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This report is based on the Scientific Investigation Plan for NNWSI WBS Element 1.2.2.3.4 (non EQ3/6 Data Base Portion) Integrated Testing. This SIP should be used as the reference document.

PLAN FOR INTEGRATED TESTING FOR NNWSI
NON EQ3/6 DATA BASE PORTION

Virginia M. Oversby

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1.0 Purpose and Objectives

1.1 Regulatory Requirements

The purposes of the Integrated Testing Task (NNWSI WBS 1.2.2.3.4) are

(1) Develop laboratory data on thermodynamic properties for actinide and fission product elements for use in the EQ3/6 geochemical modelling code;

(2) Determine the transport properties of radionuclides in the near-field environment;

(3) Develop and validate a model to describe the rate of release of radionuclides from the near-field environment.

Activities to achieve item (1) have been described in the Scientific Investigation Plan for EQ3/6, where quality assurance levels were assigned to the activities. This Scientific Investigation Plan describes activities to achieve the second and third purposes. The information gathered in these activities will be used in the following ways:

(1) to assess compliance with the performance objective for the Engineered Barrier System (EBS) to control the rate of release of radionuclides if the repository license application includes part of the host rock in the EBS (10 CFR 60.113);

(2) to provide a source term for release of radionuclides from the waste package near-field environment to the system performance assessment task for use in showing compliance with the Environmental Protection Agency requirements contained in 40 CFR 191.13;

(3) to provide a source term for release of radionuclides from the waste package near-field environment to the system performance assessment task for use in doing calculations of cumulative releases of radionuclides from the repository over 100,000 years as required by the site evaluation process specified in 10 CFR 960.3-1-5.

The scientific investigations discussed herein are intended to address directly the following information needs taken from the Nevada Nuclear Waste Storage Investigations (NNWSI) Project Issues Hierarchy (version dated 8/07/86):

Issue 1.5: Will the waste package and repository engineered barriers meet the performance objective for radionuclide release as required by 10 CFR 60.113?

1.5.3 Scenarios and models needed to predict the rate of radionuclide release from the waste package and engineered barrier system.

1.5.5 Determination of the amount of the (sic) radionuclides leaving the near-field environment of the waste package.

Through input to the above information needs, the results of the integrated testing activities will provide data to help resolve Issues 1.1, 1.5, and 1.9.

The structure of this integrated testing plan parallels the information needs listed above and the discussions in Chapter 8 of the NNWSI Project Site Characterization Plan (SCP) of the studies to be undertaken to provide information to resolve Issue 1.5. In summary, interactions between waste package components or between components and the environment will be evaluated (where the work is not already covered in another WBS element) and interactions between radionuclide-bearing solutions and the welded, devitrified Topopah Spring tuff (Tpt) will be studied. The results of these activities will be used to develop a source term model for radionuclide transport in the near-field environment. This model, when combined with the results of geochemical and fluid transport modelling, will provide a description of the release of radionculides from the near field environment. The model for radionuclide transport and the results of the geochemical modelling calculations will be validated under an activity described in this SIP; the fluid transport model will be validated under an activity described in the Performance Assessment SIP.

1.2 Integrated Testing Activities Grouped by SCP Study

Waste Package performance assessment model development (SCP Information Need 1.5.3, Investigation 1.5.3.5, Activity 1.5.3.5.3)

G-20-5 Interaction of materials under repository conditions

Determine Radionuclide Transport Parameters (SCP Information Need 1.5.5, Investigation 1.5.5.1, Activities 1.5.5.1.1 and 1.5.5.1.2)

G-20-2 Determination of elemental profiles in rocks, minerals, and glasses using the Ion Microscope

G-20-3 Interaction of actinide bearing solutions with rock core samples

G-20-8 Planning and experimental design

Radionuclide Transport Modeling in the near-field waste package environment (SCP Information Need 1.5.5, Investigation 1.5.5.2, Activities 1.5.5.2.1 and 1.5.5.2.2)

G-20-6 Source term model development

G-20-7 Source term model validation

1.3 Information Flow

The goal of the integrated testing activities is to determine how the radionuclides that escape from breached waste packages interact with the repository rock and fluid system. Activity G-20-5 investigates interactions of materials with each other or with the environment if those interactions are not included in other waste package activities. New analytical methods and experimental designs are developed and evaluated under activity G-20-8. Information developed under Waste Package Environment, Container Material Testing, and Waste Form Testing will be combined in the source term model development activity (G-20-6) to provide the boundary conditions for source term calculations. This combination will give estimates of the volumes of fluids that might escape from breached waste packages and the concentrations of radionuclides in those fluids. Information gathered under activities G-20-2 and G-20-3 will provide parameters needed to describe the interaction of the radionuclide-bearing fluids with the repository rock and fluid system. The source term model developed under activity G-20-6 and validated under G-20-7 will be used in conjuction with fluid flow and transport models developed under the Performance Assessment task to provide estimates of the quantity of radionuclides that travel through the near field rock. A boundary will be selected within the near-field environment to serve as the transfer point for source term estimates from the waste package performance assessment models to the system performance assessment models.

2.0 Rationale for Selected Studies and Quality Assurance Level Assignments

2.1 Introduction

In this section, the technical rationale for the listed activities are given by type, corresponding to the three areas of study listed in section 1.2. A rationale for each activity is given.

2.2 Waste Package Performance Assessment Model Development

The development of performance models for the waste forms, the container, and for the waste package environment are handled under the WBS elements for these entities. In some cases there is an interaction between two or more of these entities that does not logically fit into the work plan for a single area. These items are handled as part of integrated testing under activity G-20-5. This activity investigates the interactions among waste package, engineered barrier system, and waste package environment components. Interactions are investigated at QA level III; if the interactions are found to be significant in terms of waste package or engineered barrier system performance, QA level I activities will be planned. At present, the only interaction that has been identified for study under this activity is characterization of water flow through breaches in metals. The objective of the study will be to determine what fraction of water that drips onto a container under repository conditions, such as dripping from a fracture, would enter the container through a breach in the container.

Activity No.	Name	QA Level
G-20-5	Interaction of materials under repository conditions	III

2.3 Determine Radionuclide Transport Parameters

This study area consists of three activities. The first involves the investigation of diffusion of radionuclides into rock under static, water-saturated conditions. The second activity investigates the interaction of radionuclide-bearing solutions with core samples of rock under flowing conditions. The third activity covers the development and assessment of new analytical methods and the design of new experiments to investigate materials interactions. The last activity includes the assessment of natural analog systems.

The experiments that are done under glass waste form testing to investigate geochemical interactions and radiation effects sometimes contain wafers of Topopah Spring tuff rock. As the glass waste form dissolves, radionuclides are released into the solution. These dissolved, or possibly colloidal, radionuclides can then diffuse into the rock and migrate through the rock. Activity G-20-2 uses the CAMECA ion microscope to determine the distribution of radionuclides in the rock at the end of the waste form tests. All of the waste form tests that form the basis for G-20-2 studies have been conducted at QA level III; therefore, G-20-2 has been assigned QA level III. Should any waste form tests conducted at QA level I contain rock or mineral samples that require analysis, a new activity would be undertaken at QA level I.

In the repository setting, the interaction of radionuclides with the host rock will generally occur under conditions of fluid flow. The distribution of radionuclides between fluid and solid phases might be affected by the fluid flow process and by whether the flow occurs under saturated or unsaturated conditions. Activity G-20-3 will develop methods to conduct experiments and tests of radionuclide transport using core samples of Topopah Spring tuff. Method development and initial applications will be done at QA level III. Once the methods are adequately developed, they will be applied to experiments and tests done under the laboratory hydrology study area (activities B-20-1 and B-20-2). The QA level assignment for work conducted under activity G-20-3 will then be the same as that for the hydrology study. It is probable that activities B-20-1 and B-20-2 will be at different levels for some time; thus, two level assignments are needed for this work. If the hydrology study is at QA level I, the radionuclide transport activity will be designated G-20-3.1

Advances in analytical methods in recent years have opened the way for studies that could not have been contemplated 5 to 10 years ago. The development of a two dimensional ion counting detector for the CAMECA ion microscope is an example of such a development. This detector, which is based on a resistive anode encoder, will allow us to map in three dimensions the distribution of actinides in samples of tuff. The resolution achievable is approximately 1 micrometer in each of two dimensions (the horizontal analytical plane) and less than 0.05 micrometers in the third dimension. To allow the NNWSI Project to benefit from this and future analytical developments, activity G-20-8 is included in the integrated testing task to evaluate analytical methods and experimental design.

Activity No.	Name	QA Level
G-20-2	Determination of elemental profiles in rocks, minerals, and glasses using the Ion Microscope	III
G-20-3	Interactions of actinide-bearing solutions with rock core samples	III
G-20-3.1	QA Level I applications of activity G-20-3	I
G-20-8	Planning and experimental design	III

2.4 Radionuclide Transport Modeling in the near-field waste package environment

The information developed under the activities described above must be combined with data obtained as the results of studies conducted under the Waste Package Environment, Waste Form Testing, and Container Materials Testing tasks so that a model can be developed for the source term for radionuclide release from the repository near-field environment. This is the model that will be used to provide input to the repository system modeling task. Activity G-20-6 covers the accumulation of data from other tasks, integration of the data for input to the source term model, and development of the source term model. Model development will be done at QA level III. The model will then be validated for the range of conditions required by NNWSI performance assessment tasks by conducting tests at QA level I. Final model validation may be accomplished through a peer review process.

Activity No.	Name	QA Level
G-20-6	Source term model development	III
G-20-7	Source term model validation	I

3.0 Description of Tests and Analyses, and Previous Work

3.1 Introduction

Detailed plans for the activities covered by this Scientific Investigation Plan are given in sections 3.2 through 3.4. The relative timing for activities is given where it is relevant to the planning and the QA level assignments. Each section contains a summary of any work previously conducted as part of the NNWSI Integrated Testing WBS element related to the activities covered by the section. The discussion of previous work is not intended to cover work conducted under WBS elements other than Integrated Testing or work conducted outside the NNWSI Project. Such work will be cited only where it helps to identify issues to be addressed in the planned work for Integrated Testing activities. Test plans will be developed for the QA level I activities described in sections 3.3 and 3.4. If the preliminary investigations of fluid flow into breached containers provide results that indicate further study is warranted, a test plan will be developed for that activity. All expected use of computer codes is discussed in section 3.4.

A separate WBS element titled Integrated Testing was introduced into the WBS Dictionary for the NNWSI Project in FY 1985. Because of the timing of the introduction, no funding was provided to the new WBS element until FY 1986. Thus, the amount of previous work conducted under the Integrated Testing task has been rather limited.

3.2 Waste Package Performance Assessment Model Development

3.2.1 Interaction of materials under repository conditions (G-20-5)

The purpose of this activity is to investigate interactions between two or more engineered barrier system components that might have significant effects on the performance of the engineered barrier system. In some cases, interactions of this type were already included in the plans for other WBS elements at the time the Integrated Testing element was created. These interactions are frequently central to the performance of a system element, such as the effects of container materials on waste form performance. For this reason, it was considered more appropriate to leave the work on those interactions in the WBS element where the work was originally identified as needed. The Integrated Testing task, then, was reserved for the investigation of materials interactions that had not yet been identified as significant to performance by other WBS elements, but that might have a significant effect on the performance of the total engineered barrier system.

To date, only one interaction has been identified that might effect the performance of the engineered barrier system, but was not included in the work plans for a waste package WBS element. That interaction is the characterization of water flow through breaches in the metal container. The capillary barrier of the unsaturated zone will normally prevent liquid water from contacting the waste container; however, under some conditions water flow in the unsaturated zone can result in mechanisms for water contact with the waste container. The most likely mechanism for water contact is probably by wicking from the partially saturated rock where the container is in direct contact with the rock. A second possible contact mechanism is by water dripping from a fracture onto the container. This mechanism would operate under conditions of higher flux than the first mechanism.

Where water drips onto the container, it is possible that the dripping would occur onto a region that contained a breach. Experiments will be conducted under this activity to determine the effect of water drip rate, water temperature, breach location, and breach geometry on the fraction of water that contacts a breach, but does not flow through the breach. The experiments will use small metal cylinders that contain a well-characterized defect, which has been intentionally induced into the cylinder. The fraction of water that enters through the breach will be determined as a function of breach size, breach shape, drip rate, and orientation of the breach relative to the water source. The effect of water temperature will be studied in a separate series of experiments using one or two breach configurations. Results of the experiments will be modelled to give an estimate of the significance of the water flow effects on the ability of water to enter breached containers. If the results indicate that the effects provide a significant reduction in water flow into the container, the study will be expanded to investigate the effects of corrosion products at the breach location on fluid flow.

Based on the results of these experiments and model calculations, some larger scale tests may be designed and executed. These tests would be done at QA level I.

3.3 Determine Radionuclide Transport Parameters

3.3.1 Determination of elemental profiles in rocks, minerals, and glasses using the Ion Microscope (G-20-2)

Diffusion of radionuclides into the rock matrix and sorption reactions with the rock surfaces are two mechanisms that can retard the transport of radionuclides with respect to the flow rate of water through the rock. Conventional measurements of these parameters rely on the use of changes in the concentration of dissolved species in solutions before and after contact with rock materials. For diffusion experiments, the rock itself is either not examined to determine radionuclide content, or surface techniques such as radiography are used. The surface techniques give a measure of the quantity of material adhering to or contained in the rock samples and, in some cases, its distribution in the plane of the sample surface. All material present in the rock within a distance equal to the penetration depth of the measurement technique is included in the surface value determined.

Phinney et al. (1987) used the CAMECA Ion Microscope to examine Topopah Spring tuff rock wafers that had been part of glass waste form dissolution tests. The waste form tests were conducted with the glass samples submerged in J-13 well water at 90°C in a gamma radiation field. Dissolution of the glass waste form introduced elements such as plutonium and uranium into the water. These elements were then able to diffuse into the rock under essentially static conditions, and to interact with the rock surface. Because flow of fluid was not forced through the rock, these measurements will give data that is not affected by advective flow effects.

The results obtained by Phinney et al. (1987) showed that a very slow diffusion process occurred in the rock. The diffusion profiles obtained for lithium, uranium, and plutonium gave very similar diffusion coefficients with an average value of approximately 10^{-16} cm^2/sec. This value is about 11 orders of magnitude smaller than that calculated by Travis (1984) using data obtained from a two day experiment in which an aqueous solution containing stronium-90 was equilibrated with a wafer of tuff. Travis (1984) modelled the changes in concentration of the solution in contact with the tuff to deduce values for the sorption coeffiecient and the diffusion coefficient. He did not report results of any examination of the tuff wafer itself. It is possible that the slow diffusion pathway existed in his experiments, too, but was not detected because of the dominance of a rapid diffusion pathway during the short time period of the experiment.

In the repository setting, where long times and distances are involved, a slow diffusion pathway could act as an important sink for radionuclides. This would occur because radionuclides, once they became entrained in the slow diffusion process, would take a long time to reach a crack or other microstructural feature that would allow more rapid transport to occur. Recent, unpublished work, using the detector system discussed in section 3.3.3, suggests that the tuff wafers examined by Phinney et al. (1987) may contain evidence for a more rapid transport pathway as well as the slow diffusion pathway. Thus, modelling of the transport of ions in the near-field environment of the waste package may require the use of two or more scale factors for the transport processes.

Examination of tuff rock wafers that have been part of waste form dissolution tests will be continued to further investigate the slow diffusion transport path. In addition, some controlled laboratory experiments using solutions doped with a single radionuclide or a simple mixture of radionuclides will be conducted to attempt to pick up evidence for the more rapid diffusion pathway. These experiments will also investigate the effects of sample surface preparation and other experimental parameters that might cause bias in the results. The methods of examination will be similar to those described in Phinney et al. (1987), but may include the use of the resistive anode encoder detector discussed in section 3.3.3. It may also be useful to examine diffusion profiles in single mineral specimens or glass samples to determine the effects of grain boundaries and cracks on the transport process. For this reason, the activity title includes minerals and glasses, as well as rock samples.

Saturated conditions, where the rock is submerged in water, are not expected for the repository horizon under anticipated processes and events. Thus, it is unlikely that tests done at QA level I under submerged conditions will need to be investigated under activity G-20-2. If a need is later identified for QA level I data from this type of test, a test plan and procedures will be developed for the work. The main purpose of activity G-20-2 as presently constituted is to provide information on the types of flow mechanisms that are relevant to the near-field environment of the waste package and to aid in the design of tests to be conducted under activity G-20-3.

3.3.2 Interactions of actinide-bearing solutions with rock core samples (G-20-3)

Radionuclide transport in the repository setting will occur by means of fluid flow through massive rock. The flow paths may be along grain boundaries, through interconnected pores, or along fractures. Transport parameters, such as diffusion coefficients and distribution coefficients, may be different for static and flowing systems. This activity will develop techniques for measuring the transport of radionuclides in rock core samples. The initial meaurements will be based on the system developed by Failor et al. (1982). The system for fluid injection will be modified to allow for slower injection rates and low flow rates. Depending on the results obtained using the modified system, some experiments will be conducted under conditions of two phase flow.

The goal of this activity is to develop procedures that can be used in conjuction with activities B-20-1 and B-20-2 of the Waste Package Environment task. Those activities cover laboratory measurement of the transport of fluid phases in samples of the Topopah Spring tuff. Tracer levels of selected radionuclides or stable isotope tracers will be added to the fluids used in the hydrologic tests and experiments. Concentrations of the tracers in fluids that exit from the core samples will be monitored. At the conclusion of the experiments, the rock samples will be sectioned and the distribution of radionuclides and other tracers will be determined using the ion microscope and other methods developed as part of activity G-20-8. The QA level for this work will be level III during the technique development stage. When the work is linked to activities B-20-1 and B-20-2, the work will assume the same QA level as those activities. For work done at QA level I, the activity number for radionuclide and tracer distribution work will be G-20-3.1. Prior to the initiation of work at QA level I, a test plan and procedures will be written to cover the planned work.

The purpose of this work is to determine the nature of the transport mechanisms for radionuclides in the near-field environment of the waste packages. The existence of more than one transport mechanism for fluid and ionic transport through the rock is suspected, based on the results discussed in section 3.3.1. If more than one scale of diffusive transport exists, provision for two or more transport parameters for diffusion must be included in the flow and transport model for the near-field environment (G-20-6 and Performance Assessment Scientific Investigation Plan Activity I-20-1). The existence of more than one transport mechanism could also affect the interpretation of test results in the waste package environment test planned for the exploratory shaft.

3.3.3 Planning and Experimental Design (G-20-8)

Development of new analytical methods and the application of existing methods to new situations are frequently beset by "teething problems". For this reason, an activity set at QA level III is included to allow for the development of techniques that can later be applied to QA level I activities if warranted. One of the areas where this activity may prove to be particularly useful is the investigation of possible natural analog systems. Such systems might be suitable for use in the model validation activity (G-20-7); however, before QA level I work is initiated, it is more cost and time effective to explore the potential for use at QA level III.

There are presently two techniques that will be evaluated under this activity. Others may be added as they become available. The first technique is the use of a special ion-counting detector for the CAMECA Ion Microscope. This detector is based on a resistive anode encoder (RAE) and will allow the full imaging capabilities of the microscope to be exploited. Samples studied under activity G-20-2 will be examined using the RAE detector and the integrated RAE response will be compared with the data obtained using the conventional detector system. The purpose of this comparison is to determine whether any analytical bias that might compromise the quality of the quantitative results obtained occurs when the RAE is used.

The second technique that will be examined is the field measurement of sorption and desorption rate constants using the short half-life members of the uranium and thorium decay series. Krishnaswami et al. (1982) developed a method to estimate these rate constants and applied the method to the study of several ground waters. Their method holds promise as a possible validation technique for laboratory-based models of sorption processes. Two developments are needed before the method could be used as a validation tool. First, extension to shorter-lived members of the decay chains is needed to allow data to be gathered for more elements. Second, a modification of the technique for use under unsaturated flow conditions is needed. Extension to shorter half-lived species will be tested by conducting an experiment using J-13 well water. Following these experiments, adaptation of the method for use in the unsaturated zone will be begun. If adaptation for unsaturated flow conditions is successful, a validation test will be planned and included under activity G-20-7.

3.4 Radionuclide Transport Modeling in the near-field waste package environment

3.4.1 Source term model development (G-20-6)

Calculation of the performance of the respository system will use a source term for radionuclide release from the near-field environment of the waste packages. The integrated computer model for the source term is developed under the Waste Package Performance Assessment task. Input of data to the model is done through the development of modules for the individual components of the waste package system. The source term model development to be conducted under this activity is the work related to developing a physical-chemical model for radionuclide interactions with the near-field environment rock and fluid systems.

The main features of the model to be developed will be a description of the interaction of radionuclide-bearing solutions with the porous, fractured Topopah Spring tuff in the vicinity of the waste package. The model will describe the effects of the thermal and radiation field on the interaction processes as well as the effects of variation in the chemical composition of the fluid phase. It is expected that the final form of the model will be a series of analytical expressions that would form the basis for a module to be added to the waste package performance assessment system code.

The model will be based on the results of experiments and tests conducted under activities G-20-2 and G-20-3, as well as any applicable results obtained under the studies of the geochemistry of the Yucca Mountain site during Site Characterization and Exploratory Shaft testing. Model development is done at QA level III. Prior to use in a repository license application, the model will be validated over the range of intended use under activity G-20-7.

3.4.2 Source term model validation (G-20-7)

Data that will be used to support a repository license application must be acquired at QA level I or be upgraded to level I through one or more of the processes described in NNWSI SOP-03-03 (DOE, 1986). The first portion of the model validation activity will be to screen the data to be used in the model to ensure that it meets QA level I requirements. Should any non-level I data be needed, the provisions of NNWSI SOP-03-03 will be implemented.

Validation of the source term model will be accomplished through a combination of laboratory testing, natural analog studies, and peer review. The source term model, combined with the flow and transport computer model developed under the performance assessment task, will be used to predict the results of a laboratory scale test prior to execution of the test. The test will then be performed under QA level I control and the results compared to the model predictions. The quality of the match achieved between predicted and actual results will determine the degree of validation provided by this means.

Laboratory testing cannot be done on a scale large enough in dimensions or long enough in time to validate the source term model for the full range of near-field conditions. Validation for long time periods may be achieved through the study of suitable natural analog systems. The main difficulty in the use of natural analogs for validation is the selection and matching of the analog system to the repository case. Natural analog systems will be investigated first under activity G-20-8 to assess their suitability for use in model validation. Those systems that appear to be suitable will be studied under QA level I control in this activity to provide partial validation for the source term model. The term "partial validation" is used because it is considered to be very unlikely that a perfect match for the respository situation will be found.

Peer review is considered to be an essential part of the validation activity for the source term model. There are several reasons for this. First, the use of natural analogs in the validation process will need peer review of the suitability of the analog system for validation purposes. Second, it is unlikely that any single analog system or even a combination of systems will cover the full range of conditions required for analysis of repository near-field performance. Thus, peer review of the source term model is needed to provide confidence that the model will be accepted as adequate during the licensing process.

4.0 Application of Results

The information provided by this investigation will provide the source term for radionuclide release from the near-field environment of the waste packages. This information will be used by the waste package performance assessment task to model the behavior of the ensemble of waste packages under repository conditions. The information gathered under activity G-20-5 will provide an evaluation of materials interactions that might prove significant to the performance of the repository. Where significant effects are found, they will be incorporated into the waste package performance assessment model. The information obtained in this investigation directly addresses the following information needs taken from the Nevada Nuclear Waste Storage Investigations (NNWSI) Project Issues Hierarchy (version dated 8/07/86):

Issue 1.5: Will the waste package and repository engineered barriers meet the performance objective for radionuclide release as required by 10-CFR-60.113?

1.5.3 Scenarios and models needed to predict the rate of radionuclide release from the waste package and engineered barrier system.

1.5.5 Determination of the amount of the (sic) radionuclides leaving the near-field environment of the waste package.

Through input to the above information needs, the results of the integrated testing activities will provide data to help resolve Issues 1.1, 1.5, and 1.9.

5.0 List of test plans to support this Scientific Investigation Plan

Source term validation plan

Test plan for radionuclide transport in rock core samples

Additional test plans or addenda and amendments to the above test plans will be issued should the need arise.

6.0 References

DOE, U. S. Department of Energy (1986). Acceptance of Data or Data Interpretation Not Developed Under the NNWSI QA Plan. NNWSI-SOP-03-03.

Failor, R., D. Isherwood, E. Raber, and T. Vandergraaf (1982). Laboratory studies of radionuclide transport in fractured Climax granite. UCRL-53308, Lawrence Livermore National Laboratory, Livermore, CA 94550.

Krishnaswami, S., W. G. Graustein, and K. K. Turekian (1982). Radium, thorium and radioactive lead isotopes in groundwaters: Application to the in situ determination of adsorption-desorption rate constants and retardation factors, Water Resources Research 18, 1663-1675.

Phinney, D.L., F. J. Ryerson, V. M. Oversby, W. A. Lanford, R. D. Aines, and J. K. Bates (1987). Integrated Testing of the SRL-165 Glass Waste Form, Materials Research Society Symposia Proceedings vol. 84, 433-446.

Travis, B. J. (1984) TRACR3D: A model of flow and transport in porous/fractured media. LA-9667-MS, Los Alamos National Laboratory, Los Alamos, NM 87545.