding of rivers, changes in ocean levels related to world wide glaciation, erosion of sediments in river valleys, or changes in available moisture caused by climatic changes. In northern regions the re-expansion of continental ice sheets could result in very high subglacial pressures being transmitted to aquifers.^(a) The current program thrust is toward quantifying and ranking these processes in terms of induced permeabilities, fluid potential changes, and volumetric flows.

Natural changes in the hydrologic system may be slow enough to allow the system to approach equilibrium without the development of large transient local hydraulic gradients. Davis has suggested that hydraulic gradients in excess of 0.3 are not likely in deep zones of actively circulating water ^(a). However, because extensional fractures do occur in nature and fluid pressures appear to have played a role in their development and propagation, this fracture mechanism must be considered.

Summary

This section on deformation covers: 1) undetected and/or accelerated deformation of the basalts, 2) deformation in the sub-basalt basement strata, 3) impact fracturing, and 4) hydraulic fracturing. Deformation can affect pathlengths, hydraulic conductivities, fluid potentials and effective stresses.

Undetected and/or accelerated deformation of the basalts refers to folding and associated faulting. Emphasis is placed on undetected features. An example estimate of the frequency and magnitude of undetected deformation is made based on recorded seismicity, inferred geologic slip rates, and observed anticlinal deformation. It is concluded that in any 10^2 km^2 area there is

(a) This information is based on work done by Davis which is reported in part in this document. A summary of Davis' research has been published (Davis 1979).

a 10^{-6} yr^{-1} or less probability of a strain energy release comparable to a moderately sized earthquake. This strain energy release might be in the form of a single earthquake; however, it might be that deformation will be manifested as small displacements on pre-existing joints or other planes of weakness. This small scale (microseismic) activity may prevail in the Columbia Plateau region. Permeability changes potentially associated with such deformation are being estimated based on a theoretical parallel plate model and estimated joint spacing and aperture width. This approach is anticipated to grossly overestimate the induced permeability changes. The tortuosity of the basalt fracture system may be so high that quantifying a significant flow path is not possible.

For the Columbia Plateau region, tectonic forces are assumed to be constant, but strain rates may vary in the future. Currently the regional average rate is 0.75 mm yr^{-1} . The state of effective stress and the rate of strain are two key variables in estimating the type of faulting and associated probabilities and magnitudes.

Faulting in the sub-basalt basement is estimated based on the undetected feature concept. Estimates based on geometrical manipulations of known fault density may not be conservative and, given the nature of the basalt cover, yield erroneous results. The type and magnitude of basalt deformation indicates the possibility of glide motion at depth. Additional strain rate measurements on the basalt structures and continued monitoring of deep-seated seismicity appears essential. The assumption has been made that an undetected fault may run immediately adjacent to a repository but does not initially intersect it. Such a feature might not be discovered during construction of the repository. Rupture of a fault running close to a repository but not through it might result in secondary or sympathetic displacement on joints. Fault displacement of 0.1 to 1.0 meters and joint displacement of a few centimeters are being assumed for any individual event. Results such as permeability changes, accelerations, and total duration of shaking are being estimated. These estimates are used as input in a shaft seal failure submodel. This model considers the acoustic impedance mismatch in the system.

Impact fracturing, and hydraulic fracturing are all being assumed to be relatively insignificant in the Columbia Plateau region. Figures 42, 43, and 44 present the logic flow diagrams for the basalt deformation, sub-basalt basement faulting, and shaft seal failure submodels. Tables 24, 25, and 26 list data requirements and data availability.

It should be emphasized that this section is a description of an example submodel. As such, there is reason to assume that many of the assumptions and components will be altered in the future to accommodate new understanding of the geological and geophysical characteristics of the Columbia Plateau.

METEORITES

This section is devoted to: 1) an argument for dismissing meteorite scenarios from further consideration, and 2) a logic flow and data presentation of how to handle these scenarios, if necessary.

Argument to Eliminate Future Meteorite Analyses

Assume that the probability of a single meteorite strike sufficient to breach the repository is P_o for any given year. The probability of this not taking place is $P_{1,0} = 1 - P_o$. The probability of this not taking place in n years is $P_{n,0} = (1 - P_o)^n$, and therefore the probability of it occurring at least once in n years is $P_{n,1} = 1 - (1 - P_o)^n$.

In his paper on "The Significance of the Rare Event in Geology," Gretener (1967) shows that for small P_1 , that $P_{n,1}$ can be adequately expressed in the well-known Poisson limit for the binomial distribution:

$$P_{n,1} = 1 - 1 - \left(\frac{n}{1}\right) P_o + \left(\frac{n}{2}\right) P_o^2 - \left(\frac{n}{3}\right) P_o^3 + \dots$$

The age of the earth will be used as the yardstick against which the likelihood of the meteorite impact will be measured. The age of the earth is between 3.5 and 5.5×10^9 years old (Holmes 1960). Therefore, if an event has a yearly probability P_o of 10^{-7} , it still has a 98% chance of happening in a time period equal to the age of the earth. But if $P_o = 10^{-10}$, it only has a 20% chance. An event with a yearly probability of 10^{-11} or less has virtually no chance of occurring over a time span equal to the age of the earth

FIGURE 42. Logic Flow Diagram for Deformation

FIGURE 43. Logic Flow for Faulting in the Sub-Basalt Basement

FIGURE 44. Logic Flow for Shaft Seal Failure Submodel

(Gretener 1967). For a single repository 600 m deep, the probability of excavation by a meteorite is found to be on the order of 10^{-11} to 10^{-13} per year (Hartman 1979). Thus, even if the wastes have to remain isolated for a time equal to the age of the earth, they would be exceedingly safe from meteorite impact.

TABLE 24. Deformation Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
DENSITY FUNCTION FOR 'HEALING'		ACCOUNTS FOR SUCH THINGS AS GROWTH OF CLAY MINERALS IN OPEN JOINTS
DENSITY FUNCTION FOR FOLD/ FAULT MOVEMENT IN L.E.M. GIVING CHANGE IN VERTICAL CONDUCTIVITY		EACH 'HUMP(S)' MAY REPRESENT DIFFERENT EVENT(S)
DENSITY FUNCTION FOR FOLD/FAULT MOVEMENT IN L.E.M. GIVING CHANGE IN LATERAL CONDUCTIVITY		
CHANCE FOR SHAFT SEAL FAILURE GIVEN DEFORMATION IN L.E.M.		
CHANCE FOR CREATING A 'NEW' FOLD

(a) Data is under development and is not available at this time.

TABLE 25. Sub-Basalt Basement Fault Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
DENSITY FUNCTION FOR 'SIZE' OF FAULT		ON A SCALE OF 0.0 TO 1.0
CHANGE IN STRESS IN NORTH- SOUTH DIRECTION
CHANGE IN STRESS IN EAST-WEST DIRECTION
CHANGE IN VERTICAL PERMEABILITY OF L.E.M.
CHANGE IN LATERAL PERMEABILITY OF L.E.M.
CHANCE FOR A SIGNIFICANT CHANGE IN STRESS		
CHANCE FOR A NORMAL FAULT		
CHANCE FOR A REVERSE FAULT		
CHANCE FOR A STRIKE-SLIP FAULT		
MINIMUM DISPLACEMENT		
MINIMUM WIDTH		
MINIMUM LENGTH		
MINIMUM PERMEABILITY		

CONTINUED ON NEXT PAGE

(a) Data is under development and is not available at this time.

TABLE 25. (contd)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
MAXIMUM DISPLACEMENT		
MAXIMUM WIDTH		
MAXIMUM LENGTH		
MAXIMUM PERMEABILITY		
MINIMUM PEAK ACCELERATION		
MINIMUM VELOCITIES		
MINIMUM FREQUENCIES		
MINIMUM DURATION		
STARTING NORTH-SOUTH STRESS		
STARTING EAST-WEST STRESS		
CHANCE FOR A FAULT		
MAXIMUM PEAK ACCELERATION		
MAXIMUM VELOCITIES		
MAXIMUM FREQUENCIES		
MAXIMUM DURATION		

TABLE 26. Shaft Seal Failure Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
DENSITY FUNCTION FOR CHANGE IN PERMEABILITY OF SHAFT
CHANCE OF SHAFT BEING AFFECTED BY OTHER DEFORMATION/ENERGY EVENTS IN OTHER SUBMODELS		

^(a) Data is under development and is not available at this time.

Preliminary Analysis

Based on analyses of cratering on the earth and on moon, relationships between meteorite size, excavation depth, crater diameter, and fracture zone depth have been developed (Hartman, 1979). Probabilities are assigned to each discrete excavation depth. These relationships are shown in Figures 45, 46, and 47 and Table 27.

The meteorite is treated as a random event in the submodel. If a meteorite strike is selected in a given time step, the Layer Earth Model characteristics are updated to reflect the crater and fracture zone. The fracture zone depth is considered to be up to four times the depth of the crater (Hartman 1979).

The latest study on energy partitioning during high velocity impacts (O'Keefe and Ahrens 1977) supports the following energy division: 1) 40% goes to heating of the target, 2) 50% into crushing and plastic deformation and vibratory excitation, and 3) 10% into ejector kinetic energy. The vast majority of the ejector related energy goes into lifting masses of shattered rock, which fall back into the crater to form part of the rubble zone, or fall slightly to the side of the crater to form an extended rim.

If the crater intersects the repository, 0.5 to 5.0% of the waste might be dispersed to the atmosphere. The remainder will be available for leaching by surface and ground waters. If only the fracture zone reaches the depth of the waste, ground water may leach the waste and presumably be in communication with the inundated crater. Subsequent preferential erosion is also considered. The biggest unknown is the permeability associated with such a rubble zone and the direction and magnitude of advective transport, if any.

Summary

An argument is presented to dismiss meteorites from future discussions in studies of repositories buried 300-600 m deep. This argument is based on relative probability of 10^{-11} to 10^{-13} yr^{-1} for the site being affected by excavation or impact fracturing. If further analysis is warranted, many of the necessary relationship between crater diameters, crater and fracture zone

FIGURE 45. Critical and Sensitive Damage Zones for Meteorite Impacts (Hartman 1979)

FIGURE 46. Relationship Between Crater Diameter (D), Depth of Excavation (d) and Depth of Fracturing (d_f) (Hartman 1979)

FIGURE 47. Relationship Between Crater Diameter and Total Impact Kinetic Energy

TABLE 27. Example Parameter Magnitudes for Meteorite Impact

Excavation Depth (m)	Fracture Depth (m)	Crater Diameter (km)	Time Required(a) to Affect 60% of Critical Area (yrs)
10	40	0.05	3×10^{11}
33	132	0.19	4×10^{11}
100	400	0.64	4×10^{11}
333	1332	2.50	5×10^{11}
1000	4000	9.20	6×10^{11}

(a) Note the insensitivity to excavation and fracture depth

FIGURE 48. Logic Flow Diagram for Meteorite Submodel

TABLE 2B. Data Requirements and Availability of Meteorite Submodel^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
CHANCE OF A METEORITE HITTING SITE		
SIZE DISTRIBUTION FOR CRATER DIAMETER
LIFE OF POND FORMED IN CRATER		LIFE OF POND
FRACTIONAL AMOUNT OF AIRBORNE MATERIAL FOR A BREACH BY FORMATION OF A METEORITE CRATER
CHANGE IN VERTICAL PERMEABILITY
CHANGE IN LATERAL PERMEABILITY
CHANCE OF A POND FORMING IN THE CRATER		

(a) Data is under development and is not available at this time.

depths, energy partitioning and associated probability information are presented. Meteorites are treated as a random event in the computer model. Logic flow diagrams are presented in Figure 48. Table 28 lists data requirements and data availability.

MAGMATIC ACTIVITY

In general, magmatic activity can be manifested in numerous ways, some of which are mutually exclusive, e.g., basalt lava plateaus vs. explosive volcanic eruptions. Figure 49 shows several features associated with igneous and volcanic activities. Table 29 lists the characteristics of some common volcanic features. In general, volcanic activity is quite rare in stable midcontinental areas. Only 3% of the world's volcanos are found in midcontinental areas, and most of these are associated with the African rift system. However, to dismiss the subject of volcanism affecting a waste repository in the Columbia Plateau region would be difficult. The Columbia River Plateau represents one of the few known examples of flood basalts, with a total volume probably in excess of $259,000 \text{ km}^3$ and a centerpoint thickness of 8-10 km. The basalt stratigraphy consists of a thick sequence of homogeneous lava flows varying in thickness from 3 m to perhaps 150 m. The main mass of basalt was probably extruded between 14 and 17 million years ago, although the youngest flow (Ice Harbor) may only be 8 million years old. The extent of the basalt covering is shown in Figure 50. A schematic of multiple flow stratigraphy is shown in Figure 51.

Successive flows are sometimes interrupted by weathered zones or sedimentary interbeds deposited during the quiescent period between basalt floods. In general, the basalt flows were erupted from fissures aligned in linear vent systems. Feeder dikes, chiefly vertical and oriented north to north-northwest, occur throughout the eastern two-thirds of the plateau (Tauberneck 1970, Swanson et al. 1975). To date, no feeder dikes have been found in the Pasco Basin.

The north-south alignment of dike feeders suggests an east-west crustal extension and possible subsidence of the Pasco Basin in Late Tertiary Time. Zoback and Thompson (1977) regard the northern feeder dikes as part of a major system 700 kilometers in length, extending from the dike swarms in Northern Nevada through the western Snake River Plain into the Columbia Plateau. Thus, the east-west crustal extension during the Late Tertiary, at least in the eastern portion of the Columbia Plateau, has changed to north-south compression during the present stress regime. Not only has the orientation of the principal stress been altered, but the intensity of the stress has diminished

FIGURE 49. Block Diagram of Plutonic and Volcanic Structures
(U.S.G.S. Atlas of Volcanic Phenomena)

considerably during the past several million years (Coombs 1979). Thus, the conditions for renewed flood basalt extrusion, may no longer exist. Furthermore such a tensional stress regime should not be reproduced in the next million years. Naturally, this assumes that changes in the regional stress field are gradual and not sudden. Additionally, graphs showing time versus magma volume suggest volcanic activity peaked 15 to 13 m.y. ago, decreased considerably until about 6 m.y. ago, when it ceased.^(a) Even though the

(a) This information is based on work done by Crowe, which is reprinted in this document. A summary of Crowe's research has been published (Crowe 1979).

TABLE 29. Generalized Classification of Volcanic Activity Based on Approximate Magmatic Compositions^(a)

	Major Types	Size Parameters
Basaltic	A. Strombolian	Height: 100-500 m Width: 300-100 m Disruption Depth: ± 200 m
	B. Phreatomagmatic (Magma-water steam explosions)	Height: 50-200 m Width: 0.3-3 km Disruption Depth: ± 200 m
<u>Andesitic</u>	A. Composite Volcano	Height: 0.5-3 km Width: 1 km - 5 km Disruption Depth: 0.5 - 4 km
	B. Caldera (single center)	Height: 0.5 - 3 km Width: 2 km - 10 km Disruption Depth: 0.5 - 5 km
<u>Silicic</u>	A. Dome Complex	Height: 0.5 - 2 km Width: 1 km - 10 km Disruption Depth: 0.5 - 4 km
	B. Large Cauldrons	Height: 1 - 3 km Width: 5 - 30 km Disruption Depth: 1 km - 10 km

(a) This information is based on work done by Crowe, which is reprinted in this document. A summary of Crowe's research has been published (Crowe 1979).

probability of future volcanic activity in the Pasco Basin area appears to be exceedingly low, the history of the region dictates some consideration of the consequences associated with such activity.

Magma composition is another important factor to be considered. In general, basaltic eruptions tend to be nonexplosive and highly mobile and could transport radioactive material up to about 300 km. The wastes could be entombed in the lava flow upon cooling and solidification. The Columbia River Flood Basalts are an excellent example of this magma composition. Silicic volcanic eruptions, on the other hand, are commonly highly explosive and repository material could be dispersed large distances and into the upper regions of the atmosphere.

FIGURE 50. Map Showing the Columbia and Snake River Basalts of Northwestern United States (after Waters 1955)

FIGURE 51. Schematic Diagram of Multiple Flows From Linear Fissures

The exact location of the volcanic activity relative to the repository site is of importance. Direct intersection of the repository site by the volcanic conduit could result in immediate incorporation and transport of radioactive material. The range of sizes of typical basalt feeder dikes must be estimated for the Columbia Plateau. A 0.5 to 1.5 km zone around any feeder dike or linear vent will be presumably affected in a direct manner. The probability of intersection is a function of the distance to the feeder zone, the size of the feeder zone, the size of the repository and the probability of the feeder zone being active.

Assuming that the waste is contacted by extrusive magmatic material, several dispersal mechanisms are possible. Table 30 illustrates generalized transport distances of common volcanic processes associated with various types of volcanic eruptions. Dispersal mechanisms can be divided into two classes: 1) those mechanisms that are controlled by topography and are active primarily on the steep slopes of a volcano and adjacent areas (lava flows, volcanic mudflows, pyroclastic flow), and 2) air-fall activity that is controlled by the explosiveness of an eruption and prevailing wind directions.^(a)

TABLE 30. Transport Distances and Eruption Types of Volcanic Events

<u>Magma Type</u>	<u>Lava Flows</u>	<u>Lahars</u>	<u>Pyroclastic Flow</u>	<u>Air Fall</u>
Flood basalts	300 km	--	--	--
Basaltic "cinder cones"	10 km	5 km	--	30 km
Basaltic "Phreatic"	10 km	6 km	20 km	regional
Andesitic "composite cone"	5-10 km	30 km	30 km	regional
Silicic "Crater Lake"	5 km	40 km	50 km	global
Decreasing Frequency		Slope Control		Wind Control

(a) This information is based on work done by Crowe, which is reprinted in this document. A summary of Crowe's research has been published (Crowe 1979).

A special case of magmatic activity involves an igneous body rising to an unspecified depth below the repository site. The size of such an intrusive body can vary from square meters to thousands of square kilometers. Potential consequences of such emplacement would include: broad dome uplift and development of radial and concentric fracture systems, faulting, accelerated erosion rates, juxtaposition of a hydrothermal convection system above the magma chamber, and upward propagation and eruption of surface volcanism fed from the igneous body. This could be manifested as magma or steam as in a geyser. Parameters controlling the magnitude of these potential events include: depth of the igneous mass, dimensions and volume of the body, and residence time as a molten body (a function of initial cooling mechanisms and heat replenishment mechanisms).

In addition to volcanism that might occur at or immediately adjacent to the repository, a much higher probability exists for volcanic activity located well away from the repository site. Potential effects decrease rapidly with increasing distance from the site. At distances greater than 50 km, e.g., the Cascade volcanoes, effects of many types of volcanic activity would be minimal.^(a) Major silicic volcanic eruptions would have the following possible consequences: surficial mantling by air-fall pumice, vegetation, drainage, and erosional modifications, and climatic effects.^(a) Major basaltic flows could result in surficial magma loading and potentially some diagenesis or physical alterations of sedimentary material in the vicinity of the repository. Shale and sandstone might be particularly sensitive to such burial and the associated increased pressures and temperatures.

In general, renewed volcanism in the immediate area of the repository is considered to be of only marginal significance because of its extremely small probability of occurrence. Based on a time versus magma volume graph, it can be shown that the peak of volcanic activity occurred in the range of 15-13 m.y. ago. Subsequent activity has been of considerably waning volume with no activity since the Pliocene. Additionally the stress regime active at the time

(a) This information is based on work done by Crowe, which is reprinted in this document. A summary of Crowe's research has been published (Crowe 1979).

of the major extrusions no longer exists. Although estimates of the probability have been made in other studies, such an estimate for the Columbia Plateau region is premature until more is known about the deep structure of the area and the general tectonic relationships.

Summary

The subject of magmatic activity must be considered for any site in the Columbia Plateau region. However, the tensional stress regime that may have supported the tremendous outpouring of basalts some 8 to 17 million years ago is apparently no longer active. The area now seems to be in a state of gentle north-south compression, which is far different from that existing during the time of the major extrusive activity. Naturally a compressive stress regime does not eliminate the possibility of renewed volcanic activity, but it does tend to minimize it. Time versus magma volume graphs also suggest that major flood basalt activity has ended. Furthermore, renewed extrusions of basalt lava flows might prove beneficial to a deeply buried repository as long as the feeder dikes do not result in the release of radioactive materials or initiate elevated hydrothermal conditions in the vicinity of the repository. Also, incorporation of radioactive material in molten basalt appears to be an effective method of stopping further migration of the material.

At distances greater than 50 km, the effects of most types of volcanic activity would be minimal. Climate perturbations and changes in drainage and erosion patterns might be considered for this case, however. The probability for volcanism in the Cascade Mountains has been estimated to be 10^{-2} yr^{-1} (Crandall et al. 1975). As long as the site is 50-100 km away, however, this should not pose a threat. The probability of volcanic activity within the Columbia Plateau region is considered to be an order of magnitude less likely than the rupture of a deep seated fault. The logic flow diagram is presented in Figure 52. Data requirements and availability are in Table 31.

UNDETECTED FEATURES

Undetected features include numerous features, such as boreholes, basaltic ring structures, flow terminations, lava tubes, remnant stream beds, and folds and faults, which were discussed previously. The basic consequences associated

FIGURE 52. Logic Flow for Magmatic Submodel

TABLE 31. Magmatic Activity Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
FRACTIONAL AMOUNT OF WASTE INTRODUCED INTO THE AIR IN A "NORMAL" MAGMATIC BREACH
FRACTIONED AMOUNT OF WASTE INTRODUCED INTO THE SURFACE WATER SYSTEM DURING A MAGMATIC BREACH
FRACTIONAL AMOUNT OF WASTE INTRODUCED INTO THE AIR IN A PHREATIC MAGMATIC BREACH
FRACTIONAL AMOUNT OF WASTE INTRODUCED IN THE SURFACE WATER SYSTEM BY A PHREATIC MAGMATIC BREACH
CHANCE FOR A MAGMATIC EVENT IN THE BASIN		
CHANCE FOR A MAGMATIC EVENT AT THE SITE GIVEN AN EVENT IN THE BASIN		

(a) Data is under development and is not available at this time.

with these features are: 1) they could provide a short circuit path between confined aquifers, and 2) they could be sources of significant quantities of ground water. The logic flow diagram is shown in Figure 52.

These features will not intersect the repository, because they would be discovered during excavation. Therefore, they cannot initiate breaches and are only associated with the transport paths once migration has started because of a breach initiated by some other disruptive phenomena. Furthermore, with

the exception of the borehole, the features should not create a continuous vertical flowpath to the surface. The features are likely associated with a single basalt flow, if in fact they are present at all. Therefore, the transport pathway associated with undetected features would be expected to be a stair-stepped one (Figure 53). Undetected features might result in the discharge point for the leached nuclides, if any, being somewhat different from that expected. Therefore, these possible bridges between aquifers must be studied and the possibility of shorter than expected travel times to the biosphere be analyzed. Some of these features and their possible consequences are discussed in the following text.

Undetected Boreholes

Project Salt Vault is an example of the problems associated with undetected boreholes. Speculation is that such features may have been at least partly responsible for the disappearance of a quarter of a million gallons of injected non-contaminated water during the testing of a possible waste storage site. No assessment has as yet been made of this potential problem for a site in the Columbia Plateau. Essentially all borehole holes are much shallower than the anticipated repository depth, and because control and monitoring of boreholes in the Columbia Plateau region have been good, it is anticipated that the avoidance of existing holes will be a relatively simple task.

Abandoned water wells appear to be the only major concern with respect to undetected boreholes. The problem will have to be studied when a candidate site is selected. However these boreholes are generally far shallower than the anticipated depth of the repository. The mere presence of a borehole is not a significant safety hazard though. It still requires: 1) another phenomenon to breach the repository, and 2) a driving force such as an artesian head or pumping activity to move water through the repository and up the borehole to the surface. New holes associated with resource exploration are not included in this undetected borehole category.

Basaltic Ring Structures

Basaltic ring structures are circular geomorphological anomalies that have been located on the Columbia Plateau. The best examples are found in a 60 km²

FIGURE 53. Potential Consequences Associated with Undetected Features

area within the channeled scablands around Odessa. The features are relatively small, 50 to 500 m across. Exposures are restricted largely to the scabland coulees and immediate environs where they have been exhumed from beneath widespread loess deposits (Hodges 1978).

The suggestion has been made that ring structures are restricted to a single basalt flow, in this case the Roza member of the Yakima Basalt sequence. In the Odessa area, the Roza is approximately 70-100 m thick, about twice its usual thickness elsewhere, so that a pre-Roza topographic basin is implied. Such features might be hypothesized for other flows if a specific set of conditions were met at the time of, and subsequent to, flow emplacement. Such

features could imply vertical hydraulic communication between interflow zones bounding a single basalt flow. However, superposition of these features from flow to flow such that a direct path from the repository to the surface could exist seems almost impossible.

The following sequence of events is presented as an explanation for the ring structures (Figure 54):

- A Roza flow overran a topographic basin where an exceptionally thick section of the lava was trapped.
- During the cooling and solidification process, the rising groundwater table intersected the still molten interior of the ponded flow.
- The resulting interaction of confined lava with water disrupted the crust as volatile pressures increased, and the effects at the surface ranged from venting to simple doming or cracking of the crust.
- Subsequent Missoula flooding and other erosion processes and loess deposition effectively altered the surface expressions of the features.

Remnant Stream Beds

Remnant stream beds may be of some concern. According to Brown (1978), zones of anomalously high permeability may have been formed when basalt flows overrode existing streams. These zones may be the result of brecciation at the base of the flow or of the basalt covering porous sands and gravels in the stream bed.

These features would tend to follow the ancient drainage patterns and would tend to be relatively narrow (Figure 55). According to Brown (1978) there are examples of linear or meandering zones of successful water wells. However, wells drilled a few hundred feet off the flank of the zone produce very little water production. The explanation is that the width of the successful well zone correlates with the width of an ancient stream bed, and that the linear or meandering sequence of wells are following the ancient stream course.

The implications of these zones are: 1) the volume of water available to these wells should be limited since recharge to such a feature would probably

FIGURE 54. Sequence of Events Postulated to Explain the Basaltic Ring Structures. (A) Roza Flow Ponded over a Topographic Low. (B) Intersection of Rising Groundwater Table with Molten Interior of Basalt Flow. (C) Subsidence of the Crust, with Intrusion of Lava into Fractures. (D) Present Landscape After Erosion. (Hodges 1978)

FIGURE 55. Remnant Stream Beds a) Pre-Flow Conditions b) During Flow Advance c) Post-Flow Conditions

be slight, 2) these zones may be potential migration pathways, and 3) given the narrow dimension, they may be difficult to locate during the exploratory phase of the project. The zones, however, tend to be of limited extent or discontinuous in nature.

Lava Tubes

Lava tubes are cavernous features which in some cases can extend significant distances. It is speculated that they are formed by trapped fluids existing with a cooling magma body. To date, no lava tubes have been confirmed to exist within the Columbia Plateau.

Summary

Undetected features include features such as boreholes, ring structures, breccia pipes, remnant stream beds, folds, and faults. The potential consequences of such features include: 1) a short circuit path between confined aquifer systems and thereby a possible change of transport pathlengths and hydraulic conditions, and 2) sources of significant quantities of ground water. Figure 56 presents the logic flow for this submodel. Table 32 presents the data requirements and availability.

FIGURE 56. Logic Flow for Undetected Features

TABLE 32. Undetected Feature Submodel Data^(a)

SUBJECT	ILLUSTRATIVE GRAPHICAL REPRESENTATION OR DATA	COMMENTS
VERTICAL TRANSMISSIVITY DENSITY FUNCTION		DIFFERENT 'HUMPS' MAY REPRESENT DIFFERENT FEATURES (EX. RING STRUCTURE)
DENSITY FUNCTION FOR DIRECTION IN CLOCKWISE DEGREES FROM MAIN GROUNDWATER FLOW		UNIFORM DISTRIBUTION
DENSITY FUNCTION FOR DISTANCE TO UNKNOWN FEATURE
DENSITY FUNCTION FOR DEPTH OF BORE HOLE
DENSITY FUNCTION FOR VERTICAL TRANSMISSIVITY OF A LOST BORE HOLE
CHANCE FOR AN UNKNOWN BORE HOLE		
CHANCE FOR AN UNDETECTED SUB-BASALT FAULT		
CHANCE FOR UNDETECTED FOLD		
CHANCE FOR A FOLD, IF FOUND BEING A MONOCLINE		
MAXIMUM DISTANCE TO AXIS IF EAST-WEST FOLD OR FAULT		
CHANCE FOR DESIGN ERROR IN SHIFT SEAL		
AVERAGE NUMBER OF UNDETECTED FEATURES (MAX OF 5)		FOR POISSON DISTRIBUTION

(a) Data is under development and is not available at this time.

TABLE 32. (contd)

REQUIRED INPUT	AVAILABLE DATA	COMMENTS
TRANSPORT DISTANCES FOR LAHARS	BASALTIC 6.0 km ANDESITIC 30.0 km SILICIC 40.0 km	
TRANSPORT DISTANCE FOR PYROCLASTIC FLOW	BASALTIC 20.0 km ANDESITIC 30.0 km SILICIC 50.0 km	
TRANSPORT DISTANCE FOR AIR FALL	BASALTIC REGIONAL ANDESITIC REGIONAL SILICIC GLOBAL	
PROBABILITY OF THE SITE BEING DIRECTLY INTERSECTED	INSUFFICIENT DATA ON GENERAL MAGMATIC PROBABILITY AND TYPE. GIVEN THIS, A GEOMETRICAL CALCULATION CAN YIELD THE INTERSECTION PROBABILITY	
AMOUNT OF WASTE TRANSPORTED BY LAVA	INTERSECTION - TOTAL INVENTORY NO INTERSECTION - NONE	BASED ON: 1) PROBABILITY OF ACTIVITY WITHIN 50 km 2) TYPE OF ACTIVITY, 3) DISRUPTION HEIGHT, WIDTH AND DEPTH, AND 4) THE SIZE OF THE REPOSITORY
AMOUNT OF WASTE TRANSPORTED IN A HYDROTHERMAL SYSTEM	INSUFFICIENT DATA	
EFFECT ON SURFACE DRAINAGE AND EROSION	INSUFFICIENT DATA	PRIMARILY DUE TO LAVA BLOCKING RIVER ROUTES AND ASH FALL ELIMINATING VEGETATION
EFFECT ON AQUIFER RECHARGE AND FLOW	INSUFFICIENT DATA	THIS SHOULD BE CONSIDERED SINCE THE DEEP AQUIFER RECHARGE AREAS MAY IN SOME CASES BE NEAR TO THE CASCADE VOLCANIC ZONE
LITHOSTATIC STRESS FACTOR	0.22 BARS m^{-1} OF LAVA THICKNESS	

REPORT SUMMARY

The following topics are briefly summarized in this section: 1) interface between Release Scenario Analysis and Release Consequence Analysis Tasks, 2) site specific nature of the methodology, 3) the example submodels developed for the Columbia Plateau region, 4) incorporation of results from near-field studies, 5) interface between the Release Scenario and specific site managers, 6) and the flexibility of the tool and the requirements for interactive computer graphics.

Interface Between Release Scenario and Release Consequence Studies

The repository simulation model is applicable only to a release scenario analysis. Release consequence analysis requires tools such as numerical groundwater and nuclide transport codes. The interface between these two tasks is very critical.

If operated purely in the interactive mode, a case history (scenario) can be established and simulated. If no breach is detected, then the operator can change the data distributions or select a new scenario. If a breach is detected, then the operator can record the time of the breach to specify the nuclide inventory and he can initialize the geohydrological system upon which to run the transport codes. The most important variables are pathlengths, hydraulic conductivities, fluid potentials, and lithologies along the path.

If the Monte Carlo mode is selected, thousands of case histories (scenarios) can be generated, some of which may differ only by the magnitude or rate of a single phenomenon. When the variance in the output falls within a specified interval, then the program is automatically terminated. At this point, the consequence analyst can specify any desired time, e.g., 10^3 , 10^4 , 10^5 , 10^6 yr, and receive a breach status report. If any breaches were detected in any of the simulations at the end of the selected time period, then the operator can access information concerning the range of conductivities, fluid potentials, pathlengths, etc. Alternatively, he can retrieve individual case histories with detailed descriptions and associated probability data. It is important to remember that each time a selection is made from a data density

curve, a probability number is associated with it. Therefore, a cumulative probability is associated with any given breach identified within the set of simulations.

Site Specific Nature of the Problem

A Repository Simulation model must be developed for each site and carefully tailored to the governing rules and data distributions associated with that site. Site specific assessments are mandatory and simulation modeling can only be as good as the understanding and quantifying of the physical and chemical system. The methodology is transferable from site to site, but the specific codes are not. Modularizing models may expedite the transfer from one site to another.

Columbia Plateau Submodels

Eleven submodels have been developed for the Columbia Plateau region of Eastern Washington. These submodels include:

- Climate
- Continental glaciation
- Alpine glaciation
- Sea level fluctuations
- Geomorphic events
- Deformation
- Sub-basalt basement faulting
- Shaft seal failure
- Undetected features
- Magmatic activity
- Meteorites.

It is anticipated that the preliminary submodels will generate future discussion. Such models will evolve and improve with time, and these twelve versions are designed as preliminary examples. It is anticipated that as specific site managers, e.g., Rockwell Basalt Waste Isolation Program, extend the available data base and our knowledge of the geology, geophysics, and hydrology of the Columbia Plateau, that the Release Scenario Analysis Submodels will be altered accordingly.

Incorporation of Near Field Results

By direction, the methodology described here does not explicitly include such near-field topics as mining induced stresses, thermal loading, and/or geochemical alterations produced by the repository and contents. Such phenomena tend to dominate the picture in the first hundred years or so. It is anticipated that the results of these near-field studies will be considered in initializing the Layered Earth Model. For example, if differential thermal expansion and/or contraction has a certain probability of increasing the bulk conductivity of a host rock, then the initial permeability of the host rock in the Repository Simulation model will reflect this change. Thus the initial LEM characteristics may be representative of the possible state of the system at the end of 100 years.

Interfacing With Specific Site Managers

The Columbia Plateau has been selected as an illustrative case only. In no way should this report be considered as a preliminary safety study for the area. Significant cooperation and interaction between the modeling group and the Site Contractor are necessary. As the understanding of a specific site improves, so must the Release Scenario and Release Consequence models. In addition, it is important to note that these models will both emphasize the strengths of a potential site as well as highlight any identifiable weaknesses. Parametric analyses may facilitate this effort. In other words, the primary mission of the Release Scenario task is to anticipate all of the questions that may arise in future formal proceedings. Only in this manner can defensible and logical answers be available for discussion. It is anticipated that a properly chosen site may be perturbed by disruptive phenomena discussed in this report, but should not be breached or failed with an "unacceptable" occurrence probability. The Release Scenario model may assist in demonstrating this fact or alternatively assist in disqualifying a site from further consideration.

Interactive Utilization of the Tool

The black-box syndrome represents one potential weakness of the proposed methodology. To combat this problem, emphasis is being placed on interactive computer graphics with a light-pen sensitive scope. Block diagrams similar to

that in Figure 7 can be scanned by a small group of users. If more analysis of the Glaciation submodel is desired, for example, a mere touch of the light-pen to that specific block on the screen will result in the projection of the logic flow diagrams for that submodel. Another touch of the pen to a specific component of the submodel will result in projection of the data associated with that component. In this manner, the user can interrogate the complete logic chain and change any input data distribution desired. The operator can specify the scenario components, their order, timing, magnitudes, rates and lag times. Once the operator is satisfied with his understanding of how the system works and the sensitivity of the output to perturbations of the input, he can select the Monte Carlo mode and generate multiple scenario and output distributions.

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APPENDIX

APPENDIX

GLOSSARY OF TERMS

alluvial fan: A fan-shaped deposit formed by a stream either where it issues from a narrow mountain valley onto a plain or broad valley, or where a tributary stream joins a main stream.

alluvium: The detrital materials eroded, transported, and deposited by streams; an important constituent of shelf deposits. Also known as alluvial deposit; alluvion.

anticline: A fold in which layered strata are inclined down and away from the axes.

*aquiclude: A body of saturated but relatively impermeable material that does not yield appreciable amounts of water to wells. Characterized by very low "leakance" (the ratio of vertical hydraulic conductivity to thickness) and very low rates of yield from compressible storage.

aquifer: A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

aquitard: A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed.

artesian aquifer: An aquifer that is bounded above and below by confining beds. Also known as confined aquifer.

basement: A complex, usually of igneous and metamorphic rocks, that is overlain unconformably by sedimentary strata.

basin: 1. A low-lying area, wholly or largely surrounded by higher land, that varies from a small, nearly enclosed valley to an extensive, mountain-rimmed depression. 2. An entire area drained by a given stream and its tributaries. 3. An area in which the rock strata are inclined downward from all sides toward the center. 4. An area in which sediments accumulate.

batholith: A body of igneous rock, 40 square miles or more in area, emplaced at great or intermediate depth in the earth's crust.

block faulting: A type of normal faulting in which the crust is divided into structural or fault blocks of different elevations and orientations. It is the process by which block mountains are formed.

breccia: 1. Fragmental rock whose components are angular and therefore, as distinguished from conglomerates, are not waterworn. There are friction or fault breccias, talus breccias, and eruptive breccias. 2. A rock made up of highly angular coarse fragments. May be sedimentary or formed by crushing or grinding along faults.

cap rock: 1. A disk-like plate over all or part of the top of most salt domes in the Gulf Coast states composed of anhydrite, gypsum, limestone, and occasionally sulfur. 2. A comparatively impervious stratum immediately overlying an oil- or gas-bearing rock.

chimneying: The process of progressive collapse of rock overlying an explosion-produced cavity resulting in a tall under ground cylinder (chimney).

clastic: Rock or sediment composed of fragments that have been transported from their place of origin, as sandstone and shale.

cleavage: Splitting, or the tendency to split, along parallel, closely positioned planes in rock.

columnar jointing: Cracks that break rocks into polygonal columns, usually forms in volcanic rocks because of cooling and shrinking.

conglomerate: Cemented, rounded fragments of water-worn rock or pebbles, bound by a siliceous or argillaceous substance.

consolidated (material): In geology, natural materials that have been made firm, cohesive, and hard.

crust: Outer layer of the earth above the mantle.

crystalline rock: An inexact general term for igneous and metamorphic rocks as opposed to sedimentary rock.

curie: A unit of radioactivity, defined as that quantity of any radioactive nuclide which has 3.700×10^{10} disintegrations per second. Abbreviated Ci.

depositional environment: A geographically restricted environment where sediment accumulates under similar physical, chemical, and biological conditions.

diagenesis: Process involving physical and chemical changes in sediment after deposition that converts it to consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement as in the development of dolomite.

diapirism: The process of piercing or rupturing of domed or uplifted overlying rocks by core material heated to the plastic state, either by tectonic stresses as in anticlinal folds, or by the effect of geostatic load in sedimentary strata as in salt domes or shale diapirs, or as in the case of igneous intrusions, forming diapiric structures such as plugs or batholiths. The concept was first applied to salt structures, which are the most common type of diapir.

differential erosion: Rapid erosion of one area of the earth's surface relative to another.

dike: A tabular body of igneous rock that cuts across adjacent rocks or cuts massive rocks.

dome: 1. A circular or elliptical, almost symmetrical upfold or anticlinal type of structural deformation. 2. A large igneous intrusion whose surface is convex upward.

ephemeral stream: A stream or reach of a stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table. The term may be arbitrarily restricted to a stream that does not flow continuously during periods of as much as one month. Cf: intermittent stream.

epoch: A division of geologic time; when capitalized it becomes a formal division of geologic time corresponding to a series of rock and a subdivision of a period.

erosion: The group of processes whereby soil or rock material is loosened or dissolved and removed from a part of the earth's surface.

fault: A fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture.

fault block: A rock mass that is bounded by faults; the faults may be elevated or depressed and not necessarily the same on all sides.

fault system: Two or more fault sets that interconnect.

flood plain deposit: Sandy and clayey sediment deposited by river water spreading out over a flood plain.

foliation: A laminated structure formed by segregation of different minerals into layers that are parallel to the schistosity.

geochemistry: The study of the chemical composition of the various phases of the earth and the physical and chemical processes which have produced the observed distribution of the elements and nuclides in these phases.

geohydrology: The science dealing with underground water, often referred to as hydrogeology.

geoid: The figure of the earth considered as a sea-level surface extended continuously over the entire earth's surface.

geomorphology: The study of the origin of secondary topographic features that are carved by erosion in the primary elements and built up of the erosional debris.

geophysics: The physics of the earth and its environment, that is, earth, air, and (by extension) space.

geothermal: Pertaining to the heat of the interior of the earth.

glacial lobe: A tongue-like projection from a continental glacier's main mass.

glacial maximum: The time or position of the greatest extent of any glaciation; most frequently applied to the greatest advance toward the equator of Pleistocene glaciation.

glaciation: Alteration of any part of the earth's surface by passage of a glacier, chiefly by glacial erosion or deposition.

graben: A block of the earth's crust, generally with a length much greater than its width, that has dropped relative to the blocks on either side.

granitic: 1. Of, pertaining to, or composed of, granite or granite-like rock. 2. A term applied to coarse- and medium-grained, granular igneous rocks in which all or nearly all of the mineral constituents are anhedral (xenomorphic) and of approximately the same size.

ground water or ground-water: Subsurface water occupying a saturation zone.

hydraulic conductivity: Has dimensions of length per unit time. A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of groundwater at the prevailing viscosity through a cross-section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow.

hydraulic damming: Temporary ponding of water produced by a channel constriction.

hydraulic gradient: Represents the vertical change in the ground-water surface elevations per unit of horizontal.

hydrostatic pressure: 1. The pressure at a point in a fluid at rest due to the weight of the fluid above it. Also known as gravitational pressure. 2. The negative of the stress normal to a surface in a fluid.

hydrothermal: An adjective applied to heated or hot aqueous solutions, to the processes in which they are concerned, and to the rocks, ore deposits, and alteration products produced by them. Hydrothermal solutions are of diverse sources, including magmatic, meteoric, and connate waters.

interfluve: The district between adjacent streams flowing in the same general direction.

interstice: An opening or space between one thing and another, as an opening in a rock or soil that is not occupied by solid matter. On the basis of origin, it may be classified as an original interstice or a secondary interstice; on the basis of size, as a capillary interstice, a subcapillary interstice, or a supercapillary interstice. Syn: void; pore. Adj: interstitial.

intrusion: 1. The process of emplacement of magma in pre-existing rock. Also known as injection; invasion; irruption. 2. A large-scale sedimentary injection. Also known as sedimentary intrusion. 3. Any rock mass formed by an intrusive process.

isopach: A line drawn on a map through points of equal thickness of a designated stratigraphic unit or group of stratigraphic units. Cf: isochore. Syn: isopachous line; isopachyte; thickness line; thickness contour.

joint: A fracture that traverses a rock and does not show any discernible displacement of one side of the fracture relative to the other.

laccolith: a body of igneous rock intruding into sedimentary rocks so that the overlying strata have been notably lifted by the force of intrusion.

lava: Fluid rock such as that which issues from a volcano or a fissure in the earth's surface; also the same material solidified by cooling.

lithification: 1. Conversion of a newly deposited sediment into an indurated rock. Also known as lithifaction. 2. Compositional change of coal to bituminous shale or other rock.

lithology: 1. The physical character of a rock, generally as determined megascopically or with the aid of a low-power magnifier. 2. The microscopic study and description of rocks. Petrography.

loess: An essentially unconsolidated, unstratified calcareous silt; commonly it is homogeneous, permeable, and buff to gray in color, and contains calcareous concretions and fossils.

low-angle fault: A fault, the dip of which is 45° or less. Cf: high-angle fault.

mafic: Refers to an igneous rock composed chiefly of one or more magnesium and iron-bearing, dark-colored minerals.

magmatism: The formation of igneous rock from magma.

mantle: The intermediate shell zone of the earth below the crust and above the core (to a depth of 3480 kilometers).

monocline: A stratigraphic unit that dips from the horizontal in one direction only; not as part of an anticline or syncline.

orogeny: The process of forming mountains. Especially the intense deformation of rocks by folding and faulting which, in many mountainous regions, has been accompanied by metamorphism, invasion of molten rock, and volcanic eruption; in modern usage, orogeny produces the internal structure of mountains, and epeirogeny produces the mountainous topography. Also known as orogenesis, tectogenesis.

outcrop: Exposed stratum or body of ore at the surface of the earth. Also known as cropout.

permeability: The capacity of a porous rock, soil, or sediment for transmitting a fluid without damage to the structure of the medium. Also known as perviousness.

plateau basalt: Those basaltic lavas that occur as vast composite accumulations of horizontal or subhorizontal flows and which, erupted in rapid succession over great areas, have at times flooded sectors of the earth's surface on a regional scale. They are generally believed to be the product of fissure eruptions.

pluton: In the strictest sense, a body of igneous rock that has formed beneath the surface of the earth by consolidation from magma. In a broader sense, it may include bodies composed of pseudoigneous rock that formed beneath the surface of the earth by the metasomatic replacement of an older rock.

pluvial: 1. Due to the action of rain. 2. Pertaining to deposits by rain-water or ephemeral streams.

porosity: That portion of an aquifer's volume which consists of openings or pores; that is, the proportion of its volume not occupied by solid material. Porosity is an index of how much ground water can be stored in the saturated material and is usually expressed as a percentage of the bulk volume of the material.

recharge: 1. The processes involved in the replenishment of water to the zone of saturation. 2. The amount of water added or absorbed. Also known as ground-water increment; ground-water recharge; ground-water replenishment; increment; intake.

regional metamorphism: Geological metamorphism affecting an extensive area.

rift: 1. narrow opening in a rock caused by cracking or splitting. 2. A high, narrow passage in a cave.

rift valley: A deep, central cleft with a mountainous floor in the crest of a midoceanic ridge. Also known as central valley; midocean rift.

rift zone: A system of crustal fractures and faults.

runoff: 1. Surface streams that appear after precipitation. 2. The flow of water in a stream, usually expressed in cubic feet per second; the net effect of storms, accumulation, transpiration, meltage, seepage, evaporation, and percolation.

sedimentary basin: Geologically depressed area with thick sediments in the interior and thinner sediments at the edges.

seismicity: The phenomena of earth movements. Also known as seismic activity.

shield: A continental block of the earth's crust that has been relatively stable over a long period of time and has undergone only gentle warping in contrast to the strong folding of bordering geosynclinal belts. Mostly composed of precambrian rocks.

sill: 1. Submarine ridge in relatively shallow water that separates a partly closed basin from another basin or from an adjacent sea. 2. A tabular igneous intrusion that is oriented parallel to the planar structure of surrounding rock.

sinkhole: A funnel-shaped depression in the land surface generally in a limestone region communicating with a subterranean passage developed by solution.

slickenside: A surface that is polished and smoothly striated and results from slippage along a fault plane.

static head: Pressure of a fluid caused by the head of fluid above some reference point.

stock: (Geol) See pipe. (Petr) A usually discordant, batholithlike body of intrusive igneous rock not exceeding 40 square miles in surface exposure and usually discordant.

strain: Change in length of an object in some direction per unit undistorted length in some direction, not necessarily the same; the nine possible strains form a second-rank tensor.

stratigraphy: A branch of geology concerned with the form, arrangement, geographic distribution, chronologic succession, classification, correlation, and mutual relationships of rock strata, especially sedimentary. Also known as stratigraphic geology.

stratum: A tabular or sheet-like mass, or a single and distinct layer, or homogeneous or gradational sedimentary material (consolidated rock or unconsolidated earth) of any thickness visually separable from other layers above and below by a discrete change in the character of the material deposited or by a sharp physical break in deposition, or by both; a sedimentary bed. The term should be restricted to sedimentary material and is generally considered to be synonymous with "bed". The term frequently used in its plural form, strata. Lamina.

strike slip: The component of the slip of a fault that is parallel to the strike of the fault. Also known as horizontal displacement; horizontal separation.

strike-slip fault: A fault, the actual movement of which is parallel to the strike of the fault.

syncline: A fold in rocks in which the strata dip inward from both sides toward the axis. Ant: anticline.

tectonic: Of, pertaining to, or designating the rock structure and external forms resulting from the deformation of the earth's crust. As applied to earthquakes, it is used to describe shocks not due to volcanic action or to collapse of caverns or landslides.

tectonism: 1. Crustal instability. 2. The structural behavior of an element of the earth's crust during, or between, major cycles of sedimentation.

terrace: 1. A horizontal or gently sloping embankment of earth along the contours of a slope to reduce erosion, control runoff, or conserve moisture. 2. A narrow coastal strip sloping gently toward the water. 3. A long, narrow, nearly level surface bounded by a steeper descending slope on one side and by a steeper ascending slope on the other side. 4. A benchlike structure bordering an undersea feature.

thrust fault: A low-angle (less than a 45° dip) fault along which the hanging wall has moved up relative to the footwall. Also known as reverse fault; reverse slip fault; thrust slip fault.

topography: The physical features of a district or region, such as are represented on maps, taken collectively; especially, the relief and contour of the land.

transmissivity: In an aquifer, the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width under a unit hydraulic gradient. Though spoken of as a property of the aquifer, it embodies also the saturated thickness and the properties of the contained liquid.

underfit stream: A stream that appears too small to have eroded the valley in which it flows.

underthrust: A thrust fault in which the lower, active rock mass has been moved under the upper, passive rock mass.

uplift: Elevation of any extensive part of the earth's surface relative to some other parts.

upwarping: The upwards warping or uplift of a regional area of the earth's crust, usually as the result of the release of isostatic pressure, e.g., melting of an ice sheet.

water table: The planar surface between the zone of saturation and the zone of aeration. Also known as free-water elevation; free-water surface; ground-water level; ground-water surface; ground-water table; level of saturation; phreatic surface; plane of saturation; saturated surface; water level; waterline.

underneath the thrust fault in which the lower, active rock mass has been

eroded under the upper, passive rock mass.

uplift. Elevation of any extensive part of the earth's surface relative to

some other part.

uplifted. The upward carrying or uplift of a regional area of the earth's

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