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

October 1, 1994 – September 30, 1995

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October 1, 1994 – September 30, 1995

Joseph L. Thompson

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EXECUTIVE SUMMARY

Los Alamos is a principal participant in the Hydrologic Resources Management Program (HRMP), a multi-organizational program sponsored by the US Department of Energy/Nevada Operations office. Los Alamos personnel provide expertise in field-scale engineering and testing, in explosive technology, and in chemical and earth sciences. Currently, our research has been focused on evaluating the environmental consequences of nuclear weapons testing at the Nevada Test Site (NTS). We are characterizing the physical and chemical forms of test-related radionuclides, determining their distribution in the cavity and chimney formed by the explosion, and evaluating movement of radioactive material with groundwater. This work has important implications for the NTS weapons and environmental restoration programs and for the Yucca Mountain Project. We have published our work in a series of Laboratory reports and articles in the open literature. This report covers work done during FY 1995.

Our work has been seriously impacted by budgetary cuts at the Laboratory and at the Department of Energy. Whereas in past years we benefited from facilities and personnel supported by large programs such as weapons testing, we can no longer rely on such indirect assistance. Much of our field work requires access to radionuclides deeply buried at the NTS, but without assistance, our program cannot support alone drilling or even extensive pumping operations. It is clear that unless new sources of funding are found, our field studies will have to be severely curtailed. Our research program has yielded information of interest and importance to other groups, and we maintain ties with colleagues in the NTS Underground Test Area Operable Unit and in the Yucca Mountain Project. We also consult with organizations such as the US Geological Survey and have provided assistance to students and faculty for studies at universities in California and Nevada. Cooperation with Lawrence Livermore National Laboratory personnel for field work at the NTS has been particularly beneficial to both laboratories.

Part of our mission is to aid the development of improved procedures and equipment for field operations at the NTS. In this report we illustrate the utility of high-sensitivity gamma logging in drill-back holes to locate regions for side-wall sampling for nuclear debris. We also report on the modification and field testing of a bailer which enables us to sample water that has a high particulate content. This modification proved so successful that we are applying it to more bailers; an engineering drawing is attached as Appendix B of this report so that others may benefit from our work.

Groundwater contamination by radioactive material and the movement of radionuclides with groundwater are major concerns at the NTS. We are serving as consultants on a research project to model the transport of colloids labeled with the fission product ^{137}Cs through geomedial.

This is a laboratory study, financed by the Yucca Mountain Project, that may increase our understanding of colloid transport of radionuclides away from nuclear test cavities. We also are assisting in an effort to model the observed elution of ^{85}Kr from the pumped well at the Cambric site. This work has produced a novel hypothesis which suggests that tritium and inert gases may be differently distributed around some nuclear test sites because of CO_2 generation. If this hypothesis can be validated, there are implications for the distribution of other gaseous materials during formation of nuclear test cavities and chimneys and for their subsequent availability for transport with groundwater.

This year we completed our analysis of 48 solid samples recovered during the drill-back into the BASEBALL nuclear test cavity. These samples provide a unique opportunity to determine the spatial distribution of radionuclides in the cavity and chimney of a nuclear test. We found that there was extreme heterogeneity in these materials. However, collectively there was a pattern of separation between more volatile and more refractory elements. Of particular significance was our observation that even the most mobile radionuclides (e.g., tritium as water) appear to have maintained a distribution pattern established at or shortly after the time of the nuclear event, even though the cavity refilled with water many years ago. If this interpretation of the data is correct, it suggests that migration of radionuclides away from this site is not occurring. The cavity is in layered tuff of low hydraulic conductivity and there are minimal hydraulic gradients. It is obviously important to know if there is no migration of radionuclides from BASEBALL and whether similar situations occur elsewhere at the NTS.

Whenever possible, we attempt to collect water from nuclear test cavities so that we can measure the hydrologic source term (*i.e.*, those radionuclides present in a form which can be transported in groundwater). During the summer of 1995, we collaborated with Lawrence Livermore National Laboratory personnel in water sampling at two sites. In both cases, access to the cavity or chimney was through 7.3-cm OD tubing. The water in the tubing was stagnant and heavily contaminated with drilling fluids. At site U-4u ps2a we attempted to clear the hole by air-lifting the water to the surface, but were unable to do so. Apparently, the formation at this site is too porous and the water head in the tubing is too small for this technique to work, and we had to abandon our sampling effort. At U-7ba ps1as (the BASEBALL site), we utilized our modified bailer to successfully sample the entire water column. Our analyses of the collected material verified the large extent of contamination by drilling fluids. The tubing in this hole has the stator of a Moyno pump in place and we hope to secure funding to insert a rotor and pump out the stagnant water so we can take samples representative of the water in the cavity.

LABORATORY AND FIELD STUDIES RELATED TO THE HYDROLOGIC RESOURCES MANAGEMENT PROGRAM

October 1, 1994–September 30, 1995

by

Joseph L. Thompson

ABSTRACT

In this report we describe the work done at Los Alamos National Laboratory in FY 1995 for the Hydrologic Resources Management Program funded by the US Department of Energy/Nevada Operations office. Budgetary cuts have required us to scale back our activities, particularly field work at the Nevada Test Site. We have collaborated with a number of government agencies and universities in work related to radionuclide migration through geologic media. In cooperation with Lawrence Livermore National Laboratory, we have demonstrated the utility of high-sensitivity gamma logging and have successfully improved the design of a bailer routinely used for water sampling. We analyzed a suite of side-wall samples from the BASEBALL drill-back and have interpreted the distribution pattern of test-related radionuclides. Though heterogeneously distributed, they show a general separation of volatile and refractory fractions. The distribution pattern suggests that there has been little movement of radioactive material within this cavity, which is 13 years old and below the static water level. This characterization of the BASEBALL cavity/chimney complex may have important implications for radionuclide migration elsewhere at the Nevada Test Site.

I. INTRODUCTION

In 1973, the US Department of Energy/Nevada Operations office (DOE/NV) began sponsorship of a research program evaluating the environmental impact of underground nuclear testing at the Nevada Test Site (NTS). Los Alamos National Laboratory has participated in this program since its inception; other principal organizations involved are the Lawrence Livermore National Laboratory (LLNL), the US Geological Survey (USGS), and the Desert Research Institute (DRI). This research program is now called the Hydrologic Resources Management Program (HRMP). Los Alamos personnel have contributed their expertise in earth and chemical sciences, in explosive technology, and in field scale engineering and testing. Since the end of nuclear weapons testing in 1992, we have concentrated on studying the consequences of having deposited large quantities of fission products, nuclear fuel elements, and neutron activation products in the underground environment of the NTS. In particular, we wish to determine the physical and chemical characteristics of test-related radionuclides, their distributions in the immediate vicinity of the explosion cavity, and the probability of their transport with groundwater. This knowledge base is essential for several DOE/NV programs: the weapons program, which is responsible for groundwater stewardship and for future uses of the NTS; the environmental monitoring and remediation program, which must decide what remediation efforts are appropriate; and the Yucca Mountain Project, which is evaluating a site on the western edge of the NTS for a nuclear waste repository. Los Alamos contributions to HRMP research have been detailed in annual reports¹⁻¹⁸, in topical summary reports,¹⁹⁻²³ and in journal articles.²⁴⁻³⁴ The present report describes our work for FY 1995. The report is organized into the four traditional sections: program coordination and technical support, operational support, groundwater protection, and groundwater monitoring.

II. PROGRAM COORDINATION AND TECHNICAL SUPPORT

Program coordination involves the usual management functions internal to the Laboratory (budgeting, equipment and supply management, personnel administration, regulatory compliance) as well as interfacing with other organizations internal and external to Los Alamos. Technical support includes providing data and expertise to other participants in the HRMP and to other DOE programs. During the past year Los Alamos has experienced loss of budgetary support and personnel down-sizing. This has impacted the HRMP because we are dependent on the Laboratory infrastructure for support functions. We must now contribute HRMP funds to stockroom maintenance, counting room equipment and personnel support, and computer system support in addition to the usual group and division overhead. Also, about mid-year, the HRMP budget was reduced 10% by the DOE. We have consolidated our laboratory operations so that we occupy about 30% less space

and we have discarded a large number of 55-gallon barrels containing water samples archived from the NTS (thus reducing storage costs). We hold fewer HRMP meetings which require travel and rely more on e-mail and conference calls for sharing information. The most critical impact of declining budgets, however, is on our ability to do field work. Support for contractors at the NTS as well as for Los Alamos field testing has diminished considerably, and our program can no longer "piggy-back" on field operations largely paid for by other activities. Currently, only the Underground Test Area Operable Unit (UGTA OU) program is doing any drilling at the NTS. The HRMP participants, singly or in concert, cannot finance a drilling operation. Unless the funding situation improves, we will all be constrained to relatively less expensive field sampling of existing holes and to laboratory experimentation.

Whenever possible, Los Alamos HRMP personnel work cooperatively with other organizations and programs. We have close ties with the UGTA OU program through participation in their information exchange meetings and membership in their technical working group. We consult regularly with Los Alamos personnel in the Yucca Mountain Project. We are working with Dave Sawyer (USGS geologic division, Denver) to review data from the Cheshire event on Pahute Mesa. Finally, we continue to work with Professor James Hunt and students (UC Berkeley) to explain the movement of ^{85}Kr during the pumping experiment at the Cambrian site. The technical aspects of these programs and their relevance to the HRMP is given below in the appropriate sections of this report. In Appendix A we have listed meetings related to HRMP work and publications produced during the past year as a product of this program.

III. OPERATIONAL SUPPORT

We seek to develop and apply new techniques for solving specific problems in NTS operations. For example, we have championed the use of a high-sensitivity, small-diameter logging tool to locate radionuclides in drill holes adjacent to or within nuclear test cavities. The successful use of this tool is described in our discussion of the BASEBALL drill-back in Section IV of this report.

During the past year we designed and tested a modification of the stainless steel pressure tubes (bailers) used for many years in this program to collect water samples down hole. The pressure tube is evacuated and lowered by a wire line into the hole being sampled; an electrically driven valve is opened and closed at the desired depth. The problem with the original design is that the inlet orifice of the tube tends to clog if the water being sampled has an appreciable loading of particulates. Sixto Maestas, an experienced Los Alamos HRMP member, designed a modification of the pressure tube that included the drilling of larger ports and the fabrication of a new plug. The engineering drawing for this new design is included in Appendix B of this

report. In July, 1995, we field tested a modified bailer in the access tube at the BASEBALL site (for a detailed description of this site, refer to Section IV of this report). Previous attempts at sampling water there had been frustrated because the large amounts of drilling mud suspended in the fluid in the access tube clogged the inlet port of the bailer. With the modified bailer we were able to sample the column of fluid from top to bottom. Partial clogging of the inlet port occurred only at the bottom of the column where the particulate loading in the fluid was over 100 g/l. Based on this success, we are modifying more pressure tubes. At this writing, a machinist at the NTS, Linda Land, is working on four pressure tubes—two each from LLNL and Los Alamos. We expect to use these for water sampling at sites where the water contains significant amounts of solids.

IV. GROUNDWATER PROTECTION

At the NTS, some groundwater has been contaminated with radionuclides as a consequence of nuclear weapons testing; more may become contaminated as radionuclides move through the geosphere. We are attempting to learn more about the spatial distribution of radionuclides in the cavity/chimney region at a nuclear test site, about the physical and chemical forms of these materials, and about mechanisms by which they may move through the geosphere. During the past year we have been involved in projects addressing all three of these topics.

A. Colloid Transport

One means by which radionuclides may move in the underground environment is colloid transport. The radioactive material may comprise the whole colloid, or only be sorbed on the colloid surface. The colloid moves with flowing groundwater. A pre-doctoral student at Los Alamos has been studying the flow of glass colloids labeled with ^{137}Cs through columns of glass beads. The intention of this study is to validate a mathematical model of colloid transport in this simple laboratory system, then to apply the model to colloid transport in NTS geomedium. Los Alamos HRMP personnel are assisting in an advisory capacity only; the work is paid for by the Yucca Mountain Project.

B. Groundwater Transport

We know from many years of study at the CAMBRIC site that ^{85}Kr is transported with groundwater when it is pumped away from the cavity and chimney region. However, the elution pattern of the krypton differs from that of tritium.²² Professor James Hunt and students at UC Berkeley have hypothesized that the ^{85}Kr was distributed differently than the tritium because of the effect of carbon dioxide gas generated from carbonate rock at the time of the nuclear explosion. They are attempting to use the code TRACR3D to

model the elution of the krypton from the pumped well (RNM-2S) assuming this different initial distribution pattern. The Los Alamos HRMP is the source of the data for these studies and our personnel are serving in an advisory capacity. The work is funded by the Los Alamos Cooperative Research (LACOR) program.

C. Radionuclide Distribution in a Nuclear Test Cavity

The movement of radionuclides away from a nuclear test cavity and chimney may be influenced by the distribution within these regions as well as by the chemical and physical state of the radioactive materials. Last year we reported¹⁸ on studies we conducted at the BASEBALL site. We have now completed our analyses of materials returned from that site and can present a full report of our work there.

1. Introduction. When a nuclear explosion occurs underground, the cavity is initially filled with vaporized material derived from rock, nuclear fuel, fission products, and device construction materials. As the region cools, some of this material condenses to the liquid and then to the solid state and is concentrated in the bottom of the cavity as an obsidian-like glass known as "shot glass." Refractory radionuclides are concentrated in the shot glass. More volatile radionuclides end up coating the surfaces of the cavity and may penetrate fractures in the cavity walls. This initial separation of more volatile and more refractory material is disturbed when the cavity collapses, mixing together materials with differing volatilities. Material separation may be further perturbed if water re-enters the cavity region, because some radionuclides are more soluble than others and may preferentially dissolve and leach out of their original deposition sites. The phenomena controlling radionuclide distribution in the post-shot environment are discussed by Borg³⁵ and, more recently, by Smith.³⁶

Most drill-backs into nuclear test cavities have been done in order to obtain shot glass for diagnostic purposes rather than to measure radionuclide distributions. However, we do have limited information on vertical distributions of tritium and fission products in a few sites at the NTS. These data were acquired in recent years during drill-backs and were based on only a few measurements at each site.¹⁴⁻¹⁶ In mid-1994, the cavity produced by the nuclear test BASEBALL (U-7ba) in the Yucca Flat area of the Nevada Test Site (NTS) was re-entered. Since the BASEBALL test took place in 1981, all short-lived radionuclides produced had decayed and there was not the usual urgency to collect debris in a minimum time. A re-entry hole, U-7ba ps1a, and a sidetrack, U-7ba ps1as, were drilled. After gamma logs were taken to locate regions of radioactivity, 71 side-wall samples were collected. These materials are the source of the information presented in this paper. The sidetrack hole was completed by inserting an access tube so that in the future water samples can be collected by bailing or pumping.

2. The BASEBALL Site. Information pertaining to the emplacement hole, U-7ba, and to the drill-back holes, U-7ba ps1a and U-7ba ps1as, is tabulated below. Note that depths throughout this report (unless otherwise indicated) are the *measured* depths along the slant axis of the holes.

Table I. Drill Holes at the U-7ba Site

U-7ba

location	NV coordinates N259466m, E207691m
drill date	1980
drill depth	609.6 m
diameter	1.2 m
depth of burial (DOB)	563.9 m vertical
detonation	January 15, 1981
announced yield	20 - 150 kT
depth static water level (SWL)	512 m vertical
geologic medium at DOB	Tunnel bed tuff (<20% montmorillonite; 17 - 21% water by weight)

U-7ba ps1a

location	NV coordinates N259576m, E207898m (~235 m NE of U-7ba)
drill date	June 6-8, 1994
drill depth	711 m (665 m vertical depth)
diameter	25 cm

U-7ba ps1as

location	same as U-7ba ps1a
drill date	June 13-15, 1994
drill depth	same as U-7ba ps1a
diameter	same as U-7ba ps1a
separation from U-7ba ps1a	6 m @ 585 m depth; 9 m @ 620 m; 12 m @ 655 m
inserted tubing	7.3 cm carbon steel, slotted @ 603 m depth, cemented from 345 m to surface, stator for Moyno pump in place

3. Logging and Sampling. During the drilling of the first re-entry hole, U-7ba ps1a, drilling was stopped at approximately the working point depth in order to measure radiation levels in the upper part of the cavity. A high-sensitivity

396 m to 588 m. Figure 1 is the lower section of this gamma log; it shows the presence of gamma-emitting radionuclides in the upper cavity and chimney regions. No appreciable gamma activity was detected higher than about 540 m in the U-7ba ps1a hole (i.e., about 504 m vertical depth). After the hole was drilled to its final depth, samples were collected from the bottom cavity region as is the usual procedure in drill-back operations. In addition, seven more samples were taken from the upper cavity using the gamma log as a guide. Sampling was done using a Hunt side wall tool which scrapes material into a retrievable shoe and generally delivers about 120 g of material per sampling run.

Fig. 1. Gamma log of a part of U-7ba ps1a.

After the second re-entry hole, U-7ps1as, was drilled, a gamma log was taken with a tool somewhat less sensitive than the Haliburton tool. In this case, the log was run from about 366 m to 688 m. The portion of this log showing gamma activity associated with residues from the nuclear test is displayed in Fig. 2. Using the log as a guide, side-wall samples were taken with the Hunt tool from the bottom of the hole to the uppermost region with gamma activity. Figure 3 illustrates the positions of the two re-entry holes and the sampling locations. Note that all samples were from the rubble-filled zone of the cavity and lower chimney and were taken below the static water level (SWL).

Fig. 2. Gamma log of a part of U-7ba ps1as.

Fig. 3. U-7ba ps1a and ps1as re-entry holes. The crosshatched area depicts the approximate boundaries of the cavity and lower chimney.

4. Sample Analysis. The Hunt tool discharged samples into plastic bags that were taped shut and transported to the Laboratory for analysis. The water content in these samples varied considerably; some samples were nearly dry while others were a heavy, viscous mud. At the Laboratory, a number of samples were selected for chemical analysis to obtain weapon diagnostic information. The remaining 48 samples are the material on which this report is based.

Each sample was dried in a vacuum apparatus and the water collected in an ice-cooled trap. Aliquots of the water were counted (in duplicate) in a liquid scintillation counter (Packard, Model 4530) using Ultima Gold (Packard) cocktail to determine the tritium content. The dried samples were broken up into a coarse powder and 30-gram aliquots taken for gamma counting on a calibrated germanium detector. The gamma spectra were analyzed using a computer code (GAMANAL) that reports the activity per gram of each radionuclide corrected back to the shot time (January 15, 1981). The precision of the counting data ranged from about 1% standard deviation for the more abundant radionuclides to 10% for those in lower concentrations.

5. Results and Discussion. The analytical data are given in Table II for tritium and in Table III for gamma-emitting radionuclides. These data are also displayed in as a series of graphs (Figs. 4-11) in which we compare the distribution patterns of tritium and gamma-emitting radionuclides in both re-entry holes. Several characteristics of these data stand out. One characteristic is the extreme variability of radionuclide content in samples taken close to one another or even at the same depth. For example, three samples were collected from 572 m, and the Cs-137 content varies by more than three orders of magnitude in this set (Table III and Fig. 6). Note that in the same sample set, the Co-60 varies only by a factor of 3 (Table III and Fig. 8). These variations are in the radionuclide content of the samples; they far exceed any possible lack of precision in counting or weighing. It appears that we withdrew samples from an environment in which there were extreme differences in concentrations of radionuclides over intervals as small as a meter. There is no control over the orientation of the shoe of the Hunt tool, so samples collected from the same nominal depth may contain material from different sides of the borehole. Another indication of the varying radionuclide content is seen in the gamma spectra; large changes in radiation levels occur over narrow depth intervals. All these data are consistent with our picture of the cavity after it is filled with rubble from collapsed walls and ceiling. The radionuclides initially contained in the melt glass at the bottom of the cavity or condensed on the cavity walls or uniformly distributed in the cavity as gases are chaotically mixed as the cavity collapses.³⁶ Consequently, the disposition of radionuclides in the underground environment in the cavity region is very heterogeneous. Despite this heterogeneity, there are patterns of distribution for particular radioactive materials. The refractive

element europium is largely concentrated in the shot glass and not found in appreciable concentrations elsewhere. In contrast, tritium and Cs-137 are much more widely distributed. Both these materials are volatile (Cs-137 is the result of a series of radioactive decays of volatile parent radionuclides, including the noble gas Xe-137, half-life = 3.8 min.) and are found in the highest concentrations at locations outside the region of the melt glass. The general pattern of distribution is that refractory elements are largely confined to melt glass and volatile elements are broadly distributed.

Several of the radionuclides identified (Ba-133, Eu-152, Eu-154) were activation products produced in relatively small amounts; these were detectable only in the region of highest concentration. Cs-134 (half life 2 y) was detectable only in the region of its highest concentration because radioactive decay had progressed to the point that there was little of this material left. The distribution of Sb-125 is almost as broad as that of Cs-137; this would be expected since it and its precursors are relatively volatile. But Sb-125 has a half-life of 2.8 y so its initial concentration has decreased considerably over the 13 y time span between the nuclear test and the drill-back, and there is little Sb-125 present now. Cobalt-60 is an activation product with a 5.3 y half-life. It is largely concentrated in the melt glass, but is also found at very low concentrations in samples taken well above the bottom of the cavity. The favorable half-life and high-energy gamma rays from this radionuclide make for relatively low detection limits.

Table II. Activity of Tritium in Re-entry Holes

Sample #	Depth (m)	Wt. Analyzed (g)	% Water	H-3 (Bq/ml)	H-3 (Bq/ml) @ 15% Water
U-7ba ps1a					
45	559	31.07	15	9.15E+2	9.15E+2
44	559	25.45	34	3.62E+2	8.20E+2
43	570	29.63	20	2.62E+3	3.48E+3
40	572	31.22	20	2.97E+2	3.95E+2
39	572	30.69	8	2.42E+2	1.29E+2
38	572	27.88	66	1.95E+2	8.58E+2
37	582	30.17	36	5.10E+3	1.22E+4
28	659	35.83	25	2.22E+3	3.70E+3
27	659	38.14	18	1.73E+3	2.03E+3
18	662	35.53	11	2.32E+3	1.70E+3
17	663	33.47	14	4.22E+3	3.94E+3
16	664	34.55	16	3.45E+3	3.68E+3
15	664	17.85	0		
14	667	29.84	26	2.21E+3	3.83E+3
13	665	36.31	12	3.84E+3	3.07E+3
12	665	34.59	20	3.00E+3	4.00E+3
11	666	35.71	5	3.03E+3	3.03E+3
10	667	33.19	7	3.05E+3	1.42E+3
9	668	35.03	18	2.43E+3	2.92E+3
8	668	32.01	14	2.16E+3	2.02E+3
7	669	37.74	23	7.90E+2	1.21E+3
6	670	33.54	14	1.91E+3	1.78E+3
5	670	32.25	18	1.27E+3	1.52E+3
4	671	34.91	13	2.28E+3	1.98E+3
3	671	34.02	19	1.28E+3	1.62E+3
2	672	31.02	11	8.20E+2	6.01E+2
1	677	27.58	42	3.94E+2	1.10E+3
U-7ba ps1as					
71	588	27.46	13	7.32E+3	6.34E+3
70	590	24.09	36	1.44E+3	3.46E+3
69	615	28.64	19	2.03E+3	2.57E+3
68	623	25.01	49	3.02E+3	9.87E+3
67	627	25.52	18	6.70E+3	8.04E+3
66	632	27.07	39	1.92E+3	4.99E+3
65	638	26.01	16	4.95E+3	5.28E+3
64	639	29.55	15	5.02E+3	5.02E+3
63	643	29.8	14	3.85E+3	3.59E+3
61	649	28.31	19	4.53E+2	5.74E+2
60	650	28.89	20	6.72E+2	8.96E+2
59	650	27.37	2	2.62E+2	
57	654	26.36	18	4.93E+2	5.92E+2
55	655	29.42	18	2.57E+2	3.08E+2
54	657	29.55	20	4.10E+2	5.47E+2
53	657	30.44	21	8.52E+1	1.19E+2
51	658	33.36	17	9.65E+1	1.09E+2
50	659	32.2	23	7.07E+1	1.08E+2
48	660	27.74	18	5.45E+2	6.54E+2
47	669	29.65	25	2.02E+2	3.37E+2
46	674	31.82	15	3.40E+1	3.40E+1

Table III. Activity of Gamma-emitters in Re-entry Holes

Sample #	Depth (m)	WT. (g) Analyzed	Cs-137 (Bq/g)	Sb-125 (Bq/g)	Eu-155 (Bq/g)	Co-60 (Bq/g)	Cs-134 (Bq/g)	Eu-152 (Bq/g)	Eu-154 (Bq/g)	Ba-133 (Bq/g)
psla										
45	559	31.07	8.60E-2			8.00E-2				
44	559	25.45	2.50E-1			3.20E-1				
43	570	29.63	1.13E+0			7.00E-2				
40	572	31.22	3.73E+1			5.00E-2				
39	572	30.69	1.00E-2			4.00E-2				
38	572	27.88	6.60E-2			1.20E-1				
37	582	30.17	2.20E-1			8.00E-2				
28	659	35.83	8.46E+1	2.71E+2	1.70E+2	2.75E+2	4.30E+1	4.40E+0	3.90E+0	
27	659	38.14	8.57E+1	3.00E+2	1.80E+2	3.77E+2	5.29E+1	5.50E+0	4.60E+0	2.40E-1
18	662	35.53	6.80E+0	3.60E+1	8.40E+0	2.80E+1	5.40E+0	7.70E-1	4.90E-1	
17	663	33.47	2.54E+0	1.30E+1	5.20E+0	1.53E+1	2.80E+0	8.20E-1	2.90E-1	
16	664	34.55	5.50E-1	5.90E+0	1.20E+0	3.24E+0	T	8.40E-1	1.00E-1	
15	664	17.85	1.43E+1	5.22E+1	3.40E+1	9.28E+1	2.10E+1	2.40E+0	1.80E+0	1.20E-1
14	667	29.84	4.48E+0	1.72E+1	9.10E+0	2.16E+1	5.20E+0	7.90E-1	5.20E-1	
13	665	36.31	7.54E+0	2.49E+1	1.25E+1	2.81E+1	6.30E+0	1.40E+0	5.30E-1	
12	665	34.59	3.17E+0	7.30E+0	4.10E+0	7.07E+0	1.43E+0	2.50E-1	9.00E-2	
11	666	35.71	7.74E+0	1.57E+1	7.00E+0	1.30E+1	2.50E+0	4.60E-1	2.20E-1	
10	667	33.19	1.69E+1	6.56E+1	3.00E+1	7.60E+1	1.30E+1	1.40E+0	1.10E+0	7.00E-2
9	668	35.03	5.63E+1	1.62E+2	1.00E+2	2.15E+2	3.00E+1	2.70E+0	2.90E+0	2.00E-1
8	668	32.01	9.80E-1	2.40E+0	1.40E+0	2.77E+0	T	7.00E-2	5.00E-2	
7	669	37.74	1.89E+1	6.94E+1	3.50E+1	9.74E+1	2.00E+1	2.40E+0	1.40E+0	
6	670	33.54	4.04E+0	1.03E+1	7.20E+0	1.56E+1	3.30E+0	2.00E+0	3.60E-1	
5	670	32.25	2.12E+0	5.00E+0	2.90E+0	4.61E+0	T	9.20E-1	1.20E-1	
4	671	34.91	2.91E+1	1.18E+1	1.41E+1	2.31E+1	3.80E+0	2.80E-1	3.10E-1	
3	671	34.02	6.30E+0	9.55E+0	6.30E+0	9.71E+0	1.40E+0	1.20E-1	1.40E-1	
2	672	31.02	2.49E+0	4.90E+0	4.00E+0	5.99E+0	T	7.00E-2	8.00E-2	
1	677	27.58	1.29E+1	1.99E+1	1.80E+1	2.82E+1	3.90E+0	3.20E-1	3.80E-1	
pslas										
71	588	27.46	4.45E+0	1.63E+1		1.50E-1				
70	590	24.09	3.27E+0	1.00E+0		2.00E-1				
69	615	28.64	1.01E+2	1.00E+1		3.80E-1				
68	623	25.01	1.80E-1	1.50E+0		3.00E-1				
67	627	25.52	5.10E-1	9.20E+0	5.00E-1	7.90E-1				
66	632	27.07	1.77E+1	4.21E+1	6.00E-1	1.55E+0				
65	638	26.01	2.13E-1	6.80E+1	3.10E-1	4.90E-1				
64	639	29.55	7.90E-1	8.30E+1	7.60E-1	1.07E+0				
63	643	29.8	2.72E+3	5.88E+2		7.79E+1				
61	649	28.31	2.45E+0	8.00E-1	5.00E-1	6.60E-1				
60	650	28.89	4.60E-1	1.40E+0	8.40E-1	1.28E+0				
59	650	27.37	6.90E-1	3.00E+0	1.80E+0	2.69E+0				
57	654	26.36	3.05E+2	4.17E+2	3.11E+2	5.93E+2	7.70E+1	5.30E+0	6.70E+0	
55	655	29.42	1.97E+1	6.20E+0	2.40E+0	4.15E+0		8.00E-2		
54	657	29.55	9.54E+0	1.52E+1	8.75E+0	1.43E+1	1.90E+0	1.40E-1	1.60E-1	
53	657	30.44	6.30E+1	1.19E+2	6.30E+1	1.34E+2	1.90E+1	9.30E-1	1.20E+0	
51	658	33.36	2.59E+1	5.80E+1	4.74E+1	7.85E+1	9.90E+0	1.40E+0	1.00E+0	
50	659	32.2	9.65E+1	3.32E+2	2.26E+2	3.59E+2	4.90E+1	4.70E+0	4.80E+0	
48	660	27.74								
47	669	29.65				5.00E-2				
46	674	31.82	5.00E-2			4.00E-2				

T = Trace

Fig. 4. Tritium distribution in U-7ba ps1a

Fig. 5. Tritium distribution in U-7ba ps1as

Fig. 6. Cs-137 and Sb-125 distribution in U-7ba ps1a

Fig. 7. Cs-137 and Sb-125 distribution in U-7ba ps1as

Fig. 8. Eu-155 and Co-60 distribution in U-7ba ps1a

Fig. 9. Eu-155 and Co-60 distribution in U-7ba ps1as

Fig. 10. Cs-134, Eu-152, Eu-154 and Ba-133 distribution in U-7ba ps1a

Fig. 11. Cs-134, Eu-152 and Eu-154 distribution in U-7ba ps1as

It is particularly remarkable that these radionuclides appear to have remained in patterns established at the time of the nuclear test. Even tritium, present in the form of water, preserves a distribution pattern such that large concentration differences exist over narrow intervals both vertically and horizontally. As an exercise, we tried to calculate the concentrations of tritium without dilution effects by the free water captured with the samples. The preshot water content of the Tunnel Bed tuff was 17 - 21% by weight. Our samples rarely were less than 15% water. If we assumed any water in excess of this amount was free water introduced during drilling and re-calculated our tritium concentrations, a few changed considerably, but we were still left with large concentration differences in samples taken close together (see Table II). We do not see evidence of homogenization of tritium such as would be expected if this radionuclide were diffusing around its original deposition site. Thus, over a 13 y time span there seems to have been little vertical or horizontal migration of tritium--the most mobile radionuclide present. At this site there may be no mechanism for radionuclides to migrate, since there are no appreciable hydraulic gradients³⁷ and the hydraulic conductivity is low.³⁸ Apparently, local convective water movement in the (initially) hot cavity after refilling did not result in homogenization of source material. Our observations are consistent with the hypothesis that at this site the radioactive materials have remained where they were deposited during the formation of the cavity and chimney.

6. Implications for the NTS. The information we have obtained from the BASEBALL drill-back holes does not prove that radionuclides have not migrated away from this site. It would be necessary to drill a number of other wells close to the cavity/chimney to establish unequivocally that migration has not occurred. But the existence of sharp concentration gradients within the cavity region strongly suggests that radionuclide movement is minimal. Taken in context with other data collected at the NTS, the BASEBALL study offers further evidence that extensive migration of radioactive material away from underground nuclear test sites does not occur in the absence of appreciable groundwater movement. We know from studies conducted at the CAMBRIC site that tritium, ⁸⁵Kr (a noble gas), and certain anionic species can be induced to move by pumping large volumes of water away from the cavity region.²² We also have evidence for radionuclide movement by other mechanisms (prompt injection and colloid transport) at a few locations on the NTS.²³ The BASEBALL data provide insight about the radionuclide distribution in the cavity/chimney complex of a nuclear test conducted in a location without much groundwater movement. In this situation, the distribution pattern established by the time of the chimney collapse appears to be preserved for many years. As we drill into and near more nuclear test cavities with other groundwater characteristics, we will build a data base sufficient to support confident predictions about what conditions are

necessary for radionuclide movement through the underground environment at the NTS. This will enable us to assess the risk associated with such movement and to design strategies to minimize the impacts to our environment of past nuclear testing. Information about radionuclide transport in this setting may also help in determining the suitability of Yucca Mountain on the western edge of the NTS as a repository for nuclear waste.

V. GROUNDWATER MONITORING

The inventory of radionuclides at a particular nuclear test site (*i.e.*, the radiologic source term) can generally be determined with fair accuracy.³⁹ What is very difficult to predict, and what has rarely been measured in the field, is the hydrologic source term—the amount of radioactive material which is available for transport with moving groundwater. There are many problems in drilling into an expended test cavity and retrieving water samples which are representative of formation water in the cavity/chimney region. The HRMP seeks every opportunity to measure hydrologic source terms at the NTS. During the past year, Los Alamos personnel participated in efforts to obtain water from the cavity or chimney at two drill sites. These attempts are described below.

A. U-4u ps2a

In May, 1995, Los Alamos personnel made an attempt to extract enough water from U-4u ps2a to clean the hole of stagnant water left over from the drilling operation. We planned to then collect enough water to fully characterize any radionuclides present in water at the depth penetrated by the access tubing (the lower chimney region). Water had been sampled in U-4u ps2a in 1992 and 1993 using our pressurized bailers.^{16,17} Two things were apparent about these samples: the radionuclide content was not changing with time and there was a large amount of drilling fluid present. It was obvious that the water in the tubing would have to be removed if we were to obtain water samples representative of formation water. We spent some time calling manufacturers and talking with drilling personnel at the site in the hope of locating a pump small enough to fit into the 7.3-cm OD casing and powerful enough to lift water about 550 m. This quest was unsuccessful, but we were assured that it would be possible to air lift (jet) the water out, and we proceeded on the assumption that this method would work at this site as it had at many other locations on the NTS. On May 31 the Cardwell 100 drill rig was set up at U-4u, and on June 1 small diameter (4.1- to 4.8-cm) tubing was inserted into the hole to 538 m measured depth (about 1 m off the bottom of the 7.3-cm casing). The bottom joint of the tubing string was a bull nose with 4 holes (~ 1.3 cm diameter) oriented so that exiting air would be directed upward. Three compressors were available to pump air into the inner tubing and water jetted to the surface was to be contained in a Baker tank. We turned

on the compressors near the end of the day and ran them for about 20 minutes. No fluid was brought to the surface. On June 5 the LLNL logging team ran a probe inside the inner tubing and confirmed that the water level was about 495 m—the expected height. On June 6 we tried several variations of air pressure and water additions to the annulus in an effort to get the air lifting process initiated. Nothing worked, and we again asked for logging support from LLNL. We discovered that adding as much as 1 m³ of water per minute to the annulus did not raise the water level within the inner tubing. Furthermore, it became obvious that only a fraction of the air sent down the hole was returning to the surface through our casing. Apparently the formation was sufficiently transmissive that additions of water or air simply dispersed out into the formation. We tried one last time to trigger jetting in the hole; we raised the jets so that they were just above the uppermost slots in the 7.3-cm casing. This left about 6 m of water head in the annulus; we could not raise it to the surface. Our sampling efforts at U-4u were then terminated; the rig was demobilized on June 7.

There are several lessons to be learned from our experience at U-4u. One is that the completion of drill-backs with 7.3-cm casing is a poor procedure if there is an intent to do future water sampling at the site. We have learned from our sampling at other locations (UE-3e#4 especially¹⁵) that the water in tubing of this size does not circulate and remains contaminated with drilling fluids. The small diameter of the tubing makes pumping impossible, save with a Moyno pump. Our experiences with this type of pump have been less than satisfactory and it appears that it is not useful for sustained sampling operations. If water sampling is to be part of the long-term use of drill-back holes, the holes should be completed with tubing large enough to permit insertion of a positive displacement pump.

Another lesson learned (in hindsight) is that we might have anticipated that the formation at U-4u would be very fractured and transmissive. A test of the hydraulic response of the hole would probably have indicated that air-lifting water would not be feasible at this site. Even often-used and proven techniques may not be applicable at particular sites!

B. U-7ba ps1as

We have described the modification of an HRMP bailer in Section III and the layout of the BASEBALL site in Section IV. On July 19, 1995, a team of Los Alamos and Livermore laboratory personnel sampled water from the BASEBALL site with the modified bailer. As mentioned previously, we were able to collect samples from the surface of the water down to the top of the Moyno stator. The modified bailer worked well; clogging of the ports occurred only for the deepest sample after the bailer was partly filled. We observed that the bailer always picked up appreciable amounts of grease as it rubbed along

the tubing walls during entry and retrieval. This suggests that the tubing contains enough grease to contaminate water samples with hydrocarbons, so analysis for organics in water withdrawn from the tubing will not be meaningful. The collected water samples were split between the two laboratories. The data in the tables below are from the Los Alamos splits. We distilled enough water from each sample to measure the tritium content, then dried the sample and measured the gamma activity on a Ge counting system.

Table IV. Water Samples from U-7ba

Measured Depth (m)	Volume Analyzed (ml)	Dry Weight (g)	Particulate Loading (g/ml)
366	200	0.42	2.1E-3
427	915	87	9.5E-2
488	855	80	9.4E-2
549	680	36	5.3E-2
584	295	33	1.1E-1

Table V. Sample Activities (at $t_0 = 1/15/81$)

Measured Depth (m)	H-3 (Bq/ml)	Cs-137 (Bq/g)	Co-60 (Bq/g)	Sb-125 (Bq/g)	Eu-155 (Bq/g)
366	4.6E2	1.6E0			
427	6.4E2	2.6E1	4.2E1	3.9E1	2.4E1
488	8.2E2	3.8E1	6.6E1	5.9E1	3.8E1
549	1.9E3	3.3E1	4.2E1	4.5E1	2.4E1
584	3.6E3	6.2E1	1.2E2	1.1E2	7.2E2

In addition to the more abundant radionuclides listed in Table III, we detected smaller amounts of other isotopes. Europium-152 and Eu-154 were in all samples save that from 366 m. Cesium-134 was present in samples from 488 m, 549 m, and 584 m. And in the sample from 584 m, Ba-133 was detected at trace level. Thus, even in these small-volume water samples, we were able to identify all of the radionuclides found when the drill-back holes were made in 1994. The important question remaining is "How are the radionuclides distributed between the aqueous and solid phases in the cavity/chimney region?" The samples we collected with our bailer were from essentially stagnant material that has had little communication with

formation water since the time the tube was cemented in place. Any circulation of water would have to take place through the slotted screens and up through the Moyno stator; we believe this circulation is minimal. Until we can install rotors and use the Moyno pump to clear out the stagnant material in the tube, the question posed above will remain unanswered. We continue to believe that characterizing hydrologic source terms at the NTS is one of the most challenging and important tasks of the HRMP.⁴⁰

ACKNOWLEDGMENTS

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APPENDIX A
Program Activity

Meetings Attended (HRMP and Related Programs)

HRMP/Los Alamos	October 12-13, 1994
HRMP/USGS	January 18-19, 1995
UGTA OU/DOE	February 8, 1995
UGTA OU/DOE	April 27, 1995
UGTA OU/DOE	May 2-3, 1995
HRMP/DOE	June 7, 1995
HRMP/LLNL	June 21-22, 1995
UGTA OU/DOE	August 31, 1995

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APPENDIX B **Modification of 2-1 Pressure Tube (Bailer) for Collecting Fluid Samples**

-27-

Joseph L. Thompson