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ABSTRACT

Recent drilling affords new opportunities to investigate the occurrence, distribution and transport of radionuclides in the unsaturated and saturated zone at the Nevada Test Site (NTS), Nye County, Nevada. This program is unique because of the elevated activities of radionuclides encountered during drilling (> 3.7E+6 Bq/L ^3H), extreme completion depths (> 950 m), the expense of constructing new wells (> $1E+6/borehole), and collaboration of government, academic, and industrial partners in the planning and execution of the program. The recent drilling is significant because it substantively augments earlier field studies of radionuclide migration at NTS, most notably the 1974 CAMBRIC RNM experiment. Sites of five nuclear tests fired below or adjacent to the saturated zone have been drilled. Three of the events were fired in Yucca Flat which is a hydrologically closed basin and two were fired in fractured volcanics of Pahute Mesa. Results from Yucca Flat indicate that volatile and refractory radionuclides, fractionated at zero time, are not highly mobile under saturated conditions. In contrast, boreholes completed on Pahute Mesa indicate high concentrations of tritium (> 3.7E+6 Bq/L ^3H) and other radionuclides may be transported more than 300 m from event cavities as dissolved species or as colloids.

INTRODUCTION

A near-field drilling program, completed between 1994 and 1996, supports a regulatory agreement between the State of Nevada, the U.S. Department of Energy, Nevada Operations Office (DOE/NV), and the Department of Defense to address potential contamination posed by the more than 800 underground nuclear tests conducted at the NTS between 1955 and 1992 (Figure 1). Of these, greater than 300 were located within or may otherwise impact the saturated zone (Laczniak et al., 1996). Because of the extreme depths to the water table throughout much of the NTS (> ~ 600 m), complex underground radiologic source terms, and great expense associated with drilling and well installation (> $1E+6/ borehole), much of the potential impact to groundwater resources will be predicted using coupled groundwater flow and radionuclide transport models. However, the accuracy of the models depends in large part on the ability to estimate radionuclide concentrations in groundwater (Kersting, 1996). The resulting hydrologic source term can be either estimated from laboratory experiments or measured directly (Smith, 1995). Drilling-based studies of the diverse NTS source term provide a unique opportunity to observe contaminant fate and transport on a field-scale and are critical to our understanding of radionuclide movement in the sub-surface.

PREVIOUS FIELD-SCALE INVESTIGATIONS

Prior to recent drilling at NTS, Nimz and Thompson (1992) reported on the migration of radionuclides in the saturated zone away from underground nuclear tests. In nine locations, radionuclides were traced back to a specific source. In five cases, the transport of radioactivity was the result of the prompt injection of high pressure-temperature plasma at zero (firing) time along geologic contacts or fractures susceptible to mechanical failure. The remainder involved radionuclides transported by groundwater. Of these, two were dedicated experiments which provided data for the first time on the field-scale transport of radionuclides under saturated conditions. Differences in the geologic setting of the CAMBRIC and CHESHIRE events afforded an opportunity to compare radionuclide migration respectively in alluvial basins with lower (~ < 20 m/year) hydrologic gradients and fractured volcanic rocks with higher hydrologic gradients (~ > 30 m/year). Satellite wells were constructed downgradient from the CHESHIRE and CAMBRIC explosion cavities, and pumping allowed a measure of the elution of radionuclides. These experiments determined that long-lived anionic (e.g. ^{36}Cl, ^{99}Tc, ^{106}Ru, ^{129}I) and neutral (e.g. ^{3}H, ^{85}Kr) radionuclide species were dissolved in groundwater and migrated without attenuation. Cationic species (e.g. ^{90}Sr, ^{125}Sb, ^{137}Cs) were variably attenuated during transport due to interactions with the aquifer matrix. Reviews of these experiments are provided by Bryant (1992), Buddemeier et al. (1991), and Kersting (1996).

STRATEGY

DOE/NV's remedial strategy for the underground testing area of the Nevada Test Site identifies six separate corrective action units (CAUs) corresponding to geographic areas where underground nuclear tests and supporting experiments were conducted. CAUs are listed in order of the number of corrective action sites (in parentheses) contained within each: Yucca Flat (717), Rainier Mesa - Shoshone Mountain (66), Central Pahute Mesa (64), Western Pahute Mesa (18), Frenchman Flat (10), and Climax Mine (3) (Figure 1). The corrective action leading to closure of each CAU involves modeling of groundwater flowpaths, determining potential down-gradient receptors, determining which radionuclides will be transported, the magnitude of this flux, and quantifying the risk to potential receptors.

A field program was initiated in 1991 to understand the regional hydrology, hydrostratigraphy, and aquifer properties throughout the NTS. More than ten far-field wells have either been drilled or recompleted to date. However, with the exception of

CAMBRIC and CHESHIRE field-scale experiments, only limited data existed on the transport of radionuclides away from underground nuclear test centers. The hydrologic complexity of each CAU and number of underground nuclear tests conducted at the Nevada Test Site emphasized the need for additional near-field data. For this reason, since 1994, the drilling program has concentrated on solid and fluid sampling and well completion within a 300 m radius of the working point of individual tests within the Western Pahute, Central Pahute and Yucca Flat CAUs. This report will focus on the results to-date of the five events targeted for drilling. Each will be discussed chronologically in the order drilled.

RECENT DRILLING

U-2gg PSE3A (INGOT)

The INGOT event was fired in 1989 in hole U-2gg and was selected for drilling in 1994 to collect samples for nuclear test diagnostics and as well as investigate the occurrence of radioactivity adjacent to a detonation cavity created during a nuclear explosion. A compete description of the drilling program is provided by Smith et al. (1996). The INGOT event was fired in the unsaturated zone at a depth of 500 m.. The static water level was measured at a depth of 565 m. For the purposes of environmental characterization, the drill rig was angled to pass within 10 m of the edge of the cavity at the level of the working (firing) point (500 m) and bottom below the cavity at a total depth beneath the static water level. After drilling the hole was logged with high sensitivity spectral gamma ray tool (Gadeken et al., 1988). One discrete zone of radioactivity was encountered at the level of the working point; ^{137}Cs was the only γ-emitting radionuclide identified in the spectral data. Based on the field logs, a sidewall tool was used to collect solid samples from this interval. After all logging and sampling runs were completed, stainless steel casing was run in the hole to allow for subsequent groundwater sampling below the cavity.

γ and β-counting confirmed the presence of ^{137}Cs and ^{90}Sr. ^{137}Cs and ^{90}Sr are fission products produced from the burn-up of primary nuclear weapon fuels; these two radionuclides are unique because they are each produced in part from the decay of a gaseous parent. ^{137}Cs is produced from the decay of ^{137}Xe with a 229.2 second half-life; ^{90}Sr is produced from the decay of ^{90}Kr with a 32.2 second half-life. The ^{137}Cs and ^{90}Sr decay scheme with cumulative fission yield of precursor species for actinide nuclear weapons fuels is provided in Table I (R.J. Nagle, LLNL, pers. comm.). The fission product data are notable for two reasons: 1) ^{137}Cs and ^{90}Sr are the only fission products detected within a confined zone of radioactivity ten meters away from the edge of the INGOT cavity and 2) there is an appreciable enrichment in ^{137}Cs relative to ^{90}Sr compared to a ratio of the same radionuclides calculated from a radionuclide inventory for this event.

TABLE I

	PRECURSORS	HALF-LIFE	CUMULATIVE SNM[a] FISSION CHAIN YIELD
^{137}Cs			
	^{137}Sb	0.284 seconds	0.0025%
	^{137}Te	2.5 seconds	0.4377%
	^{137}I	24.5 seconds	2.56%
	^{137}Xe	229.2 seconds	5.92%
	^{137}Cs	30.1 years	6.09%
^{90}Sr			
	^{90}Se	0.55 seconds	0.025%
	^{90}Br	1.9 seconds	0.56%
	^{90}Kr	32.3 seconds	4.46%
	$^{90}Rb^{4-}$	258 seconds	1.17%
	$^{90}Rb^{1-}$	156 seconds	4.25% (^{90}Rb: 5.42%)
	^{90}Sr	29.1 years	5.46%

a) SNM: Special nuclear materials as actinide nuclear weapon fuels

Drilling outside the cavity in the vadose zone insured that any observed radionuclide signatures would be the result of transport associated with the explosion and not transport by groundwater. The distribution of radionuclides within three cavity radii of the INGOT working point is likely controlled by fractures associated with the explosion. Re-activated and explosion induced fissures are likely conduits for the extremely confined zone of radioactivity noted in the spectral gamma log.

The extreme temperatures and pressures generated during an underground nuclear explosion create a shock wave that forms a cavity and induces radial fracturing out to a distance of two cavity radii away from the working point and reactivates, extends, and interconnects existing fractures out to a distance of three cavity radii (U.S. Congress OTA, 1989). Rock strength is inversely correlated to water content. The presence of hydrated (>20 weight% H_2O) smectites at the depth of burial results in a discrete interval of lower rock strength. At zero time, a fracture exploits this horizon. Mechanical stresses from the expansion of steam rapidly promotes fracture growth (Butkovich and Lewis, 1973). The 32.3 second and 229.2 second half lives of the parent isotopes ^{90}Kr and ^{137}Xe allow these radionuclides to be transported as gases before decay to their longer-lived daughters. Rather than a pressure-temperature pulse which 'promptly injects' a plasma which condenses volatile and refractory radionuclides (i.e. Nimz and Thompson, 1992), the results from INGOT suggest that some nuclear test cavities exhibit an irregular perimeter defined by volatile radionuclides transported in late-time by fractures created or re-activated by the explosion. The prevalence of volatile radionuclide species is significant because these radionuclides may be largely deposited on free surfaces and available to groundwater through processes including ion exchange, desorption, and surface layer alteration associated with dissolution.

A water well completed beneath the unsaturated INGOT nuclear test cavity produced only dilute levels of ^{3}H ($< \sim$ 185 Bq/L), ^{14}C, ^{85}Kr, and ^{137}Cs and suggests only a small fraction of the soluble radionuclides descend more than 65 m from the working point to the water table.

U-7ba PS1A and PS1AS (BASEBALL)

The BASEBALL event was fired in 1981 in hole U-7ba and, like INGOT, was also selected for drilling in 1994 to collect samples for nuclear test diagnostics and as well as investigate the occurrence of radioactivity within a nuclear test cavity. A compete description of the drilling program is provided by Thompson (1996). Drilling at the BASEBALL event is significant because the test was fired 52 m below the static water level in Yucca Flat at a depth of 564 m. Thirteen years elapsed between the time of detonation and the drill-back. A re-entry and a sidetrack hole were slant drilled into the BASEBALL cavity. After spectral gamma logs were taken to identify regions of radioactivity, 71 side-wall samples were collected and 48 were analyzed for ^{3}H and γ-emitting radionuclides. This large number of samples provided, for the first time, a nearly continuous profile of radioactivity ascending from the cavity upward through the collapse chimney.

The occurrence and distribution of tritium and γ-emitting radionuclides in these samples is consistent with conceptual models of the phenomenology of a nuclear explosion. There is extreme variability in radioactivity between samples collected within restricted depth intervals. Radionuclides initially contained in the melt at the bottom of the cavity or condensed on the cavity walls are chaotically mixed as the cavity collapses and the rubble chimney propagates towards the surface (Smith, 1995). The resulting distribution of radionuclides is extremely variable on a local scale. Despite this heterogeneity, there are systematic patterns for the distribution of individual radionuclides on the scale of the cavity-chimney system (Figure 2). Elements with higher boiling points (e.g. ^{152}Eu, ^{154}Eu) are largely concentrated in the melt debris and not found in appreciable concentrations elsewhere. Tritium is produced atomically at the time of explosion but very shortly condenses to steam; approximately 98% of the tritium occurs as HTO and 2% as HT (B. Hudson, LLNL, pers. comm.). HTO and fission products, some with gaseous parents, have lower boiling points (e.g. ^{137}Cs) and are more volatile. These volatile species are found in the highest concentrations in the chimney away from the working point. The general pattern of radionuclide distribution is that the refractory species are largely confined to the region containing the melt-debris while the volatile elements are more broadly distributed.

As noted by Thompson (1996), the persistence of large and small scale radioisotopes signatures at BASEBALL is unique. Despite saturation for more than ten years, the distribution of tritium - the most mobile radionuclide present - has not been disturbed. Other volatile and refractory radionuclides remain similarly unaffected (Figure 2). At the BASEBALL site there may be little reason for radionuclides to migrate since hydraulic gradients and hydraulic conductivity in the Yucca Flat alluvial basins are low (Hawkins et al., 1989; Hale et al., 1995; Laczniak et al., 1996). These results are not a guarantee that radionuclides will not migrate in basinal environments; however the persistence of fractionated radionuclide signatures for more than ten years under saturated conditions suggests that the movement of radionuclides is minimal.

ER-20-5 #1, #3 (TYBO)

Thick sequences of fractured rhyolite lavas and tuffs beneath Pahute Mesa hosted higher yield nuclear tests that for purposes of containment had to be buried deeply within rocks of higher confining strengths. While drilling at INGOT and BASEBALL concentrated on the occurrence of radionuclides in closed basins with low hydrologic gradients and permeabilities, the nature and extent of radionuclide migration at depth in the fractured and more permeable rocks of Pahute Mesa also required investigation. For this reason, a drilling site was selected adjacent to the TYBO event which was fired in 1975 at a depth of 765 m in hole U-20y. TYBO offered advantages as a drilling target: it is strategically located near the north-western boundary of the NTS, the working point was only 135 m below the static water level, and a twenty year interval between detonation and drilling allowed more time for the transport of contaminants. For these reasons, the TYBO near-field offered high probability of intercepting a plume of down-gradient radioactivity and was drilled to characterize the nature and extent of contamination beneath western Pahute Mesa.

ER-20-5 consisted of three individual wells drilled on the same pad. Drilling commenced in late 1995. Details of the ER-20-5 drilling program are provided in a completion report (DOE, 1996a). Well ER-20-5 #1 was completed at a depth of 860.5 m approximately two cavity radii southwest of the TYBO collapse chimney in a welded ash-flow tuff aquifer. Well ER-20-5 #3 penetrated a deeper lava-flow aquifer at a total depth of 1,308.8 m. Well ER-20-5 #2 collapsed during drilling and was abandoned before completion. Composite drill cutting were taken at regular intervals from the surface to TD in each of the three holes. Sidewall cores were also collected in ER-20-5 #3.

Tritium concentrations detected in the formation during drilling averaged approximately 2.96 E+6 Bq/L in Well ER-20-5 #1 and averaged > 4.07 E+6 Bq/L in Wells ER-20-5 #2 and ER-20-5 #3 (DOE, 1996a). Unless otherwise indicated, activities of all radionuclides are reported relative to count time.

Water samples were also collected from Wells ER-20-5 #1 and ER-20-5 #3. 205L water samples were concentrated by evaporation prior to analysis of the salts by γ-counting. The ER-20-5 #1 samples contained 2.4 E+6 Bq/L of ^{3}H, 4.4 E-1 Bq/L of ^{137}Cs, and 6.9 E-2 Bq/L of ^{60}Co which are not unexpected for species dissolved in groundwaters downgradient from expended nuclear test centers (Nimz and Thompson, 1992; Buddemeier et al., 1991). Water samples from Well ER-20-5 #3 indicated tritium concentrations a factor of 1000 less and ^{137}Cs and ^{60}Co concentrations a factor of 100 less than in Well ER-20-5 #1. The ER-20-5 #1 water samples also contained ^{152}Eu, ^{154}Eu, and ^{155}Eu. The presence of Eu isotopes in groundwater is notable because Eu is refractory, relatively insoluble, and not typically transported in groundwater as a dissolved species (see Thompson, 1996; Failor et al., 1983). At the Nevada Test Site, ^{152}Eu, ^{154}Eu, and ^{155}Eu were only detected once before bound to colloids (1000 to 6 nm size fraction) in groundwaters produced from a satellite well ~ 300 m downgradient from the edge of the CHESHIRE (U-20n) event cavity (Buddemeier and Hunt, 1988). Serial filtration of a separate aliquot of ER-20-5 #1 well water indicated measurable γ-activity was trapped on the ~ 800 nm and ~ 7 nm effective pore size filters. Eu was not detected by γ-counting in waters produced from Well ER-20-5 #3. A subsequent report will describe these results in more detail.

Smaller aliquots of water from Wells ER-20-5 #1 and #3 were analyzed for ^{14}C and ^{36}Cl by accelerator mass spectrometry and for ^{85}Kr by thin window β-counting. ^{14}C and ^{36}Cl are both activation products known to be mobile in groundwater. ^{85}Kr is a soluble long-lived ($t_{1/2}$ = 10.7 year) fission product. The ^{14}C activity of the ER-20-5 #1 water produced nearest to the TYBO cavity is 28169 percent modern carbon. $^{36}Cl/Cl$ ratios and ^{85}Kr concentrations are enriched similarly.

Sidewall cores and cuttings were analyzed for γ-emitting radionuclides produced on the TYBO event. Approximately 1 E-2 Bq/g of ^{137}Cs and ~ 8 E-3 Bq/g of ^{155}Eu was detected in the ER-20-5 #1 solids at the level of the working point (765 m). Like the fluid samples, the presence of ^{155}Eu is unusual due to its refractory nature.

U-3bh #1, #2 (HYRAX)

Radiologic characterization of the transport of gaseous fission products in the unsaturated zone followed the discovery of gamma activity in boreholes drilled in the bottom of the subsidence crater created by the 1962 HYRAX underground nuclear test. The HYRAX event was detonated at a depth of 216 m in hole U-3bh in the unconsolidated alluvium of Area 3. The working point was 272 m above the static water table.

Two vertical boreholes (U-3bh #1 and U-3bh #2) were drilled in 1996 to a depth of 64 m before encountering a broad front of radioactivity. Cores were obtained by ODEX casing advance "dry" drilling. By eliminating the circulation of drilling fluids over the bit and core barrel as samples are collected, potential contamination by drilling fluids is kept to a minimum; similarly the distribution of soluble radionuclides is preserved.

Data returned from the two boreholes indicate that significant transport of radionuclides can occur in the disturbed chimney region of a nuclear test conducted in the vadose zone. A complete description of the occurrence of radioactivity at U-3bh is provided in a report of the hydrogeology of the U-3bh collapse zone (Bechtel-Nevada, 1996). At HYRAX, radionuclides ascended 152 m into the collapse chimney to the horizon at 64 m where ^{137}Cs was encountered. Transport up to this level was due to movement of gas at the time the cavity and chimney formed. γ-counting of the cores from both holes indicate the singular presence of ^{137}Cs. As noted earlier, over 90% of the ^{137}Cs is produced from β-decay of a gaseous ^{137}Xe parent with a 229.2 second half-life. Other ^{137}Cs precursors including I (and Cs itself) are relatively volatile and susceptible to transport. When the cavity collapsed 7.9 minutes after zero time, much of the ^{137}Cs chain-yield was still in the form of ^{137}Xe; probably most of the migration of this isotope occurred at this time as the cavity collapsed and the chimney propagated upward. ^{90}Kr may be transported similarly prior to decay to ^{90}Sr. ^{90}Sr analyses are currently in progress.

While discovery of gamma activity in a nuclear test chimney is not unexpected, the relatively shallow depth (64 m) and lateral extent of the contamination encountered between the two separate boreholes is significant. The absence of fission and activation products of low (e.g. ^{144}Ce, ^{95}Zr, ^{155}Eu) or intermediate (e.g. ^{54}Mn, ^{60}Co) volatility in the core samples argues that ^{137}Cs was emplaced by the transport of precursor gases through the unconsolidated event chimney. The identical depth and concentration of gamma activity encountered in both boreholes is strong evidence that transport was the result of a single front of radioactive gas that ascended as the chimney collapsed.

An abundance of calcite in all size fractions of the core (approaching 50% in the 150 mm and finer size fraction) implies significant fusion of carbonate at the time of the HYRAX explosion. Based on studies of the mineralogy of the alluvium in this portion of Yucca Flat, the CO_2 content at U-3bh may be estimated. Assuming 8 weight% for the CO_2 content at the U-3bh working point, ~ 1.12 x 10^6 kilograms of CO_2 were produced during the HYRAX event. As CO_2 and fission product gases were channeled upwards they breached the cased emplacement hole and migrated through the formation as a broad front. Mechanical failure of carbonate along grain boundaries enhanced the permeability. The ascent of the radioactive gas was facilitated by the porosity of the unconsolidated alluvium and vitric clasts. The incondensible and radioactive gases continued to migrate up the subsidence chimney after the cavity collapsed eight minutes after the explosion. Further migration of the radioactive gases continued until ^{137}Xe precursor completely decayed to ^{137}Cs; at 152 m above the working point the ^{137}Xe reached its maximum height in the chimney.

The data returned from the U-3bh cores is significant because it emphasizes the ability of radionuclides to migrate significant distances (~ 5 cavity radii) in the vadose zone and be deposited near the surface. ^{137}Cs surface-deposited on fines is susceptible to release by ion-exchange under saturated or partially saturated conditions. Experience at HYRAX suggests the potential for radionuclide migration is greatest associated with older (pre-

1970) events where modern containment practices were not implemented as well as in areas of lower formation strength.

ER-20-6 #1, #2, #3 (BULLION)

A companion well cluster to ER-20-5 was drilled in zeolitized rhyolite lavas and zeolitic bedded tuffs of Pahute Mesa hydrologically down-gradient of the BULLION event. BULLION was fired in hole in emplacement hole U-20bd in June, 1990. The BULLION working point was 674 m below ground surface and 53 m below the measured static water level. The primary objective of drilling the ER-20-6 well cluster was to complete an outboard pumping well and two intermediate monitoring wells in a lava flow aquifer believed to be hydrologically connected to the BULLION working point (Figure 3). The wells were completed along a radial transect that includes ground zero and is parallel to the regional fracture network and presumed groundwater flow direction for central Pahute Mesa. Drilling commenced in early 1996. The well heads of ER-20-6 #1, #2, and #3 are located 166, 207 and 296 m southwest of the BULLION surface ground zero. The pumping well at ER-20-6 #3 is estimated to be less than five cavity radii from the edge of the cavity-chimney complex. All three wells were drilled to a depth of 975.4 m. The ER-20-6 drilling program is described comprehensively in a completion report (DOE, 1996b). The well configuration was designed for a forced hydraulic gradient experiment to collect data on the transport of radionuclides in groundwater as well as to determine aquifer transport parameters including effective porosity and dispersivity for fractured volcanic rocks which incorporate all of the Pahute Mesa underground testing area (IT Corporation, 1996). Pumping will be limited by a fluid management plan that allows contaminated discharge into five lined sumps with a combined capacity of 17,034 m^3. The forced gradient experiment is scheduled to begin in the spring of 1997.

Initial radiochemical results from the ER-20-6 drilling program are summarized below. Tritium activities (at count time) detected in drilling returns peaked at 2.5 E+6 Bq/L and 2.8 E+6 Bq/L in Wells ER-20-6 #1 and #2 respectively. Tritium in Well ER-20-6 #3, farthest from the BULLION working point, peaked at approximately 1.3 E+4 Bq/L before decreasing to background levels below a depth of ~ 820 m. 204L groundwater samples were collected from these wells as part of the initial development of the well line. Water samples collected from Wells ER-20-6 #1 and #2 indicated the presence of ^{60}Co, ^{102m}Rh, ^{106}Ru, ^{125}Sb, and ^{137}Cs in addition to ^{3}H. In Well ER-20-6 #2, the tritium concentration is less by a factor of 2 relative to Well ER-20-6 #1; the other radionuclides are down approximately a factor of 4. No ^{3}H or other radionuclides were detected in groundwater produced from Well ER-20-6 #3.

Of note, a discrete interval of radioactivity was detected above the water table at a depth of ~ 580 m in ER-20-6 #1. A spectral gamma log run in this hole indicates the presence of ^{106}Ru, ^{125}Sb, ^{134}Cs, and ^{137}Cs between the depth of 579 m and 582 m. These radionuclides were likely injected promptly at zero time along fractures induced or reactivated by the explosion (e.g. Nimz and Thompson, 1992). ^{3}H and ^{137}Cs were the only radionuclides detected in sidewall core returned from Well ER-20-6 #1 with the exception of ^{125}Sb introduced by prompt injection. Approximately 9 m segments of continuous core were also returned from ER-20-6 #1; geologic description and radiochemical characterization of these samples is in progress.

DISCUSSION and CONCLUSIONS

Drilling for the purposes of characterizing radionuclide transport in groundwater and the vadose zone indicates that radionuclides have been transported away from the sites of underground nuclear explosions at the Nevada Test Site. The extent of this contamination is not yet known. Since 1994, the drilling program has returned valuable information on the occurrence and distribution of radionuclides residual within underground nuclear test cavities as well as an initial estimate of the hydrologic source term. This field-scale investigation will also provide information on transport mechanisms and aquifer properties including permeability, effective porosity, and dispersivity. This data is important to constrain numerical modeling of coupled groundwater flow and contaminant transport.

While sampling and analyses are still continuing at all the drill-sites, several preliminary observations can be made. The detonation of nuclear explosions creates an extremely heterogeneous underground environment. Despite variability on a local scale, on the scale of the cavity-chimney system, radiochemical fractionation separates volatile from refractory radionuclides. The former are deposited in fracture surfaces where they maybe more susceptible to transport under saturated or partially saturated conditions. Refractory species are generally volume incorporated in glasses produced by the explosion. The role of early-time gaseous transport of radionuclides is significant. In particular, the generation of steam and noncondensible carrier gases including CO_2 can facilitate the movement of ^{90}Kr and ^{137}Xe precursors which may permeate the formation up to 2-3 cavity radii adjacent to the working point. Gaseous transport of radionuclides in the collapse chimney may be even greater.

Preliminary evidence indicates that radionuclides may not be transported appreciably by groundwater in the absence of a significant hydrologic gradient. Water level data and potentiometric contours drawn for Yucca Flat indicate the presence of a broad hydraulic sink (Hale et al., 1995). As such, groundwater flow in Yucca Flat is minimal (Laczniak et al., 1996). In this environment, volatile radionuclides which are known to be soluble are not remobilized on a field scale. Tritium extracted from post-shot samples preserves its pattern of original distribution. Other soluble radionuclides are not significantly remobilized.

Secondary permeability plays a significant role in control of groundwater flow under Pahute and Rainier Mesa. Enhanced permeability is the result of joints, fractures, and faults which disrupt the thick sequences of lavas, welded tuffs and nonwelded tuffs associated with eruptive calderas in this area (Laczniak et al., 1996). In addition, potentiometric contours indicate significant hydraulic gradients across Pahute Mesa (O'Hagan and Laczniak, 1996). Downgradient wells completed in hydrologic connection with events fired beneath Pahute Mesa have regularly intercepted radionuclides transported by groundwater over distances of ~ 300 m. The presence of refractory and high concentrations of volatile radionuclides in groundwater associated with these deeply buried (~ 700 m) events suggests that fractures, joint, and faults provide preferential pathways for radionuclide migration. Additionally, the detection of ^{152}Eu, ^{154}Eu, and ^{155}Eu and other fission and activation products in groundwater associated with the colloidal size fraction emphasizes transport by means other than as dissolved species. This data confirms earlier findings from the CHESHIRE event. More field studies are required before systematic statements can be made with certainty. Important questions remain including the exact role of advective flow, matrix diffusion, and colloids as agents for radionuclide migration in saturated, highly fractured volcanic rocks. On-going investigations, including the forced gradient experiment at ER-20-6, promise to further elucidate the nature of and controls on radionuclide transport at the Nevada Test Site.

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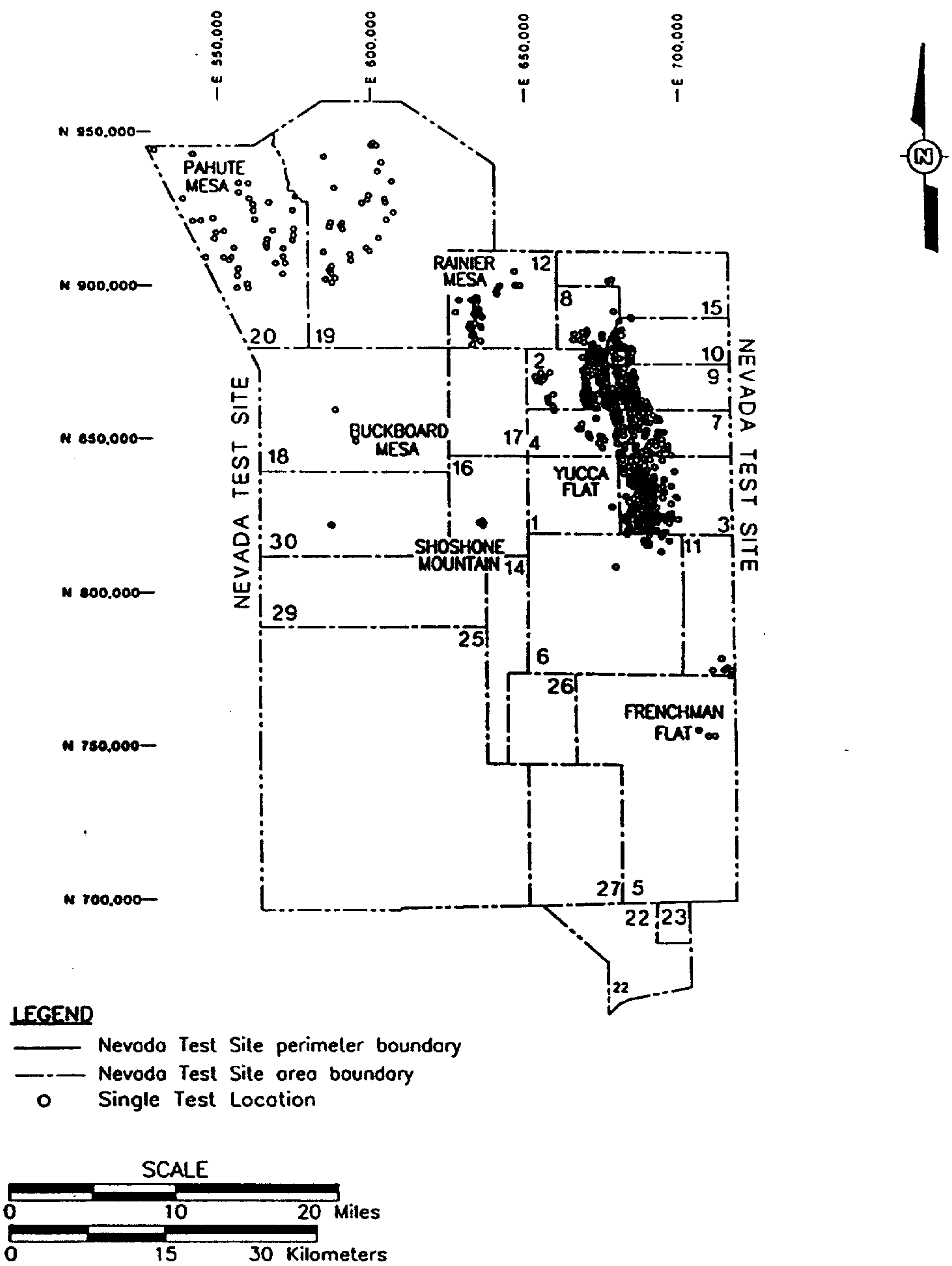
BIBLIOGRAPHY

1. R.J. LACZNIAK, J.C. COLE, D.A. SAWYER, D.A. TRUDEAU, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada, Water Resources Invest. Report 96-4109, U.S. Geological Survey, 1996.
2. A.B. KERSTING, State of the hydrologic source term, UCRL-ID-126557, Lawrence Livermore National Laboratory, 1996.
3. D.K. SMITH, Challenges in defining a radiologic and hydrologic source term for underground nuclear test centers, Nevada Test Site, Nye County, Nevada, UCRL-JC-120389, Lawrence Livermore National Laboratory, 1995.
4. G.J. NIMZ, J.L. THOMPSON, Underground radionuclide migration at the Nevada Test Site, DOE/NV-346, Reynolds Electrical and Engineering Co., 1992.
5. E.A. BRYANT, The Cambric migration experiment: a summary report, LA-12335-MS, Los Alamos National Laboratory, 1992.
6. R.W. BUDDEMEIER, R.C. FINKEL, K.V. MARSH, M.R. RUGGIERI, J.H. REGO, R.J. SILVA, Radiochim. Acta, 52/53 (1991) 275.
7. D.K. SMITH, R.J. NAGLE, J.M. KENNEALLY, Radiochim. Acta, 73 (1996) 177.
8. L.L. GADEKEN, H.D. SMITH, Jr., D.J. SEIFERT, Log Analyst, 29 (1988) 159.
9. R.J. NAGLE, Lawrence Livermore National Laboratory, pers. comm.
10. U.S. CONGRESS, OFFICE OF TECHNOLOGY ASSESSMENT, The containment of underground explosions, OTA-ISC-414, U.S. Government Printing Office, 1989.
11. T.R. BUTKOVICH, A.E. LEWIS, Aids for estimating effects of underground nuclear explosions, UCRL-50929 Rev. 1, Lawrence Livermore National Laboratory, 1973.
12. J.L. THOMPSON, Radiochim. Acta, 72 (1996) 157.
13. D.K. SMITH, Radiochim. Acta, 69 (1995) 157.
14. G.B HUDSON, Lawrence Livermore National Laboratory, pers. comm.
15. W.L. HAWKINS, D.A. TRUDEAU, T.M. MIHEVC, Proceedings of the fifth symposium on containment of underground nuclear explosions, CONF-8909163, Lawrence Livermore National Laboratory (1989) 141.
16. G.S. HALE, D.A. TRUDEAU, C.S. SAVARD, Water-level data from wells and test holes through 1991 and potentiometric contours as of 1991 for Yucca Flat, Nevada Test Site, Nye County, Nevada, Water Resources Invest. Report 95-4177, U.S. Geological Survey, 1995.
17. U.S. DEPARTMENT OF ENERGY, NEVADA OPERATIONS OFFICE, Completion report for well cluster ER-20-5, Draft.
18. R.A. FAILOR, D.G. COLES, J.H. REGO, A leaching study of nuclear melt glass: part I, UCID-19729, Lawrence Livermore National Laboratory, 1983.
19. R.W. BUDDEMEIER, J.R. HUNT, Applied. Geochem., 3 (1988) 535.
20. BECHTEL-NEVADA CORPORATION, Hydrogeologic characterization of the U-3bh collapse zone, 1996.
21. U.S. DEPARTMENT OF ENERGY, NEVADA OPERATIONS OFFICE, Completion report for well ER-20-6, Draft.
22. IT CORPORATION, Criteria for the forced gradient experiment at the BULLION event location, ITLV-10972-182, 1996.
23. M.D. O'HAGAN, R.J. LACZNIAK, Ground-water levels beneath eastern Pahute Mesa and vicinity, Nevada Test Site, Nye County, Nevada, Water Resources Invest. Report 96-4042, U.S. Geological Survey, 1996.

Figure 1: Location of more than 800 underground nuclear explosions fired on the Nevada Test Site between 1955 and 1992. Principal testing areas included the closed basin of Yucca Flat and fractured volcanic rocks of Pahute Mesa.

Figure 2: Volatile (^{137}Cs and ^{125}Sb) and refractory (^{152}Eu and ^{154}Eu) radionuclides plotted verses depth in U-7ba PS1AS (BASEBALL). After thirteen years under saturated conditions, refractory species remain confined to the cavity region; volatile species remain dispersed throughout the cavity and chimney.

Figure 3: Wells ER-20-6 #1, #2, #3 and the BULLION (U-20bd) event cavity. Well ER-20-6 #3 will be pumped inducing a hydraulic gradient and the transport of radionuclides away from the cavity. Wells ER-20-6 #1 and ER-20-6 #2 will monitor the breakthrough of radionuclides in the aquifer.



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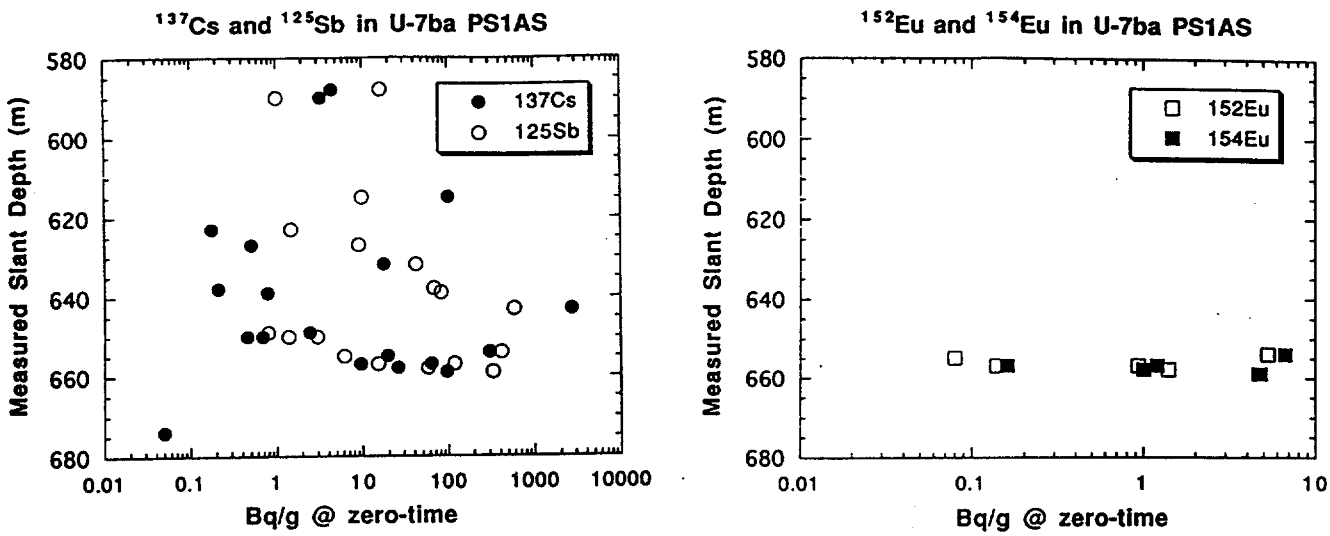

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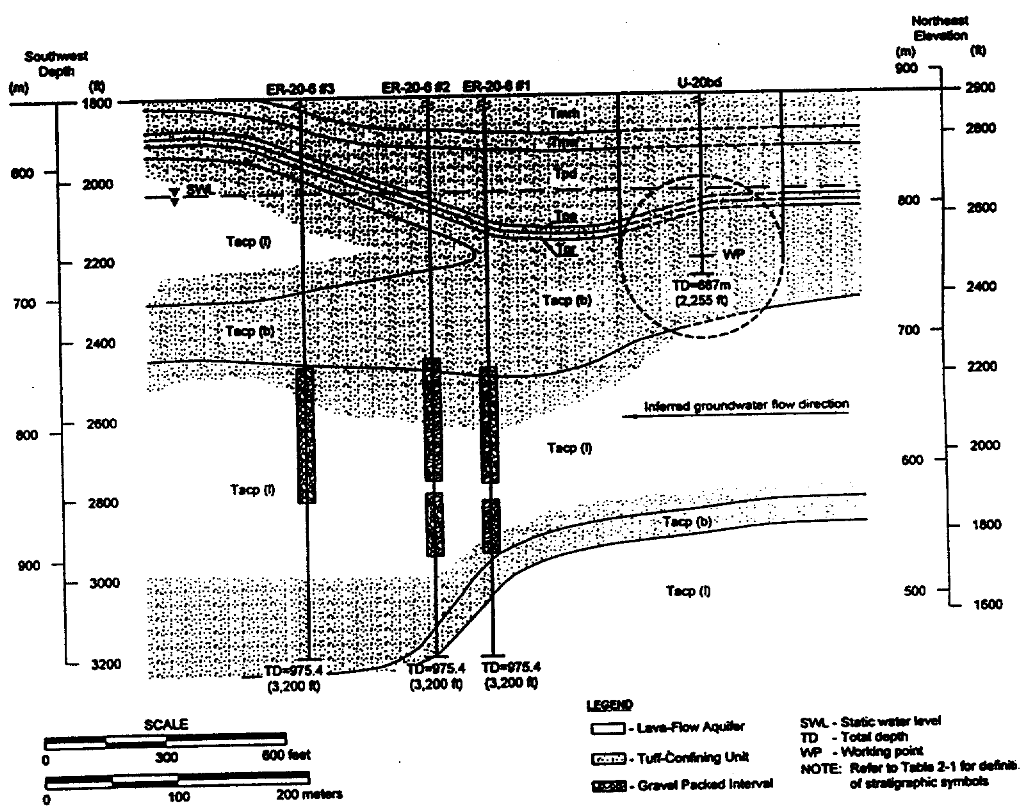

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