MASTER

27
6/8/81
240 NT 1-5
RH884
(1)

Assessment of Effectiveness of Geologic
Isolation Systems

**Use of Geohydrologic Response
Functions in the Assessment of Deep
Nuclear Waste Repositories**

May 1981

Prepared for the U.S. Department of Energy
Office of Nuclear Waste Isolation
under Contract DE-AC06-76RLO 1830

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

PNL-3817

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

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

Assessment of Effectiveness of
Geologic Isolation Systems

USE OF GEOHYDROLOGIC RESPONSE
FUNCTIONS IN THE ASSESSMENT OF
DEEP NUCLEAR WASTE REPOSITORIES

R. W. Nelson

May 1981

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

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof; nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Pacific Northwest Laboratory
Richland, Washington 99352

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ACKNOWLEDGMENTS

This research, supported by the Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program, was conducted by Pacific Northwest Laboratory, managed by Battelle Memorial Institute for the Department of Energy under Contract DE-AC06-76RLO 1830. The AEGIS Program is sponsored by the Office of Nuclear Waste Isolation (ONWI).

The author expresses special appreciation to Ms. Brenda Marshall, technical editor/writer, for her numerous suggestions and helpful editorial improvements. Special thanks are also given to Ms. Toni Jewell, who efficiently performed the many word processing and typing responsibilities involved in this report.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SUMMARY

Geohydrologic Response Functions (GRFs), developed through the efforts of the Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program, summarize key geohydrologic effects that are important in site selection and repository evaluation. They efficiently interrelate the three vital factors needed in the repository decision-making process, i.e., the quantity, arrival time, and location of contamination reaching the biosphere.

Through the definition of the interdependence of these three factors, the response functions (i.e., GRFs) further focus attention upon two related and effectively additive parameters, namely, the initial delay time, and the delay spread time. The initial delay time is the time between contamination departure from the repository and first arrival at the biosphere. The delay spread time is the elapsed time between first and last contaminant arrival at the biosphere, as represented by the GRFs.

The delay and spread times are useful measures of overall repository system performance. Longer initial delay times coupled with longer delay spread times indicate the more adequate hydrologic performance of a particular repository system. Shorter initial delay times and smaller delay spread times represent poorer performance of a particular repository system. Accordingly, the overall hydrologic transport performance of several repository systems may be easily scrutinized, screened, and evaluated by directly comparing the several GRFs. This screening and evaluating process enables preferential ordering of the several candidate repository systems based upon the response functions. Such a selection process, based upon hydrologic transport performance, coupled with other performance assessment issues provides the basis for realistic site selection.

After the principal site selection, the GRFs may be applied to obtain more detailed performance evaluations concerning specific nuclides or waste components, specific results for various types of accidental release, and effects of a variety of contaminant source terms or leach models. The response functions may be applied to consider contaminant reductions and delays through material sorption as well as through a variety of other interactions and effects.

Experience in the application of GRFs as repository performance evaluators has led to mounting evidence of their utility, flexibility, and simplicity. Because of this the GRFs facilitate communication between the technical evaluator and the decision maker by allowing sharper definition and qualification of the requirements for realistic site selection and repository evaluation.

CONTENTS

ACKNOWLEDGMENTS.	iii
SUMMARY	v
INTRODUCTION	1
BACKGROUND FOR GEOHYDROLOGIC RESPONSE FUNCTIONS	3
GEOHYDROLOGIC RESPONSE FUNCTIONS	5
THE FIRST (QUANTITY/TIME) GEOHYDROLOGIC RESPONSE FUNCTION	5
THE SECOND (QUANTITY/LOCATION) GEOHYDROLOGIC RESPONSE FUNCTION	7
GEOHYDROLOGIC RESPONSE FUNCTIONS AND HYPOTHETICAL WASTE REPOSITORY SITING CONDITIONS	9
PREFERENTIAL RANKING OF WASTE REPOSITORY SYSTEMS WITH GEOHYDROLOGIC RESPONSE FUNCTIONS	14
MORE DETAILED PERFORMANCE ASSESSMENTS FOR A REPOSITORY SYSTEM	18
USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS TO ANALYZE A SPECIFIC HYPOTHETICAL REPOSITORY SITE WITH UNIFORM SOURCE TERMS	18
A Hypothetical Repository Site	18
Application of Uniform Source Terms	23
USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS WITH VARIABLE SOURCE TERMS	25
USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS IN ANALYZING A TIME-DEPENDENT NUCLIDE SOURCE	28
USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS WITH EQUILIBRIUM DISTRIBUTION COEFFICIENTS TO EVALUATE MATERIAL SORPTIVE EFFECTS	33
REFERENCES	41

FIGURES

1	Schematic Diagram of Flow and Contaminant Pathlines from a Repository to a River	5
2	Geohydrologic Response Function (Quantity/Time) for Sample Repository	6
3	Geohydrologic Response Function (Quantity/Location) for Sample Repository	8
4	One-Dimensional GRF. Sample Repository No. 1	10
5	Effect of Rotating Repository on the GRFs. Sample Repository No. 2	11
6	Effect of a Permeability Change on the GRFs. Sample Repository No. 3	12
7	Effect of Several Variations on the GRFs. Sample Repository No. 4	13
8	GRFs for the Four Sample Repository Systems	15
9	Comparison of Contaminant Outflow Rates to Biosphere Using GRFs for the Four Sample Repository Systems	17
10	The Gradual Movement of Contaminated Fluid from a Repository Toward the River (sample case)	19
11	Use of Quantity/Arrival Time Response Function to Determine the Release into the River from a Constant Contaminant Input at the Repository	24
12	Use of the Quantity/Location Response Function to Determine the Contaminant Outflow Location	25
13	Input Concentration Source Term at Repository	26
14	Arrival Distributions at the River for Variable Input Concentrations	27
15	Concentration and Cumulative Water Outflow into the River at Various Times	28
16	Mass Outflow Rate of Contaminant into the River with Time	29
17	Input Technetium-99 Activity at Repository	30
18	Arrival Distribution of Technetium-99 Activity at the River	31
19	Tc-99 Activity Outflow Rate into the River at Various Times	32
20	Nuclide Response Function for Sn-126 with Sorption	35
21	Arrival Distribution of Sn-126 Activity at the River	37
22	Sn-126 Activity and Cumulative Water Outflow into the River at Various Times	38
23	Sn-126 Activity Outflow Rate into the River with Time	39
24	Contaminant Outflow to River from 750-Yr Uniform Repository Release and Sorption	39

USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS IN THE ASSESSMENT OF DEEP NUCLEAR WASTE REPOSITORIES

INTRODUCTION

Over the past four years hydrologic system modeling has been applied to evaluate hypothetical waste-repository sites in various geologic media through efforts supported by the AEGIS Program (Cole 1980; Cole and Bond 1980; Raymond et al. 1980; Cloninger, Cole and Washburn 1980). The purpose of these analyses has been to gain experience in using the AEGIS model sequence, to improve performance assessment methods, and to identify and define analytical deficiencies in the AEGIS methodology.

Among the important results obtained from the research and development activities of AEGIS are the Geohydrologic Response Functions (GRFs), which summarize key subsurface hydrologic features important in deep geologic nuclear waste repository site selection and in the subsequent more detailed repository safety performance evaluations. Through the use of response functions the technical factors required for the decision-making process are readily summarized and are provided in an easily communicated form to the public.

The purpose of this report is to introduce the GRFs; indicate the origin or basis of the approach, consider strengths and weaknesses, and (through sample applications) acquaint the reader with some of the ways these summary tools can be used in making efficient far-field repository evaluations. The examples use the response functions in two decision areas, i.e., in waste repository site-selection strategies, and in more detailed repository performance evaluations. In both cases the response functions are the central assessment tools, though the ways in which they are used differ considerably.

The site-selection decision may be accomplished by the direct comparison of the individual GRFs for the several candidate sites under consideration. By contrast the more detailed repository performance evaluation must be much more definitive in terms of the specific results or numbers obtained. The detailed performance evaluations also involve inputs to the GRFs in terms of potential disruptive processes and associated repository source terms.

The presentation of the GRFs in this report is organized around the two application modes represented by the site selection and subsequent more detailed performance assessments. Specifically, the response functions are introduced and illustrated as two graphs, which interrelate and summarize the three primary variables (quantity, arrival time, and location of contaminants reaching the biosphere) of importance in considering the adequacy of overall waste repository performance. Four simplified repository systems, involving different overall complexities and siting characteristics, are next illustrated (with the accompanying GRFs provided for each system). Comparison of the four response functions shows the preferred selection order for the repository systems, beginning with the most effective and sequentially proceeding to the least desirable site or repository system.

The report next discusses the use of the GRFs in more detailed aspects of evaluating repository performance. This includes describing the use of the response functions with various source terms, ranges of disruptive sequences, and different sorptive characteristics for the materials in the far-field evaluations. Although several useful ways of applying the response functions are presented in this report, starting with the simpler cases and gradually becoming more involved, there are many additional uses of the GRFs.

BACKGROUND FOR GEOHYDROLOGIC RESPONSE FUNCTIONS

The response functions can be developed either by starting from their theoretical origin and logically progressing through the analytical steps to their ultimate use, or by conversely beginning with the needs of the decision-making process and showing how the response functions satisfy those needs. We will focus on the ultimate use of the GRFs by considering the pertinent factors in an evaluation of the contamination potential of a repository.

The major analytical need is to estimate the extent, if any, of contamination that will reach the biosphere from a loss of repository integrity. Specifically, three factors are of major significance to the decision-making process:

- quantity of contaminants reaching the biosphere
- time of contaminant arrival at the biosphere interface
- location of contaminant emergence.

The quantity of contaminant reaching the biosphere (expressed as contaminant mass, concentration, or activity) is perhaps the most important of the three factors. Small amounts of contaminant may be negligible, while larger quantities may constitute a serious hazard.

The time needed for a contaminant to reach the biosphere interface is the second vital factor. Time (through decay) directly reduces the activity reaching the biosphere. This decay, however, represents only part of the overall importance of arrival time to subsurface evaluations. Arrival time is also the linking factor to many other aspects of repository analyses such as nuclide-material sorption interactions.

The last of the three factors, the location of contaminant emergence, is important because a contaminant isolated from the biosphere may represent little or no hazard, even in rather large quantities. Under other conditions, small amounts of contaminants arriving at critical locations over short periods of time would involve severe hazard.

Data concerning quantity of contaminants, time of contaminant arrival, and location of contaminant emergence to the biosphere enables the decision

makers to choose between site alternatives and to specify margins of safety in the repository design.

The three factors of contaminant quantities, arrival times, and outflow locations can be interrelated in two ways. The first and most general approach is to use the outflow location as the predominant variable. This approach provides the arrival distribution summary, which is described in detail elsewhere (Nelson 1976, 1978a, 1978b, 1978c, 1978d). The second approach uses the cumulative quantity of outflow containment as the predominant variable and has become known as the Geohydrologic Response Functions. Response functions, though somewhat less general than arrival summary distributions because they are restricted to analyzing steady-flow systems, are simpler to apply and are particularly useful in the site-selection and the subsequent more detailed repository performance evaluations.

GEOHYDROLOGIC RESPONSE FUNCTIONS

Geohydrologic Response Functions (GRFs) are a pair of summary relationships that interrelate the three factors of contaminant quantity, arrival times, and outflow locations. The first, or quantity/time, response is the more useful of the response function pair, while the second, quantity/location response function is of particular importance when considering the outflow location. These outputs are the major result of the hydrologic evaluations and are the specific factors needed in the decision-making process when assessing the far-field repository performance. As the name response functions suggests, they summarize all of the hydrologic effects between the contaminant input and outflow of the subsurface system.

THE FIRST (QUANTITY/TIME) GEOHYDROLOGIC RESPONSE FUNCTION

Interrelationships between quantity, arrival time, and outflow locations, are perhaps easier to visualize and discuss if displayed graphically. Figure 1 is a schematic diagram of fluid flow and contaminant pathlines from a repository, through the ground and into a river. The figure is helpful in visualizing the movement of contaminants from a repository to the biosphere (river) and in understanding the quantity/time GRF.

FIGURE 1. Schematic Diagram of Flow and Contaminant Pathlines from a Repository to a River

The first (quantity/time) GRF for the repository system illustrated in Figure 1 is shown in Figure 2. The vertical straight line to the left of the figure represents the instantaneous input pulse of contaminated water leaving the repository at time zero. In Figure 1 water particles leave the repository wall and follow various pathlines toward the river. (The labeled particles leaving the repository at zero time are denoted by the instantaneous pulse-- q/Q --in Figure 2). The time at which the labeled fluid particles arrive at the river bank in Figure 1 is represented by the right-hand curve, or response curve, in Figure 2. In effect the quantity/time GRF (right-hand curve in Figure 2) depicts the cumulative arrival rate, q/Q , of contaminated water reaching the river bank as a function of time from an instantaneous fluid pulse that departed from the repository at zero time.

FIGURE 2. Geohydrologic Response Function (Quantity/Time) for Sample Repository

The quantity/time GRF depicts the amount of contaminated fluid leaving the subsurface flow system with time as a result of an instantaneous pulse input at time, t_0 . Three items are important in this definition and its use:

- The response function gives the cumulative quantity of outflow as the overall system response to all the factors affecting the flow paths and interim delays in the subsurface system.
- Each response curve is the result of a specific infinitesimal volume leaving the contaminant source.
- For each successive infinitesimal volume of fluid or contaminant leaving the repository there is a specific departure time, t_0 ; hence, for each t_0 , there is an associated response or arrival curve.

We define two reference times from the quantity/arrival time curve to facilitate the comparison of several geohydrologic functions. As shown in Figure 2 the initial delay time is defined as the time between departure from the repository and first contaminant arrival at the river. The delay spread time is the duration between first and last arrival of contaminant into the river. Experience indicates that the greater the initial delay and delay spread time, the more effective the repository system. Conversely, the shorter the delay and spread times, the poorer the repository performance. This is a very useful comparison for the overall performance of a repository system.

THE SECOND (QUANTITY/LOCATION) GEOHYDROLOGIC RESPONSE FUNCTION

Although the quantity/time response function is of primary usefulness, an auxiliary response function is introduced here to further explain how the response functions perform. The quantity/location GRF is useful for those cases where the outflow location may be particularly important.

The auxiliary response function, as shown in Figure 3, interrelates the quantity of contaminant outflow with the location where that contaminant leaves the subsurface flow system and enters the river. Used in connection with the principal response function, it is easy to determine where the contamination is entering the river for various contaminant inputs to the overall subsurface flow system.

FIGURE 3. Geohydrologic Response Function (Quantity/Location) for Sample Repository

GEOHYDROLOGIC RESPONSE FUNCTIONS AND HYPOTHETICAL WASTE REPOSITORY SITING CONDITIONS

Four hypothetical waste repositories are considered here to indicate the summarizing capacity of the GRFs and their usefulness in the repository site-selection process. The intent is to explain and demonstrate the response functions for four examples, rather than to imply that the sample repositories are representative of specific sites considered by the AEGIS Program.

The four hypothetical repository systems, and the associated sample response functions, are shown in Figures 4 through 7. The first and simplest example, Figure 4, involves the standard unit pulse input to a rectangular repository that is aligned with the regional subsurface seepage velocity. The output to the river is the single right-hand graph of the quantity/time response function, which in this very simple example is only a single delayed output response. The single output pulse with only a delay time, T_d , occurs as a result of the special alignment of the repository and the uniform flow velocity in the system.

The second example repository, Figure 5, is the same as example No. 1 except that the rectangular repository is rotated with respect to the uniform subsurface flow field. The unit input pulse to repository No. 2 yields the output response functions shown as the two right-hand curves representing output into the river. The rotation of the repository in the uniform flow field yields both an initial delay time, T_d , and provides the added delay spread time, T_s .

Example repository No. 3, shown in Figure 6, is a natural extension of the previous two examples, with the introduction of a distinct permeability change between the upper and lower halves of the geohydrologic system. The distinct changes caused by the different permeabilities are observed in the GRFs (right-hand graphs in Figure 6). The permeability changes introduce two effects. First, the initial delay time, T_d , is longer because both of

FIGURE 4. One-Dimensional GRF. Sample Repository No. 1.

FIGURE 5. Effect of Rotating Repository on the GRFs. Sample Repository No. 2.

FIGURE 6. Effect of a Permeability Change on the GRFs. Sample Repository No. 3.

FIGURE 7. Effect of Several Variations on the GRFs. Sample Repository No. 4.

the permeabilities in repository No. 3 are lower than in the previous two examples. Second, the permeability contrast between the upper and lower parts of the flow system result in the longer delay spread time, T_s , in the output quantity/time response function.

Repository No. 4, shown in Figure 7, is the most realistic of the four sample repositories. It includes nonuniformity in the flow field (as indicated by the pathlines of different lengths), contains permeability variations, and has an irregular river bank configuration. Again the two output response functions summarize the significant effects by interrelating the three primary decision factors, i.e., the outflow quantity, outflow times, and outflow locations. These various combinations of effects have resulted in longer delay time, T_d , and delay spread time, T_s , which are convenient ways to qualitatively observe overall response function changes.

The four sample repository systems, though idealized, suggest the flexibility of the GRF approach, indicate some siting aspects perhaps not previously considered, and most importantly, give insight to the utility of GRFs as effective summary evaluation tools.

PREFERENTIAL RANKING OF WASTE REPOSITORY SYSTEMS WITH GEOHYDROLOGIC RESPONSE FUNCTIONS

The GRFs are useful in preferential ranking, or comparing the overall expected performance, of several waste repository systems. For example, the four repository systems illustrated in Figures 4, 5, 6, and 7 can be preferentially ranked by comparing the response functions.

Figure 8 shows the response functions for the four repository systems illustrated and discussed in the previous section. Considering the response curves, with the knowledge that the safest repository will have a longer delay time and a longer delay spread time, provides a simple judgmental basis for the preferential ranking of the four repository systems. Repository system No. 4 is the best, No. 3 is next best, repository No. 2 is somewhat poorer, and repository system No. 1 is the poorest of the four systems, as demonstrated by the smallest response function delay time.

FIGURE 8. GRFs for the Four Sample Repository Systems

The use of the delay times and delay spread times is a sound method of comparing a number of repository system performances. By using the response functions of the four sample repositories with a uniform repository source term release of 750 yr, the actual expected outflow rates into the river may be compared. In Figure 9 the outflow rates to the river for the 750-yr uniform release are shown as a function of time. Figure 9 corroborates the earlier performance sequence, with repository system No. 4 as the best and repository system No. 1 as the poorest. More sophisticated methods of using the GRFs are discussed in the following sections, giving further evidence of the value of response functions in a repository system site-selection process.

FIGURE 9. Comparison of Contaminant Outflow Rates to Biosphere Using GRFs for the Four Sample Repository Systems

MORE DETAILED PERFORMANCE ASSESSMENTS FOR A REPOSITORY SYSTEM

For introductory purposes it has been sufficient to determine the preferential rankings of hypothetical repository system sites based only on GRFs. For detailed performance assessments, however, the actual expected values in terms of concentrations, activities, and mass outflow rates of contaminants to the biosphere are the required results. The GRFs are equally valuable in these more complicated situations, but require a more sophisticated application.

USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS TO ANALYZE A SPECIFIC HYPOTHETICAL REPOSITORY SITE WITH UNIFORM SOURCE TERMS

A sample repository system (from which Figures 2 and 3 were derived) is described in this section to provide a more complete discussion of GRFs in repository performance evaluations and their use in analyzing uniform source terms.

A Hypothetical Repository Site

A sample subsurface flow system is shown in Figure 10 for an accidental release from a hypothetical repository. The shape and location of the contaminated front depicts the gradual movement of contaminant from the repository toward a river. Beginning at the repository, the contaminated front slowly moves outward in expanding and extending areas. Contaminants seeping along the shortest paths first reach the river about 15,000 yr after the initial contaminant release from the repository.

The longer more or less horizontal curves in Figure 10, starting at the repository and extending to the river, represent some of the flow paths of contaminated water. The first contaminated water to reach the river moves along Pathline Number 1, and would arrive in slightly more than 15,050 yr. More time is required for the fluid moving in the longer flow paths. For example, Pathlines 5 and 9 require about 15,495 yr and 17,337 yr, respectively, for the contaminated water to reach the river. For longer pathlines, such as 12 and 13, the elapsed times are 22,289 yr. Although not all pathlines are

FIGURE 10. The Gradual Movement of Contaminated Fluid from a Repository Toward the River (sample case)

shown in Figure 10, there is a complete spectrum of pathlines covering the entire range of travel times between 15,053 and 23,000-plus yr. Additional arrival times for other flow paths and data are summarized in Table 1.

TABLE 1. Summary of Contaminated Water Arrival Data at River Bank for Sample Repository Analysis

<u>Pathlines or Streamlines (Number)</u>	<u>Cumulative Relative Outflow Rate Into River (q/Q^(a))</u>	<u>Arrival Time at River (T in Years)</u>	<u>Location of Contaminant Outflow into River (S in Feet)</u>
1	0.00	15053	0
2 and 23	0.10	15079	± 248
3 and 22	0.20	15159	± 496
4 and 21	0.30	15299	± 745
5 and 20	0.40	15495	± 993
6 and 19	0.50	15768	± 1242
7 and 18	0.60	16134	± 1490
8 and 17	0.70	16629	± 1739
9 and 16	0.80	17337	± 1988
10 and 15	0.90	18546	± 2237
11 and 14	0.96	20300	± 2393
12 and 13	0.98	22289	± 2456

(a) $Q = 3.785 \times 10^5 \text{ ft}^3/\text{yr}$ or $7.757 \times 10^3 \text{ gal/day}$ ($2.932 \times 10^4 \text{ l/day}$)

Paths of flow are often referred to as pathlines when discussing travel times, and as streamlines when discussing quantity or amount of flow. The pathlines and streamlines are the same in Figure 10 because the flow system is steady. Pathlines and streamlines will be used interchangeably in the following discussion.

The streamlines shown in Figure 10 are spaced so that the same amount of fluid passes between successive streamlines. For example, 0.05 or 5% of the total outflow rate from the repository passes between Streamlines 1 and 2. Similarly, another 0.05 or 5% of the total flow rate enters the river between Streamlines 23 and 1.

The incremental outflow rates of the contaminated water entering the river are easily correlated with the arrival times at the river bank; in fact, the response functions are a result of this correlation. In Figure 10, the contaminated fluid gradually moves along Streamline 1 and reaches the river at 15,053 yr (see Table 1). Before that first arrival time, the cumulative amount of contaminated fluid (denoted by q/Q) that has entered the river is zero. Our correlation in interrelating quantities, arrival times, and outflow locations has established the first row of entries in Table 1. Specifically, for the contaminated fluid traversing Streamline 1, (first column in Table 1) the cumulative amount of fluid that has entered the river (second column) is $q/Q = 0$, by the first arrival time, $T = 15,053$ yr after the hypothetical repository release. Streamline 1, with the first contaminated fluid, reaches the river at outflow location $S = 0$.

For the second example of correlating quantities, arrival time, and locations, consider Streamlines 2 and 23 in Figure 10. Because of the symmetrical shape of the advancing contamination fronts, the contaminated water moving along Pathlines 2 and 23 could be expected to outflow into the river at the same time, i.e., $T = 15,079$ yr for both. The cumulative quantity of contaminated fluid that has entered the river by time ($T = 15,079$) is the sum of the fractional flows between Streamlines 23 and 2, i.e., $q/Q = 0.05 + 0.05 = 0.1$. By the time the contaminated fluid traverses Streamlines 23 and 2 to reach the river, the cumulative outflow rate of contaminated water to the river includes all of the flux between those streamlines that have arrival times less than or equal to those of Streamlines 23 and 2. The second row of entries in Table 1 interrelate all of the factors associated with Streamlines 23 and 2, 1) the cumulative quantity of contaminated fluid in terms of q/Q , 2) the arrival time, T , and 3) the location, S , along the river bank where the contaminated fluid emerges into the river.

Interrelationships between quantity (q/Q), arrival time (T), and outflow location (S) are displayed graphically in Figures 2 and 3, under the initial discussion of the quantity/time and quantity/location GRFs. The quantity/time response function, shown in Figure 2, has been discussed in terms of the

continuous system flow of the advancing contaminated fluid front, gradually progressing from the repository through the subsurface flow system and emerging at the river. The advancing front in Figure 10 depicts the locations at various times of an instantaneous contaminated fluid pulse leaving the repository at time zero.

The instantaneous pulse idea is illustrated in Figure 2. In this figure, a single vertical line is seen at $T = 0$, which is the contaminant input entering the subsurface flow system at the repository. The single vertical line at $T = 0$ represents the instantaneous input pulse of contaminated water of height $q/Q = 1.0$ but lasting for only an infinitesimal time, Δt . If we consider the product of the repository outflow rate, Q , and Δt , the result is a small volume of contaminated water departing from the repository at zero time. We can visualize Δt as smaller and smaller until a sufficiently small volume is reached to allow distributing fluid particles around the entire periphery of the repository. The pulse of height equal to unity and of infinitesimal width represents the line up of all the contaminated water particles around the edge of the repository, each one starting along its particular pathline at zero time. Along any of the paths, each contaminated fluid particle encounters permeability variations, different flow lengths and velocities that will affect the time when the fluid particle emerges from its streamline at the river.

The response function or right-hand curve in Figure 2 is the time history of all the individual fluid particles emerging from their respective flow paths at the river. All of those factors causing changes in the system alter the time when the contaminated fluid particles arrive; hence, each system effect changes the response function, and thus springs the real utility of GRFs.

Although the quantity/time response function just discussed is of primary usefulness, the auxiliary quantity/location response function is used as an aid in considering those cases where the outflow location may be particularly important. Its origin is in interrelating the location where contaminated fluid leaves the subsurface system as related to the cumulative outflow rates.

From Figure 10 and Table 1, we note that associated with each pair of streamlines there is a cumulative flux ratio q/Q as a function of the outflow locations, S . The outflow locations are a double valued function of the cumulative flux because there are always two bounding streamlines associated with each cumulative relative flux. For example, in Figures 3 and 10 $q/Q = 0.40$ or rather 40% of the cumulative outflow has emerged between the locations of $S = -993$ ft and $S = +993$ ft where streamlines 20 and 5 enter the river, respectively. The quantity/location response function, as shown in Figure 3, interrelates the quantity of contaminant outflow with the location where that contaminant leaves the subsurface flow system and enters the river.

Application of Uniform Source Terms

Response functions may be used for a variety of repository source terms. We begin here by considering a steady constant release of 750-yr duration of contaminated wastes from the repository. In Figure 11 the response functions for the first and last parts of the constant release are shown. The first pulse input at time $t_0 = 0$ and the associated response curve to the left represents the first contaminated water departing from the repository and its later arrival at the river, respectively. The right side of the square input pulse departing the repository at $t_0 = 750$ yr and the associated right-hand response curve represents the last of the $t_0 = 750$ -yr pulse of contaminated water to reach the river. Accordingly, only the stippled area between the two response curves represents contaminated water entering the river. If at any one time the difference in the cumulative relative fluxes (i.e., q/Q values from the two curves) is taken, the result is the actual outflow rate of contaminated water into the river. (Note for example the difference at $T = 16.5$ thousand years.) If several other times are chosen, the difference in q/Q values between the upper and lower curves gives the outflow rate of contaminated water into the river at that time. The complete result is the lower cross hatched curve in Figure 11, which is the contaminated water outflow rate with time resulting from the 750-yr release at the repository.

The outflow/location response curve can be examined by beginning with Figure 11 which shows that at a time of 16.5 thousand yr, $q/Q = 0.675$, as

FIGURE 11. Use of Quantity/Arrival Time Response Function to Determine the Release into the River from a Constant Contaminant Input at the Repository

observed from the upper response curve ($t_0 = 0$), and the lower response curve ($t_0 = 750$ yrs) is $q/Q = 0.485$. These two values are transferred to Figure 12, which is a quantity outflow/location response curve. The upper $q/Q = 0.675$ value shows two outflow locations along the river at $S = \pm 1680$ ft. The lower response curve value of $q/Q = 0.485$ gives the lower contaminated water outflow locations of $S = \pm 1200$ ft. These results show that at 16.5 thousand yr, contaminated water is entering the river between -1680 and -1200 ft along the river bank and also between +1200 ft and +1680 ft along the river bank. At all locations between -1200 ft and +1200 ft, uncontaminated water that departs from the repository after the 750-yr contaminated pulse is entering the river. Also between ± 2400 ft and ± 1680 ft, respectively, uncontaminated water that departs from the repository before the 750-yr pulse is also entering the river. This example provides insight concerning the location and amount of contamination that finally enters the river.

FIGURE 12. Use of the Quantity/Location Response Function to Determine the Contaminant Outflow Location

USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS WITH VARIABLE SOURCE TERMS

Variable source terms more complex than the simple square pulse input previously considered are often required. Contaminant concentration inputs of essentially any distribution can be used with the GRFs, as is illustrated below using a sample repository system. A particular input of contaminant concentration for the repository is given in Figure 13. The concentration of contaminant leaving the repository is expressed as the fraction, C/C_0 , with the peak concentration occurring at 1000 yr following the initial release. The entire release ends before 2500 yr have elapsed. Note that the input concentration is expressed as a function of the departure time, t_0 , so there is a unique C/C_0 associated with each t_0 .

For example, at $t_0 = 140$ yr from Figure 13, C/C_0 equals 0.05, which is plotted in Figure 14 as the second response curve for $C/C_0 = 0.05$. Similarly, successive response curves are included, each one representing the arrival of the particular C/C_0 concentration selected from Figure 13 for the specific departure time, t_0 .

FIGURE 13. Input Concentration Source Term at Repository

Figure 14 represents a sequence of concentration fluid outflow response curves. The curves represent the quantity of water outflow for various contaminant concentrations entering the river with time. The input concentration, C/C_0 , is the parameter in Figure 14. A more convenient arrangement would be to have the arrival time, T , as the parameter (shown in Figure 15).

In Figure 15, the cumulative relative flow arriving at the river is plotted as a function of the concentration, and the individual curve parameter is the arrival time, T . To obtain the mass of contaminant outflow rate, W , into the river at a particular time, T , the appropriate integral is:

$$W = C_0 Q \int_{\left(\frac{q}{Q}\right)_{\min}}^{\left(\frac{q}{Q}\right)_{\max}} \frac{C}{C_0} \bigg|_T d\left(\frac{q}{Q}\right) \quad (1)$$

FIGURE 14. Arrival Distributions at the River for Variable Input Concentrations

where

W is the mass outflow rate of contaminant into the river

C_0 is the input scaling concentration from Figure 13 (i.e., $C_0 = 5 \mu\text{g/l}$)

Q is the total outflow rate of water from the repository from Table 1 (i.e., $2.932 \times 10^4 \text{ l/day}$)

C/C_0 is the relative concentration of the water outflow into the river

T is the particular time when W is being evaluated.

The integral in Equation (1), as one example, is the area within the darkened curve ($T = 17,000 \text{ yr}$) in Figure 15. As the integrals for additional curves in Figure 15 are evaluated, the outflow curve (i.e., contaminant outflow rate)

FIGURE 15. Concentration and Cumulative Water Outflow into the River at Various Times

in Figure 16 is generated. In a like manner, nuclide decay and other variable input parameters to the subsurface system may be used with the response functions to effectively evaluate the final system results.

USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS IN ANALYZING A TIME-DEPENDENT NUCLIDE SOURCE

Time-dependent nuclide source terms are evaluated in much the same way as the concentration-dependent case just discussed, with the addition of decay. The analysis begins with the particular input activity as a function of time (Figure 17). The figure gives the activity of technetium (Tc-99) departing from the repository as a function of time. It is expressed as the input ratio,

FIGURE 16. Mass Outflow Rate of Contaminant into the River with Time

A/A_0 , with A_0 being a convenient reference activity. An input relative activity from Figure 17 is associated with each departure time, t_0 , from the repository.

The GRF in Figure 2 is used much as in the concentration sample case already described, and the resulting activity arrival distributions at the river are shown in Figure 18. For each arrival curve in the figure there is a corresponding activity A/A_0 that is associated with the particular departure time, t_0 . In each instance the particular A/A_0 curve is represented by a response function, which is translated in time by an amount t_0 .

In Figure 18 each river arrival curve is labeled by the activity, A/A_0 , of the nuclide departing from the repository at time, t_0 . Conversion of that departing activity to the relative activity entering the river at time, T , is provided by:

$$\frac{A_r}{A_0} = \left(\frac{A}{A_0} \right)_{t_0} \exp \left[-\lambda (T - t_0) \right] \quad (2)$$

FIGURE 17. Input Technetium-99 Activity at Repository

where

$\frac{A_r}{A_0}$ is the relative activity entering the river at time, T

$\frac{A}{A_0}$ is the input activity to the repository, which departed from the repository at time, t_0

λ is the decay constant for the nuclide considered

T is the arrival time at the river

t_0 is the departure time from the repository.

It is convenient to use the decayed activity just calculated and reorder the other variables in Figure 18. This simply involves letting the arrival time, T , be the parameter and considering the resulting interrelationship between water outflow and nuclide activity entering the river.

FIGURE 18. Arrival Distribution of Technetium-99 Activity at the River

The activity outflow rate into the river, W_a , at a particular time, T , is given by the integral:

$$A_{Tc} = A_0 Q \int_{\left(\frac{q}{Q}\right)_{\min}}^{\left(\frac{q}{Q}\right)_{\max}} \left. \frac{A_r}{A_0} \right|_T d\left(\frac{q}{Q}\right) \quad (3)$$

where

A_{Tc} is the nuclide activity outflow rate into the river

A_0 is the input scaling activity

Q is the total outflow rate of water from the repository, i.e., from Table 1 ($Q = 2.932$ l/day)

$\frac{A_r}{A_0}$ is the relative activity entering the river at time, T

$\frac{q}{Q}$ is the cumulative water flow rate.

The integral in Equation (3) is evaluated for several times, T, to obtain the relative nuclide (in this case Tc-99) activity outflow rate into the river, as is shown in Figure 19.

FIGURE 19. Tc-99 Activity Outflow Rate into the River at Various Times

USE OF GEOHYDROLOGIC RESPONSE FUNCTIONS WITH EQUILIBRIUM DISTRIBUTION COEFFICIENTS TO EVALUATE MATERIAL SORPTIVE EFFECTS

GRFs may be used to consider the effects of nuclide sorption on repository system performance through use of equilibrium distribution coefficients K_d 's for the materials. When considered as a material sorption capacity, the K_d can be used to give the traditional relationship between ion or nuclide travel times and water travel times, (see for example Freeze and Cherry 1979) i.e.,

$$\frac{T_n}{T-t_0} = \left(1 + \frac{B_d K_d}{P}\right) \quad (4)$$

where

T_n is the travel time of a specific nuclide or species through the material

$T-t_0$ is the water travel time through the material

T is the arrival time of water at an outflow boundary such as a river

t_0 is the time when the water entered the material (i.e., left the repository)

B_d is the bulk density of the porous material

P is the porosity of the material

K_d is the appropriate equilibrium distribution coefficient for the porous material.

Equation (4) may be used with the GRFs (as in Figure 2) to derive a nuclide or individual constituent response function. As the name suggests it represents a response function for that particular nuclide's performance in the overall repository system. An example illustrates the application of the GRFs for the particular repository system described in the earlier sections. The specific material characteristics used are a bulk density $B_d = 1.65 \text{ g/cm}^3$, a porosity of $P = 0.32$, a sample isotope, tin, ($^{126}\text{Sn(II)}$) with a half-life of 1×10^5 yrs), and a K_d for the material considered here of 2.72 ml/g. Substituting these characteristics into Equation (4) yields:

$$T_n = 15.0 (T) \quad (5)$$

where T is the water travel time, T_n the tin nuclide migration time, and t_0 is set equal to zero (response input is at zero time). Equation (5) is used in Table 2 to obtain the Sn-126 arrival times needed to obtain the nuclide response function for Sn-126.

TABLE 2. Summary of Sn-126, Water, and Arrival Data at River Bank for Sample Repository Analysis with Equilibrium Sorption

<u>Pathlines or Streamlines (Number)</u>	<u>Cumulative Relative Flow Rate Entering River ($q/Q(a)$)</u>	<u>Water Arrival Time at River (T in Years)</u>	<u>Calculated Sn-126 Arrival Time at River, (T in Years)</u>
1	0.00	15053	225795
2 and 23	0.10	15079	226185
3 and 22	0.20	15159	227385
4 and 21	0.30	15299	229485
5 and 20	0.40	15495	232425
6 and 19	0.50	15768	236520
7 and 18	0.60	16134	242010
8 and 17	0.70	16629	249435
9 and 16	0.80	17337	260055
10 and 15	0.90	18546	278190
11 and 14	0.96	20300	304500
12 and 13	0.98	22289	334335

(a) $Q = 3.785 \times 10^5 \text{ ft}^3/\text{yr}$ or $7.757 \times 10^3 \text{ gal/day}$ ($2.932 \times 10^4 \text{ l/day}$)

The nuclide quantity/time response function for the Sn-126 is shown in Figure 20 where the instantaneous unit input pulse is indicated at zero time. The Sn-126 response curve to the right in Figure 20 is a plot of columns 2 and 4 from Table 2, and represents the relative tin arrival quantities at the river.

FIGURE 20. Nuclide Response Function for Sn-126 with Sorption

The use of the q/Q values from Table 2 as the ordinate in Figure 20, but labeled q_{Sn}/Q_{Sn} , warrants explanation. The cumulative ratio of Sn-126 quantities dissolved in the water, either as system input or output, is the same as the cumulative water quantity, q/Q , because the subsurface flow system is steady. In such systems the flow paths are streamlines, which are unchanged in shape with time. As already discussed, the cumulative relative flow, q/Q , between any two streamlines is also constant. Accordingly, the Sn-126 in solution may be retarded by material sorption, along the individual paths to give the different arrival times. The relative quantities are unchanged because the flow paths are unchanged. Hence, the cumulative relative quantity of dissolved Sn-126 is unchanged or is equivalent to the ratio of q/Q . Therefore, Figure 20 is a nuclide response function for the system with equilibrium exchange retardation or delay effects incorporated for Sn-126. The large effect of sorption on the nuclide response function, even for so small a K_d as 2.72 ml/g, is readily apparent in terms of the much greater

initial delay time and delay spread times seen in Figure 20. As shown in the figure and Table 2, the initial delay and delay spread times are 225,759 yr and >108,500 yrs, respectively. By comparison, the sorption of $K_d = 2.72 \text{ ml/g}$ with no sorption represents a 15-fold increase in delay and delay spread times. If the K_d for Sn-126 were a factor of five larger, which may be common in many conditions, then according to Equation (4) both the delay and delay spread times increase by more than 70 times. Simple calculations of this type are often useful in qualitatively considering sorption or other effects. Judgmental evaluations are facilitated by the visualization of such calculations as the effects on initial delay and delay spread times, which are in turn considered as nuclide response functions.

With the nuclide response function available, Figure 20 may be used to display individual nuclide activities reaching the biosphere in the same way as has been described for GRFs. For example, if the input source term for Sn-126 activity were assumed to be the same distribution as the Tc-99 input in Figure 17, the Sn-126 arrival at the river is as shown in Figure 21. Reordering of variables is shown in Figure 22 where the arrival time, T , at the river is the parameter designating the particular curves rather than the relative activity as in Figure 21. The decay effect is directly seen in Figure 22 as a reduction in A_r/A_0 for the increase in time parameter, T . Successive evaluation of Equation (3) for consecutive T 's then yields the final activity outflow rate to the river as a function of time, as is shown in Figure 23.

The magnitude of the initial delay and delay spread times of the nuclide response functions are an important part in the activity decay reduction of outflow into the river (see Figure 23). However, there is an additional effect of the delay spread time (other than decay) that further reduces the contaminant outflow rate to the river. This second effect of delay spread time is not easily observed in the evaluation just illustrated because it is intermingled with the decay reduction. To isolate and illustrate this peak reduction effect from the direct activity decay, the response function is applied to reevaluate the Sn example, but not including the decay. To facilitate the evaluation we will also use a uniform 750-yr input at the repository (see Figure 24).

FIGURE 21. Arrival Distribution of Sn-126 Activity at the River

The first and last arrival curves, using the response function for tin sorption from Figure 20, are shown as the upper curves to the right. The stippled area between the two bounding arrival curves represents the cumulative tin contamination entering the river. The difference in ordinates then gives the lower cross-hatched curve, which is the contaminant outflow rate entering the river (see right ordinate of Figure 24).

The effective reduction in contaminant outflow to the river with an increased delay spread time becomes apparent through comparison of the low peaking outflow curves in Figures 24 and 11 (i.e., 0.1 as compared to 0.5, respectively). The longer spread time of the response function resulting from

FIGURE 22. Sn-126 Activity and Cumulative Water Outflow into the River at Various Times

ion sorption reduces the contaminant outflow rates to the river by a factor of five. The five-fold reduction comes about because the same release time at the repository is smaller, in relation to the delay spread times for the nuclide response function (with no decay), than the GRF, which has the smaller spread time. The longer delay spread time effectively reduces the outflow rates but extends the outflow over longer times. Such reductions are a result of longer delay spread times. Longer initial delay times do not alter the outflow rates, but only extend the beginning time of the outflow occurrence. Experience suggests that this reduction of outflow rates by longer spread times is a significant effect, which is automatically incorporated by the GRFs approach, but appears not to have been widely recognized or discussed.

FIGURE 23. Sn-126 Activity Outflow Rate into the River with Time

FIGURE 24. Contaminant Outflow to River from 750-Yr Uniform Repository Release and Sorption ($K_d = 2.72$ ml/g)

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

REFERENCES

- Cloninger, M. O., C. R. Cole and J. F. Washburn. 1980. An Analysis of the Use of Engineered Barriers for Geologic Isolation of Spent Fuel in a Reference Salt Site Repository. PNL-3356, Pacific Northwest Laboratory, Richland, WA.
- Cole, C. R. 1980. Radionuclide Transport Sensitivity Studies. PNL-SA-8927, Pacific Northwest Laboratory, Richland, WA.
- Cole, C. R. and F. W. Bond. 1980. Summary of Four Release Consequence Analyses for Hypothetical Nuclear Waste Repositories in Salt and Granite. PNL-3548, Pacific Northwest Laboratory, Richland, WA.
- Freeze, R. A. and J. A. Cherry. 1979. Groundwater, pp. 403-405. Prentice Hall, Inc., Englewood Cliffs, N.J.
- Nelson, R. W. 1976. Evaluating the Environmental Consequences of Groundwater Contamination. BCSR-6/UC-11, BCS Richland, WA.
- Nelson, R. W. 1978a. "Evaluating the Environmental Consequences of Groundwater Contamination, 1, An Overview of Contaminant Arrival Distributions as General Evaluation Requirements." Water Resources Research, Vol. 14, No. 3, p. 409-415.
- Nelson, R. W. 1978b. "Evaluating the Environmental Consequences of Groundwater Contamination, 2, Obtaining Location/Arrival Time and Location/Outflow Quantity Distribution for Steady Flow Systems." Water Resources Research, Vol. 14, No. 3, p. 416-428.
- Nelson, R. W. 1978c. "Evaluating the Environmental Consequences of Groundwater Contamination, 3, Obtaining Contaminant Arrival Distributions for Steady Flow in Heterogeneous Systems." Water Resources Research, Vol. 14, No. 3, p. 429-440.
- Nelson, R. W. 1978d. "Evaluating the Environmental Consequences of Groundwater Contamination, 4, Obtaining and Utilizing Contaminant Arrival Distributions in Transient Flow Systems." Water Resources Research, Vol. 14, No. 3., p. 441-450.
- Raymond, J. R., et al. 1980. Test Case Release Consequence Analysis for a Spent Fuel Repository in Bedded Salt. PNL-2782, Pacific Northwest Laboratory, Richland, WA.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

UNITED STATES

	2	Brookhaven National Laboratory Reference Section Information Division Upton, Long Island, NY 11973
		Harry C. Burkholder Office of Nuclear Waste Isolation Battelle Memorial Institute 505 King Avenue Columbus, OH 43201
		Neville G. W. Cook Dept. of Materials Science and Mineral Engineering Hearst Mining Building University of California Berkeley, CA 94720
27	DOE Technical Information Center	
2	Argonne National Laboratory Technical Information Services Report Section Building 2 of 3, CE 125 9700 South Cass Avenue Argonne, IL 60439	
10	Battelle Memorial Institute Office of Nuclear Waste Isolation Attn: Beverly Rawles 505 King Avenue Columbus, OH 43201	Carl R. Cooley DOE Office of Nuclear Waste Management Washington, DC 20545
	Michael J. Bell, Chief High-Level Waste Technical Development Branch Waste Management Division U.S. Nuclear Regulatory Commission Washington, DC 20555	Mike Cullingford Probabilistic Analysis Staff Nuclear Regulatory Commission Mail Stop 3103 Washington, DC 20555
	John Bird Geology Department Cornell University Ithaca, NY 14853	Stanley N. Davis, Hydrologist The University of Arizona College of Earth Sciences 6540 W. Box Canyon Drive Tucson, AZ 85705
	Albin Brandstetter Office of Nuclear Waste Isolation Battelle Memorial Institute 505 King Avenue Columbus, OH 43201	James O. Duguid Battelle Memorial Institute Office of Nuclear Waste Isolation 505 King Avenue Columbus, OH 43201

No. of
Copies

Dan Egan
Environmental Protection Agency
Office of Radiation Programs
Technology Assessment Division
M/S AW559
Washington, DC 20460

Warren Eister
Department of Energy
Division of Waste Isolation
Washington, DC 20545

Bruce R. Erdal
Los Alamos Scientific Laboratory
CNC-11, MS-514
Los Alamos, NM 87545

Larry R. Fitch
Office of Licensing
Systems Integration
Basalt Waste Isolation Project
Rockwell Hanford Operations
P.O. Box 800
Richland, WA 99352

Robert M. Garrells
Dept. of Geologic Sciences
Northwestern University
Evanston, IL 60201

Mark A. Harwell
P.O. Box 667
Cannon Beach, OR 97110

Colin A. Heath
DOE Office of Nuclear Waste
Management
Washington, DC 20545

William M. Hewitt
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

No. of
Copies

Peter L. Hofmann
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

Muzaffer Kehnemuyi
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

John F. Kircher
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

C. Kreitler
Texas Bureau of Economic Geology
University Station
P.O. Box X
Austin, TX 78712

Terry R. Lash
Director of Science and Public
Policy
Keystone Center
Box 38
Keystone, CO 80435

2 Lawrence Berkeley Laboratory
Reference Library
University of California
Berkeley, CA 94720

2 Lawrence Livermore Laboratory
Reference Library
P.O. Box 808
Livermore, CA 94550

Stan E. Logan
Los Alamos Technical Assoc.
P.O. Box 410
Los Alamos, NM 87544

No. of
Copies

- Tom Longo
Department of Energy
Division of Waste Isolation
Washington, DC 87544
- 2 Los Alamos Scientific Laboratory
Reference Library
P. O. Box 1663
Los Alamos, NM 87544
- J. B. Martin
Asst. Director for Radioactive
Waste Management Branch
NRC Division of Materials and
Fuel Cycle Facility Licensing
Washington, DC 20555
- John T. McGinnis
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201
- M. Merritt
WIPP, Division 4512
Sandia Laboratories
Albuquerque, NM 87115
- Martin A. Molecke
Nuclear Waste Experimental Programs
Division 4512
Sandia Laboratories
Albuquerque, NM 87185
- 2 Barry N. Naft
NUS Corporation
4 Research Place
Rockville, MD 20805
- 2 Jeff O. Neff
Department of Energy
Columbus Program Office
505 King Avenue
Columbus, OH 43201

No. of
Copies

- 2 Neil A. Norman
Environmental Sciences Department
Bechtel National Inc.
P.O. Box 3965
San Francisco, CA 94105
- 2 Oak Ridge National Laboratory
Central Research Library
Document Reference Section
Oak Ridge, TN 37830
- Frank L. Parker
Dept. of Environmental Engineering
Vanderbilt University
Nashville, TN 37235
- T. H. Pigford
University of California
Berkeley, CA 94720
- George F. Pinder
Dept. of Civil Engineering
Princeton University
Princeton, NY 08540
- Robert O. Pohl
Laboratory of Atomic and
Solid State Physics
Cornell University
Ithaca, NY 14853
- H. L. Ragsdale
Department of Biology
Emory University
Atlanta, GA 30322
- Gilbert E. Raines
Office of Nuclear Waste Isolation
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201
- Herbert R. Shaw
U.S. Department of the Interior
Geological Survey
Branch of Experimental Geochem.
and Mineralogy
345 Middlefield Road
Menlow Park, CA 94025

No. of
Copies

D. B. Shipler
Battelle Memorial Institute
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

2 Savannah River Laboratory
Reference Library
Aiken, SC 29801

Arthur J. Soinski
Energy Resources Conservation
and Development Commission
1111 Howe Avenue
Sacramento, CA 95825

Howard P. Stephens
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87115

David B. Stewart
U.S. Geological Survey
National Center 959
Reston, VA 22092

Martin S. Tierney
Environmental Assessment
Division 4514
Sandia Laboratories
Albuquerque, NM 87115

Newell J. Trask, Geologist
U.S. Department of the Interior
Geological Survey
Reston, VA 22092

Bob E. Watt
1447 45th Street
Los Alamos, NM 87544

R. E. Wilems
INTERA Environmental
Consultants, Inc.
11999 Katy Freeway, Suite 610
Houston, TX 77079

No. of
Copies

Robert Williams
Electric Power Research Inst.
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304

Paul A. Witherspoon
Earth Sciences Division
Lawrence Berkeley Laboratory
Building 90
Berkeley, CA 94720

ONSITE

5 DOE Richland Operations Office

O. J. Elgert
R. B. Goranson
H. E. Ransom
J. J. Schreiber
F. R. Standerfer

12 Rockwell Hanford Operations

R. C. Arnett
R. G. Baca
R. L. Bielefeld
D. J. Carrell
R. A. Deju
F. A. Deluca
L. R. Fitch
R. E. Gephart
L. S. Leonhart
Rockwell Document Control
Rockwell Library (2)

86 Pacific Northwest Laboratory

E. M. Arnold
G. L. Benson
D. J. Bradley
T. D. Chikalla
M. O. Cloninger
C. R. Cole
W. J. Deutsch
P. G. Doctor

No. of
Copies

F. H. Dove (20)
M. G. Foley
F. N. Hodges
C. T. Kincaid
M. R. Kreiter
J. W. Lindberg
B. K. Marshall
G. L. McVay
R. W. Nelson (25)
R. D. Peters
G. M. Petrie
A. M. Platt
J. V. Robinson
R. J. Serne
J. W. Shade
D. J. Silveria
J. K. Soldat
J. T. Zellmer
Technical Information Library (5)
Publishing Coordination (2)
Water and Land Resources Dept.
Library (10)