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*Laboratory and Field Studies Related to the
Hydrologic Resources Management Program*

October 1, 1992–September 30, 1993

Compiled and Edited by Joseph L. Thompson

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LABORATORY AND FIELD STUDIES RELATED TO THE HYDROLOGIC RESOURCES MANAGEMENT PROGRAM

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Joseph L. Thompson**

Contributors

W. L. Hawkins, M. Mathews, R. W. Henderson, J. L. Thompson, and S. Maestas

ABSTRACT

This report describes research done at Los Alamos in FY 1993 for the Hydrologic Resources Management Program. The US Department of Energy funds this research through two programs at the Nevada Test Site (NTS): defense and groundwater characterization. Los Alamos personnel have continued to study the high-pressure zone created in the aquifer under Yucca Flat. We analyzed data from a hole in this area (U-7cd) and drilled another hole and installed a water monitoring tube at U-4t. We analyzed water from a number of locations on the NTS where we know there are radionuclides in the groundwater and critiqued the effectiveness of this monitoring effort. Our program for analyzing postshot debris continued with material from the last nuclear test in September 1992. We supported both the defense program and the groundwater characterization program by analyzing water samples from their wells and by reviewing documents pertaining to future drilling. We helped develop the analytical methodology to be applied to water samples obtained in the environmental restoration and waste management efforts at the NTS. Los Alamos involvement in the Hydrologic Resources Management Program is reflected in the appended list of documents reviewed, presentations given, papers published, and meetings attended.

EXECUTIVE SUMMARY

Los Alamos actively participates in the Hydrologic Resources Management Program (HRMP), which is a multi-agency research program funded by the US Department of Energy. The work done at the Laboratory during FY 1993 for the HRMP is documented in this report. We do field work at the Nevada Test Site (NTS) and laboratory studies at Los Alamos. The NTS programs in defense and groundwater characterization support our research on the underground migration of radioactive materials and the geologic and hydrologic effects of nuclear testing.

Los Alamos is experiencing a sharply declining budget for weapons-related activities, and this change is affecting our work for HRMP. We can no longer take advantage of services and facilities (for example, chemical supplies or counting-room support) paid for by weapons research. The HRMP is now expected to pay for use of the central computer facility and other centralized laboratory or division services. Our programmatic budgeting will have to reflect the changed environment in which we are operating. We are attempting to combine with other organizations to pay for cooperative projects that are too expensive for any one group to undertake alone. For example, we are working with elements of the Field Testing, Earth and Environmental Sciences, and Isotope and Nuclear Chemistry divisions in a proposed drillback at the NTS. We also are proposing a cooperative study of a Rainier Mesa site involving the Yucca Mountain Project, the HRMP, and the Groundwater Characterization Project (GCP). We have joined the University of California at Berkeley in a study of ^{85}Kr transport in groundwater. We hope that participation in cooperative research will enable us to field the large-scale experiments required for the HRMP.

For several years we have been observing the effects of nuclear testing on the confined aquifer beneath at Yucca Flat. The latest example of artificially high pressures in this area is at the emplacement hole U-7cd, where water has risen more than 30 m above the expected level. In this report, we document our measurements of the water incursions at U-7cd and at a nearby satellite hole U-7cd Sat#1. We also describe in detail the drilling of postshot hole U-4tps3a. This hole was drilled beside and under the cavity/chimney formed by a nuclear test conducted in 1986. We were looking for (a) evidence that radionuclides were injected into fractures radiating from the cavity, as well as (b) indications of downward movement of radionuclides beneath the cavity. We encountered tritium at an elevation slightly higher than the working point of the nuclear device, but the tritium concentration did not increase as we sampled deeper in the hole. A high-sensitivity gamma log run in the hole showed no evidence of fission products. We installed a piezometer tube for continued water monitoring, and in September 1993 we collected the first water sample at depth.

During the summer of 1993 we began a joint exercise with LLNL to systematically sample those NTS holes that we know contain water contaminated with radionuclides.

After substantial delays caused by permitting requirements, we were successful in collecting water samples at a number of sites. In most cases, our samples were collected in 2- ℓ pressure tubes and can be analyzed for both tritium and ^{85}Kr . We have completed only tritium analyses thus far. Based on our experience with this sampling exercise and our experience in sampling several holes in previous years, we have come to several conclusions.

1. It is of little value to sample holes that have not been thoroughly pumped to remove drilling fluids and residual materials like uncured cement. If not pumped out, these materials remain in and around the hole for years and make it impossible to collect samples that are characteristic of formation water.
2. It is difficult to interpret data on radionuclide concentrations when the collection conditions vary—that is, when the hole is pumped on a very irregular basis. At the Cambric site, for example, we saw tritium concentrations change by a factor of 10 during the pumping of $<50\text{ m}^3$ of water.

Los Alamos provides water analyses for radionuclides on request by both the defense programs and groundwater characterization program at the NTS. Our analyses serve as a quality assurance check and confirmation of results from other analytical laboratories. During the past year, we analyzed one water sample for defense programs and three samples for the GCP. Los Alamos also assists these NTS programs by reviewing the planning documents for new drill holes or well recompletions. Appendix B of this report lists the documents we reviewed during FY 1993.

One of the HRMP's primary goals is to measure the concentrations of radioactive material in the groundwater at the NTS. We need accurate information about the amount of radioactive material left after nuclear testing (the radiologic source term) as well as an understanding of how the radionuclides interact with the groundwater to become the hydrologic source term. During the past year, Los Alamos initiated plans to inventory the radiologic source term for each underground nuclear test conducted by the Laboratory. This inventory, to be completed in FY 1994, will result in a data base that will enable us to calculate the cumulative source term for any region of the NTS and will serve as the starting point for calculations of transport and risk assessment. In addition to this initiative, we are continuing to study the relationship between radiologic and hydrologic source terms. This research involves acquiring postshot debris and measuring the leachability of each radionuclide as a function of its deposit location in the cavity/chimney complex. As we have reported in previous annual reports, our research suggests that the leachability of fission products in the postshot environment depends on whether they were incorporated in the melt glass at the bottom of the cavity or were deposited on surfaces in the cavity and chimney. These effects are clearly shown in the data we obtained from the last nuclear test conducted before the testing moratorium went into effect. Although there are no current nuclear tests, we hope to continue our studies with debris from earlier tests.

I. INTRODUCTION

The Hydrologic Resources Management Program (HRMP) — formerly the Hydrology/Radionuclide Migration Project — is part of the US Department of Energy's (DOE) effort to be a responsible steward of the environment. The DOE has sponsored underground nuclear testing at the Nevada Test Site (NTS) since the 1960s. The HRMP is a multi-agency program intended to characterize the NTS geology and hydrology, assess the impact of nuclear testing there, and seek ways to mitigate adverse effects of this testing. Participating agencies include Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the US Geological Survey (USGS), and the Desert Research Institute (DRI). The US DOE/Nevada Field Office manages the project with funding from Defense Programs and the Groundwater Characterization Program (GCP), which is part of the Environmental Restoration and Waste Management project at the NTS. Los Alamos' contribution to the HRMP includes expertise in nuclear containment issues as well as radionuclide detection and measurement. Los Alamos personnel working in the HRMP are from the Isotope and Nuclear Chemistry Division and the Earth and Environmental Sciences Division but often collaborate with members of the Field Test Division. In this report we describe the work done for the HRMP by Los Alamos during FY 1993. Work done in previous years has been described in other annual reports,¹⁻¹⁶ topical summary reports,¹⁷⁻²¹ and journal articles.²²⁻²⁶

II. DEFENSE PROGRAMS

A. PROGRAM COORDINATION AND TECHNICAL SUPPORT

1. Program Management

Some changes in program management are apparent this year. At Los Alamos, the recent trend toward increased centralization of accounting and other support functions has had an impact both on the way the HRMP program is managed and on our allocation of resources. For example, it is increasingly difficult to obtain sample analyses without charges to the program or to use supplies purchased under a broad program such as weapons research. Even small programs such as the HRMP are expected to pay for their own use of Laboratory services such as the central computer facility. This trend will probably continue, and it will be necessary to allocate an increasing portion of our budget to support services.

2. Planning and Reporting

In this past year, the HRMP adopted many of the elements of the performance measurement system being used in the DOE Office of Environmental Restoration and Waste

Management. In fact, all HRMP activities supported by the GCP are reported under this system. We have also placed increased emphasis on early planning for program initiatives that involve commitments from multiple organizations. For example, during the HRMP meeting hosted by Los Alamos in August, we and representatives from several other Laboratory divisions discussed ways in which they might participate in a future drillback. We hope that such discussions, held well in advance of the event, will enable us to avoid some of the problems we have experienced in past multiple-organization efforts.

3. Cooperative Work

Restricted budgets make it very difficult for single organizations to field a major drilling experiment, and the HRMP is trying to establish partnerships for such endeavors. In August we met with representatives from the Yucca Mountain Project (YMP) and the GCP to discuss drilling beside and under a collapse zone on Rainier Mesa in order to investigate radionuclide movement within unsaturated media. By pooling our resources, we may be able to carry out this expensive experiment, which would yield data that is important to each organization. Another example of cooperative work is the joint research project between Los Alamos and the University of California at Berkeley to model ^{85}Kr transport at the Cambria site at the NTS.

B. OPERATIONAL SUPPORT

1. Yucca Flat High-Pressure Zone — U-7cd (W. L. Hawkins)

Hole U-7cd was drilled in central Yucca Flat (see Fig. 1), where high formation pore pressures have caused fluid levels in boreholes to rise above the water table.²⁷ The area is a well-characterized, west-dipping structural block between the north-south-trending Topgallant and Yucca Faults (Fig. 2). Physical properties of these tuffs are very accurately predicted from their stratigraphy and lithology. The strata at the U-7cd site are typical for holes in the eastern portion of this structural block (Fig. 3). All the geologic data from U-7cd are as expected.

The 2.44-m-diam U-7cd emplacement hole was completed in April 1992 to a total depth of 495.3 m—20 m above the predicted depth of the water table. This depth was chosen to avoid having fluid enter the hole; however, we realized that this hole is located in an area of pressurized aquifers and, if a high-pressure zone were penetrated, the water level could rise to >470 m. Immediately after it was drilled, Hole U-7cd began to fill with water (Fig. 4). The fluid rose to 469.4 m before dewatering in early November 1992. After the water drained, the level rose steadily again from less than 488 m to 462.7 m on July 14, 1993. The hole was pumped intermittently from July 14, 1993, through August 11, 1993. During this period, the deepest level was 489.4 m (last day of pumping: August 11, 1993) and the fluid again resumed a steady rise. On September 21, 1993, the fluid was at a depth of 484.9 m.

Fig. 1. Location of U7cd within central Yucca Flat; solid circles represent emplacement sites. The labeled sites required remedial action because of their elevated fluid levels.

Fig. 2. West-to-east geologic cross section through the U7cd site.

Fig. 3. Stratigraphy at U7cd site. Data from the U7cdSat#1 satellite hole. (From information provided by R.L. McCall, Raytheon Services Nevada, Las Vegas, Nevada, 1993.)

In September 1992, a 0.31-m-diam satellite hole (U-7cd Sat#1) was drilled 10.5 m to the east of U-7cd and to a depth of 518.2 m. The fluid in this hole rose to 432.8 m on November 5, 1992 (Fig. 5). Dewatering of the original U-7cd emplacement hole between November 3 and 6, 1992, and again on November 10, 1992, caused a gradual decrease of ~0.8 m in the fluid level (Fig. 6). After about a month, the fluid level in the satellite hole resumed a steady rise to 432.2 m on April 16, 1993, just before the instruments were emplaced and the hole was filled with cement.

A preliminary report on thermal flowmeter measurements taken at depths of 448.7, 467.0, 487.7, 502.9, and 515.1 m in U-7cd Sat#1 indicates that the fluid in that hole is not flowing below 503 m and that above 503 m the fluid is moving upward at a fairly constant rate. Flow rates are too low to be accurately quantified; however, calculations suggest an inflow rate of $\sim 0.003 \text{ l/s}$ (0.05 gpm) above 503 m to just below the top of the fluid, where it decreased to 0.001 l/s (0.02 gpm). The slower rate near the top of the fluid was expected because the formation will take fluid more rapidly until it becomes saturated.

From the flowmeter data as well as temperature and electrical conductivity log data, it appears that the inflow is coming from the zone of 491- to 503-m depth. This supposition is supported by the lack of inflow observed above 486 m during TV logging after the U-7cd emplacement hole was dewatered. No radiation above background level has been detected in any of the samples from these holes.

The attempt to drill a dry emplacement hole at U-7cd was unsuccessful. Before this site can be used at the optimum depth, remedial action is needed. Obviously the water table elevation for this area is unknown, but limited flowmeter and other data suggest that the source of the fluid in U-7cd Sat#1 could be a very narrow zone near the bottom

Fig. 4. U7cd fluid level history.

Fig. 5. U7cd Sat#1 fluid level history.

Fig. 6. U7cd Sat#1 fluid level record during dewatering of U&cd. [From information provided by R.J. Lazniak, U.S. Geological Survey (1992)]

of the hole—perhaps associated with the Grouse Canyon tuff. More work is necessary to characterize the hydrogeology of this area where numerous underground nuclear tests have been conducted below the water table.

2. High-Sensitivity Gamma Logging (M. Mathews)

In recent years, we have employed high-sensitivity gamma logging as a tool for defining radionuclide distribution in postshot or exploratory drill holes. The use of high-sensitivity gamma logging to obtain gamma spectral information is discussed in a recent report.²⁸ During FY 1993, we used a Halliburton TracerScan logging tool in two drillbacks. We were not successful in obtaining useful information from the tool in the postshot drillback at U-3ml for several reasons. The operators logged the hole from bottom to top and, because of the high-radiation environment at the bottom, gain stabilization, pulse pile-up, and detector deadtime problems compromised the quality of the spectra. The two logging runs did not agree with each other, possibly because of telemetry problems. There were some indications that radionuclides are present high in the hole, but time constraints prohibited using the Hunt sidewall tool to sample this region. A more detailed discussion of the U-3ml logging is contained in a Los Alamos memorandum.²⁹ At the second drillback, where we used the TracerScan logging tool, we were able to avoid these difficulties; however, no radioactivity was detected in the hole.³⁰ The next section provides more details about the drillback at U-4tps3a.

3. Drilling of U-4tps3a (S. Maestas, R. W. Henderson, and J. L. Thompson)

Postshot hole U-4t3a was drilled May 3–7, 1993, and a gas sampling tube was installed the following week. One purpose of the drillback was to maintain personnel skills and verify the equipment functionality required for this type of operation. Another purpose was to gain information about both the hydrology in the area and possible radionuclide transport from the test cavity. The postshot hole was constructed so that it did not enter the cavity or chimney. It came within ~54 m of the cavity wall and extended underneath the cavity. Material returned to the surface during drilling was checked for radioactivity. A core was cut at about the level of the working point so that changes in rock properties caused by shock effects could be investigated. The slotted gas-sampling tube was set well below the water table; it provides a point just outside the cavity for monitoring the pressure and the radionuclide content of the groundwater. A more detailed account of our work at U-4tps3a is given below, and a geological report has been issued.³¹

Background. Emplacement hole U-4t was drilled in 1985 to a depth of 616 m, and a liner was installed. The expected water level at this site was ~506 m; however, the hole penetrated a confined aquifer under high pressure. The liner partially collapsed and leaked, so a second liner was cemented into the first. In a satellite hole, U-4t#1, drilled 12 m to the west, water rose in the shaft to a level 323 m from the surface. In 1986,

U-4t#1 was instrumented and sealed, and a test was fired in U-4t. Just before the test in U-4t was fired, a ton of sodium bromide was placed in the bottom of the hole so that we could trace water movement from this site. Two months after the test, the exploratory hole UE-4t was drilled about 170 m to the south to investigate the hydrology of the area. The water level and pressure in this hole were monitored, and straddle packer tests were conducted. In September and October 1990, two strings of 73-mm tubing were cemented into UE-4t; the slotted joints at the bottoms of these tubes are at depths of 607 and 525 m. The tubes were swabbed and flushed in June 1992, and since then the water level differential has been ~260 m which reflects the higher hydrostatic pressure in the deeper hole. We have never detected any tritium or other radionuclide from U-4t in water from UE-4t.

Three drillbacks were done at the U-4t site. Los Alamos drilled U-4tps1a to a 733-m slant depth immediately after the test to collect radiochemical samples from the cavity and gas samples from the chimney. In 1988, DRI personnel installed a pressure transducer in the 73-mm tubing in this hole (the water level was then at 521-m slant depth). In May 1993, during an attempt to remove the failed transducer, it became stuck in the tubing. The cable broke at the surface and remains in the hole with the transducer, so access to the water level is currently blocked. Immediately after the test, LLNL drilled U-4tps2a into the chimney and installed a 73-mm gas sampling tube. After gas sampling was completed, this hole was capped. We do not know if the perforated section of this tubing is below the present water level. In May 1993, U-4tps3a was drilled. The section below provides details of this operation. Figure 7 shows data for all of the holes discussed above as well as a plan view of their locations. More details of the drilling operations may be found in the weekly drilling reports issued by Los Alamos Field Engineering (Group J-6) and in the drilling supervisor logs.

Drilling of U-4tps3a. This drillback was designed to come close to the walls of the cavity and chimney, but not actually penetrate them. Because we were particularly interested to learn whether radioactive material had been injected into fractures extending outward from the cavity, airfoam was used as long as possible to maximize our chance of detecting any radionuclides. Only when appreciable amounts of radioactive material were being returned to the surface did we switch to bentonite mud and force lost circulation. Appendix A of this report provides details of the tritium measurements made while drilling with airfoam. We logged the hole with a high-sensitivity gamma detector to locate any radioactivity external to the cavity. We collected core at a depth opposite the working point to investigate any changes in the rock properties caused by shock effects. Finally, we inserted a 73-mm tube with slots, which allowed us to monitor water pressure changes with time and provided a sampling point for detecting any radionuclide migration away from the cavity region. It should be noted here that we have not found any radioactivity in UE-4t during the 6 years it has been monitored.

Hole	Nevada Coordinates (ft)		Diameter (m)	Shaft Length (m)	Angle	Date Drilled
U-4t	N856115	E680400	3.05	616	Vertical	5/85
U-4t#1	N856115	E680360	0.31	640	Vertical	4/86
U-4tps1a	N855292	E680506	0.25	733	Slant	11/86
U-4tps2a	N855955	E681214	0.25	568	Slant	11/86
U-4tps3a	N856259	E681219	0.25	766	Slant	5/93
UE-4t	N855565	E680350	0.25	736	Vertical	1/87

Fig. 7. Plan view and data for holes around U-4t.

Drilling with airfoam began May 3 and proceeded with only minor delays from equipment failure. By midnight on May 4, the hole was ~556 m and generally followed an inclination of 13° from vertical. Samples of effluent collected periodically from the flowline up to 23:00 hours on May 4 showed no radioactivity. At 01:00 on May 5 at a bit depth of 564 m, a seal in the power swivel failed and drilling stopped. Drilling resumed at 11:45 and continued to 14:45, when the drill reached a depth of 616 m, where coring was to begin. While the core barrel was being installed, reports of samples taken from

the flowline at 13:00 and 14:20 indicated the presence of tritium. In the sample taken at 13:00, the tritium concentration was $\sim 18 \text{ Bq/ml}$ (480 pCi/ml); the later sample's concentration was lower by a factor of 10. It appeared that we had drilled through a region of high tritium concentration, so we decided to do the coring with airfoam and monitor the returns frequently. We collected the samples from a bucket hung directly under the flowline (providing a sample that integrated between sampling periods), and from the sump (providing a sample integrating the entire drilling operation). Coring began $\sim 22:20$ on May 5 and ended at 01:30 hours on May 6. Approximately 5.8 m of core was recovered from the 6.1-m core barrel. Because the returns from the flowline were still above the tritium concentration allowed in drinking water, we decided to switch to bentonite drilling mud and force the loss of circulation. Drilling in this mode continued from 18:50 May 6 to 06:40 May 7, when we reached a depth of 766 m. Haliburton Logging Services, Inc., logged the hole with a tracer logging tool from 749 to 479 m. No evidence of gamma activity other than normal background was found. We collected no sidewall samples from this hole because there was no indication of high gamma activity in any region.

Hole Completion. On May 10, 1993, installation of 73-mm tubing began. After unsuccessful attempts to locate the water level with fluid density tools, two additions of water (500 gals each) were made at ~ 610 and 518 m. A packer was set in at 493 m with three joints of solid tubing below it and then alternating slotted and solid joints to the final tubing depth of 650 m. Cementing of the tubing was completed on May 12, 1993.

Conclusions. The drilling operation at U-4tps3a achieved the planned objectives. The drilling equipment and procedures were tested; personnel received training and were certified; core was recovered for analysis of alteration of properties; radioactive materials external to the cavity/chimney were detected; and a sampling point for hydrologic and radiochemical monitoring was established. The Los Alamos Field Testing Group's cooperative spirit enabled several other Laboratory divisions to benefit considerably from this exercise.

Data obtained to date from U-4tps3a do not give us a clear indication of how the tritium came to be outside the cavity. We would like to know whether the tritium brought to the surface was drawn from a confined region—into which it might have been injected at the time of the test—or whether it indicates transport by water long after the test. An order-of-magnitude calculation sheds little light on the situation. The sump capacity is $\sim 9\text{E}3 \text{ ft}^3$ ($2.6\text{E}8 \text{ ml}$), and it was about one-half full when tritium began to enter it. We found $1.7\text{E}8 \text{ Bq}$ of tritium in the sump water, which indicates a concentration of $1.1\text{--}1.5 \text{ Bq/ml}$ ($30\text{--}40 \text{ pCi/ml}$). The volume of returns entering the sump per meter of drilling was $\sim 1.3\text{E}8 \text{ ml}/6\text{E}2 \text{ m}$, or $2.1\text{E}5 \text{ ml/m}$. Because tritium entered the sump during

the last 90 m of drilling, it was contained in the last $1.9\text{E}7$ ml of water. A uniform concentration during this last drilling period would be $1.7\text{E}8$ Bq/ $(1.9\text{E}7)$ ml, or 9 Bq/ml. However, a concentration of $7.8\text{E}2$ Bq/ml over any 1 m of drilling would have produced the same result. The highest tritium concentrations we actually measured were ~ 18 Bq/ml in two samples from the flowline (see Appendix A). We do not know what the concentrations might have been at other times during the last drilling stages, and therefore we do not know—and cannot tell from the data—whether we drilled through a concentrated pocket of tritium (as at UE-3e)¹⁸ or through an extensive zone of less-concentrated tritium. Perhaps continued periodic monitoring of the tritium concentration will give us an indication of tritium mobility in the region adjacent to the cavity.

We recently analyzed several samples of drilling-returns (collected during latter stages of drilling) for the presence of bromide ion. If the tritium present was from the test at U-4t, bromide could also have migrated from that site. Our analyses were complicated by the presence of nitrate and other components of the drilling fluid, and we were able to conclude only that bromide was not present at concentrations above ~ 5 ppm. At the end of September, we collected water samples from the piezometer tube in U-4tps3. Only one of these samples was analyzed for tritium; the concentration was 1.06 Bq/ml. The piezometer tube has not been bailed or swabbed since its installation, and therefore the fluid in it is probably not representative of formation water at this site.

C. GROUNDWATER PROTECTION

1. Colloid Studies

Colloids in groundwater may provide a pathway for radionuclide migration. For example, it appears that several of the radioactive species identified at the Cheshire site were associated with colloids.³² At Los Alamos, the HRMP has supported research in colloid transport for many years. This past year that support has consisted primarily of assisting the direction of a predoctoral student who is doing laboratory-scale research in colloid movement through columns and fractures. His work is funded by the YMP. At this time, the research is focused on developing techniques and models to describe the transport of silica colloids through columns of glass beads. The next stages will include labeling the colloids with radioactive materials, doing studies with columns of crushed tuff, and eluting labeled colloids through rock fractures. Our collaboration with the YMP allows us to conduct some research on this topic at almost no cost to the HRMP.

2. Analysis of Water from UE-20bh-1 (S. Maestas and J. L. Thompson)

The hole UE-20bh-1 drilled by the HRMP in 1991 is the site of a proposed study of hydrologic and radiochemical effects of nuclear testing. We reported last year that

samples taken during drilling contained no detectable tritium or gamma-emitting fission products.¹⁶ This year we received a 4-ℓ water sample from this hole, collected on June 6, 1993, by J. Kenneally of LLNL. Aliquots were counted for tritium; then the sample was dried and the residue was examined for gamma activity. No tritium or fission products were detected; hence the tritium concentration is $<3.7\text{E-2 Bq/ml}$ and fission product concentrations are very low (for example, ^{137}Cs is $<2\text{E-5 Bq/ml}$).

3. Document Review

As part of the DOE/NV effort to protect the groundwater at the NTS, the HRMP provides outside review of proposed drilling operations sponsored by defense programs. In this capacity we reviewed plans for the two recompletion wells and two emplacement holes listed in Appendix B. We also reviewed a document assessing the risk associated with radionuclides in the groundwater of the NTS.

D. GROUNDWATER MONITORING (S. Maestas and J. L. Thompson)

1. Sampling at Cambric

Since 1974, the HRMP has studied the movement of radionuclides with groundwater at the site of the Cambric test. We pumped water from the RNM-2S well located 91 m from the test cavity and monitored the radionuclide concentration changes in the RNM-1 well penetrating the cavity. The concentrations of tritium, ^{85}Kr , ^{90}Sr , and ^{137}Cs decreased from 1974 to 1991 at the RNM-1 well, whereas at the RNM-2S well the elution of tritium and ^{85}Kr peaked and gradually declined. (The results of this part of the study have been summarized in a recent publication.²⁰) Since pumping stopped in 1991, we have periodically sampled both wells to see how the system responds in the absence of an imposed hydraulic gradient. The water sampling at Cambric this year was delayed until September, so only preliminary tritium results are available for this report. In Table I we list the tritium concentrations measured in RNM-1 samples and in Table II give similar results for RNM-2S samples. For comparison, we also list the concentrations measured in 1992 and in 1991 at the end of pumping. Measurements of other radionuclides at this site will be provided in a later report.

The tritium concentration in RNM-1 water remains quite low, but it may be increasing slightly since the hydraulic gradient toward the RNM-2S well has been removed. If the observed increase results from the diffusion of tritium from regions closer to the pumped well—where it is more concentrated—we would expect similar increases for several years in the future.

The tritium concentration at RNM-2S continues to decrease with time, presumably as a result of tritium diffusion. Because there are no strong natural hydraulic gradients at this site, we may be able to measure the rate at which tritium is diffusing into alluvial soil.

In one of the water samples taken at RNM-2S last year, we detected a trace of ^{137}Cs .¹⁶ We have since repeated this analysis and do not find any indication of this radionuclide. This later result is consistent with previous work—indicating that cations from the Cambrian test cavity are not being eluted in RNM-2S water.

2. Disposal of Fluids at the NTS

Because of concerns about contamination of the environment, we are not able to discharge into the NTS soil any water containing radionuclides in concentrations above drinking water standards. The water at the RNM-2S well at Cambrian has a present activity of $\sim 3 \text{ Bq/ml}$; the drinking water concentration limit is 0.74 Bq/ml . To obtain a RNM-2S sample that is representative of groundwater, we must first pump a significant amount of water to clear the well; thus, we create a disposal problem. Last year, pumped water at RNM-2S was left in a 56-m^3 (15 000-gal.) holding tank from which it slowly evaporated. This year we are using a solar-powered system designed and installed by DRI to increase the rate of evaporation from the tank. Early indications

Table I. Tritium Concentrations in RNM-1 Water

Sample Number	Collection Time (09/14/93)	Type	Concentration (Bq/ml) ^a
pump on	10:00		
Z-1	10:10	500 ml poly bottle	$(2\pm 3)\text{E-2}$
Z-2	11:50	same	$(1.8\pm 0.7)\text{E-1}$
Z-3	13:22	same	$(1.6\pm 0.9)\text{E-1}$
Z-4	15:50	same	$(1.7\pm 0.9)\text{E-1}$
434-3-93-001	15:51	pressure tube (HPW2)	$(1.4\pm 0.2)\text{E-1}$
434-3-93-002	15:53	pressure tube(INC15)	archived
434-7-93-002	15:55	barrel (#7)	$(1.0\pm 0.8)\text{E-1}$
434-7-93-001	16:01	barrel (#98)	$(1.3\pm 0.9)\text{E-1}$
Z-5	16:08	500 ml poly bottle	$(1.8\pm 0.9)\text{E-1}$
pump off	16:08		
Average			$(1.5\pm 0.3)\text{E-1}$
1991 samples			$<3.7\text{E-2}$
1992 samples			$(1\pm 1)\text{E-1}$

^aAll activities are corrected to Cambrian zero time (May 14, 1965); $1 \text{ Bq} = 27 \text{ pCi}$.

Table II. Tritium Concentrations in RNM-2S Water

Sample Number	Collection Time (09/14/93)	Type	Concentration (Bq/ml) ^a
pump on	11:20		
434-1-93-001	11:25	pressure tube(CNC12)	1.5±0.1
434-1-93-002	11:27	pressure tube(CNC10)	(8.2±0.4)E-1
434-9-93-001	11:34	barrel (#8)	2.1±0.1
434-9-93-002	11:36	barrel (#9)	3.3±0.1
RNM-2S	11:46	500 ml poly bottle	(1.6±0.1)E1
pump off	11:46		
1991 samples			4.9E1
1992 samples			(2.4±0.4)E1

^aAll activities are corrected to Cambrian zero time (May 14, 1965); 1 Bq = 27 pCi.

are that this system has increased the rate of evaporation from the tank by a factor of 5. If the system continues to perform well, it may be useful at other sites where water containing tritium must be managed.

3. Sampling at Yucca Flat and Pahute Mesa

Los Alamos and LLNL cooperated in sampling a number of shot sites where radioactivity had previously been measured in the water. This sampling exercise was delayed until the end of the fiscal year because of a permit requirement. Consequently, we can only report preliminary tritium concentrations in this document. Most of the samples analyzed were splits between LLNL and LANL. We will report later on ⁸⁵Kr concentrations from samples taken in pressure tubes.

UE-7ns. This satellite well was drilled in 1976 to a depth of 672 m; it was completed with slotted casing in the bottom 62 m. This well is 137 m from the Bourbon event, a test fired near the boundary of tuff and paleozoic carbonate rocks and close to the carbonate aquifer. A LLNL report summarizes the data for the intermittent pumping and water sampling done at UE-7ns up until 1984.³³ Tritium concentrations were 1E-2–1E-1 Bq/ml; the last LANL measurement in 1984 was 4.4E-2 Bq/ml. The following information pertains to the sampling at UE-7ns this year:

<i>date</i>	<i>depth</i>	<i>tritium concentration</i>
08/24/93	617 m	<3.7E-2 Bq/ml

UE-2ce. The Nash test was conducted in 1967 at U-2ce. The resulting cavity is probably just above the water table. Soon after the test, the satellite well UE-2ce was drilled 183 m away. This well extended into the aquifer and was cased to draw only from that source. It was pumped and sampled intermittently from 1977 to 1984. Analytical data from this period have been compiled in a LLNL document.³³ Los Alamos measurements of the tritium concentration in 1984 ranged from 4.8E2 to 1.2E3 Bq/ml (activity at the time of counting).⁸ Our results from this year's sampling are shown below.

<i>date</i>	<i>depth</i>	<i>tritium concentration</i>
08/25/93	445 m	5.4±0.3 Bq/ml

U-4ups2a. The Dalhart test was conducted in 1988 at a vertical depth of 640 m—well below the preshot standing water level at 508 m. In 1990, we drilled U-4ups2a into the cavity region and emplaced tubing with slots at a depth of 474 to 502 m (vertical). The postshot water level in this hole has been slowly rising and was about 480 m in July 1993. A 1992 water sample from a depth of 504 m contained tritium at a concentration of 2.15E3 Bq/ml. Our values from this year's sampling are shown below:

<i>date</i>	<i>depth</i>	<i>tritium concentration</i>
08/31/93	496 m	2.18E3 Bq/ml
08/31/93	504 m	2.14E3 Bq/ml
08/31/93	484 m	2.22E3 Bq/ml

The water in this hole contained a good deal of suspended material. The sample from 484 m was a light tan fluid; that from 496 m was a brown thin sludge; and that from 504 m was a thick brown sludge with black particles. We centrifuged the samples to separate the bulk of the suspended material and then filtered the supernate through 45-nm-pore-size Nuclepore filters before liquid scintillation counting. Despite the different appearances of these samples, the tritium content is rather uniform and unchanged from last year.

U-4tps3a. Drilling of this hole was discussed in detail in Sec.II.B.3. of this report. The slotted tubing is in the depth range of 527 to 640 m. This was the first water sampling from the completed hole.

<i>date</i>	<i>depth:</i>	<i>tritium concentration</i>
09/01/93	529 m	1.06 Bq/ml

This water sample was a dark gray sludge. We centrifuged and filtered it in the same manner as the U-4ups3a samples.

UE-3e#4. This hole was drilled in 1990 to a depth of 701 m. Three tubes with slots over the following intervals were cemented into the hole: tube 1, 655 to 662 m; tube 2, 575 to 582 m; and tube 3, 493 to 500 m. The history of this hole is described in detail in Ref. 18. In last year's annual report we summarized the tritium analyses from the three tubes, noting that there were particulates in all three tubes and a nonuniform tritium distribution in tube 1.¹⁶ Water from UE-3e#4 collected in 1993 has not yet been analyzed.

4. Conclusions

For many years the HRMP and its predecessors have supported monitoring of groundwater from selected sites at the NTS. These sites were generally locations where water was being pumped more or less continually (as at Cambric and Cheshire) or were holes where we could obtain grab samples during drilling operations (as at UE-3e#4, U-4tps3a, and U-4ups2a). Now an increasing number of holes are being fitted with piezometer tubes that are not pumped, but from which grab samples may be collected. The data on tritium presented above illustrate many of the problems associated with monitoring water from locations that are not being pumped and from which introduced materials have not been removed. For example, it is quite clear that U-4ups2a and U-4tps3a are contaminated with substantial amounts of material associated with drilling the wells and setting the piezometer tubes. Our tritium measurements in these holes are uncertain because of dilution effects; measurement of fission products would be almost meaningless because of possible interactions between the fission products and these extraneous materials. Furthermore, measurement of formation water parameters such as pH, conductivity, and dissolved constituents is quite impossible. An additional problem in effectively sampling water in tubes of relatively small diameter is that there may not be mixing between various depths in the tubing. Experimental evidence for poor mixing was discussed in last year's annual report as part of the interpretation of UE-3e#4 data.¹⁶ In short, these piezometer tube sampling stations are providing little useful data (other than water levels). We must devise ways to pump the stations long enough to get formation water if the stations are to be used to their full potential.

This year we sampled U-7ns and UE-2ce for the first time since 1984. It must be noted that data were taken during the earlier period while these holes were being pumped for extended periods. The tritium concentrations we measured this year from bailed samples may not be representative of formation water because of poor mixing within the well bore; certainly the samples cannot be easily related to concentrations

measured while the holes were being pumped. Even at RNM-2S we see how tritium concentrations may change over the course of a rather short pumping operation. The tritium concentration increased more than 10 times over a 20-min period; we do not know how high the concentration might have risen had we been able to pump longer. Again, obtaining meaningful water-quality data is dependent on being able to pump until representative formation water is sampled.

III. GROUNDWATER CHARACTERIZATION PROJECT

A. DATA ACQUISITION

1. Analysis of Water Samples (S. Maestas and J. L. Thompson)

Los Alamos provides analyses of water from GCP drilling sites as a confirmation and quality assurance check of results from other laboratories. We routinely analyze these samples for tritium and gamma-emitting radionuclides. Tritium is measured by liquid scintillation counting; our detection limits are $\sim 3.7\text{E-}2$ Bq/ml (1 pCi/ml). Our detection limit for gamma-emitting fission products depends on the sample size because we evaporate the sample to dryness and count the residue on germanium detectors. The detection limit is also somewhat dependent on the individual radionuclide; we estimate the limit based on our results with ^{137}Cs . The results of analyses from three sites measured during the past fiscal year are listed below:

12/22/92	ER-6-1	$^3\text{H} < 4\text{E-}2$ Bq/ml	fission products $< 1\text{E-}6$ Bq/ml
03/30/93	ER-12-1	$^3\text{H} < 3.7\text{E-}2$ Bq/ml	fission products $< 3.7\text{E-}7$ Bq/ml
05/28/93	UE-10j	$^3\text{H} < 3.7\text{E-}2$ Bq/ml	fission products $< 3.7\text{E-}5$ Bq/ml

2. U-4tps3a (S. Maestas and J. L. Thompson)

Drilling and sampling operations at U-4tps3a were a cooperative venture involving several organizations and supported by both defense programs and the groundwater characterization project. We have described in detail the drilling and sampling of this hole in Sec.II.B.3 and Sec.II.D.3., respectively.

B. DATA ANALYSIS/MODELING

1. Document Reviews

The GCP uses Los Alamos personnel to provide expert reviews of plans for recompletion of existing NTS wells and for drilling, testing, and completion of new wells. During the past year we reviewed documents for two recompletion wells and

three new wells (see Appendix B). Because there is increased concern that tritium discharged in drilling-returns to sumps should not exceed regulatory limits, we recommended several procedures that could be incorporated in drilling plans for wells where tritium might be encountered in the groundwater. Our experience at the NTS has shown that tritium is often confined within depth intervals of >1 m, and thus sharp spikes of tritium concentrations may appear (and disappear) in the return fluids. If the sampling interval (usually 1 hour) does not coincide with the appearance of tritium, its presence may be missed for some time. Our recommendation was that the sump be sampled periodically—especially if there is any indication of tritium in samples taken at the return line. We further recommended that a HRMP representative of LANL or LLNL be notified if tritium is encountered in significant levels so that we might offer advice to field personnel from our experience with similar situations. As the GCP drilling program enters areas where nuclear testing was more concentrated, the probability of encountering tritium and other radionuclides will increase considerably, and advance planning becomes very important.

2. Protocols for Water Analyses

The IT Corporation is the principal contractor to DOE/NV for the environmental restoration and waste management effort at the NTS. Los Alamos personnel provide assistance to IT Corporation on subjects in which we have expertise. During the past year we participated in a working group that defined the sampling protocols and analytical limits to be applied to water samples collected by the IT Corporation for the GCP. This group reviewed the organic and inorganic materials to be measured in groundwater samples, analytical methods to be employed, sampling protocols, detection limits, and laboratories that would do the work. We established which radionuclides would be routinely measured and determined the concentration limits that would trigger a detailed analysis for classified fuel analytes. We identified isotopes that were important for studies of age, migration, and flow modeling of groundwater. The decisions made by this working group will have considerable impact on the future of the GCP.

3. Inventory of Los Alamos Test Residues

At the request of the GCP, Los Alamos is preparing an inventory of residual radioactive materials associated with nuclear tests we have conducted underground in the continental US. This inventory, along with one being prepared by LLNL, will make it possible to calculate the maximum possible concentration of any fission product, fuel radionuclide, or activation product in the cavity produced by each past nuclear test. These radiologic source-term data will provide the basis for estimating the hydrologic source term at each site and permit further calculations of risks caused by transport to the accessible environment. The Los Alamos inventory will consist of three reports: a database with descriptive (classified) information on each nuclear event; a detailed

description (also classified) of how this data base was assembled (including sources and calculation algorithms); and an unclassified report providing the total radionuclide inventory as of a certain date for specified regions of the NTS. Los Alamos personnel have attended several meetings on this subject with GCP and LLNL representatives and have engaged in numerous internal discussions on the topic. Assembling this inventory is clearly a difficult undertaking that will involve a significant commitment of resources. Los Alamos is benefiting from LLNL's experience and will produce a report that may readily be combined with theirs. To assist those who will use the data, we have designated a staff member who will serve as interpreter or interface between the data and the user.

4. Analysis of Postshot Debris (J. L. Thompson)

If we are to understand how underground nuclear testing has impacted the environment at the NTS, we must be able to acquire data on the source term at particular sites. That is, we must measure the types and quantities of radioactive materials that remain after the shot and determine how these materials are distributed in the immediate vicinity of the test. Furthermore, since groundwater provides the principal means for transport, we must learn how the radiologic source term evolves to the hydrologic source term. In recent years, the Los Alamos Field Testing Group has assisted the HRMP in acquiring such data. We have received debris collected from the bottom of the cavity and from the collapse zone in the upper cavity or chimney. We have analyzed this material to determine which radionuclides are present in each region, and we have conducted leaching studies to determine the relative rates with which each species dissolves in groundwater. As we indicate in our reports on this work, in many tests there is some separation between refractory elements that concentrate at the bottom of the cavity and volatile elements that concentrate in the upper cavity and chimney regions.¹³⁻¹⁶ However, both volatile and refractory materials are found to some extent in each region of the cavity/chimney complex. These observations are in agreement with literature reviews of the subject.³⁴ We have also found that materials deposited in the upper cavity and chimney (presumably as surficial deposits) dissolve more readily than their counterparts, which are incorporated in melt glass. Our leaching studies were for short periods and used fresh debris. An extensive review of the literature dealing with leaching of melt glasses has recently been published.³⁵

In September 1992, Los Alamos conducted its last nuclear test before the current testing moratorium went into effect. We received samples from the drillback of this test and report here on our work with them. The test was conducted in tuff above the water table (75% saturation). Our sample taken from the bottom of the cavity (cavity debris) was 140 mg of particulates resembling sand grains. The other sample (collapse debris) was 330 mg of clay-like material collected ~0.4 cavity-radii above the cavity bottom. We measured the gamma activities of these samples with a calibrated germanium

counter to quantify the radionuclides, then placed each sample in a sealed tube with deionized water (20 ml water:1 g solid) on a constant temperature shaker bath at 70°C. After 4 days, we removed the samples, separated the phases by centrifugation, and filtered the water through 50-nm-pore Nuclepore filters. We then measured the radionuclide concentrations of those species dissolved in the water. Because the particulate sizes in the two samples were dissimilar, we ground both to a fine powder with an agate mortar and pestle and repeated the leaching in the constant temperature shaker, using fresh water. After 5 days, the second leaching experiment was stopped, the phases were separated as before, and the leachate was counted. The data from this experiment are shown in Table III.

Table III. Concentration of Radionuclides in Test Debris and Leachates					
Radionuclide	Cavity Debris		Collapse Debris		
	Solid (atoms/g)	Liquid (atoms/ml)	Solid (atoms/g)	Liquid (atoms/g)	
	Original (Ground)		Original (Ground)		
⁹⁵ Zr	6.0E12				
⁹⁹ Mo	6.8E12	(4.3E9)	3.8E11	1.8E9	
¹⁴⁴ Ce	6.5E12				
¹⁴¹ Ce	4.0E12	9.6E6	1.6E11		
¹⁴⁷ Nd	2.3E12				
¹⁰³ Ru	2.4E12	3.0E7	1.9E12	2.6E9	(1.5E8)
¹⁰⁶ Ru			1.3E12	1.7E9	
¹⁴⁰ Ba	2.5E12		4.7E11	3.9E6	
¹³² Te	1.0E12		1.7E12	3.8E9	(2.4F9)
²³⁹ Np	1.6E13				
²³⁷ U	6.7E11				
¹³⁷ Cs			2.4E12		
¹³¹ I	9.0E11	8.9E7 (9.3E8)	7.1E11	8.5E9	(1.8E9)
¹²² Sb	7.9E11		3.2E11	5.3E9	
¹²⁴ Sb	4.6E11	1.8E7 (1.5E8)	1.3E11	3.1E9	(1.2F9)
¹²⁷ Sb	7.7E10		1.6E11	4.2E8	(1.9E8)
¹³³ Xe	1.1E12		1.3E12		

The refractory elements zirconium, molybdenum, cerium, and uranium are either absent in the collapse debris or present at lower concentrations than in the cavity debris. Volatile elements such as tellurium, iodine, antimony, and xenon are more uniformly distributed. The fact that the most volatile elements are present at all in the cavity debris is probably related to the lesser volatility of their precursors. The major separation between true gases and vaporized solids probably takes place 1 to 3 min after the explosion, so precursors often determine the disposition of the radionuclides. For example, ^{137}Cs escaped entirely from the cavity debris in this case because of its very volatile precursors. Likewise, ^{106}Ru is found only in the collapse debris, whereas one-half of the ^{103}Ru is held in the melt glass because of the ~1-min half-lives of its ^{103}Mo and ^{103}Tc precursors.

The concentrations of radionuclides in the leachate relative to the debris is in each case higher for the collapse material than for the cavity material. We believe this is because the radionuclides are deposited on the surface of rocks, which end up as rubble in the upper cavity and chimney but are incorporated into the melt glass in the lower cavity debris. The surficial material dissolves more readily in these short-term leaching experiments. Grinding the debris to a powder did enhance the leaching of molybdenum, iodine, and antimony from the cavity debris; the effect of grinding was less apparent in the collapse debris that was already finely divided.

This study illustrates the fact that a detailed analysis of a particular test site may be required to determine the distribution of radionuclides making up the radiologic source term or to predict the probable magnitude of the hydrologic source term. Such details may be essential in situations in which the bottom of the cavity and the upper cavity and chimney are exposed to groundwater in different quantities and flow rates. In general, however, the experience at the NTS indicates that most radionuclides are confined within a few cavity radii of the working point and a test site may be treated as a single source for the purpose of large-scale modeling.

ACKNOWLEDGMENTS

We appreciate the assistance of M. R. Betts and R. A. Beaty in gamma counting and J. H. Heiken for editorial review.

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APPENDIX A

Los Alamos

NATIONAL LABORATORY

memorandum

Health Physics Policy & Programs

To/MS: File

From/MS: Richard Henderson
HS-12, MS G732

Phone/FAX: 7-3362/5-5302

Symbol: HS-12-FTHP-93-65

Date: June 3, 1993

**SUBJECT: ANALYSIS OF DRILLING THIRD SAMPLES FROM THE POST SHOT
3A HOLE AT U4T - GASCON**

Samples of the returns were collected by ReeCo HPD and delivered to Building 701 in Mercury for analysis. The results of these analyses are attached. "Flowline" samples were collected as grab samples from the end of the blooie line at the times shown. "Bucket" samples were taken from a bucket hanging under the end of the blooie line at the times shown. The depth is the reported drill depth at the times shown.

Collected Date	Collected Time	Depth (ft.)	Tritium pCi/ml	Gamma pCi/ml	Comment
5/3/93	NR	50	ND	NDG	Flowline
5/3/93	NR	194	ND	2.5	Flowline
5/3/93	NR	383	ND	4.4	Flowline
5/3/93	23:00	757	*ND	2.8	Flowline
5/4/93	3:00	1008	ND	.2	Flowline
5/4/93	7:10	1163	ND	.8	Flowline
5/4/93	10:00	1258	ND	3.3	Flowline
5/4/93	19:30	1569	ND	2.1	Flowline
5/4/93	20:15	1569	ND	1.5	Flowline
5/4/93	22:15	1700	ND	1.8	Flowline
5/4/93	23:00	1745	ND	2.5	Flowline
5/5/93	13:00	1910	480	1.3	Flowline
5/5/93	14:20	2005	46	.5	Flowline
5/5/93	22:30	2020	470	2.7	Bucket
5/5/93	22:30	2020	490	2.5	Flowline
5/5/93	23:15	2025	160	2.6	Bucket
5/5/93	23:15	2025	26	.3	Flowline
5/6/93	0:01	2035	25	.8	Flowline
5/6/93	1:00	2040	15	NDG	Flowline
5/6/93	1:30	2040	83	2.8	Bucket
5/6/93	13:08	---	41	.5	Sump

* NR - Not Recorded

* ND - Non-Detectable <1 pCi/ml

** NDG - Non-Detectable Gamma <.1 pCi/ml

RH:jr

Cy:

J. Spoeneman, J-6, MS J900
J. Peterson, J-6, MS C 925
HS-12 File, MS G732

APPENDIX B

Program Activity

Meetings Attended (HRMP and Related Programs)

HRMP/USGS	October 22–23, 1992
Working group/IT Corporation	January 14, 1993
HRMP/DRI	January 20–21, 1993
Working group/IT Corporation	February 23, 1993
Working group/IT Corporation	March 25, 1993
HRMP/LLNL	April 20–21, 1993
High-Level Radioactive Waste Management	April 26–27, 1993
DOE/NV Earth Sciences Advisory Panel	May 11–12, 1993
GCP	July 27, 1993
HRMP/LANL	August 4, 1993
YMP/GCP/HRMP	August 24, 1993
GCP	September 27–28, 1993

Documents Reviewed

Defense Programs:

- Recompletion Plans UE-18r
- Recompletion Plans UE-16d
- Drilling Plans for Emplacement Hole U-19bl
- Drilling Plans for Emplacement Hole U-4aq
- Risk Assessment from Ingestion of NTS Ground Water (Daniels, *et al.*)

GCP:

- Recompletion Plans U-10l-1
- Recompletion Plans U9ITS/UE-U22
- Sampling, Testing and Completion ER-20-1
- Sampling, Testing and Completion ER-20-2
- Sampling, Testing and Completion ER-11-1

Presentations

"Fission Product Distribution in Nuclear Test Cavities/Chimneys," International High Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 26-30, 1993.

"The LANL Postshot Inventory," GCP meeting, Las Vegas, Nevada, July 27, 1993.

Publications

"Studies of Fission Product Movement in Tuffaceous Media," J. L. Thompson, *Radiochim. Acta* 58/59, 273-276 (1992).

"Laboratory and Field Studies Related to the Hydrology/Radionuclide Migration Project, October 1, 1992 — September 30, 1993," J. L. Thompson, Comp. and Ed., Los Alamos National Laboratory report LA-12498-PR (January 1993).

M. Mathews, K. Hahn, J. Thompson, L. Gadeken, and W. Madigan, "Dalhart Post Shot Investigation," in *Proceedings of the Fourth International Symposium of the Minerals and Geotechnical Logging Society, Toronto, Canada, August 1991*, (Society of Professional Well Log Analysts, Houston, Texas, 1993).

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