ORNL/GWPO-013

RECEIVED

NOV 21 1995

OSTI

**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

**Lockheed Martin Energy Systems, Inc.
Groundwater Program Office Annual
Report for Fiscal Year 1994**

September 30, 1994

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

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.**

ORNL/GWPO-013

LOCKHEED MARTIN ENERGY SYSTEMS, INC.
GROUNDWATER PROGRAM OFFICE
ANNUAL REPORT FOR FISCAL YEAR 1994

September 30, 1994

Prepared by the
Environmental Sciences Division
Oak Ridge National Laboratory
ESD Publication 4401

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. Department of Energy
under contract DE-AC05-84OR21400

CONTENTS

CONTENTS	iii
FIGURES	v
TABLES	v
ABBREVIATIONS	vii
EXECUTIVE SUMMARY	1
1. INTRODUCTION	3
1.1 PURPOSE	3
1.2 ORGANIZATION	4
1.2.1 Relationship of GWPO to Site GWPPs	7
1.2.2 Relationship of GWPO to ORHSP	8
1.3 FUNDING SOURCES	9
2. GWPO ACTIVITIES DURING FY 1994	10
2.1 COORDINATORS' MEETINGS	10
2.2 PROGRAM MANAGEMENT PLAN	11
2.3 PROCEDURE REVIEW/PREPARATION	11
2.4 TECHNICAL EXCHANGES WITH THE REGULATORS	11
2.5 ADVISORY COMMITTEE	12
2.6 GWPO RETREAT	15
2.7 CONTRACTS	15
2.8 OTHER STAFF ACTIVITIES	16
2.9 FY 1995 PLANS	17
3. ORHSP ACTIVITIES DURING FY 1994	17
3.1 TECHNICAL SUPPORT	17
3.1.1 Oak Ridge National Laboratory	17
3.1.2 Y-12 Site	18
3.1.3 K-25 Site	21
3.1.4 Paducah Gaseous Diffusion Plant (PGDP)	21
3.1.5 Portsmouth Gaseous Diffusion Plant (PORTS)	23
3.1.6 Other Staff Activities	24
3.1.7 FY 1995 Plans	25

3.2	OAK RIDGE RESERVATION HYDROLOGIC AND GEOLOGICAL STUDIES DURING FY1994	26
3.2.1	Shallow Subsurface Flows and Transport	26
3.2.2	Fractured Shale Tracer Experiments	29
3.2.3	Phage Tracer Experiments	29
3.2.4	West Bear Creek Valley Noble Gas Tracer Test	30
3.2.5	Stormflow Geophysics Experiment	38
3.2.6	Characterization of Groundwater Flow System Dynamics at the Oak Ridge Reservation Through Statistical Analysis of Water Level Data	39
3.2.7	Sampling Protocols For Fractured Media	41
3.2.8	East Oak Ridge Reservation Spring and Seep Survey	43
3.2.9	Exit Pathways	44
3.2.10	Deep System Dynamics	45
3.2.11	A review of the hydraulic conductivity testing data obtained from bedrock of the Oak Ridge Reservation	49
3.2.12	Use of borehole geophysics to identify porosity changes and fractures	53
3.2.13	Fracture Toughness Testing of Bedrock Core Samples from the Oak Ridge Reservation	56
3.2.14	Design, Fabrication, and Testing of a Purge and Trap, Gas Chromatographic System for Groundwater Dating with CFCs	61
3.2.15	Background Groundwater Quality Assessment for the Oak Ridge Reservation: Results of Exploratory Probability Plotting	63
3.2.16	Point Dilution Tests	68
3.2.17	Modeling of Radionuclide and Transition Metal Mobility Around Low-Level Waste Disposal Sites	69
3.2.18	Fracture Flow Modeling	72
3.3	REPORTS, PUBLICATIONS, TECHNICAL PRESENTATIONS, AND OTHER STAFF ACTIVITIES	74
3.4	SUMMARY OF ORRHAGS FY 1995 PLAN	77
4.	REFERENCES	78
APPENDIX A		LETTER FROM C. C. HOPKINS TO DISTRIBUTION
APPENDIX B		GWPO ADVISORY COMMITTEE REPORT

FIGURES

Figure 1.	Organization chart illustrating the relationship between GWPO, DOE-OR, Energy Systems Management, and the GWPP coordinators managers	5
Figure 2.	Organization chart illustrating the components of ORHSP	6
Figure 3.	Breakthrough of bacteriophage through Saproliite column	31
Figure 4.	West Bear Creek Valley Tracer Site Well Location Base Map ...	33
Figure 5.	BTC and Rainfall	35
Figure 6.	Heads and Rain	37
Figure 7.	Well Hydrographs showing variations	39
Figure 8.	EM Flowmeter results'	42
Figure 9.	Map of wells used to monitor Deep System Dynamics	46
Figure 10.	Borehole conductivity graphs of deep water system	48
Figure 11.	Pressure history for test CH4-5	51
Figure 12.	Deviation trends on the neutron log	55
Figure 13.	Deviation trends neutron behavior over gamma ray change	55
Figure 14.	Load vs. Displacement plot	59
Figure 15.	Crack tip stress vs. Crack length	60
Figure 16.	Probability plots	64
Figure 17.	Probability plots	66
Figure 18.	Filtered and Unfiltered samples	67
Figure 19.	Co Specie	71
Figure 20.	Relative concentrations in randomly fractured matrix	73

TABLES

Table 1.	Wellbore Storage Factor	53
Table 2.	Preliminary fracture toughness results	58

ABBREVIATIONS

BCV	Bear Creek Valley
CERCLA	Comprehensive Environmental Restoration, Compensation and Liability Act
DOE	U.S. Department of Energy
DOE-OR	U.S. Department of Energy Oak Ridge Site Office
EPA	U.S. Environmental Protection Agency
ER	Environmental Restoration
FY	Fiscal Year
GWPO	Groundwater Program Office
GWPP	Groundwater Protection Program
IA	Interagency Agreement
IRM	Interim Remedial Measure
LMES	Lockheed Martin Energy Systems, Inc.
OREIS	Oak Ridge Environmental Information System
ORHSP	Oak Ridge Hydrology Support Program
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
ORRHAGS	Oak Ridge Reservation Hydrology and Geology Studies
PGDP	Paducah Gaseous Diffusion Plant
PORTS	Portsmouth Gaseous Diffusion Plant
RCRA	Resource Conservation and Recovery Act
RMO	Resource Management Organization
SWSA	Solid Waste Storage Area
TDEC	Tennessee Division of Environment and Conservation
UEFPC	Upper East Fork Poplar Creek
UST	Underground Storage Tank
WAG	Waste Area Grouping
WSRC	Westinghouse Savannah River Corporation

EXECUTIVE SUMMARY

This edition of the Lockheed Martin Energy Systems, Inc., (Energy Systems) Groundwater Program Annual Report summarizes the work carried out by the Energy Systems Groundwater Program Office (GWPO) for fiscal year (FY) 1994. The GWPO is responsible for coordination and oversight for all components of the groundwater programs at the three Oak Ridge facilities [Oak Ridge National Laboratory (ORNL), the Oak Ridge Y-12 Plant, and the Oak Ridge K-25 Site], as well as the Paducah and Portsmouth Gaseous Diffusion Plants (PGDP and PORTS, respectively.)

This report describes the administrative framework of the GWPO including staffing, organization, and funding sources. In addition, summaries are provided of activities involving the Technical Support staff at the five facilities. Finally, the results of basic investigations designed to improve our understanding of the major processes governing groundwater flow and contaminant migration on the Oak Ridge Reservation (ORR) are reported. These investigations are conducted as part of the Oak Ridge Reservation Hydrology and Geology Studies (ORRHAGS) program. The relevance of these studies to the overall remediation responsibilities of Energy Systems is discussed.

1. The first part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

2. The second part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

3. The third part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

4. The fourth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

5. The fifth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

6. The sixth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

7. The seventh part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

8. The eighth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

9. The ninth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

10. The tenth part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

1. INTRODUCTION

1.1 PURPOSE

On April 25, 1991, the Groundwater Program Office (GWPO) was authorized for establishment at ORNL, within the Environmental Sciences Division (Appendix A). This central coordinating office was established to develop a consistent technical and administrative direction for the groundwater programs of all facilities and result in compliance with all relevant U.S. Environmental Protection Agency (EPA) regulations such as the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Restoration, Compensation and Liability Act (CERCLA) as well as U. S. Department of Energy (DOE) requirements and orders. DOE Order 5400.1, issued on November 9, 1988, called for each DOE facility to develop an environmental monitoring program for all media (e.g., air, surface water, and groundwater). With respect to groundwater, the requirements of this Order go beyond regulations promulgated by the states and the EPA.

This edition of the Lockheed Martin Energy Systems, Inc., (Energy Systems) Groundwater Program Annual Report summarizes the work carried out by the Energy Systems GWPO for FY 1994. This introductory section describes the GWPO's staffing, organization, and funding sources. The GWPO is responsible for coordination and oversight for all components of the groundwater program at the five Energy Systems operated DOE facilities (3 in Oak Ridge, the Portsmouth Gaseous Diffusion Plant, and the Paducah Gaseous Diffusion Plant). A more detailed discussion of the GWPO is contained in the Program Management Plan (ORNL/GWPO-001, 1994).

In addition to an administrative coordination and oversight role, the GWPO has a technical mission that is fulfilled by the Oak Ridge Hydrology Support Program (ORHSP). The coupling of the technical functions of ORHSP with the program management functions of the GWPO is both a unique feature and a strength of the current groundwater program. One guideline of the technical mission of ORHSP is the responsibility for providing technical support to the five site Groundwater Programs to ensure consistency of approach and technical guidance. Hydrogeologists on the staff of ORHSP work as an integral part of the site Groundwater Programs providing a broad range of technical assistance.

ORHSP also sponsors a spectrum of focused hydrogeologic investigations designed to develop a fundamental understanding of groundwater flow and contaminant migration on the ORR that can directly impact potential remediation strategies. These investigations are performed by a team of scientists associated

with the ORRHAGS group. ORRHAGS was established because geologists and hydrogeologists working on the ORR have recognized for many years that the geology and hydrology of this region is complex and the ability of groundwater programs on the Reservation to successfully meet regulatory requirements depends on enhanced knowledge of how groundwater flow, geology, and contaminant migration interrelate. Several examples of benchmark investigations undertaken by ORRHAGS staff include completion of a revised geologic map of the ORR (R. D. Hatcher et al., 1992) and a hydrologic framework for the reservation (Solomon et al. 1992). In addition, an update to the conceptual model was issued recently (Moore et al, 1993).

In summary, the GWPO has developed a groundwater program that:

- complies with all applicable federal and state environmental laws, DOE orders, Executive Orders, and Energy Systems policies and procedures;
- is comprehensive and technically sound;
- ensures consistency of well installation, development, sampling, maintenance, plugging and abandonment, and data management and reporting throughout Energy Systems;
- ensures consistency in the technical approach that is used for all components of the groundwater program at all sites;
- provides a basis for trend analysis and predictive capability; and
- effectively communicates with DOE, EPA, the states, and the public.

1.2 ORGANIZATION

Figure 1 illustrates the organization of the Energy Systems GWPO. There are three key components of this organization: ORHSP, Site Groundwater Protection Programs (GWPP), and Energy Systems central organizations.

GWPO provides the overall administrative coordination for the Energy Systems groundwater program. ORHSP is responsible for the leadership and technical coordination of the program (e.g., Technical Support staff and generic studies conducted by ORRHAGS) that benefit each site. The Environmental Surveillance activities of ORHSP are limited to oversight and coordination of site environmental surveillance activities as defined in DOE Order 5400.1. Figure 2 presents a more detailed organization of ORHSP.

Figure 1. Organization chart illustrating the relationship between GWPO, DOE-OR, Energy Systems Management, and the GWPP coordinators managers.

Figure 2. Organization chart illustrating the components of ORHSP.

1.2.1 Relationship of GWPO to Site GWPPs

Each site has a GWPP coordinator/manager¹ who is responsible for integrating all components of the groundwater program at that site. Because groundwater interests and responsibilities are spread among several organizations (primarily site Compliance and ER organizations), the GWPP coordinator/manager guides all of these individual programs to promote consistency and efficiency.

GWPO interfaces with each of the five Energy Systems facilities through the respective site GWPP coordinators/managers. The GWPP coordinator/manager is the single point of contact at each facility for all activities related to groundwater. The GWPP coordinator/manager has established a matrix organization for administrative purposes that includes those functions associated with groundwater (Compliance, ER, Waste Management, Engineering, quality assurance, field sampling, and laboratory analysis).

The site groundwater programs include certain monitoring activities that lie beyond the boundaries of DOE land. For example, studies being conducted along East Fork Poplar Creek and off-site monitoring associated with the environmental monitoring plans fall into this category. In addition, certain parts of the DOE land on the ORR are the direct responsibility of organizations other than Energy Systems. To ensure that all parts of the ORR have groundwater oversight, key groundwater personnel from each of the ORR sites subdivided all DOE land into areas of groundwater oversight responsibility for respective GWPP coordinators/managers. Insofar as possible, the boundaries between areas of responsibility are defined by natural surface-water and groundwater flow divides. The GWPP coordinator/manager oversees any activity related to monitoring well installation (location, depth, or purpose), well inspection, maintenance, plugging and abandonment, groundwater sampling, analyses, data interpretation, and reporting within his/her area of responsibility.

As a result of extensive investigations during the past 6 years, especially on the ORR (e.g., Solomon et al. 1992), it has become apparent that a close relationship exists between the shallow groundwater flow system (and associated contaminant migration) and surface water. Consequently, the GWPPs at each of the five sites have established the appropriate interfaces with the respective surface water

¹Recent reorganization of the groundwater programs at three Energy Systems sites will result in formation of a groundwater organization headed by a GWPP Manager with line responsibilities and authority for implementing all groundwater programs. The other two sites preferred to retain a more decentralized groundwater organization in which the different components are linked by a GWPP Coordinator. With respect to insuring integration of the site groundwater programs, the roles and responsibilities of both the GWPP Manager and Coordinator are identical.

programs to ensure that surface water-groundwater interactions are addressed.

1.2.2 Relationship of GWPO to ORHSP

ORHSP represents a key technical support component of the Energy Systems groundwater program. Jointly, GWPO and ORHSP provide the site GWPPs with an integrated approach to groundwater issues; GWPO provides administrative guidance and ORHSP is responsible for the direct technical leadership. Three components comprise ORHSP: Technical Support, Environmental Surveillance, and ORRHAGS. The organization chart for ORHSP is presented in Figure 2.

For the Technical Support function, ORHSP has assigned a team of technically qualified hydrogeologists to work with the GWPP coordinators/managers. They assist the GWPP coordinators/managers in all technical questions related to groundwater and serve as a conduit for communicating technical guidance related to the site groundwater programs. The scope of their involvement includes but is not limited to:

- assisting in planning, review, and technical guidance for groundwater (and closely related surface water) projects;
- reviewing geologic, hydrologic, and geochemical data obtained by the site groundwater program, assisting in its evaluation and integrated analysis;
- reviewing procedures to ensure their consistency;
- participating in meetings with regulators and the site environmental advisory committee;
- assisting in audits of the technical components of the groundwater program;
- reviewing technical documents developed by the plant and their subcontractors;
- preparing selected documents; and
- providing an interface between ORRHAGS and the site groundwater programs.

The environmental surveillance component of ORHSP is intended to ensure consistency and technical sufficiency for surveillance activities mandated by DOE Order 5400.1. With respect to groundwater, environmental surveillance refers to perimeter and exit pathway monitoring of contaminants associated with groundwater. This is to guard against the potential for contaminants to cross facility boundaries as well as define the location and extent of potential contaminant migration pathways. Environmental surveillance also includes privately owned domestic water supply wells located beyond the boundaries of DOE land. The strategy to be followed for environmental surveillance of

groundwater for the Energy Systems facilities is described by Forstrom (1990b and 1994).

ORRHAGS is the third component of ORHSP that and is responsible for developing a fundamental understanding of the underlying principles that control groundwater flow and contaminant migration on the ORR. These studies included revision of the geologic map and development of a soils map for the ORR, evaluation of background hydrochemical properties of groundwater, development of appropriate computer models and data bases for ORR applications, and exploration of the interaction of the hydrologic and geologic regimes on contaminant migration. With the incorporation of ORRHAGS into ORHSP, the scope of the ORRHAGS activities contributes, where possible, to groundwater projects at Paducah and Portsmouth.

Technical support personnel of ORHSP communicate the technical problems at each site to ORRHAGS and work with the GWPP coordinator/manager to understand and implement the results of ORRHAGS technical studies into site groundwater programs. The ORHSP staff resides in the Environmental Sciences Division at ORNL and also employs scientists from academic institutions. While GWPO and ORHSP report to Energy Systems management through the Senior Staff Assistant to the ORNL Director, the management of the GWPO and ORHSP resides within the Environmental Sciences Division.

1.3 FUNDING SOURCES

The GWPO is funded from two sources. During FY 1994, approximately 65% of the funding support came from the Environmental Restoration (ER) Division. The other component of funding for GWPO and ORHSP is provided by the Corporate Services function of LMES which funds other multi-site programs.

GWPO and ORHSP technical staff work directly with the ER Program, the site GWPP coordinators/managers, and ORNL's financial organization to develop scopes of work, budget requirements, performance schedules, and appropriate milestones and deliverables. GWPO and ORHSP administrative staff are responsible for budget tracking and preparation of financial reports to support financial audits and budget validation activities.

The site GWPPs are funded by each facility in a manner deemed appropriate by the site. Funding responsibilities may be shared by the major components of the site groundwater programs (i.e., DOE ER Division and the DOE site office) or be covered by a single organization.

2. GWPO ACTIVITIES DURING FY 1994

One of the primary reasons that GWPO was established was to provide a single point of contact for and improve communications among the different components of the groundwater program within Energy Systems (e.g., among the sites and between site Compliance and ER programs) and between Energy Systems and the U.S. Department of Energy Oak Ridge Site Office (DOE-OR), the regulatory agencies, and the public.

Successful recruitment of the full contingent of technical support staff was a major objective for FY 1994. The GWPO began the year with two vacancies in this area (for support to the Y-12 and PGDP groundwater programs). The program was very fortunate, however, to successfully recruit two qualified individuals to fill these positions

2.1 COORDINATORS' MEETINGS

During FY 1994, the GWPO hosted quarterly meetings for the benefit of the groundwater programs at the three facilities managed by LMES and the two managed by Lockheed Martin Utility Services for USEC (US Enrichment Corp.). Attendance at these meetings includes the staff of the GWPO, the site Groundwater Coordinators, representatives of the LMES ER Program and Environmental Compliance organization, the DOE-OR Groundwater Program Manager, a representative of the DOE-OR Environmental Protection Division, and other interested individuals. The objectives of these meetings are to:

- provide a forum for each site Groundwater Coordinator/Manager to review progress on groundwater-related activities at his/her site and to take advantage of lessons learned to build consistency into the overall program;
- inform attendees about relevant meetings, workshops, and regulatory issues that may have an impact on the site groundwater programs;
- introduce information on new characterization and remediation technologies that might be beneficial to the sites;
- demonstrate applications of software that might assist the sites in data management and mapping requirements, and

- review the progress of basic investigations being conducted by scientists associated with ORRHAGS.

2.2 PROGRAM MANAGEMENT PLAN

In the Annual Report of the GWPO for FY 1993 (GWPO, 1994, ORNL/GWPO-005) we noted that a draft management plan for the Energy Systems Groundwater Program had been prepared. This management plan was issued during FY 1994 (Early, T. O., 1993, ORNL/GWPO-001). The purpose of this plan is to identify the primary objectives of the GWPO, present the organization chart, and define the roles, responsibilities, and authority of the key positions in the program including the GWPO, ORHSP, and ORRHAGS staff and the site Groundwater Coordinators. This plan has been approved by the plant manager at each facility as well as the LMES Vice Presidents for Environmental Compliance and ER and Waste Management.

2.3 PROCEDURE REVIEW/PREPARATION

In FY 1994, the GWPO contracted to have a review completed of the Energy Systems Procedures that refer to groundwater (HSW, 1994). The contractor assessed the existing procedures for completeness and accuracy and is preparing a contractor's report that will document their findings. In addition, the contractor is conducting similar reviews of the groundwater procedures for each of the five facilities. The result of these evaluations will be documented in a contractor's report.

The final product of this activity is for the contractor to develop a guidance document on assessing the quality of groundwater data. This document will consider both physical and chemical parameters and will focus on evaluation procedures to determine the representativeness of the data. This final report is expected to be completed during FY 1995.

2.4 TECHNICAL EXCHANGES WITH THE REGULATORS

During FY 1994 the Groundwater Program staff continued and expanded its interactions with personnel of the Tennessee Division of the Environment and Conservation (TDEC). The scope of these interactions were broad and included continuing discussions associated with the development by LMES of a comprehensive groundwater program as specified in the Tennessee Oversight Agreement. In addition, the Technical Support staff frequently is involved in

discussions with TDEC and similar state regulatory agencies in Kentucky and Ohio in their capacity as technical advisors to the groundwater programs at the five facilities. Likewise, there are similar interactions with the US EPA in Region IV (Tennessee and Kentucky) and Region V (Ohio).

In July, 1994, the GWPO held a technical information meeting with TDEC technical staff in order to provide them with an update on our conceptual understanding of groundwater flow and contaminant migration on the ORR. This was the second such meeting since the GWPO was formed. The first meeting of this nature was during FY 1992. The purpose of this meeting was to describe information obtained from field investigations and modeling studies conducted on the ORR during the past two years and show how these studies augment our understanding of the conceptual model and have an impact on recommendations for future remediation of groundwater. The meeting was an opportunity to discuss the results of some long-term field investigations (eg. noble gas tracer test see Sect. 3.2.4) and some new efforts related to determination of background groundwater compositions and demonstrating the importance of using slow/low purge and sampling techniques to obtain more representative groundwater samples. The presentations focused on investigations being conducted by ORRHAGS and ORHSP staff. Furthermore, it is a valuable forum for exchanging ideas and information with the technical staff of the regulatory agencies. Our original intent was to make these technical information meetings an annual event where results of ongoing research are presented and the impact of these investigations on the conceptual model and remediation activities is discussed. However, we have found that conflicting schedules with the staff of the regulatory agencies have been a problem. We are attempting to establish a regular schedule for future meetings with both TDEC and EPA Region IV.

2.5 ADVISORY COMMITTEE

The Groundwater Program Management Plan specifies that an advisory committee shall be appointed to review the activities of the program on an annual basis. The committee evaluates the program and recommends future improvements. For FY 1994 the committee comprised the following people:

- Dr. Stanley N. Davis, Univ. of Arizona (emeritus)
- Dr. William B. White, Pennsylvania State University
- Dr. N. H. Cutshall, Deputy Director, Office of Environmental Technology Development, Energy Systems

The committee met in Oak Ridge on July 26-27, 1994 with the GWPO staff and a large cross section of the LMES staff associated with groundwater programs at all

five facilities. Based on their visit, the committee prepared a report that identified the strengths of the program and some concerns that require attention. A copy of their report appears in Appendix A.

The Committee considered the credibility of the GWPO staff vis-à-vis their colleagues on the groundwater monitoring and compliance staffs. All conversations with staff and managers indicated that GWPO scientists were held in esteem and their advice and opinions were valued.

The Committee concluded that the projects undertaken by various elements of the GWPO were technically and scientifically sound as well as essential for the economic fulfillment of compliance and remediation requirements. The various investigative techniques used by hydrogeologists at the ORR were judged to represent state-of-the-art procedures. Furthermore, in many projects some useful innovations have been developed.

The working relationship between hydrogeologists in the GWPO and parallel professionals in agencies and organizations outside of ORR was not fully explored due to time constraints. However, working relations with individuals in the DOE appeared to be very good.

The Committee ranked their concerns with the GWPO as follows:

- The Committee was very pleased to see that their concern from last year of the need for each of the five sites managed by Energy Systems to have assigned a full-time technical professional was resolved. However, the lack of a karst specialist is still a primary concern. GWPO's expertise in karst hydrology was again found to be severely limited, and the recruiting of a karst hydrologist should be given high priority.
- The Committee noted the attention being given to last years recommendation that GWPO take more account of surface water and seeps and springs. It was stressed that a water balance study of the watersheds on the ORR be undertaken. A study of the water balance can add much to the hydrogeologic knowledge of an area.
- The Oak Ridge Environmental Information System (OREIS) database has not reached a level of usefulness which the Committee could embrace. They noted the large amount of resources being consumed by the project versus the results. It was noted that DOE approval of the system had been received in early June. The Committee recommended that an attempt be made to make the system functional as soon as possible and that the entry of data into the system be given high priority.

- A system of ranking and prioritizing current and future projects should be implemented. This will assist both internal and external entities in defining resource allocation into and out of the GWPO.
- A clear avenue for conflict resolution between GWPO and site perspectives was not clearly recognized by the Committee. It noted that the GWPO Management Plan gave reference to periodic meetings where these issues could possibly be dealt with but they were not completely clear on the current resolution hierarchy.
- The Committee expressed the need for early publication of results from GWPO research and projects. In addition, participation by the staff in professional society activities to remain abreast of state-of-the-art technologies was recommended.
- Office space was again a concern. The Committee noted the cramped and unsatisfactory arrangements that continue to exist from last year. The possibility that space would become available to GWPO personnel in a new building that is currently under construction was hailed by the Committee as an overdue and welcome change. They noted that the current arrangements were not conducive to efficient and effective execution of duties by GWPO personnel.
- The Committee is concerned with the continuation of problems surrounding the issue of shipping samples offsite for analysis. This unresolved issue could impact the effectiveness of the program through delays, inefficient processing, and inadequate analysis.
- The Committee expressed a concern in protecting current and future sites for research. They noted that area for future work is limited and that land where research projects are currently underway is in jeopardy of being lost before research in those areas is completed. This would be a great waste of resources and effort if these areas were to be developed prior to completion of the research.
- The Committee is concerned that considering drilling a construction rather than service activity will greatly impede the effectiveness of the GWPO by imposing additional and unnecessary constraints through increased costs and decreased flexibility.

2.6 GWPO RETREAT

In late July, 1994, GWPO staff associated with ORHSP and ORRHAGS met for a one-day offsite retreat. The retreat was held several days after the Advisory Committee visit. The primary objective was to allow people associated with the Groundwater Program to reflect on what we see as our strengths and weaknesses within the context of the evaluation of the Committee.

2.7 CONTRACTS

The GWPO recognizes the necessity to provide certain types of services to the site Groundwater Programs to ensure consistency of approach and promote efficiency of operation. Consequently, during FY 1994 the GWPO took steps to establish a number of contracts to facilitate these objectives. Specific examples include:

- University of Utah - Study of the role of matrix diffusion as a control on contaminant transport on ORR.
- University of Waterloo - 3-D transient groundwater flow and transport modeling.
- HSW - Assist in determining background groundwater concentrations for the ORR, QA plan preparation, and procedure review and revision.
- GWPO assisted MK-Ferguson in establishing technical specifications for a construction subcontract to drill wells on the ORR. Final bidders will be selected for pre-bid packages in early FY 1995.
- An administrative support services contract to handle a variety of administrative duties that allows groundwater professionals in the program to spend more time addressing technical activities
- Contracts for technical support in hydrogeologic, data base, and modeling activities

Many of these subcontracts were initiated in FY 1993, but have carried forward into FY 1994. At present, it appears most will terminate near the end of the 1994 calendar year or sooner. Resources are not available to maintain the same level of work in FY 1995.

2.8 OTHER STAFF ACTIVITIES

In addition to normal day-to-day activities, staff of the GWPO participate in a variety of special activities that either broaden their experience or provide representation and leadership of Groundwater Program personnel at meetings, symposia, and workshops external to LMES. Part of the outreach function of the GWPO is to keep the LMES groundwater programs aware of these activities, provide technical summaries of meetings and workshops that might be of interest to the sites, and encourage appropriate participation of site groundwater staff in similar activities. Examples of these types of activities include:

- Technical session chairs and participants at the National Technology Information Exchange Workshops
- Participation in the DOE-HQ (EM) initiative to develop a new strategy for doing R&D research (see Sect. 2.8)
- Attendance at a variety of short courses and workshops:
 - * Karst hydrology
 - * Geostatistics
 - * Expedited Site Characterization Demonstration
 - * Chapman conference on fracture flow and transport
- Participation in national professional society meetings, both in organizing symposia and presenting work
- Session co-chair at ER 94 meeting in Augusta, GA
- Session co-chair at Spectrum 94 meeting in Atlanta, GA
- Symposium Organizer and session chair at the AWRA national meeting in Nashville, TN
- Participation in US EPA Research and Development Technology Forum
- Participation in US EPA Groundwater Sampling Workshop in Dallas

2.9 FY 1995 PLANS

During FY 1995 the GWPO will continue in its primary mission of providing technical guidance to the site Groundwater Programs in an effort to promote consistency of approach across all facilities. In addition, the following activities are planned:

- Hire one replacement staff member for the Technical Support function
- Begin development of a formal program to investigate the importance of the karst system on flow and transport on the ORR
- Improve the oversight of ORRHAGS studies to provide for more rigorous reviews of proposals, test plans, and funded projects to ensure that they are addressing important needs.
- Provide personnel to coordinate evaluation of perimeter monitoring systems at the five plants.

3. ORHSP ACTIVITIES DURING FY 1994

This section summarizes the activities of the ORHSP staff during FY 1994. Section 3.1 focuses on the Technical Support function and highlights the major areas of activity during the year. Section 3.2 presents a synopsis of investigations conducted by the ORRHAGS staff during the year.

3.1 TECHNICAL SUPPORT

The following subsections summarize the major activities of ORHSP Technical Support staff members during FY 1994 at the five DOE facilities operated by LMES.

3.1.1 Oak Ridge National Laboratory R.H. Kettle

The following is a summary of the significant contributions of the GWPO staff to the Groundwater Program at ORNL:

- GWPO staff served as technical lead for the ORNL Groundwater Operable

Unit and had oversight for preparation of the Characterization Plan for the Oak Ridge National Laboratory Area-Wide Groundwater Program (DOE/OR/01-1252&D2).

- Provided numerous briefings for ER, DOE, TDEC, and EPA on groundwater conditions and issues at ORNL from the site-wide scale and from individual WAG scales including WAGs 4 and 5.
- Participated in ORNL ER technical integration with representatives of the ER program, surface water program, and risk assessment staff to direct the ORNL ER program activities toward implementing effective current risk reduction of major contributors to the contaminant discharges.
- Worked interactively with WAG 2 surface water staff and risk assessment staff to prepare an integrated analysis of potential risk in groundwater, seeps, and surface water for the ORNL site. This potential risk information is being used to prioritize ER activities in groundwater/seep control actions.
- Served as a member of the empowered team for WAG 5 Seeps Removal Action. This activity required contributions to and review of the WAG 5 Seeps Removal action plan as well as general support to the empowered team in providing technical input relative to geology and hydrogeology of the Melton Valley and WAG 5 areas.
- Provided technical support to the WAG 5 Seeps Removal project in design and construction phases during which many decisions had to be made to actually obtain the desired project result. Practical hydrogeologic decision information was provided to the project team.

3.1.2 Y-12 Site

D. A. Watson

The following is a summary of the significant contributions of the GWPO staff to the Groundwater Program at Y-12:

- Participated in weekly meetings for Upper East Fork Poplar Creek (UEFPC) OU-1 and Bear Creek Valley (BCV) OU-4. Also attended meetings on special issues related to BCV or UEFPC.
- Attended and presented materials at monthly regulators briefing.
- Attended occasional meetings with TOA to brief them and answer questions on Y-12 groundwater issues.

- Provided input to PEIS risk assessment process
- Provided miscellaneous reviews and comments on documents such as:
 - 1) Groundwater Surveillance plan,
 - 2) Y-12 Groundwater Protection Program quality program plan,
 - 3) Evaluation of cavity occurrence in the Maynardville Limestone and Copper Ridge Dolomite at the Y-12 plant using logistics and general linear models,
 - 4) Oak Ridge Reservation Environmental Monitoring plan.
- Acted as a liaison between ER, GWPP, and ORNL ESD and facilitated, to the extent possible, developing research projects that focus on filling specific RI/FS data gaps.
- The GWPO is taking the lead on estimating background groundwater concentrations for inorganics and radionuclides at Y-12. An innovative approach is needed because of the limited number of uncontaminated upgradient monitoring wells and multiple hydrogeologic regimes. Other sites are participating in development of the approach because it is intended that it will be applicable to other ORR sites.

Upper East Fork Poplar Creek

- Evaluated the potential for offsite groundwater contamination on the east end of Y-12 near Scarboro Rd. After it was determined that contamination detected offsite probably is from Y-12, the GWPO participated in several related activities:
 - Helped develop and implement action to notify the public. This included participating in a presentation to the landowners and directly contacting selected landowners to determine if groundwater is being used for drinking water purposes.
 - Assisted in developing a short-term plan of action that could be implemented to insure that there is no immediate health risks from the groundwater plume discharging to springs.
 - Conducted a field survey to identify springs and other surface water features that will be sampled as part of the short-term plan of action.
 - Provided DOE and Energy Systems personnel with a list of properties that needed to be accessed and the rationale for obtaining access.
 - Directed a PhD student who is working on identifying larger scale fault and

fracture planes and evaluating their impact on groundwater flow and contaminant transport. This activity involved mapping the geology of Rogers Group Quarry to help identify structural relationships to springs, seeps and topography in Bear Creek Valley.

- Participated in the preliminary planning, scoping and costing of the RI/FS for UEFPCC OU-1 (groundwater/surface water integrator unit).
- Reevaluated conceptual model of groundwater flow for the Y-12 hydrogeologic regime. This included specifically evaluating the potential impact on groundwater flow and contaminant movement from the closing of New Hope Pond and opening Lake Reality with associated drains and sump pumping.
- Reevaluated the potential source areas of groundwater contamination in the Maynardville Limestone and presented this information at a regulators meeting.
- Participated in the Data Quality Objectives (DQO) workshop for BCV O-1 (Source Unit).
- Evaluated the scope of work proposed for BCV OU-4 RI (groundwater/surface water integrator unit). Partially based on this evaluation, the scope has been revised which could lead to a savings of hundreds of thousands of dollars.
- The existing data were compiled and presented in summary form to the regulators and other participating parties. Completed, planned, and ongoing work being conducted by ORNL staff was compiled. Existing data were evaluated and a conceptual model of groundwater and surface water transport which included identifying data gaps was prepared and presented to Y-12 ER and the regulators at the DQO workshop.
- Participated and presented material at a focussed mini FS to identify and cost remedial alternatives for drain water being collected at the Burial Ground (LSF/GWTF). Helped develop the passive treatment option.

Chestnut Ridge

- Presented materials on groundwater and contaminant transport and participated in the DQO workshop for Chestnut Ridge OU-1 (Security Pits).
- Reviewed and commented on the Chestnut Ridge OU-2 filled coal ash pond

RI report.

3.1.3 K-25 Site

T. F. Zondlo

- GWPO staff provided a leadership role in developing the scope of the GW OU characterization plans, establishing subcontractor support contracts, and providing oversight of field activities. We provided day-to-day interpretation of newly acquired data and integration of historic data. Additionally, GWPO staff directed specific tasks related to that scope, including a groundwater modeling workshop, identification of groundwater discharge using thermal infrared flyover data, development of a "cut and fill" map for the K-25 site, and initiation of 3D visualization models for the site using Dynamic Graphics Earthvision. GWPO staff provided additional direct support by performing a karst inventory of the site, conducting a subsurface seep and spring survey of the Clinch River and Poplar Creek, and, development and maintenance of various technical databases. GWPO staff are responsible for introduction of state-of-the-art groundwater sampling methodologies which are expected to yield more reliable analytical results and reduce overall waste management costs.
- GWPO staff provided technical oversight of the K-1070C/D RI and introduced technology to that program which improved the quality of the data acquired and reduced costs.
- GWPO staff have evaluated available offsite analytical and hydrologic data to assess the potential for off-site migration of contaminants from the K-25 facility. In one instance, in response to concerns raised by State regulators, GWPO staff evaluated offsite drinking water results and in conjunction with analysis and integration of hydrologic data, demonstrated that low levels of gross alpha and beta contamination observed in an offsite drinking water well in the next valley were unrelated to K-25 operations, thus calming a potentially expensive and sensitive situation.

3.1.4 Paducah Gaseous Diffusion Plant.- (PGDP)

A. Diefendorf

The following is a summary of the significant contributions of the GWPO staff to the Groundwater Program at PGPD:

- Full-time participation on the LASAGNA Consortium Committee, a public-private consortium consisting of research specialists from Energy Systems, DOE, GE, DuPont and Monsanto. GWPO has been providing

significant input and critique regarding the design and installation of the LASAGNA method which involves the proposed use of electrokinetics as a means of removing DNAPLs from fine-grained media at PGDP.

- Provided formal review of the INTERA surfactant injection demonstration project, and was successful in having preinjection pumping test added to the project prior to attempts to solubilize DNAPLs using surfactants.
- Continue to provide review of various iron-filings laboratory and field demonstration projects at PGDP. This method of reducing chlorinated hydrocarbons from groundwater using zero-valence metals is also proving useful in removal of Tc-99. GWPO is closely observing current work by PGDP and ORNL research staff to assure that the mechanisms of removal are fully explained.
- GWPO has initiated an evaluation of existing PGDP groundwater data to evaluate the presence and extent daughter degradation compounds from the Northwest and Northeast TCE plumes. Work to date suggests that plumes of cis-DCE and 1,1-DCE are present. These evaluations point to the possibility of significant natural removal of chlorinated compounds from the groundwater. GWPO will continue these evaluations focusing on the extent of mass removal and whether the mechanism is related to formation bacteria or abiotic.
- PGDP has been supporting the use of high-powered microwave as a method to remove sources of subsurface DNAPL. GWPO and ORHSP have been facilitating the dissemination and review of technical information on the methodology. A seminar to present the information to ORNL and DOE-OR staff was recently organized at ESD. ORHSP is continuing to provide critical review and input to DOE on the potential for the methodology.
- ORHSP has been assisting PGDP efforts to establish groundwater and soil background chemistry levels at the site. Using existing data and log-normal distribution plots, ORHSP has drafted a comparative analysis of soil and groundwater concentrations of inorganic analytes with establishment of background levels. The work will support future risk assessment methods by establishing representative background levels for contaminants of concern. The methods used will allow for determination of background levels without additional costly drilling and sampling.
- To support Human Health and Environmental Risk Assessments of the Northwest Plume, GWPO prepared a internal report estimating the loading of contaminants of concern to the Ohio River. The estimates were successful in

eliminating several potential exposure pathways from the risk assessment.

- Prepared formal document reviews and traveled to PGDP to participate in comments resolution meetings for the following:
 - Baseline Risk Assessment and Tech Investigation Northwest Dissolved Phase Plume
 - Focused Feasibility Study of Northwest Plume Source
 - Treatability Study Program Plan for WAG 23
 - Feasibility Study Work Plan of Northwest Dissolved Plume
 - Integrated Feasibility Study/Corrective Measure Work Plan WAG 17
 - RCRA Facility Investigation Work Plan WAG 13
 - ROD for Interim Action Source Control/North-South Diversion Ditch
 - Interim Corrective Measures Work Plan for Northeast Plume
 - Iron Filings Treatability Study Work Plan
 - Revised Groundwater Strategy Document.
- GWPO has been active in the development and initiation of Phase 4 and Phase 5 investigative work. In particular GWPO is assisting in the integration of data on both Northeast and Northwest Plumes to better understand the nature of source areas and contaminant transport. GWPO is facilitating with assistance from ORRHAGS and PGDP staff the development of Earth Vision models of lithology and contaminant extent.
- GWPO continues to provide direct support to PGDP Hydrogeologic Services Staff on a daily basis and with frequent travel to the PGDP facility. The support includes research and evaluation of drilling methods and problems, development and transfer of data bases, interpretation of hydrogeologic data, and global oversight.

3.1.5 Portsmouth Gaseous Diffusion Plant (PORTS)

C. T. Rightmire

The following is a summary of the significant contributions of the GWPO staff to the Groundwater Program at PORTS:

- Developed the conceptual plan that led to the "expedited site characterization" of the X-749 plume. The approach led to rapid decisions, involving the regulators, on well locations and the need to drill, install, sample and analyze fewer monitoring wells.
- Served as acting GWPP Manager to allow for the recruiting and hiring of a permanent GWPP Manager for PORTS. Also led effort to recruit and hire

GIS/Data Management person for GWPP.

- Developed and implemented the "barrier wall" concept for the X-749 plume which allowed additional time for the completion of the Corrective Measures Study (CMS) process for the plume. This approach permitted deferral of remediation decision pending consideration of all of the appropriate remedial options for the area.
- In conjunction with the PORTS GWPP, GWPO forced acknowledgement of the continuing presence of a DNAPL (TCE with PCBs) source in the vicinity of X-701B and of the awareness that attempts to locate and recover all the DNAPL (TCE) are doomed to failure using current technology. It must be noted that (1) we will never locate all the DNAPL and (2) if we could locate all of it, it could not all be recovered. The activities associated with the closure of the X-701B Holding Pond were terminated and this closure will be integrated into the CMS process to address both the DNAPL source and the groundwater plume emanating from that source. Current activities in the area will involve establishing the extent of the DNAPL and, where DNAPL is encountered in this activity, attempting to lessen the mass of the source by extraction.
- Led effort to minimize expenditure of funds for seep remediation at the Peter Kiewitt Landfill. When it appeared that the cost of the proposed interim remedial activities would be in excess of \$5 million for minimal reduction in risk, the issue was elevated within LMES ER management. The level of expenditure subsequently was reduced to about \$3 million for activities required by the state of Ohio. Any additional remediation will be rolled into the CMS.
- Enlisted DOE support for aerial photography of PORTS and the surrounding area to develop the first topographic map that extends beyond the reservation boundary. These photos will be used to develop digitized topographic maps with a 2 ft contour interval that can serve as the base for on site and off site hydrogeologic studies. These maps will play a major role in the conduct of the X-749 interim remedial measures (IRM) and its associated off site investigation.

3.1.6 Other Staff Activities

Data Management

B. K. Thompson and D. D. Huff

During FY 1994, there were three main areas of focus for data management: Data

base maintenance and updates; Geographic Information System projects; and Development of three-dimensional visualization applications and products. Data base activities included addition of groundwater chemical data for 1991 for the Y-12 plant, and groundwater chemical data for 1992 for both the K-25 and Y-12 plants. In addition, the data base structure was updated and revised to allow more efficient access and processing. Groundwater chemical data for the Oak Ridge Reservation were provided for an ORRHAGS study of statistical properties of background water chemistry. In addition, cooperative interaction with the OREIS team assisted in the evaluation of the OREIS data base structure and functionality, based on several years of experience with the ORRHAGS system.

The use of geographical information systems (GIS) has continued to grow. On the ORR, several geologic features were incorporated into GIS coverages. An annotation layer for dip and strike coverage was created, line and polygon coverages of geologic units were created, and a wall-sized color geologic map including geologic contacts, formations and strike and dip measurements was produced. In response to discovery of an off-site carbon tetrachloride contaminant plume in Union Valley, several data files and pie-chart figures were created for use in briefing the property owners. This work demonstrated the value of having GIS coverage that could be used to quickly produce graphic materials to explain technical findings. Finally, GIS coverage that includes well locations and attributes was updated for the Oak Ridge Reservation, and new coverage was created for the Portsmouth Gaseous Diffusion Plant.

The final area of new activity has been in developing a three-dimensional visualization capability for display of hydrogeologic information. A Dynamic Graphics 3-D software package (Earthvision) has been applied to groundwater and soil contamination sites on the ORR and at Paducah. Sub-surface geologic models have been created to show the three-dimensional configuration of formations, and how they relate to groundwater and soil contaminant plumes. These visualization tools are very powerful aides to the analysis of controls on plume development, and their use is expected to grow in FY 1995. There has been a growing emphasis on training staff in the use of these tools on the GWPO OREIS workstation.

3.1.7 FY 1995 Plans

FY 1995 will be a year of challenge for the GWPO. Because the lead manager will be leaving the program to take up new responsibilities in the EM Plume Focus Area (see Sect. 2.8) and will be replaced by one of the staff, recruiting for a new technical support person was initiated. Subsequent funding reductions caused a cancellation of this initiative. Total funding for the program for FY 1995 is approximately \$2.69 million, including carryover, which represents a decline of

10 % from the FY 1994 budget level. Further reductions are anticipated. The major impact will be reductions in support to the basic studies conducted by ORRHAGS. In addition, it will be necessary to further postpone new positions in karst hydrology and evaluation of perimeter monitoring systems. Both these needs have been recognized previously by our advisory committee (Appendix A).

Finally, as discussed in Sect. 2.10, in FY 1995 the GWPO will continue a process begun last year of improving the manner in which basic investigation projects are defined, reviewed and evaluated, funded, and considered for continuation. It is mandatory that these projects be closely tied to critical needs. Furthermore, for the first time, projects that are directly tied to developing remediation technologies for groundwater will be funded.

3.2 OAK RIDGE RESERVATION HYDROLOGIC AND GEOLOGICAL STUDIES

The ORRHAGS investigations are being conducted by a multidisciplinary team of environmental scientists. The primary objective of ORRHAGS is to develop an understanding of contaminant transport mechanisms, rates, and pathways relevant to the ORR so that technically credible waste management and ER decisions can be made. To fulfill this objective the following investigation themes have been established:

Shallow Subsurface Flows and Transport
Karst Systems
Deep Groundwater
Modeling

Significant progress was made during FY 1994 in each of the theme areas. Highlight summaries of the progress of each project are presented in the following section of this report.

3.2.1 Shallow Subsurface Flows and Transport

R. Shropshire and D. K. Solomon

Matrix diffusion, a process whereby solutes diffuse between permeable subsurface pathways (e.g. fractures) and porous but relatively impermeable matrix, has been implicated as an important transport mechanism on the ORR. In particular this process results in the following:

1. Significant retardation of the bulk movement of solutes relative to preferred permeability pathway fluid velocities.

2. Creation of secondary sources of contamination within the porous matrix that may persist for decades or longer.
3. Severe limitations on conventional remediation strategies, such as pump and treat, that rely upon flushing of the pores.

In order to further evaluate and quantify matrix diffusion for the ORR, a variety of laboratory and field studies are being conducted. Field studies include a tritium tracer test and a noble gas tracer test that are described elsewhere in this report (sections 3.2.4 and 3.2.3, respectively). Laboratory studies on both undisturbed cores of saprolite and with small sand lenses (that mimic fracture pathways) surrounded by silt size material loaded in Plexiglas tanks are described herein.

Column Studies. An undisturbed core of saprolite oriented parallel to bedding planes was collected by ORNL/ESD staff (P. Jardine and R. O'Brien). The column is 40 cm long with a cross sectional area of 221 cm². Paraffin wax was used to seal and mechanically maintain the column during collection. An aqueous solution saturated with a mixture of He, Ne, and SF₆ was prepared by installing thin walled Teflon tubing inside a carboy and then allowing a gas mixture to flow through the tubing and equalize through diffusion with the water in the carboy. The mixture of dissolved gases along with dissolved Br⁻ was passed through the column at flow rates of 14 to 90 ml/min during two separate experiments. Hydraulic gradients of 0.85 and 2.6 respectively were maintained during the two tests using a marriott bottle.

Helium and Ne samples were collected using an in situ headspace technique by installing a length of thin-walled Teflon tubing into the effluent end of the column. After a predetermined equilibration time gas samples were removed from tubing using a syringe; the removed gas was replaced with high purity N₂. Simultaneous He and Ne analyses were carried out on a Varian Model 3400 Gas Chromatograph with a thermal conductivity detector. Sulfur Hexafluoride samples were collected by filling 40 ml vials with Teflon-faced silica septa. Each vial was later given a 5 ml headspace and shaken vigorously for 1 minute. SF₆ analyses were then conducted using a Hewlett Packard Gas Chromatograph with an electron capture detector.

Because each injected tracer has a different aqueous diffusion coefficient, we anticipated matrix diffusion would cause the initial effluent to be enriched (relative to the influent source) in the tracer with the lowest diffusion coefficient. A clear separation of tracers occurred with the ratio of Br to He being nearly 2 during the initial breakthrough of the tracers. After approximately 4 pore volumes of tracer solution had eluted from the column, the injection of tracer water ceased and untagged water then flowed through the column in an attempt to flush the

tracers. Shortly after removing the tracer source, the Br to He ratio declined to approximately 0.5. Flushing of the column continued for approximately 15 pore volumes; however a significant amount of tracer was still present after sample collection ceased.

The observed results are consistent with matrix diffusion theory in that the He diffusion coefficient is greater than Br- and thus He more readily diffused into the matrix during the initial portion of the test. After the tracer source was removed, He was more readily removed from the matrix due again to its larger diffusion coefficient. Numerical modeling of these tests also indicates that curves of the ratio of tracers are sensitive to fracture spacings. Fitting the observed data to a numerical model suggest fracture spacings of approximately 3 cm. While the model was reasonably successful at matching the early portion of the data, an extremely long elution curve "tails" for the dissolved gases were observed and not readily predicted by the model. Additional analysis of the tracer data suggests that the column was not fully saturated and some of the tailing may be due to exchange between liquid and gas phases. Additional modeling is underway to evaluate the effects of trapped air.

Tank Studies. As noted above, numerical simulations of matrix diffusion indicate that tracer tests conducted with a suite of tracers that have distinctly different diffusion coefficients are sensitive to fracture spacings. The ultimate strength of the matrix diffusion process, and, in particular, the time required to flush solutes from the matrix, is proportional to the square of the fracture spacing. However, effective fracture spacings are extremely difficult to determine because only a small fraction of the total fracture population typically conducts nearly all fluid flow. The sensitivity of the multiple tracer approach to fracture spacings suggests that such tests can be used to derive effective field-scale values.

In order to verify the use of multiple tracers to determine effective fracture spacings we have constructed several Plexiglas tanks filled with thin layers of sand (to mimic fractures) surrounded by thick layers of silt-sized crushed dolomite. The tanks are approximately 1 m long by 13 cm wide. Initial work has focused on constructing the tanks, generating a fully saturated flow system, measuring the hydraulic properties of the sand and silt, and constructing an analytical system for measuring dissolved gases. Tracer experiments will begin in September of 1994 and will consist of injections of dissolved He and Ne along with a fluorescent dye. Breakthrough curves for each tracer will be combined into ratio plots and fit to model results in order to estimate "fracture" spacings based on the solute concentrations alone. The results of this study will aid in interpreting the results of the noble gas tracer test being conducted by ORRHAGS in West Bear Creek Valley.

3.2.2 Fractured Shale Tracer Experiments

L. D. McKay, D. D. Huff, D. Webster, L. E. Toran, and
D. K. Solomon

Data from two tracer experiments carried out by USGS staff in the 1970's in the weathered and fractured shales near BG 4 and BG 6 at ORNL are being qualitatively and numerically evaluated. At each site, respectively, 50 and 100 Curies of tritiated-water was introduced to a shallow (6.3 and 8.9m deep) borehole and concentrations were monitored in the injection well and in a series of downgradient wells. The low-concentration tritium front advanced very rapidly, moving in the order of 0.1 m/day, but the center of mass of the tritium plume moved much slower, about 0.002 m/day at the BG4 site (with similar values observed at BG6). This is due to the diffusion of most of the mass of tritium into the relatively immobile pore water of the matrix between fractures (similar to what was noted in 3.2.1). As a result of this storage in the matrix it takes a very long time to naturally flush out the solute and at the BG4 site, which is still intact, there remains a measurable tritium plume 16 years after the initial injection.

The data are currently being evaluated with a 1D (quasi-2D) discrete-fracture/matrix-diffusion model and a 1D equivalent porous media (EPM) model to determine whether the system can be approximated with an EPM approach and to identify the influence of key parameters such as fracture aperture, fracture spacing and matrix porosity. Further modeling using 3D fracture and EPM models is planned for 1995. Bacteriophage tracer experiments (section 3.2.3) are also being used to estimate typical ranges of fracture flow velocities for this type of deposit.

3.2.3 Phage Tracer Experiments

L. McKay, A. Harton, and R. O'Brien

A phage tracer experiment was carried out in June, 1994 in an undisturbed column of fractured shale saprolite obtained by R. O'Brien (ORNL/ESD) from a depth of 1 m at the Melton Branch instrumented watershed. The objective of the experiment was to determine whether colloid-sized bacteriophage (viruses that replicate in bacteria) and fluorescent latex microspheres were sufficiently mobile in the fractured saprolite to be useful as analogies of colloidal contaminants. Previous experiments carried out by the Principal Investigator in fractured clay tills in Canada and Denmark had shown that colloid-sized bacteriophage could migrate at significant rates (m's per day) that were several orders of magnitude faster than non-reactive solute tracers such as bromide. The solutes are strongly retarded by diffusion into the very small pores between fractures (matrix diffusion), while the colloids are size-excluded from these pores and hence remain in the faster moving water within the fractures. Colloidal tracers can be used as

indicators of fracture flow velocity in such deposits. As well, in some settings colloids may be contaminants of environmental importance or may facilitate the transport of solutes sorbed to the colloids.

Two strains of bacteriophage (PRD-1 and MS-2) and 3 types of fluorescent microspheres (0.1 to 0.5 μm diameter) were introduced to water flowing through a 40 cm long saturated column of fractured shale saprolite at a rate of 0.33 ml/min, with a hydraulic gradient of 0.0125. The saturated hydraulic conductivity of the sample was 1.4×10^{-5} m/sec. Even at this very low flow rate the phage were relatively mobile and they appeared in the effluent within 12 hours of the start of the injection (Figure 3). Although initial breakthrough was rapid, the maximum effluent concentration of both strains was 10^{-2} to 10^{-4} times lower than the injection concentration, indicating a high degree of filtration. Following completion of the experiment the column was dismantled and the distribution of the microspheres was mapped under ultraviolet light. The microspheres showed up on some, but not all, of the fracture surfaces and often occurred in faint "channels" that were not visible in plain light.

A natural gradient field-tracer experiment using colloidal tracers (bacteriophage, microspheres and bacteria) is planned for the fall of 1994 using existing wells at the noble gas tracer site. The objective is to measure colloid (and hence fracture flow) velocities at a site where the solute transport behavior has already been determined and to investigate differences in colloid filtration.

3.2.4 West Bear Creek Valley Noble Gas Tracer Test

W. E. Sanford and D. K. Solomon

Introduction. The burial of wastes on the ORR generally has been in the shales of the Conasauga Group. It is believed that the shallow subsurface flow of groundwater and transport of contaminants within these units occur in discrete, fractured zones of relatively high permeability located within the water table interval. As a result of the weathering process, saprolite has formed in the upper portion of the water table interval. Saprolite can be described in broad terms as having a low permeability yet a relatively large porosity. As a consequence, there is great potential for diffusive exchange to occur between the groundwater in the fractured zones and the groundwater in the matrix (unfractured saprolite).

As noted in sections 3.2.1 - 3.2.3, matrix diffusion can have a significant effect on contaminant transport and site remediation. Wastes buried many years ago have had ample time to diffuse from the fractured zones into the low permeability matrix. Site remediation typically is performed over a relatively short period of time compared to the time that the wastes have been buried. As a result, groundwater in the permeable fracture zones can be cleaned but contamination in

EXP 1 SAPROLITE COLUMN X=.0125

Figure 3 Breakthrough of bacteriophage through a 40 cm long column of fractured saprolite taken from a depth of 1 m. Phage were injected, at room temperature, from 0 to approx. 8000 minutes and then were flushed with fresh water. Source concentrations of PRD-1 and MS-2 were approx. 10^9 and 10^7 pfu/ml, respectively. Flow rate was 0.33 ml/min., hydraulic gradient was 0.0125 and hydraulic conductivity was 1.4×10^{-5} m/sec.

the matrix, which can be of a large volume, slowly diffuses back into the permeable zones. This acts as a secondary source of contamination and limits the rate at which remediation can take place.

Objective. The West Bear Creek Valley noble gas tracer test is designed to study the effects of matrix diffusion on the transport of dissolved helium and neon in the groundwater. The two noble gases have different molecular diffusion coefficients so diffusion into and out of the matrix porosity at different rates will cause a separation of the gases (see section 3.2.1). Modeling of the breakthrough and elution of the gases will provide valuable information on fracture spacing, aperture and matrix porosity for groundwater models developed for the optimization of remediation. In addition, the test will be used to develop the technique of using dissolved gases as groundwater tracers in the shallow subsurface.

Results (Laboratory Work). Work in the laboratory during the past year has led to the development of a passive diffusive sampler for the sampling of dissolved gases from groundwater. The device consists of a tire valve stem soldered to a length of copper tubing. The tubing is sealed so that the interior of the sampler is isolated from the atmosphere. A piece of silicon tubing filled with sand is attached to the valve stem with a steel cap. With the cap threaded on, the valve is opened. Dissolved gases can then diffuse through the silicon tubing and within about 1.5 days, the gas in the sampler equilibrates with the dissolved gases in the groundwater. When the sampler is removed from the groundwater, the cap is removed and the valve closes, sealing the sample. The sample is then injected into the gas chromatograph and the He and Ne content is measured. These samplers can also be used to collect other dissolved gases such as oxygen, nitrogen, argon, etc.

A system for introducing the gases into ground water was also developed where the gases are circulated through a coil of Teflon tubing that is in the injection well. The gases diffuse through the Teflon and into the groundwater. The gases diffuse in Teflon at approximately the same rate as in water. This injection method minimizes the formation of bubbles in the groundwater that might otherwise get trapped in the pores. Bubble formation would likely occur if the gases were directly bubbled into the water. This would cause a reduction of hydraulic conductivity near the vicinity of the injection well.

Field Work. Seven multilevel groundwater sampling wells were installed in the core holes that were drilled last year (Figure 4). The depth levels at which the samples are collected were determined from the results of the rhodamine analysis and point dilution tests performed last year. The multilevel wells were installed by injecting alternating layers of sand and bentonite to isolate permeable zones.

- ✱ 6" AUGER HOLE
- AUGER HOLE WITH BEDROCK CORE
- CORE HOLE
- △ NESTED PIEZOMETERS
- 2" WELLS
- SOURCE WELL

WEST BEAR CREEK VALLEY TRACER SITE WELL LOCATION BASE MAP

ORNL-DWG-95-9133

The gas samples are collected by dropping the sampler down the small well and allowing time for equilibration. The samplers are retrieved and then taken to the lab for gas analysis.

The injection well consists of several hundred feet of 0.125" Teflon tubing wrapped around a ten-foot length of slotted 0.5" pvc pipe. The tubing is wrapped with filter fabric to prevent bubbles that may form from entering the porous medium. The Teflon tubing is connected to a gas cylinder at the surface with 0.125" copper tubing. The cylinder contains a mixture of 60% Ne and 40% He which is injected continuously. Concentration of the gases in the source well is measured by placing the sampler down the pvc well into the screened section. In addition, a Br solution is added periodically to measure the flux out of the source well.

Three wells at the field site are instrumented with pressure transducers: the source well #484, #486, and #499A (Figure 4). A thermistor is installed in the source well to measure the temperature of the groundwater because the solubility of the gases is temperature dependent. There is also a tippingbucket rain gauge on site to measure precipitation. All instrumentation is wired to a data logger on site.

Tracer Test. The field tracer test was started on March 11, 1994. Surprisingly, breakthrough of the gases was first seen in Well 487, located 14 m from the source, in 4 days (Figure 5), yielding a minimum velocity of greater than 3 m/d. This time includes the time it takes to saturate the source well and to have the sampler come to equilibrium. Lee et al. (1989) reported an initial velocity of rhodamineWT at the same site of 5 m/d. We at first thought the initial high velocity of the rhodamine was in part due to the increased head in the source well caused by the addition of 10 L of the rhodamine solution. However, it appears that the initial high apparent velocity is a characteristic of transport through the saprolite.

The breakthrough curve for Well 487 in Figure 5 is for the first 83 days after injection started and shows a separation of He and Ne occurring, as expected. These samples show an enrichment in Ne relative to He, which is interpreted as being a result of the larger diffusivity of He, which causes it to migrate into the matrix faster than Ne. Also plotted on Figure 5 is the daily rainfall amount for the same period of time. Around Day 15 there was a storm in which nearly 6 inches of rain fell over a weekend. The sample collected from #487 had no noble gases in it. Yet the next sample, collected 2 days later, had concentrations nearly as high as before the rain. This behavior suggests that there is flushing of water at a fast rate through the permeable interval, causing a decline in concentration. As flow slows, the concentrations rise rapidly because the matrix between the source and #487 still has He and Ne in it, thereby slowing the rate of diffusion from the

Figure 5

permeable interval into the matrix. Sharp decreases and increases in concentrations just after heavy rains are also seen around Days 30 and 35. A possible explanation for the tracer behavior can be found by examining Figure 6, which is a plot of the heads in the three wells with time compared to the daily rainfall amounts. It can be seen that the storm occurring around Day 15 caused a rapid rise in the water table in the source well of nearly 8 ft, indicative of fractured media. Rapid water table rises were also seen in the other 2 wells. This increase in head and corresponding increase in gradient would cause faster flow of water through the permeable interval. Rapid water table rises were also recorded as a result of other large storms before Day 40. The head data after Day 40 are characterized by a gradual decline with little or no sharp increases, even after fairly heavy rainfall. These differences in head response correspond to the time when tree leaves appeared and evapotranspiration became important. This correlation suggests that the vadose zone, which is several meters thick, is close to saturation during the rainy season and that the precipitation that falls is enough to saturate the soil and cause rapid increases in head at depth. When evapotranspiration is high, the moisture content in the vadose zone is reduced and more of the precipitation is taken up in the unsaturated zone. To study the variation in water table behavior between the wet and dry seasons, the injection of the gases will continue into the next wet season. The large and rapid fluctuations in water table elevation may play an important role in the short term migration of contaminants on the ORR. Therefore, any model developed to explain the long term data collected at this site must also be able to explain the short term fluctuations that are observed.

Future Work. Future work includes the continuation of the tracer test with gas injection until March of 1995, when the source will be turned off and the elution of the gases will continue. Plans are being developed to perform a colloid tracer test in conjunction with L. McKay and J. McCarthy in early fall using bacteriophage and bacteria. The bacteria are about 2 orders of magnitude larger than the phage so this should allow an excellent comparison between the migration of the two colloid sizes.

The development of appropriate computer models will begin during FY 1995. These models will be used to explain the data collected to date, but will be modified as more data are collected and new information on the hydraulics of the site is learned.

Currently a manuscript is in preparation on the methods of performing a dissolved gas tracer test in a shallow aquifer. Also planned is a manuscript describing the characterization techniques (point dilution tests and rhodamine distribution) used to determine the sampling intervals at the field site.

Heads and Rain

Figure 6

3.2.5 Stormflow Geophysics Experiment

J. Nyquist, G. Wilson, L. Toran, and M. Emery

The purpose of this experiment was to remotely sense stormflow zones using spontaneous potential (SP). SP is a geophysical method that senses the motion of flowing groundwater with dissolved ionic species. The proposed technique was to measure currents generated by groundwater flow using small electrodes planted in the shallow subsurface (upper 20 cm). The advantage of using a geophysical technique, if successful, is that stormflow is transient and difficult to monitor with point measurements.

The technique was tested on a previously instrumented site in Melton Valley, just above an underground weir. An array of 40 electrodes was distributed over an approximately 20 by 10 meter area at the top of the hillslope. A known, artificial, discharge of rainwater was monitored using automatic data logging, then subsequent natural storms from February to May were also logged. To increase the signal to noise ratio, several low pass filters made of capacitors and resistors were installed in the monitoring system.

The experiment was successful in detecting storm pulses but not in locating stormflow zones. An increase in voltage occurred at the onset of the artificial and real storm events, even before stormflow was detected in water level monitoring ports. The electrical pulse matched the rise and decay of groundwater level hydrographs. However, because the voltage increase occurs at the onset, the transient development and spatial development of the stormflow zone could not be mapped. There are two sources of voltage from groundwater flow: one is a rise in head due to additional flux of water, and a second is a change in head across a permeability boundary. The first signal was detectable with the SP array, but the second signal, which would have mapped flow zones; was in the noise level. An additional problem in the method was an unexplained source of anthropogenic noise during normal working hours that the filters were unable to eliminate.

In conclusion, the SP system would be useful for detecting convergent sources and sinks of groundwater input (that create a change in water level). The potential for mapping karst sinks and seeps should be further explored. In fact, the technique has been successful in detecting seeps along waterways. However, the noise problems encountered in this study must be solved before SP can be used for mapping a stormflow zone.

3.2.6 Characterization of Groundwater Flow System Dynamics at the Oak Ridge Reservation Through Statistical Analysis of Water Level Data

G. R. Moline and D. E. Allred²

Investigations of groundwater dynamics on the ORR have been, for the most part, confined to local areas of interest, such as waste disposal areas, or limited to the creation of static water table maps. Results of these investigations are insufficient for large-scale applications where an understanding of regional dynamics is required. In order to guide decisions in response to questions such as the distribution of input parameters for regional groundwater models or the distribution of wells to be exempted from plugging and abandonment in order to retain representative monitoring networks, a large-scale 3D framework of groundwater dynamics is required. The need for this framework provides the motivation for this project, and historical piezometric and precipitation data are providing the information required to build it.

Figure 7 illustrates the difference in water level variations over a 2.5-year time

Figure 7. Well hydrographs from 468 (—) and 472 (...) showing variations about the mean (ft). ORNL-DWG 95-9136

period for two wells located in the same region of Melton Valley. The spatial distribution of subsurface flow properties can be investigated by examining the

²The University of Tennessee, Knoxville

variations in water level (piezometric) responsiveness within wells distributed across the region of interest. Piezometric fluctuations result from a variety of forcing events such as precipitation, air entrapment during recharge, evapotranspiration, bank-storage effects, earth tides, atmospheric pressure changes, earthquakes, and anthropogenic activities. The nature of these fluctuations is controlled by subsurface hydrologic characteristics such as specific storage, hydraulic conductivity and secondary porosity, in addition to the construction design of the well. Piezometric responses in wells located on the ORR can be expected to be heavily influenced by fracture density and geometry and by local dissolution features.

The approach being used to build a dynamic framework for Melton Valley is based on the following rationale. The relationship between forcing events, formation and well characteristics, and piezometric fluctuations can be mathematically depicted by the following equation:

$$\sum F_i * T_{ij} = R_j$$

where F_i are the forcing functions, R_j is the response in the j^{th} well, T_{ij} is the transfer function for the i^{th} forcing function at the j^{th} well location, and $*$ is the convolutional operator. This process can be viewed as something like a "black box" into which precipitation data are dumped and out of which comes a well hydrograph for that precipitation period. Within this black box are transfer functions, or mathematical representations of the effects of evapotranspiration and runoff, subsurface hydrologic properties, and well construction effects. If some assumptions are made about spatial invariance of the forcing functions (eg., equally distributed precipitation) and similarity in well design, then spatial variations in the response functions must be a result of variations in the transfer functions and the properties they represent. Thus, if the wells are clustered into groups having similar piezometric responses by using discriminator variables, then the spatial distribution of the well groupings should be an indicator of spatial distribution of hydrologic properties as well.

In order to establish the well groupings, a subset of 39 wells from the Melton Valley area were chosen. The criteria for inclusion were daily measurements over a minimum of one full year during the October 1985 to October 1988 period. These well hydrographs have been characterized in terms of discriminator variables after first subtracting the mean and linear trend and then separating out the low-frequency seasonal and high-frequency storm components. These discriminator variables capture the essence of the piezometric response to precipitation, and include: seasonal range, seasonal peak lag, seasonal recession slope, storm response variance, storm lag, and storm correlation. Multivariate

classification of the discriminator variables has been used to group the wells according to similar dynamic characteristics. As a result, seven dynamic groups have emerged.

Crossplots of well classification versus other variables such as lithology, depth, and location in recharge or discharge zones are being used to aid in the identification of key factors that control flow-system dynamics. Transfer functions are being developed for each of the seven well groups. These functions will provide a means for expanding the data set to include as many as 500 wells in Melton Valley in which the hydrographs consist of data having larger sampling intervals (weekly to monthly) and/or data outside the three-year window. Expansion of the data set will then allow an analysis of the three-dimensional distribution of dynamic groups and the hydraulic properties that they reflect.

3.2.7 Sampling Protocols For Fractured Media

G. R. Moline and M. E. Schreiber³

The complexity of the flow system at the ORR raises concerns about the representativeness of samples obtained utilizing currently prescribed purge procedures and existing monitoring well construction specifications. According to the site conceptual hydrologic model, the majority of groundwater flux within the saturated zone moves through a network of fractures that comprise only a minute percentage of the pore volume in the ORR aquitards. These fractures provide pathways for rapid transport of contaminants. Purging large volumes from low yield formations results in a large radius of influence and as a result, samples may be representative of fracture fluids outside of the local region surrounding the well, potentially causing contaminants to move through the system at accelerated rates and along disrupted flow paths. In addition, monitoring wells are constructed such that they use large screened intervals that may or may not intersect active flow zones. Thus, standard construction can mask the vertical distribution of contaminants and prevent discrimination of contributions from matrix and fracture zones.

At a field site in West Bear Creek Valley, an ongoing helium and bromide tracer test in the Nolichucky Shale has revealed complex flow dynamics wherein groundwater flows preferentially along strike-parallel fractures oblique to the hydraulic gradient in both the saprolite and shallow bedrock. The net result is greater dispersion and potentially significant differences in transport behavior for wet and dry seasons. Three boreholes were drilled and continuously cored adjacent to existing well pairs at the tracer site using an acoustic (Rotasonic)

³University of Wisconsin - Madison, Madison, WI

drilling technology. During drilling, major fracture zones that are not being captured by the existing wells were identified (Figure 8). Borehole videos, electromagnetic flowmeter tests, point dilution tests, and discrete fracture sampling were completed in the open boreholes. Results of these activities were used to identify and characterize the active transport zones and the vertical variability in groundwater chemistry and tracer concentrations, providing information to guide the location of sampling ports for multilevel well installation.

Instrumentation for continuous water level monitoring in all multilevel intervals coupled with the initiation of a sulfur hexafluoride tracer injection scheduled for

Figure 8. EM flowmeter results show major fracture zone occurring between 46-49'.
ORNL-DWG 95-9137

FY95 will allow a better understanding of the complex transport dynamics at this site and will provide a means for directly comparing the information obtained from multilevel and screened wells. These activities will be followed by pump tests in the summer of FY95 that will allow direct measurement of the region of influence and the impact on tracer concentrations and field parameters for various purge volumes and, in addition, will provide a measure of the fracture zone interconnectivity. These data will be used to define the spatial and temporal variability in transport behavior, the impact of purging on transport processes, and the impact that well construction has on measured concentrations and subsequent risk calculations using tracers as surrogate contaminants. The net result will be an evaluation of the limitations of current groundwater quality monitoring practices when applied to fractured media typical of that underlying many of the ORR waste disposal areas, and recommendations for revisions in both monitoring well construction and sampling protocols.

3.2.8 East Oak Ridge Reservation Spring and Seep Survey

S. B. Jones

Background. Assessment of natural groundwater discharge on the ORR is considered an essential element of the hydrological conceptual model recently proposed by Solomon et. al. (1992). The identification of discharge points, seasonal variations in discharge parameters, and the correlation between natural outlets and the contributing water-bearing units is imperative to understanding the flow regime in each hydrologic unit and solute transport from the subsurface to the biosphere. To date, few surveys of natural surface discharge points (springs and seeps) on the reservation and surrounding areas have been made.

Objectives. Natural outlets of subsurface flow may be controlled by surface topography, formation lithology, karst features, and geologic structure (fractures, faults, folds). It has been postulated by Solomon et. al. (1992) that there is an active shallow groundwater system (consisting of the stormflow, vadose, and water table zones), a less active intermediate groundwater interval, and a deeper saline system that is considered to be sluggish and relatively immobile. By inventorying the existence, and monitoring the hydrologic and geochemical components of spring and seep discharges, further data about the character of groundwater flow will be gained and evaluated in order to further understand the hydrologic system of the ORR and surrounding areas. Additionally, a protocol for future spring and seep research will be proposed in order to increase procedural efficiency and maximize data quality and value.

This study encompasses an analysis of hydrologic, geochemical, and isotopic characteristics of spring and seep discharge water, in an effort to better understand the subsurface flow system. The identification of geochemical groundwater facies will make it possible to classify water types and help determine relative contribution of lithologic units to natural discharge, as well as, establishing residence times within the groundwater system.

Activities. Two preliminary (or phase I) surveys of the selected study area have been completed. One during the Spring and Summer months of 1992 and one during the Winter of 1993. These surveys consisted of an intensive field search for springs and seeps. During The 1992 survey, 142 springs and seeps were located. The 1993 survey yielded an additional 74 springs and seeps due to the wetter seasonal conditions. During this survey, basic parameters (i.e. location, temperature, specific conductance, dissolved oxygen, discharge, and lithology) of each spring were obtained.

From this population of 216 springs and seeps, a subset of 30 springs was selected for chemical and isotopic sampling (phase II). Two sampling events were

performed in order to evaluate the chemical and isotopic variations between wet and dry seasonal spring discharges. A low flow sampling event was performed in early August 1993, and a high flow-sampling event was performed in March 1994. All of the chemical and isotopic analyses from these two events have been completed.

Phase II also included a monthly monitoring schedule of this subset of 30 springs. This activity was implemented to determine how spring discharge water characteristics (i.e. pH, temperature, specific conductance, dissolved oxygen, and discharge rate) vary over a period of one year due to lithologic, structural, and/or precipitation influences. This monitoring was completed on July 16, 1994.

Spring discharge waters tend to support the existing hydrologic model of an active shallow zone with little contribution from the deeper zones. Lithologic controls are apparent between the Knox Aquifer and the Aquitard units geochemistry analyses. Both the Knox Aquifer and the Aquitard Units discharge groundwater to springs and seeps of a calcium-magnesium- bicarbonate water facies. The Knox Aquifer Units spring waters have a higher Ca:Mg ratio and tend to only be influenced by variability in sulfates and chloride ions. The influences of sulfates and chlorides in the aquifer waters may indicate mixing processes of shallower and deeper groundwaters. The Aquitard spring waters tend to have more variable geochemistry since units of limestone, sandstone, and shale lithologies are contributing. The monthly monitoring data also support the existing hydrologic model. Even though continuous monitoring through a rain event was not performed, moderate to rapid response to rainfall was apparent in temperature, specific conductance, and discharge rate measurements in many of the aquitard springs and some of the aquifer springs. More stable parameters with very little rainfall response indicates longer residence time through the subsurface and potentially from deeper groundwater intervals. Presently, no conclusive evidence of contribution from the deep groundwater interval or the aquiclude was obtained; however data evaluation is ongoing.

3.2.9 Exit Pathways

C. Gorman, R. Nativ, W. Sanford, and G. Moline

The original purpose of this project was to investigate the possibility of mixing between shallow and deep aquifer systems, by looking for chemical signatures specific to deep brine within shallow wells. If mixing is discovered, it is important to establish whether contaminants within the shallow aquifer are moving off site through the deep water system. It is apparent that the data set we are using is not complete. Many of the data were eliminated from the study as the charge balances from the chemical analyses were not within a reasonable range (+10%). In addition, many of the wells in the study (especially those at Y-12) are

tapping contaminated water. Contaminated water has chemical signatures that are often indistinguishable from those of brine. This makes it difficult to determine whether a well shows evidence of brine infiltration or contamination. Finally, several wells known to contain brine are not available in the data set. Until a complete data set is compiled, including alkalinity, bromide analyses, and the chemistry of brine-containing wells, the question of mixing beneath the reservation cannot be definitively answered.

Conclusions and Future Work:. Several of the wells at Y-12 and K-25 that plot within the range for brine may be indicative of mixing between shallow and deep waters. Once a more complete data set becomes available and charge balances can be calculated, these wells may become the focus of further investigation. Ideally, a map of the reservation, showing either isochloride lines or lines of equal ion ratios (ion ratio facies map) could be created. Bromide data above detection for all three plants would be very useful in determining the presence of brine and its extent (Carpenter, 1978). Until further data become available, no conclusions about the absolute location and extent of the brine in the shallow water system may be reached. The wells that look like they have brine chemistry may be interesting to investigate further once the necessary data are collected.

3.2.10 Deep System Dynamics.

R. Nativ

Workshop. Investigations continued during FY 1994 in an attempt to understand the role of the deep groundwater flow system for the ORR in contaminant transport. Activities included convening a workshop to address the brines that are characteristic of the deep flow system and continued field work and data collection/interpretation. Available geological, hydrological, chemical and isotopic data from the deep flow system were presented at a 3 day workshop which focused on brines in the Appalachian Mountains. In addition to participation by ORRHAGS staff, S. Davis (U. of Arizona), B. Jones (US Geological Survey), E. Rosenthal (Israel Hydrological Service), S. Frape (U. of Waterloo), J. Saunders (Auburn U.), and J. Horita (ORNL, Chemical Division) joined the workshop.

Data Evaluation. Eight monthly logs of electrical conductivity and temperature in the CH-5 (Chickamauga), CH-1 (Conasauga) and WCR-2 (Knox) boreholes (Figure 9) were evaluated. Whereas the location of the interface between the saline and fresh water in the CH-1 and WCR-2 varied up to 40 ft during the logging period, no temporal variations could be observed in the CH-5 corehole.

The potential contribution of saline water into the freshwater system was assessed

Figure 9

by C. Gorman using existing chemical data from the computerized data base of ORNL, Y-12, and K-25. Salinity anomalies (Cl content > 100 mg/L) and Na/Cl mole ratio typical of the brine (< 0.7) were used as parameters for data screening. Wells which complied with these criteria were identified for further evaluation.

Groundwater sampled during the summer and fall of 1993 from the CH-5, CH-6, CH-9, HHMS6a, WOL-2, GW-241, GW-211 and WCR-2 boreholes were processed before shipping for analyses. The samples were distilled for tritium analysis, and carbonates were precipitated, acidified and CO₂ was collected for C-14 analysis. The samples were shipped for analyses to the Chemical Division in ORNL (oxygen-18 and deuterium), U. of Rochester (tritium), Lawrence Livermore National Lab (C-14), and Texas A&M (general chemistry and C-13). Following a long process of chemical data evaluation in which questions arose as to data quality, more samples were shipped for general chemistry analysis at Sandia National Lab.

Field Data Collection.

Temporal variations in the location of the brine/freshwater interface.

Monthly monitoring of electrical conductivity and temperature continued in the CH-5, WCR-2, and CH-1 boreholes through February 1994. Following EC observations in the 300-ft CH-1 borehole, it was decided to continue the monitoring in two deeper boreholes in the Conasauga Group (the CH-3 and WOL-2 boreholes, Figure 9). In both boreholes restrictions were encountered at depths of 410 and 270 ft, respectively, and interfered with the regular monitoring. The one log we have so far from the CH-3 borehole shows a gradual increase in conductivity down to a depth of 600 ft, whereas the one log we have from the WOL-2 borehole reveals two very clear, sharp interfaces at 340 (doubling the conductivity) and at 475 ft (where the probe went off scale) (Figure 10). Attempts to continuously (rather than monthly) monitor the interface location in the GW-211 borehole did not succeed because of instrumentation problems. The In Situ EC and temperature probe failed and was repaired three times between March and late June and no useful data have been collected so far.

Water level variations of the deep system. Short-term and seasonal variations were observed weekly in the GW-711 borehole (Figure 9), 660 ft deep, cased to 610 ft (Knox) from mid September 1993 through late June, 1994. Similarly to previous measurements in the HHMS2a borehole (400 ft deep), the measurements revealed a few event-base responses of the water level to specific rainstorms.

Selection of boreholes for future monitoring. Attempts were made to identify additional deep wells tapping the Knox and Chickamauga Group suitable for monitoring temporal variations of water levels and the location of the saline/freshwater interface. The GW-185, GW-189, and CH-157 holes were

Figure 10

logged for temperature and electric conductivity. The GW-185 borehole contained only saline mud at the bottom. The GW-189 and CH-157 boreholes did not contain any saline water. Grab samples collected prior to logging the CH-189 borehole showed evidence of radioactivity. The CH-143 hole was blocked at 55 ft and could not be slug-tested or logged.

Sampling of deep boreholes. The GW-121 borehole (Conasauga) was packed off in the bottom, purged and sampled. Groundwater samples were shipped to Sandia National Lab and to the U. of Rochester. The installation of packers in the WOL-1 borehole (deepest on the Reservation; contains the most saline water; monitors the Conasauga Group) proved to be a major time/labor consuming activity. The borehole was packed at 1400 ft five times and each time the tubing leaked during packer inflation. The tubing was completely replaced and the borehole was repacked for the last time at 1369 ft during June 1994. The hole has not been purged yet.

The JOY-2 borehole was slug-tested to a depth of 656 ft (Conasauga), although the total depth is 2718 ft. To avoid leakage from below the restriction, a straddle packer setup was introduced into the hole. As the packers were lowered into the uncased hole, they hit yet another restriction at 200 ft (which had not been encountered by the slug previously) and got stuck there. Efforts to manually retrieve the packers failed.

Several Rock Cover wells around the Hydrofracture Facility at ORNL were accessed this year by contractors working for the Environmental Restoration Program. Preliminary analyses show radioactive contamination at various levels in all boreholes. Plans to pack the wells and sample them were suspended because of the contamination and funding limitations.

3.2.11 A review of the hydraulic conductivity testing data obtained from bedrock of the Oak Ridge Reservation.

K. Novakowski and R. B. Dreier

Over the last decade numerous hydrogeological investigations have been conducted on the Oak Ridge Reservation for a variety of purposes including basic research, specific waste site investigations and to determine the regional hydrogeological framework. The purpose of this task is to present the results of a preliminary review of existing hydraulic testing methods and data and to provide recommendations for future hydraulic testing and data interpretation. Specific goals are 1) provide a cursory review of the Golder (1987) testing methods and data set, 2) review and re-analyze a selected number of tests conducted in the boreholes completed with multi-port monitoring systems, and 3) recommend and describe methods for conducting hydraulic tests in multi-port systems.

Review of Golder Associated Ltd. testing methods and data set. In 1987 Golder Associates Ltd conducted a series of hydraulic tests in the CH boreholes completed in the Chickamauga Group limestones and shales. The tests were conducted using a modified drill stem test (DST) method and interpretation was conducted using the Horner method. Interpretation of these hydraulic tests using the Horner method is subject to some uncertainty because of several factors:

(1) Commonly, the test sections were not allowed to achieve static equilibrium in hydraulic head prior to the start of the first flow period. This will be particularly important for low permeability zones. Figure 11 shows test results from a low permeability horizon as suggested by the nearly constant pressure during the flow periods. The rollover in the second shut-in period is caused by the superposition of the DST upon a long term trend of changing hydraulic head. Static heads estimated from each shut-in periods are radically different, a further indication of inappropriate pre-test conditions. Horner plots of test data are commonly linear ONLY near unity, and analysis of any other portion of the line segment would be erroneous. Change in slope on the Horner plot is again attributed to pre-test borehole history.

(2) It is difficult to determine the flow rate, Q . In low permeability zones, the change in water level during the flow period is minimal and probably within the range of error of the transducer (Figure 11). In higher permeability zones, both flow rate and water level change during the flow period, introducing errors into the Horner method interpretation.

Other problems resulted from the relatively short duration of the tests. It is possible to account for the errors in (2) by using a modern Laplace transform solution if equilibrium is achieved prior to the beginning of the test AND if the test is run to 95% to 98% recovery. Unfortunately, this was rarely accomplished.

Gringarten type curves for wells having wellbore storage and skin should not be used to analyze results from this type of test, although Golder Associates Ltd. did use these curves on a limited basis. During the test, the wellbore storage coefficient changes radically from an open-well condition to a shut-in condition and overcomes the more subtle effects of wellbore storage and skin that would be observed in the pressure buildup part of the test. However, it remains that there may indeed be effects due to the presence of skin, double porosity and outer boundaries on the results of hydraulic tests. It is important to note that some of the 43 tests conducted by Golder Associates Ltd may be re-interpreted to investigate skin and boundary effects.

Review and analysis of a selected number of tests conducted in multiport wells. To date, 17 wells in the Oak Ridge Reservations have been completed with

Pressure history for test CH4-5. Test section is from 260.6-296.1 ft. below casing top.

Figure 11

multilevel casings manufactured by Westbay Instruments Ltd. Open well slug tests have been conducted in many isolated intervals with varying degrees of success. Most of the tests have been initially interpreted using the Hvorslev approximation. For those intervals that were determined to be of permeability lower than practical for conventional open-well slug test, shut-in slug tests were conducted. As with the Golder Associated Ltd data set, there are some problems associated with both data acquisition and interpretation methods.

(1) The Hvorslev approximation is subject to error because of skin and other effects. When skin is present, the Hvorslev analysis measures ONLY the hydraulic properties of the skin (Novakowski, 1993). A systematic investigation of skin in the multiport wells has not been conducted to date.

(2) Several tests showed an initial head drop of over 100 psi during the period when a small volume of fluid is extracted from the zone. This creates permanent deformation of the test section (likely due to slight movement in packer gland position) and the hydraulic head does not return to the static equilibrium value measured prior to the tests. Thus standard type-curve analytical techniques cannot be used.

(3) Where test conditions were suitable, test results were interpreted as pumping recovery. Using a Theis type curve resulted in a poor overall fit, particularly at "late time". This is either due to boundary effects or uncertainties associated with the use of a pumping test interpretation.

(4) There is little late time data. Even when it was possible to produce good quality fits for type curves, because of the limited amount of late time data, it was difficult to identify skin or boundary effects.

Regardless of these problems, it was possible to re-interpret selected data using either slug test or pumping test theory (Table 1). The results show a surprising similarity between the Hvorslev and type curve analysis. We have yet to determine if this is showing us properties of the formation or of a relatively thick skin. In addition, type curve analysis shows anomalously high values of storativity, more typical of a confined porous aquifer or aquitard rather than Paleozoic consolidated rock.

Future directions. Well testing will be continued in the multiport wells. Particular attention will be given to improving data acquisition techniques that have been modified as a result of collaboration between Kent Novakowski and ORNL staff. These will address problems noted above, including uncertainties with skin effects and anomalous storativity values. Recommended methods for additional well testing in multiport well are presented in Novakowski, 1994.

Additional objectives associated with this task may include (i) Development of a modified DST model for finite skin (ii) Continuation of Golder Associated Ltd and the multiport data evaluation to investigate skin effects and double porosity. (iii) Continued interpretation of the tests conducted in the multiport wells. (iv) Development of a design that would help resolve double porosity and other transport issues. (v) Determination of the reliability of the storativity values collected to date by means of a literature review, theoretical study and statistical assessment. (vi) Assessment of the meaning of the hydraulic head distribution from selected Westbay completed boreholes.

TABLE 1

TEST ZONE	K (m/s)	S	WELLBORE STORAGE FACTOR (m ²)	OPEN-WELL K (m/s)
2	1x10 ⁻⁸	5x10 ⁻⁵	7.1x10 ⁻⁶	1x1 ⁻⁸
4	3x10 ^{-6*}	8x10 ⁻⁴	4.1x10 ⁻⁵	4x10 ⁻⁸
6	6x10 ⁻⁸	4x10 ⁻⁴	NA	7x10 ⁻⁸
9	9x10 ⁻¹²	2x10 ⁻³	2.8x10 ⁻⁶	NA
12	3x10 ⁻¹¹	5x10 ⁻⁴	7.2x10 ⁻⁶	NA
14	8x10 ⁻⁹	9x10 ⁻⁴	1.3x10 ⁻⁵	8x10 ⁻⁹

* Shut-in slug test results for test zone 4 are suspect because of a leak that developed in the port during the tests.

3.2.12 Use of borehole geophysics to identify porosity changes and fractures.

R. B. Dreier and G. L. Davidson

At the ORR, diffusion into the rock matrix and rapid flow through fractures are common processes associated with contaminant transport. As a result, characterization of fractures and matrix porosity play an important role in

understanding contaminant migration. In this study we have investigated these features through the use of borehole geophysics, in particular by examining natural gamma ray and neutron cross-plots. These log types are commonly collected from boreholes and use of this type of cross-plot will be valuable at sites where core, or an extensive suite of geophysical logs are not available.

Methods. Changes in natural gamma-ray and neutron logs are commonly related to relative changes in clay mineral content. The natural gamma log responds to gamma emitters such as ^{40}K , and the neutron log responds to bound hydrogen in clay minerals. Thus, cross-plots of these logs show linear trends as a function of the amount of clay minerals. Deviations from the trends on the neutron log may result from excess hydrogen and are attributed to a change in matrix porosity (Figure 12). In a similar manner, fractures may be identified by abrupt changes in neutron behavior over a small gamma ray change (Figure 13). That is, as the logging tool passes over a saturated fracture, there will be a relative increase in the neutron response to the water in the fracture. This will be most successful if the fracture is not lined with clay minerals and the rock porosity in the vicinity of the fracture is greater than local matrix porosity.

For this study, logs from a variety of carbonate and clastic lithologies and localities were examined. All of the logs had been acquired digitally within the past three years.

Results. Use of gamma/neutron crossplots to examine qualitative porosity changes proved useful in that it was possible to observe both spatial and stratigraphic effects on porosity. For example, of the three wells examined in WAG 5 at ORNL (Conasauga Group shales in Melton Valley), two show relatively lower neutron with respect to gamma. These two wells are located near drainages that may be controlled by geologic structures, and we could be observing an increase in bulk fracture porosity. Similarly, three wells in WAG 1 (Chickamauga Group limestones and shales in Bethel Valley) show spatial porosity variability of a particular horizon that apparently is depth independent. Neighboring strata both above and below this horizon do not show any change in porosity.

Stratigraphically controlled porosity is illustrated by examining logs from GW-722 (Maynardville Limestone in Bear Creek Valley). The Maynardville Limestone is informally divided into 6 zones based on natural gamma ray signature and core descriptions. GW-722 intersects the three lowest zones in the Maynardville and all three zones show different gamma/neutron crossplots. Zone 2 shows the greatest qualitative porosity based on the crossplot interpretation. This interpretation conflicts somewhat with preliminary core studies (Goldstrand et.al. in prep) which suggests that there is little to no porosity change within zones

ORNL-DWG-95-9141

Figure 12

ORNL-DWG-95-9142

Figure 13

2, 3 and 4. Further study is required to determine if these different results are related to the core porosity determination techniques, or if the strong segregation observed in the gamma/neutron plot is related to something other than porosity.

The use of this technique to identify fractures was only partially successful. In general, attempts to identify fractures in shale-rich strata failed. Commonly in carbonate rocks, the neutron log is just as successful in identifying fractures as the neutron/gamma crossplot, and for simplicity it would be best just to use the neutron log. However, in isolated cases (GW-722), presumably because of varying clay mineral content, the neutron/gamma cross-plot proved useful for identifying fractures, and eliminated false positives that would have been picked based on the examination of the neutron log alone. In this case, fractures identified with the gamma/neutron crossplot correspond well to fractures determined from core, temperature and flowmeter logging.

Future direction. This technique needs to be calibrated with other porosity determinations so that quantitative as well as qualitative measurements and variations can be documented.

3.2.13 Fracture Toughness Testing of Bedrock Core Samples from the Oak Ridge Reservation

P. J. Lemiszki and J.-D. Landes

Little is known about the physical characteristics of the various carbonate and clastic bedrock units underlying the ORR, which includes matrix and fracture effective porosities, density, tensile and compressive strength, fracture toughness, and elastic moduli (Young's modulus and Poisson's ratio). A better understanding of these characteristics is needed, however, to evaluate the response of the bedrock groundwater system to hydrofracture waste injections, as well as proposed pump and treat remediation methods. For example, during hydrofracture injections, the ability of overlying rocks to confine the grout sheet to a specific bedrock interval is a function of their Mode I fracture toughness. If the injection pressure is too high, then the driving stress will be greater than the Mode I fracture toughness and fracturing of confining beds can occur. On the contrary, an effective pump and treat application requires that the permeable fracture pathways remain open, even after a decrease in the fluid pressure. Although a drop in fluid pressure will cause a fracture to close, fracture wall roughness will determine how tight the open fracture pathway becomes. Rough fracture walls with weak asperities will tend to close as asperities fail under the contact pressure, but strong asperities will not fail and act to prop the fracture open. Therefore, the purpose of this study is to use rock mechanics test methods on available bedrock cores to determine some of the physical characteristics of competent lithologies (limestone, dolostone, and sandstone). Presented here are

some of the results of Mode I fracture toughness testing.

It is important to note that besides the reasons mentioned above, the results of this study are needed to constrain models that examine the development of the fracture system from the time of initial propagation at depth, to fracture opening as a result of erosion and uplift in the present day stress field. Core analysis and outcrop mapping has shown that the mechanical characteristics of the bedrock have a strong influence on the geometric characteristics (orientation, spacing, and length) of the fracture system (Hatcher et al., 1992). Such models can be used to predict the range of depths at which fractures tend to reactivate and open as a result of stress release and therefore may provide a limiting depth to active groundwater circulation. Finally, the data will be used to estimate the compressibility (poroelasticity) of the intact and fractured bedrock. By combining rock compressibility with well hydrograph analysis, Bredehoft (1967) has presented a method to determine the effective porosity and specific storage of the groundwater system, which to date are poorly constrained parameters on the ORR.

Objectives. A suitable rock mechanics test had to be chosen for the cores available because acquiring cores specifically for this study was cost prohibitive. Cores from the ORR are commonly NX size (6 cm) and cut vertically through sedimentary bedding that dips towards the southeast. In order to preclude problems associated with failure along bedding planes, a test method was chosen that provides reliable results from small disk shaped samples of core taken from intact rock between bedding planes. The method is called the Modified Ring (MR) test and is based on the standard Brazilian tensile strength test (Theircelin and Roegiers, 1986). The MR test is used to determine the fracture toughness of the material. The fracture toughness is an intrinsic material property that reflects the strength of a material that contains a defect. The fracture toughness of various rock types is correlated well with Young's Modulus.

Samples of dolostone, limestone, and sandstone from the JOY2 corehole have been selected because they are competent rock types and the core is cut nearly perpendicular to bedding. Samples are from the lower part of the Copper Ridge Dolomite, Maynardville Limestone, Nolichucky Shale, and Rome Formation. The original strike direction of the core is not known, however, so the core cannot be used to investigate changes in rock fracture toughness as a function of fracture propagation direction. Enough material was collected to test 10 to 20 test samples from each rock unit.

In order to check the quality of our data, a series of tests were conducted on samples of Berea Sandstone and Indiana Limestone. These two rock types were studied because (1) the material is fairly isotropic and homogenous and (2) their

fracture toughness has been determined from numerous tests including the MR test. Blocks of Berea Sandstone and Indiana Limestone were cored and disks were machined to nearly identical dimensions as the ORR samples. Besides checking the quality of the data, these tests also allowed us to practice coring rock blocks for suitable samples for testing, which is planned for oriented outcrop samples from rock units not sampled in core on the ORR.

Results. The MR test has produced reasonable fracture toughness values for the various rock types tested. The load versus displacement response during crack propagation is characteristic of the MR test and allowed for easy picking of the minimum load in the curve (Figure 14). Accurately constraining the minimum load during crack growth is required for finite element modeling and fracture toughness determination (Figure 15). Because we have no data with which to compare our fracture toughness results for rocks from the ORR, consider the results for the Berea Sandstone and Indiana Limestone samples (Table 2). Our results for the Berea Sandstone and Indiana Limestone fall within previously

Table 2. Preliminary fracture toughness results. Young's modulus is estimated based on correlations with fracture toughness. Extreme values for Poisson's ratio were chosen to determine the potential range for the bulk modulus and compressibility.						
Stratigraphic Unit	Lithology	Mean Fracture Toughness MPa/(m) ^{1/2}	Mean Young's Modulus GPa	Poisson's Ratio	Bulk Modulus GPa	Compressibility 1/GPa
Rome Formation	Sandstone	2.3	74	0.10-0.45	2.5-19.7	0.1-0.4
Copper Ridge Dolomite	Dolostone	1.7	52	0.10-0.45	1.7-13.9	0.1-0.6
Maynardville Limestone	Dolostone	2.4	78	0.10-0.45	2.6-20.7	0.1-0.4
		Mean Fracture Toughness MPa/(m) ^{1/2}	Published Fracture Toughness			
Berea	Sandstone	1.4	1.31-1.36	Theircelin & Roegiers(1986)		
Indiana	Limestone	1.2	1.12-1.20	Theircelin & Roegiers(1986)		

published results that used the same test method. This gives us confidence that our results for the rocks from the ORR are correct. The average fracture toughness was used to estimate the average Young's modulus for the ORR

Figure 14 Example load vs. displacement plot produced during the MR test. Inset depicts sample and loading geometry.

Figure 15 Crack tip stress intensity vs. crack length curve for sandstone from the Rome Formation. Curve maxima corresponds with Mode I fracture toughness of the material.

samples. The calculated Young's modulus falls within the range of estimates previously published for similar rock units in the Valley and Ridge. The estimate of the range in bulk modulus for the rock samples can be made by calculating the bulk modulus for a minimum and maximum of Poisson's ratio of 0.10 and 0.45, respectively. The results are listed in Table 2.

Future Directions. Future work will focus on testing the remaining competent rock units that have core available, such as limestones from the Chickamauga Group. Any additional rock units that have not been sampled by coring will be sampled at the outcrop and tested. A series of tests will be made, however, to compare the strengths between unweathered core and weathered outcrop samples to determine whether there is a significant change in rock properties with depth that could be affecting aquifer mechanics. Fracture toughness of incompetent shales cannot be determined with the MR test, but rather will be determined by using an indentation technique. In order to better compare the results from the two different techniques, samples used in the MR test will also be test by the indentation method. Additional related work will involve correlating sonic logs with test results to begin assessing the in situ rock properties, developing a test to determine the in situ fracture stiffness for various rock units, and using the results in conjunction with well hydrographs to determine aquifer properties.

3.2.14 Design, Fabrication, and Testing of a Purge and Trap, Gas Chromatographic System for Groundwater Dating with CFCs P. G. Cook and D. K. Solomon

Chlorofluorocarbons (CFCs) are synthetic compounds that were first produced in the 1940s. Due to increases in production and the stability of these compounds, atmospheric concentrations of CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) have increased by approximately 10 and 17 pptv per year, respectively, during the past decade. Because atmospheric concentrations have increased since the 1940s, groundwater that is recharged at a given point in time will be in equilibrium with a unique concentration of CFCs; thus, CFC concentrations in groundwater can potentially be used as a dating tool (Busenberg and Plummer, 1982).

The CFC analytical system is being used to (1) determine recharge rates to the shallow aquifer, (2) evaluate karst flow paths and rates, and (3) detect the presence of drilling fluids in deep boreholes. Special sampling and analysis equipment are required to use CFCs as groundwater dating tools since a groundwater sample that is contaminated with as little as 0.01 cc of modern air can result in a serious error in the apparent age of the water. A sophisticated sampling system based on the design of Busenberg and Plummer (1992) and a gas chromatograph with an electron capture detector purge and trap analytical system based on the design of Bullister and Weiss (1988), with design modifications by

Lamont-Doherty Geological Observatory and ORNL staff, has been constructed. The sample collection system has been in operation for more than a year while the analytical system became operational in July 1994.

The sample collection system consists of a series of high purity, all metal valves, borosilicate glass ampoules, and ultra-high purity (UHP) nitrogen. The system allows (1) glass ampoules to be completely purged of modern air using UHP N₂, (2) water samples to enter the glass ampoules without contact with modern air, and (3) the glass ampoules to be flame sealed in the field shortly after sample collection.

The analytical system utilizes a series of 6 multiport, two-position gas sampling valves, and 1 multi-position, eight-port sampling valve. These valves are equipped with purge housings that reduce the CFC blank to less than 0.005 picomoles of CFC-11 and CFC-12. Water samples in sealed ampoules are connected to the inlet system via a short length of tygon tubing. After purging the dead volume with UHP N₂, the glass ampoule is broken, and water is forced into a calibrated volume (42.79 ml) via a 1/8 inch stainless steel tube by pressurizing the glass ampoule. After filling the calibrated volume the sample is transferred into a stripping chamber. Dissolved CFCs are removed in the stripping chamber and trapped on a porous polymer (Porapak Q) at -30 °C. After a 4 minute stripping/trapping period, the trap is isolated, heated, and then back flushed causing CFCs to enter the gas chromatograph. The chromatography system consists of a 30 cm-long, 1/8 inch-OD stainless steel pre-column packed with Porasil C, a 3 m-long, 1/8 inch-OD analytical column packed with Porasil C, and a 10 cm-long, 1/8 inch-OD auxiliary column packed with molecular sieve 5A. The analytical columns are connected to a Shimadzu 14A gas chromatograph equipped with an electron capture detector. Processing of the chromatographic signal is accomplished by a personal computer running the EZCHROM software package.

The analytical system is calibrated using an air standard that is stored in a specially treated, high pressure cylinder. The standard was purchased from the National Oceanographic and Atmospheric Administration and was calibrated using gravimetrically prepared standards for CFC-11, CFC-12, and CFC-114. Eight calibrated sample loops ranging in volume from 0.7 to 10 ml allows preparation of a multi-level calibration curve. The standard deviation of duplicate air analyses is approximately 2% of the mean. The detection limit for CFC-12 is about 0.01 picograms/liter and is sufficient for dating water in the range of 1 to about 40 years.

With the present configuration the CFC analytical system is capable of analyzing approximately 20 samples/day including calibration and blank runs. Most of the

gas sampling valves are equipped with electric actuators and are fully capable of automation. A design for automating the thermal regime of the trap has been prepared and when implemented along with the electric valve actuators will provide fully automated calibration and semi automated sample analysis. It is anticipated that automation will increase the daily sample throughput to between 30 and 40 samples per day and, more importantly, will significantly improve the reproducibility of sample analyses.

3.2.15 Background Groundwater Quality Assessment for the Oak Ridge Reservation: Results of Exploratory Probability Plotting

S. L. Winters

Objectives. The study objectives are (1) to characterize the inorganic groundwater geochemistry of the ORR at as large a spatial scale as is technically feasible and (2) to establish baseline concentrations for ORR-wide groundwater risk assessments. The approach adopted is to consider background not as a single value, nor as a range of values, but as a statistical distribution. The statistical foundations of this approach are well established in sedimentology and mineral exploration (Sinclair, 1976). To distinguish background from anomalous concentrations, data were examined by using cumulative probability plotting techniques. If data are normally distributed, the cumulative distribution plots as a straight line. Separate populations can be distinguished by straight-line segments, joined at threshold concentrations (points of maximum mixing between two populations). Thresholds can indicate the upper limit of background or the lower limit of contamination.

Results. Thirty-five inorganic analytes were plotted. Filtered samples were plotted separately from unfiltered samples. Results from over 132,000 samples indicate that the logarithm of concentration versus the cumulative percent frequency of most inorganics fits normal distributions but that filtered and unfiltered sample populations behave differently. Generally, unfiltered sample populations fit a normal distribution more frequently than filtered sample populations. Some inorganics, e.g., beryllium, calcium, and cobalt, show apparent threshold values (Figure 16), which indicate possible separate geochemical populations or transitions from background to contamination conditions.

The dominant influences that appear to affect lack-of-fit to a normal distribution are (1) data truncation or censoring of the low-concentration data due to detection limitations and (2) the presence of aquifer colloidal material in unfiltered samples. Censoring tends to flatten the left-hand tails of plots and impart more apparent random variation or scatter to the data, e.g., beryllium data, which is highly

Al. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=2115

Be. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=196

Ca. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=4894

Co. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=210

Figure 16

Probability plots for aluminum, beryllium, calcium, and cobalt

censored (~92% below the detection limit), exhibits more flattening and scatter than calcium data, which is uncensored (~1% below the detection limit) (Figure 16).

In general, the closer the filtered and unfiltered sample populations are in concentration, the more likely that the filtered distributions will be linear, e.g., calcium (Figure 16). If the unfiltered population is weakly linear or nonlinear, the filtered population will be nonlinear, e.g., mercury (Figure 17). This generalization is true regardless of the degree of censoring, provided the analytes are not associated with aquifer colloidal material, e.g., aluminum, iron, manganese, and titanium (Figure 16 and 18). Plots of the filtered population for these analytes are generally nonlinear and are from 50% to nearly 200% less than their corresponding unfiltered population (Figure 18).

The likely cause for these anomalously large differences is excessive turbidity in the sample prior to filtration. Aluminum, iron, manganese, and titanium are associated with aquifer colloidal material or iron oxyhydroxides that tend to form abundant (and likely large) particles that cannot pass a 0.45- μm membrane filter (Figures 16 and 18). Particles generated in groundwater that contain these elements, therefore, would tend to anomalously enrich the unfiltered sample relative to the filtered sample. Groundwater sampling procedures that minimize turbidity in the well and sample would likely generate results with less divergence in filtered and unfiltered analyte concentrations.

Future Directions. Preliminary findings suggest that background distributions for some ORR inorganics may be obtained by eliminating contaminated samples at the high end of their probability ranges. This procedure, however, may work only for those constituents that show minimal separation of filtered and unfiltered populations and plot as normal distributions with distinct thresholds.

In subsequent phases, data will first be evaluated in detail before any spatial or temporal analyses are attempted. Data evaluation should help identify problems with the data set before detailed spatial and temporal analyses are attempted.

Representative background will be determined by a variety of approaches:

- Histograms, box plots, lognormal probability plots will be used to reveal whether a single set of data is described by a single distribution or by multiple distributions. Graphical and statistical techniques will be applied at a number different spatial scales across the ORR.
- Groundwater quality at designated background or reference wells will be compared to ORR-wide data collected from down-gradient and cross-gradient wells.

Fe. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=1707

Hg (CV). MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=139

Mn. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=3173

Ti. MATCHED FILTERED-UNFILTERED PAIRS
x=filtered, o=unfiltered n=665

Probability plots for iron, mercury, manganese, and titanium (all analyses by inductively coupled arc plasma except for mercury analyses by cold vapor atomic adsorption [CV]).

Figure-17 - -

Percent difference between filtered and unfiltered samples versus percent for ORRHAGS filtered-unfiltered sample pairs

Figure 18

- ORR data will be compared to regional and state-wide data.
- Background will be expressed on as large a spatial scale as is technically defensible: if data indicates that the background concentration for a given constituent is fairly constant over a wide area, then a mean and statistical distribution of values over that area will be used.

If data are normally or lognormally distributed, background will be defined at the upper 95% parametric tolerance limit with 95% coverage. Alternatively, if data are not normally or lognormally distributed, background will be defined at the upper 95% nonparametric tolerance limit with 95% coverage.

3.2.16 Point Dilution Tests

K. Black

Introduction. Point dilution tests provide an approximation to the horizontal velocity of groundwater moving through the screened section of a piezometer or through a portion of an open borehole. Thus, they provide a way to characterize active flow zones along a vertical profile. Point dilution tests involve introducing a tracer into the piezometer water and measuring the reduction in tracer concentration through time as a result of mixing with and dilution by inflowing formation water. The method assumes that the tracer is well mixed within the sampling interval in the borehole. Although many tracers could be used, some of the more common ones include table salt, fluoride, bromide, radioactive isotopes, dyes, and distilled water. The tracer concentration is measured with an appropriate instrument such as a specific conductance meter, an ion-specific probe, or a fluorometer.

Objectives of the Pilot Study. The objective of this pilot study was to design, test, and evaluate a simple point dilution test method. A simple method is desirable so that the point dilution method can be easily used for characterizing fracture flow systems.

Proposed Methodology. The basic principle of a point dilution test is to measure the concentration of a tracer within a piezometer through time. Two criteria should be met to make the method compatible with the mathematical formulation of the method. First, introduction of the tracer should not disturb the ambient groundwater conditions. Secondly, the tracer must be well mixed within the sampling interval. A third condition, defined for this newly developed method, is that packers will not be used; flow through the entire saturated screened interval will be measured (Moore, 1994, personal communication).

The proposed test methodology involves three steps. First, background concentrations of Rhodamine WT or Fluorescein dye in the piezometer are

measured using a Turner Designs fluorometer. Secondly, a very small amount of dye (a few drops) are placed into the piezometer followed by continuous recording of dye concentration using the fluorometer. The dye is introduced into the piezometer. By placing a few drops in a concave depression on top of a metal weight suspended by a string. The weight is lowered into the water and then pulled up and out of the water, thereby causing the dye to mix throughout the water column. Thirdly, a peristaltic or small electric pump will continuously pump water to the fluorometer on the surface for continuous recording of dye concentration; the water will be allowed to flow back into the piezometer after the dye concentration is measured. The test will proceed until enough data have been collected to characterize the reduction of dye concentration through time.

Summary of Pilot Scale Tests to Date: Laboratory testing of the proposed methodology is complete. Two discoveries were made with respect to fluorometer operation in the flow-through mode (continuous flow of water through the instrument). First, results indicated that the fluorometer did not respond to low concentrations as accurately as when used for discrete samples in a static mode of operation. This occurs because the optical properties of the glass used for the flow-through cell are different than that of the glass used to measure concentrations of discrete samples. This difference is significant when trying to measure low (<5 ppb) dye concentrations. The difference between the glasses causes a higher detection limit for the fluorometer in flow-through mode. Once these differences were discovered, successful calibration of the fluorometer was completed within the range of 50 to 200 ppb in flow-through mode. This operational range should be acceptable for running actual point dilution tests in the field. Secondly, bubbles in the water column caused fluctuations in apparent Rhodamine WT concentrations if a low flow rate was used to move water through the instrument. By increasing the flow rate and running the fluid upward through the instrument rather than downward through it, the fluctuations were greatly reduced. Once these problems were resolved, it was decided the method would be suitable for field testing.

Field testing of the method is ready to begin, but an attempt has not been made to date. The work has been deferred indefinitely.

3.2.17 Modeling of Radionuclide and Transition Metal Mobility Around Low-Level Waste Disposal Sites

J. A. Saunders and L. E. Toran

During the period ~1950-1975 liquid low-level radioactive wastes of variable composition were disposed of in shallow pits and buried trenches at ORNL and lagoons adjacent the Y-12 facility. Wastes came from nuclear fuel reprocessing and equipment decontamination, and consisted of fission products such as ^{137}Cs ,

^{90}Sr , and ^{60}Co , transuranics, transition metals, and organic and inorganic solvents. Waste pre-treatment and disposal practices varied from facility to facility and over time. For example, at ORNL caustic soda and sodium hydroxide were added to the waste to raise pH to ~ 12 . This procedure caused precipitation of $\text{Ca}(\text{Sr})\text{CO}_3$, which decreased the activity of ^{90}Sr significantly. Remaining liquids were pumped to trenches in weathered shale. In contrast, acidic nitric acid (with $\text{pH} < 2$) wastes were locally discharged into shallow lagoons (e.g., S-3 Ponds) on weathered carbonate bedrock at Y-12. Migration of contaminants out of the unlined trenches and lagoons has occurred over the years. For example, nitrate has been detected in monitoring wells at depths $> 300\text{m}$ around the S-3 ponds at Y-12 and radionuclide-bearing water seeps out of springs in low-lying areas near White Oak Creek at ORNL during wet seasons. Thus a better understanding of the chemical and physical processes affecting the migration of contaminants in these settings is warranted.

Objectives. The main objectives of the current study are to: 1) apply existing geochemical equilibrium computer codes, such as MINTEQA2, to model chemical processes such as organic-ligand complexing of radionuclides and heavy metals, mineral dissolution and precipitation, and sorption; 2) incorporate insights provided by (1) using new computer codes developed at ORNL such as HYDROGEOCHEM and KEMOD, which couple physical flow and chemical kinetics (respectively) with geochemical equilibrium capabilities. Anticipated results will provide new insights into contaminant transport processes under variable geochemical and soil conditions.

Results to date. Best estimates of the composition of wastes at the Pits and Trenches area at ORNL and the S-3 ponds at Y-12 have been obtained from an extensive literature search. MINTEQA2 has been used to predict results of probable mineral precipitation-dissolution and sorption-desorption reactions. Amorphous iron oxyhydroxides are extremely abundant in site soils and weathered saprolite (up to 5 wt.% as $\text{Fe}(\text{OH})_3$; Means et al., 1978; Arnseth and Turner, 1988). This has allowed the use of the amorphous iron oxyhydroxide diffuse-layer surface complexation model of Dzombak and Morel (1990) to evaluate radionuclide and heavy metal sorption at the waste disposal sites. Previous work (Means et al., 1978) considered MnO_2 phases to be most important in radionuclide and metal sorption at ORNL. The public-release version of MINTEQA2 (version 3.11) has been modified to include surface complexation reactions of Dzombak and Morel (1990) for Co and Sr; thermodynamic data for aqueous and mineral species for these components also have been added. Of particular interest is the role organic complexants play in the solubility and relative mobility of ^{60}Co and ^{90}Sr . Modeling with MINTEQA2 shows that even at EDTA concentrations as low as 1 mg/l, Co-EDTA metal-organic complex is the most important Co species (Figure 19). Thus, the relatively large affinity of EDTA for Co dwarfs the

Co Specie

Figure 19

potential sorption reactions between iron oxyhydroxides observed in model runs without EDTA. In contrast, Sr-EDTA complexes are relatively weak, but Sr is not strongly sorbed by iron oxyhydroxides.

3.2.18 Fracture Flow Modeling

L. Toran

Fracture flow modeling can be used to illustrate the concepts related to matrix diffusion of contaminants, the development of secondary sources of contamination, and the relative importance of fracture flow versus porous media flow on the ORR. This year's efforts included (1) code development, (2) secondary source modeling, and (3) porous media modeling of a tritium plume.

(1) Code Development: R. McLaren and R. Therrien, University of Waterloo

Further development of University of Waterloo's 3-dimensional fracture flow code included incorporation of tetrahedral elements which will allow fractures along tilted bedding planes and a random fracture generation routine. University of Waterloo is still testing these features. They are also working on pre-processors for fracture generation (based on workstation packages). They provided an example input file that is being used to examine transport along a suspected fracture plane from Corehole 8 to First Creek in Bethel Valley.

(2) Sensitivity analysis and secondary source modeling: L. Toran

Sensitivity analysis of hypothetical grids based on ORR characteristics indicate that matrix parameters are important in determining contaminant breakthrough times. This year, modeling indicates that large porosity (up to 10% porosity was modeled) could make fractured systems behave similar to porous media flow, with smoother concentration contours rather than irregular distributions from fracture flow. In addition, the size of the secondary source of contaminants in the matrix (Figure 20) can be estimated by modeling and should be considered as a part of the source term clean up.

(3) Tritium plume modeling: P. Stafford and L. McKay, Univ. of TN, and L. Toran

Work has begun to model a long term (15 year) tritium plume. Preliminary 1-dimensional modeling indicates that the intense fracturing of the saprolite (approximately 1 cm spacing; Dreier et al., 1987) creates breakthrough curves that are identical to porous media models for the same dispersivity and velocity. One-dimensional modeling over-predicted the breakthrough pulse, probably due to lateral spreading not modeled in one dimension. Lateral spreading is enhanced

Figure 20 Relative concentrations in randomly fractured matrix after 50 years of source input.

by fluctuating water tables which change flow directions seasonally (P. Stafford, Masters Thesis proposal, July 1994). Three-dimensional modeling using the new University of Waterloo fracture flow code is underway.

3.3 REPORTS, PUBLICATIONS, TECHNICAL PRESENTATIONS, AND OTHER STAFF ACTIVITIES

The following is a list of professional publications and/or presentations by ORRHAGS technical staff during FY 1994:

Drier, R. B. Regulatory Status of Westbay Monitoring Data, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

Goeltz, R.T. and T.F. Zondlo. Presentation, 3D Subsurface Modeling Within the Framework of an Environmental Restoration Information System: Prototype Results Using EarthVision. Federal Geographic Technology '94., September 27, 1994, Washington, DC.

Gorman, C. Investigation of Groundwater Mixing Beneath the ORR, Final Report, ORNL, April 27, 1994.

Huff, D. D. Model for the ORR Review, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

James, B.R., and S.M. Gorelick (1994) How many monitoring wells does it take to find a groundwater contamination plume?, Presentation, First ASCE Conference on Computing in Civil Engineering, K. Khozeimeh (ed.), June 20-22, 1994, Washington, D.C.

James, B.R. and S.M. Gorelick, (in press) When enough is enough: the worth of monitoring data in aquifer remediation design, Water Resources Research.

James, B.R. and S.M. Gorelick, (1994) When enough is enough: the worth of monitoring data in aquifer remediation design, Eos, 75 (16), 178. (poster)

James, B.R. (1994) Evaluating the worth of information before it is taken, Managing Uncertainty and Decision Making for Site Remediation, July 18-20, 1994, Seattle Washington, short course by the Dept. of Engineering Professional Development, University of Wisconsin.

McKay, L.D., J. McCarthy, and K. Novakowski. Groundwater sampling in fractured clay and rock, Extended abstract presented at Environmental Protection Agency -Groundwater Sampling Workshop, Nov. 30 - Dec. 2, 1993, Dallas, TX.

McKay, L. D. Contaminant migration experiments and field studies in fractured clays, Presentation, Ohio Academy of Science Annual Meeting, Apr. 22, 1994, Toledo, OH.

McKay, L. D. Nature of contaminant transport in fractured unlithified aquitards, Presentation, Geological Society of America, Penrose Conference on Fractured Unlithified Aquitards, June 15-20, 1994, Racine, WI.

McKay, L.D., and A. Harton. Phage tracer experiments, Preliminary report submitted, ORNL, Aug. 4, 1994.

Moline, G. R. and McCarthy, J. Groundwater Sampling Methodologies, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

Moline, G. R. Deep Groundwater Flow System, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

Novakowski, K. S. A Review of the Hydrogeological Information Obtained from the Fractured Rock of the ORR, Progress Report, June 20, 1994

Toran, L. T. Modeling, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

Saunders, J.A. and Toran, L.E. 1994. Evidence for Dedolomitization and Mixing in Paleozoic Carbonates Near Oak Ridge, Tennessee. *Ground Water*. v. 32: 207-214.

Sanford, W. E. Noble Gas Tracer Test, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

Saunders, J.A. and Toran, L.E. In prep. Modeling of radionuclide and heavy metal sorption around low and high pH waste disposal sites at Oak Ridge, Tennessee. In prep for *Aqueous Geochemistry*.

Sanford, W. E., D. K. Solomon, and H. M. Ingracia, 1993, Dye tracer and point dilution tests used to determine permeable zones near the water table in fractured shales: 1993 GSA Annual Meeting, October 25-28, Boston, MA.

Sanford, W. E., and G. K. Moore, 1994, Measurement of specific discharge with pointdilution tests in the fractured rocks of eastern Tennessee: A WRA Annual Spring Symposium, April 17-20, 1994, Nashville, TN.

Sanford, W. E., D. K. Solomon, and R. G. Shropshire, 1994, Noble gases as tracers in fractured saprolite: AGU 1994 Spring Meeting, May 23-27, Baltimore, MD.

Sanford W. E., Presentation of the field technique and some data at the GSA Penrose Conference on "Fractured unlithified aquitards: Origins and transport processes": June 15-20, 1994, Racine, WI.

Stafford, P. 1994. Simulation of groundwater tritium migration patterns in fractured, weathered shale using discrete-fracture/matrix-diffusion and equivalent porous medium models. Master of Science Thesis Proposal submitted to the University of Tennessee, Department of Geological Sciences, July 25, 1994.

Toran, L., Sjoreen, A. and Morris, M. 1994. Sensitivity analysis of groundwater transport in fractured porous media, Presentation, American Geophysical Union Chapman Conference on Aqueous Phase and Multiphase Transport in Fractured Rock. Sept. 12-15, 1994, Burlington, VT.

Toran, L. 1994. How can we predict contaminant transport in fractured porous media? Presentation, Environmental Sciences Division Seminar, ORNL, Sept. 15, 1994, Oak Ridge, TN.

Toran, L. and Sjoreen, A. 1994. (Submitted) CHEMFORM: A formatting program for geochemical data. Submitted to Ground Water Program Office, ORNL.

West, O.R., B.R. James, C.K. Bayne, and R.L. Siegrist, (1994) Performance verification of in situ soil mixing and vapor stripping of VOC contaminated soils, Presentation, I&EC Special Symposium, American Chemical Society, Sept. 19-21, 1994, Atlanta, GA,

Winters, S. L., 1994. Background Groundwater Quality Characterization Study of the ORR, Presentation, American Water Resources Assoc. Annual Spring Symp. Apr. 17-20, 1994, Nashville, TN.

Winters, S. L. Background Groundwater Quality, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN

Winters, S. L., 1994. Background Groundwater Quality Characterization Study of the ORR, Presentation, Bridging the Gaps in Environmental Management, 6th Natl. Technology Information Exchange Workshop. May 10-12, 1994, Kennewick, WA.

Winters, S. L., 1994. Background Groundwater Quality Characterization Study of the ORR, Presentation, Proc. Symp. on Responses to Changing Multiple-use Demands: New Directions for Water Resources Planning and Management. Apr. 17-20, 1994, Nashville, TN.

Zondlo, T. Z. Karst, Presentation, TDEC/DOE-O Technical Information Meeting, June 23, 1994, Oak Ridge, TN.

3.4 SUMMARY OF ORRHAGS FY 1995 PLANS

The primary objectives for ORRHAGS are to provide technical results and methods that support the characterization, control and remediation of contaminants in groundwater and receiving surface water bodies and to provide technical guidance to Energy Systems site groundwater programs based on scientific principles. In FY 1995, the Deep Groundwater theme will be concluding its work with a report summarizing a three year study and making recommendations for long-term goals in assuring adequate monitoring and understanding of the deep (saline) groundwater flow system. Some planning will occur to facilitate a transition to a new remediation theme area. Studies of the relation of mechanical rock properties to fractures and the associated flow of groundwater will also be completed, along with development of some basic information concerning the porosity of the rock system, which was defined as a key data gap by recent modeling studies. The noble gas tracer study, initiated in FY 1994, will continue collecting data to quantify matrix diffusion effects on transport of solutes in groundwater and will focus on model comparisons of simulations of pump and treat systems for source control or remediation. Studies of methods for obtaining representative samples of groundwater quality from fractured rock systems will evaluate the adequacy of current methods and suggest modifications in sampling method or data interpretation. New work on water budget computational methods will begin. The goal is creating and documenting an objective method to calculate monthly water budgets for a range of catchment sizes, and to simulate hourly hydrographs, including components of base flow and storm runoff. These results will be used in associated karst basin studies to examine data for gaining and losing streams. A related effort, use of CFC and helium analyses to estimate recharge rates will complement the water budget calculation studies. Finally, a project to develop a small scale constructed wetland prototype will be initiated. The goal is a portable wetland that can be

taken to a selected site and used for pilot scale evaluations of the effectiveness of a constructed wetland to deal with water quality issues at small seeps.

4. REFERENCES

- Arnseth R.W. and Turner R.S. (1988) Sequential extraction of iron, manganese, aluminum, and silicon in soils from two contrasting watersheds. *Soil Sci. Soc. Am. J.* 52, 1801-1807.
- Bodenstein, G. W., R. R. Bonczek, T. O. Early, T. B. Hale, D. D. Huff, M. D. Nickelson, C. T. Rightmire. 1992. Evaluation of the Proposed Pilot Groundwater Pump and Treat Demonstration for the Paducah Gaseous Diffusion Plant. KY/ER-15. Paducah, KY.
- Bodenstein, G.W., R.R. Bonczek, T.O. Early, D.D. Huff, K.S. Jones, M.D. Nickelson, and C. T. Rightmire. 1994. Paducah Gaseous Diffusion Plant Proposed Pilot Pump-and-Treat Project. GWPO-002. Oak Ridge National Laboratory, Oak Ridge, TN. In press.
- Bredehoft, J.D., Response of well-aquifer systems to earth tides: *Journal of Geophysical Research*, v. 72, p. 3075-3087, 1967.
- Chapman-Bailey Z., and R.W. Lee. 1991. Hydrogeology and geochemistry in Bear Creek and Union Valleys, near Oak Ridge, Tennessee. U.S. Geological Survey Water Resources Investigation Report 90-4008.
- Dreier, R.B., and L.E. Toran. 1989. Hydrogeology of Melton Valley determined from head measuring station data. Environmental Science Division Publication No. 2836, ORNL/TM-11216, Oak Ridge National Laboratory, Oak Ridge, TN.
- Dreier, R.B., T.O. Early, and H.L. King. 1991. Groundwater studies at the Oak Ridge Y-12 Plant using multiport monitoring systems installed in coreholes. *Proceedings of Focus Conference on Eastern Regional Groundwater Issues*, NWWA, pp. 239-53.
- Drost, W., D. Klotz, A. Koch, H. Moser, F. Neumaier, and W. Rauert. 1968. Point dilution methods of investigating ground water flow by means of radioisotopes, *Water Resources Research*, v. 4, no. 1, pp. 125 - 146.

- Dzombak D.A. and Morel F.M.M. (1990) Surface complexation modeling, hydrous ferric oxide. John Wiley & Sons, New York.
- Early, T.O. 1993. Groundwater Program Management Plan, GWPO-001, Oak Ridge National Laboratory, Oak Ridge, TN.
- Ford, D.C. and R.O. Ewers. 1978. The development of limestone cave systems in the dimensions of length and depth. *Canad. J. Earth Sci.* 15, 1783-1798.
- Ford, D.C. and P.W. Williams. 1989. Karst Geomorphology and Hydrology. London, Unwin Hyman.
- Forstrom, J. M. 1990a. Oak Ridge Gaseous Diffusion Plant Groundwater Protection Program Management Plan. K/HS-258, Rev. 1. Prepared for Martin Marietta Energy Systems, Inc. Oak Ridge K-25 Site, Oak Ridge, TN.
- Forstrom, J. M. 1990b. Strategy for conducting environmental surveillance of groundwater to comply with DOE orders: ES/ESH-17. Martin Marietta Energy Systems, Inc., Oak Ridge, TN.
- Forstrom, J. M., E. D. Smith, C. S. Haase, W. M. McMaster, H. L. King, S. L. Winters 1994. Groundwater Surveillance Plan for the ORR. ES/ESH-20. Martin Marietta Energy Systems, Inc., Oak Ridge, TN.
- Geraghty and Miller, Inc. 1987. Preliminary evaluation of the hydrogeologic and water-quality data from phase 4 wells located in the Bear Creek Valley Waste Disposal Area for the period summer 1985-September 1986. Oak Ridge Y-12 Plant, Y/Sub/85-00206C/9, Oak Ridge, TN.
- Groundwater Program Office, 1994, ESD Groundwater Program Office Annual Report for Fiscal Year 1993. ORNL/GWPO-005, Martin Marietta Energy Systems, Inc., Oak Ridge, TN.
- Haase, C.S., and H.L. King. 1990. Report and preliminary assessment of the occurrence of dense, nonaqueous phase liquids in the Bear Creek Burial Grounds Hazardous waste disposal unit and the Oak Ridge Y-12 Plant. Y/TS-629, Oak Ridge Y-12 Plant, Oak Ridge, TN.

- Hatcher, R.D., Jr., P.J. Lemiszki, R.B. Dreier, R.H. Ketelle, R.R. Lee, D.A. Leitzke, W.M. McMaster, J.L. Foreman, S.Y. Lee. 1992. Status Report of the Geology of the Oak Ridge Reservation. ORNL/TM-12074, Rev. 1. Oak Ridge National Laboratory, Oak Ridge, TN.
- Hicks, D.S., D.K. Solomon, and N.D. Farrow. 1992. Investigation of groundwater flow zones and contaminant transport in Solid Waste Storage Area 5 at Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/ER-154, Environmental Sciences Division Publication 3977, 25 pp.
- HSW Environmental Consultants, Inc., 1994. Review and Evaluation of Martin Marietta Energy Systems, Inc. Environmental Surveillance Procedures for Groundwater, Oak Ridge, Tennessee.
- Lee, R.R., R.H. Ketelle, J.M. Bownds, and T.A. Rizk. 1992. Aquifer analysis and modeling in a fractured, heterogeneous medium, *Ground Water*, v. 30, no. 4, pp. 589 - 597.
- Means J.L., Crerar D.A., Borcsik M.P. and Duguid J.O. (1978a) Adsorption of Co and selected actinides by Mn and Fe oxides in soils and sediments. *Geochim. Cosmochim. A.* 42, 1763-1773.
- Novakowski, K. S. 1993. Interpretation of the transient flow rate obtained from constant-head tests conducted in situ in clays. *Can. Geotech. J.*, 30(4): 600-606.
- Novakowski, K. S., 1994. A review of the hydrogeological information obtained from the fractured rock of the Oak Ridge Reservation: A progress report. June 20, 1994, presented to the Ground Water Program Office.
- Ogden, A.E. 1992. Methods for Predicting the Directions of Contaminant Transport in Flat-Lying and Folded Carbonate Rocks. Tennessee Water Resources Symposium (5th, Nashville, TN, Oct. 1992). Proceedings. American Water Resources Association, Nashville, TN, p.16-20.
- Olsen, C.R., P.D. Lowery, S.Y. Lee, I.L. Larsen, and N.H. Cutshall. 1986. Geochemical and Environmental Processes Affecting Radionuclide Migration from a Formerly Used Seepage Trench, *Geochimica et Cosmochimica Acta*, v. 50, pp. 593 - 607.

- Rubin, P.A., and P.J. Lemiszki. 1992. Structural and Stratigraphic Controls on Cave Development in the Oak Ridge Area, Tennessee. Tennessee Water Resources Symposium (5th, Nashville, TN, Oct. 1992). Proceedings. American Water Resources Association, Nashville, TN, p.111-117.
- Rubin, P.A., and D.A. Lietzke, and V.A. Schmidt. 1992. Aspects of the Geomorphology of Oak Ridge, Tennessee. Abs. National Speleological Society Convention, Salem, IN.
- Sinclair, Alastair J., 1976. Applications of Probability Graphs in Mineral Exploration, Special Volume No. 4, The Association of Exploration Geochemists
- Solomon, D.K., G.K. Moore, L.E. Toran, R.B. Dreier, and W.M. McMaster. 1992. A Hydrologic Framework for the Oak Ridge Reservation, Status Report. ORNL/TM-12053, Oak Ridge National Laboratory, Oak Ridge, TN.
- Stow, S.H., and C.S. Haase. 1986. Subsurface disposal of liquid low-level radioactive wastes at Oak Ridge, Tennessee. In Proceedings of the International Symposium on Underground Injection of Hazardous Wastes, New Orleans, LA. National Water Well Association.
- Theircelin, M., and Roegiers, J.C., Toughness determination with the modified ring test: 27th U.S. Symposium on Rock Mechanics, Alabama, p. 615-622, 1986
- Thompson, B.K. 1993. Database Dictionary for the Oak Ridge Reservation Hydrology and Geology Study Groundwater Database, ORNL/TM-11909, Oak Ridge National Laboratory, Oak Ridge, TN.
- Thompson, B.K. 1993. Management Plan for the Oak Ridge Reservation Hydrology and Geology Study Groundwater Database, ORNL/TM-12048, Oak Ridge National Laboratory, Oak Ridge, TN.
- Toth, J.A. 1963. A theoretical analysis of ground-water flow in small drainage basins. *J. Geophysical Res.*, (6) 84, 792-811.
- Worthington, S.R.H. 1991. Karst Hydrogeology of the Canadian Rocky Mountains. PhD thesis: Department of Geography, McMaster University, Canada, 227p.

Appendix A

LETTER FROM C. C. HOPKINS TO DISTRIBUTION

April 25, 1991

D. J. Bostock
C. A. Hall
J. R. Merriman
K. W. Sommerfield
A. W. Trivelpiece

Groundwater Program Management

In order to manage the groundwater monitoring and data analysis program for the Energy Systems facilities, I have asked Oak Ridge National Laboratory to establish a Groundwater Project Office. This office will be responsible for coordinating all activities associated with monitoring of groundwater on the Oak Ridge Reservation.

Each facility will continue to be responsible for establishing wells, sampling groundwater, and analyzing data that are unique to their site. However, all data will be provided to the consolidated environmental data base with oversight and coordination from the Groundwater Program Office. This office is charged with responsibility of seeing that an integrated analysis is conducted of all data gathered so that an integrated picture of groundwater contamination is available.

The Groundwater Program Office will be responsible for establishing standards, ensuring that groundwater data are managed in a manner consistent with reporting requirements (e.g., the groundwater data reports should look the same independent of which facility is involved) and for serving as a single point of contact for DOE. Costs for operating the Program Office will be shared by the sites and the Environmental Restoration Division with the exact allocation yet to be worked out.

It is expected that this project officer will also serve as chairman of an Energy Systems wide groundwater project committee that will meet periodically to discuss standards, quality assurance, lessons learned, etc. This committee will include representatives from all five sites as well as the Environmental Restoration Division.

Please work and cooperate fully with the project office personnel as soon as they are identified. This is an important part of our business and one which we must continue to do very well.

C. C. Hopkins, 9704-2, MS-8001 (6-5663)

CCH:THRow:lc

Appendix B

**GROUNDWATER PROGRAM ADVISORY COMMITTEE
REPORT**

GROUND WATER PROGRAM OFFICE ADVISORY COMMITTEE

FINAL REPORT AND RECOMMENDATIONS

August 17, 1994

The Ground Water Advisory Committee met on July 26-27, 1994, to review the Martin Marietta Energy Systems Ground Water Program Office (GWPO). During the review, the Committee participated in a quarterly meeting of the Energy Systems Groundwater Coordinators and met separately with the Ground Water Coordinators, GWPO technical staff, Oak Ridge Reservation Hydrology and Geology Studies (ORRHAGS) staff, and representatives of the Energy Systems offices which support the GWPO. The review agenda is Attachment 1. This report documents the conclusions and recommendations of the review.

Membership of the Advisory Committee is:

Dr. Stanley N. Davis, Professor of Hydrology and Water Resources (Emeritus), University of Arizona, Tucson, Arizona;

Dr. William B. White, Professor of Geochemistry, Pennsylvania State University, University Park, Pennsylvania;

and

Dr. Norman H. Cutshall, Deputy Director, Office of Environmental Technology Development, Martin Marietta Energy Systems, Inc. Oak Ridge, Tennessee.

The bulk of this report deals with concerns or issues. The Committee intends its comments to be constructive. The bias of text toward issues is not meant as a criticism of the program (which is exemplary), but rather to indicate the desire of the Committee to support a continued improvement of quality and performance.

General Comments

The GWPO provides an excellent support to Oak Ridge Environmental Restoration and Environmental Compliance organizations. DOE and Energy Systems are to be complimented for their forward thinking establishment of the GWPO and for its effective integration into remediation and compliance activities. While there are larger ground water contamination zones at other DOE sites, Oak Ridge, Paducah, and Portsmouth constitute the greatest ground water challenge in the DOE Complex when the diversity of contaminants, proximity to offsite populations, and, especially, hydrogeologic complexity are taken into account. The two most difficult settings for characterization and remediation are: 1) karst systems, and 2) fractured, low-porosity media. These are the rule on the Oak Ridge Reservation. The most difficult technical challenge for characterization and remediation is that of non-aqueous-phase liquids, NAPLs. NAPLs, both denser than water (DNAPLs) and lighter than water (LNAPLs), are know at all of the Oak Ridge sites. The presence of DNAPLs

in fractured, low-porosity media (or karst systems) is daunting to the most ambitious remediation specialist.

Status of 1993 Concerns

The Advisory Committee report from 1993 was used to benchmark progress for the GWPO. Attention was focused on the current status of concerns noted during the 1993 review.

1. **Staffing levels** Concern was expressed in 1993 that the GWPO level of staffing was inadequate to perform the tasks at hand. Staffing levels have increased through the addition of two new persons and enabled the assignment of individual points-of-contact for each of the five sites. The Support Program has been greatly improved by the new staffing.

Concern remains, however, for the lack of a karst specialist. The organizational plan for ORRHAGS lists karst hydrology as one of four main areas of emphasis. Although work involving carbonate rock hydrology is underway as part of the support program, particularly at the K-25 site, it appears that little backup research has been initiated as part of the ORRHAGS program. There are important issues at the Oak Ridge Reservation that involve carbonate rock hydrology. Examples include:

- (a) Exit pathways along bands of carbonate rock on both northeast and southwest sides of the Reservation;
- (b) water balance studies to investigate the mixing of ground water and surface water in Bear Creek, Poplar creek, and other streams crossing carbonate rock;
- (c) characterization of the permeability in the various carbonate units especially the relative importance of fracture flow, flow in solutionally widened fractures and flow in conduits and their interrelationships;
- (d) investigation of the relationship of the shallow karst ground water system and possible deep karst ground water systems; and
- (e) modeling of ground water flow in the carbonates and the interface between carbonate and clastic rocks.

2. **Roles and Responsibilities** The GWPO operates within an extremely complex organizational matrix. In 1993, it was recommended that the roles and responsibilities of the various organizations be better defined. The Ground Water Management Plan (ORNL/GWPO-001) published in May 1994 defines roles and responsibilities and confirms the complexity of the structure. Success for such a program is highly dependent upon the dedication of key participants inside and outside the program to ensuring quality performance. To the credit of the participants, the GWPO appears to be functioning very

well and is performing an essential service for the Environmental Restoration and site Compliance offices.

3. **Water balance studies** in surface streams to determine the location of gaining and losing reaches were recommended in 1993. Such studies are essential to identifying the surface water interconnection with ground water. A careful study of the water balance in small and intermediate-size watersheds can commonly add much to the hydrogeologic knowledge of an area. This is particularly true of karst regions where gaining or losing streams are common. The Committee notes the current effort to develop an inventory of seeps and springs and hopes that the results are quantified sufficiently to be integrated into the more difficult task of assessing the water balance in the watersheds on the Oak Ridge Reservation.
4. **OREIS development** was noted in 1993 as requiring major resources and effort and the Committee recommended that some resources be devoted to filling the data base in addition to constructing it. In 1994 the Committee heard numerous comments concerning the status and value of OREIS. These ranged from "who needs it" to frustration that the data base is not yet available. Most of the comments suggested that the status of the system had changed little since last year from the perspective of would-be technical users. It was also indicated, however, that DOE approval of the OREIS system had been received in early June and that data were now being ported into the system.

The Committee feels that substantial resources have been invested in OREIS and that every effort should be made to get a functional and useful system online as soon as possible. It will be the quantity and quality of data in OREIS rather than the elegance of the software that will determine the value of the system to potential users. To this end the Committee recommends that:

- (a) The system be made available to potential users as soon as possible so that they can assist in shakedown and debugging the system;
 - (b) porting of current data into the system be given a high priority; and
 - (c) a program should be initiated for transferring existing records into the data base. Recognizing that many of these older data may exist only as paper copy in scattered reports, some arrangement for student or other part time staff may be needed for data entry.
5. **Technical support to PAD and PORTS** was raised as a concern in 1993 and a recommendation that ORHSP professional staff assigned to Paducah and Portsmouth sites should spend 80-90 percent of their time at those sites. With the establishment of Ground Water Coordinators at each site and growth of the GWPO to enable assignment of dedicated points-of-contact, the need for near-full-time relocation to the sites is abated. Maintenance of a coherent technical group in Oak Ridge so that the support provided to each site is

consistent is also important. So long as the ORHSP individuals are onsite enough to remain abreast of needs for their assistance and of site developments, the value of their service will be realized.

6. **Priority setting** for future work is especially important to a small office like GWPO that provides service in the rapidly changing environmental restoration program. A number of very important projects and activities were discussed with the Committee. These current projects, however, were not ranked nor was a system of ranking their importance discussed. In an organization where available money is decreasing, or at best staying constant, careful attention should be paid to this item. This is not only important in the short-term budgetary process, but is also related to the long-term status of the GWPO. Regulators and management groups both inside and outside of Martin Marietta will have an improved understanding of the vital importance of the GWPO's activities as a result of a clear statement of priorities.
7. **Effective integration** of GWPO with site monitoring and compliance activities was questioned by the 1993 Committee. In particular, formal mechanisms for identification and resolution of divergences between GWPO and site perspectives. Since that time, a management plan has been developed to define roles and responsibilities. Nonetheless, the Committee still sees a serious potential for disconnect between GWPO and site programs without a specified conflict resolution hierarchy. It has been and will continue to be preferred to resolve issues through interpersonal communications. The management plan loosely specifies (5.2.1) that there should be periodic meetings between an Energy Systems management forum and the GWPO manager. Presumably, this represents the avenue for conflict resolution.
8. **Engineering assignment** to GWPO, and
9. **ORRHAGS and small R&D subcontracts** The Committee has no further comments on these 1993 concerns.
10. **Lessons learned** and the effective examination of the factors that have affected the success of past activities is essential to progress. A lessons learned program must be viewed as constructive and not simply fault-finding. The 1993 Committee recommended that the GWPO take a leadership stance in effecting a lessons learned program and specifically suggested attention to the Y-12 Soil Management Plan. At the Quarterly Ground Water Coordinators meeting, the Committee heard some discussion of lessons learned from the false-start at remediation of the PORTS 701B pond site. A remediation approach that had been satisfactory for a nearby site was found to be ineffective at the pond. A lessons learned exercise for this experience could be potentially very productive if it is properly conducted so as to avoid a 'witch hunt.'
11. **GWPO consultation on ground water contracts** was recommended by the 1993 Committee as a standard requirement. This concern appears to be

resolved at least on an informal basis. The site support personnel have done a good job of maintaining communication and providing inputs to the sites from GWPO at early stages in any proposed ground water projects.

12. **Research within the GWPO** and the mix between research and service work was a concern of the 1993 Committee. The primary goals of the GWPO are clearly utilitarian. However, this does not negate the need for forward-looking research. A number of the projects which were described to the Committee were focused not only on the local needs at Oak Ridge but will also produce information and concepts which will be of widespread importance to hydrogeologic theories and technologies. Early publication of results in technical journals is strongly recommended. Publication and participation in professional society activities is essential to enable GWPO staff to remain abreast of their technical field and, in turn, to keep the Oak Ridge Environmental Restoration and Compliance activities at state-of-the-art.
13. **Vehicle and space needs** were highlighted in the 1993 concerns. This year the Committee was pleased to learn that the vehicle situation had greatly improved by the assignment of a mini-van to the GWPO. However the Committee also noted that office space for GWPO personnel remains in the same cramped and unsatisfactory arrangement as last year.

The Committee was informed that several new buildings are either planned or under construction and that GWPO expects to be assigned space in one of these buildings.

The Committee strongly supports an arrangement whereby GWPO activities would be consolidated in contiguous space to promote effective interaction among personnel. The Committee strongly supports individual GWPO staff receiving sufficient office space to permit them to carry out their assignments in an effective manner.

Additional Concerns and Recommendations

1. **Shipment of samples offsite** was raised as a problem. The Committee was surprised by the news that considerable difficulty still exists with the shipment of samples for analyses offsite. We understand that this critical problem has been discussed by GWPO personnel within the Energy Systems organization without resolution. The Committee is distressed by this unfortunate situation.
2. **Concern** was expressed to the Committee that certain unmodified and uncontaminated tracts within the Oak Ridge Reservation that are now used for research might be reassigned as storage or waste disposal areas.

The Committee strongly supports the concept that designated research areas be preserved and protected for future research use. Substantial investments have been made in monitoring well networks and instrumentation. These

facilities have long term value for future investigations if they are not compromised.

3. The Committee considers drilling associated with hydrogeologic investigations to be a service activity rather than construction and therefore not properly subject to administrative controls governing construction. If drilling is to be subject to scheduling uncertainties and additional red tape associated with construction procedures, a major impediment to efficient hydrogeologic work will have been unnecessarily created.

INTERNAL DISTRIBUTION

1. L. V. Asplund
2. R. O. Barnett
3. L. D. Bates
4. F. P. Baxter
5. H. L. Boston
6. R. B. Clapp
7. K. W. Cook
8. T. K. Cothron
9. J. H. Cushman
10. N. H. Cutshall
11. F. P. Delozier
12. A. F. Diefendorf
13. R. B. Dreier
14. T. O. Early
15. C. D. Farmer
16. J. M. Forstrom
17. D. E. Fowler
18. C. W. Gehrs
19. P. A. Gourieux
20. J. P. Gwo
21. J. T. Grumski
22. C. S. Haase
23. S. G. Hildebrand
24. R. J. Hopta
25. D. D. Huff
26. A. Hunley
27. W. K. Jago
28. K. G. Kahl
29. P. Kanciruk
30. C. M. Kendrick
31. R. H. Ketelle
32. A. J. Kuhaida
33. S. Y. Lee
34. D. A. Leitzke
35. P. J. Lemiszki
36. T. P. McKenzie
37. G. R. Miller
38. G. R. Moline
39. G. K. Moore
40. C. A. Motley
41. J. B. Murphy
42. R. Nativ
43. M. J. Norris
44. J. E. Nyquist
45. D. E. Reichle
46. C. T. Rightmire
46. T. H. Row
47. W. E. Sanford
48. F. E. Sharples
49. D. S. Shriner
50. E. D. Smith
51. S. H. Stow
52. B. K. Thompson
53. L. E. Toran
54. L. O. Vaughan
55. D. B. Watson
56. S. H. Welch
57. O. M. West
58. R. K. White
59. S. L. Winters
60. B. Zerr
61. T. F. Zondlo
62. Central Research Library
- 63-78. ESD Library
- 79-80. Laboratory Records Dept.
81. Laboratory Records, ORNL-RC
82. ORNL Patent Section
83. ORNL Y-12 Technical Library

EXTERNAL DISTRIBUTION

84. P. E. Barnt, DOE Oak Ridge Field Office, P. O. Box 2001, Oak Ridge, TN 37831-SE 31
85. Robert Benefield, Tennessee Division of Environment and Conservation, 761 Emory Valley Road, Oak Ridge, TN 37831
86. G. W. Bodenstein, DOE Oak Ridge Field Office, P. O. Box 2001, Oak Ridge, TN 37831-8541
87. S. N. Davis, University of Arizona, 6540 W. Box Canyon Drive, Tucson, AZ 85745
88. R. N. Farvolden, Professor, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1 Canada
89. D. W. Freckman, Director, College of Natural Resources, 101 Natural Resources Building, Colorado State University, Fort Collins, CO 80523
90. R. C. Harriss, Institute for the Study of Earth, Oceans, and Space, Science and Engineering Research Building, University of New Hampshire, Durham, NH 03824
91. P. Hofmann, DOE Oak Ridge Field Office, P. O. Box 2001, Oak Ridge, TN 37831-8541
92. S. B. Jones, Tennessee Division of Environment and Conservation, 761 Emory Valley Road, Oak Ridge, TN 37831
93. G. Y. Jordy, Director, Office of Program Analysis, Office of Energy Research, ER-30, G-266, U.S. Department of Energy, Washington, DC 20545
94. A. Patrinos, Director, Environmental Sciences Division, Office of Health and Environmental Research, ER-74, U.S. Department of Energy, Washington, DC 20585
95. Robert Poling, Building 1432-D, MS-7468, The Pennsylvania State University, Oak Ridge, TN 37830
96. D. K. Solomon, Department of Geology and Geophysics, 717 W. C. Browning Building, Salt Lake City, UT 84112-1183

97. W. B. White, Pennsylvania State University, 542 Glenn Road, State College,
PA 16803
98. F. J. Wobber, Environmental Sciences Division, Office of Health and
Environmental Research, ER-74, U.S. Department of Energy, Washington,
DC 20585
99. Office of Assistant Manager for Energy Research and Development, U.S.
Department of Energy Oak Ridge Operations, P.O. Box 2001, Oak Ridge, TN
37831-8600
- 100-101. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge,
TN 37831