ERID# 240120
ENTERED

Results of Tracer Testing in the Saturated Alluvium South of Yucca Mountain

Paul Reimus[(1)], Robert Jones[(2)], Ezra Wasson[(3)], John Kelly[(2)], Alexander Sanchez[(2)], Walter Slack[(3)], and Jeanette Daniels[(4)]
[(1)]Los Alamos National Laboratory, Los Alamos, NM
[(2)]Sandia National Laboratories, Las Vegas, NV
[(3)]Bechtel-SAIC, LLC, Las Vegas, NV
[(4)]University of Nevada-Las Vegas, Harry Reid Center for Environmental Studies, Las Vegas, NV

Abstract - *Estimates of important flow and transport parameters in the saturated alluvium south of Yucca Mountain, Nevada were obtained from two single-well tracer tests and two cross-hole tracer tests conducted at Nye County Site 22 in 2004 and 2005. The single-well tests yielded estimates of specific discharge in the alluvium of 0.55 to 4.7 m/yr, compared to a range of specific discharge estimates of 3.1 to 12.7 m/yr based on estimates of natural gradient and hydraulic conductivity at Site 22. The cross-hole tracer tests showed evidence of a small amount of diffusion between flowing and stagnant water in the alluvium, yielding an estimate of the ratio of stagnant to flowing water volumes of 1.9:1, which would result in an effective retardation factor of 2.9 for nonsorbing tracers over long time and distance scales. The cross-hole tracer tests also yielded flow porosity estimates ranging from 0.076 to 0.118 for the north-south flow direction and 0.27 for the east-west flow direction at Site 22, resulting in horizontal flow anisotropy ratio estimates of 2.3:1 to 3.5:1, oriented in the north-south direction. Perrhenate was used as a surrogate for pertechnetate (the expected ^{99}Tc species in oxidizing groundwaters) in one of the cross-hole tracer tests. The response of the perrhenate relative to iodide was consistent with a small amount of reversible sorption in the stagnant porosity of the flow system. Perrhenate sorption was invoked as a process in the test interpretation because the perrhenate had a lower normalized peak concentration and longer tail than the iodide. This result would normally be attributed to greater diffusion of perrhenate into stagnant water in the flow system, but the free-water diffusion coefficient of perrhenate is less than that of iodide, so the only way perrhenate could appear to be diffusing more than iodide is if it were sorbing in the stagnant porosity. The implication is that ^{99}Tc (as pertechnetate) may also exhibit sorbing behavior in the alluvium and may therefore be retarded over long time and distance scales in the alluvium.*

I. INTRODUCTION

The saturated alluvium south of Yucca Mountain, Nevada represents the final barrier to radionuclide migration from the proposed high-level nuclear waste repository at Yucca Mountain before radionuclides reach the regulatory compliance boundary. The alluvium will serve as a barrier if radionuclides breach the engineered barriers in the repository, move through the unsaturated zone beneath the repository to the water table, and then migrate through saturated volcanic tuffs to the alluvium.

In 2004 and 2005, two single-well injection-withdrawal tracer tests and two cross-hole forced-gradient tracer tests were conducted in the saturated alluvium at NC-EWDP Site 22 (called Site 22) to evaluate conceptual models of flow and transport in the alluvium. Site 22 is a Nye County-Early Warning Drilling Program (EWDP) site located about 14 km south of Yucca Mountain with one large-diameter (6.75") well that can be pumped at a relatively high rate (22S) and three 2-inch piezometers (22PA, 22PB, and 22PC) that can be used as observation wells in hydraulic testing or injection wells in cross-hole testing. The site location and layout are shown in Figure 1. The site is situated along a projected flow pathway from the proposed repository, so it is a good location for assessing flow and transport in the saturated alluvium. Details of the well completions, and the local geology and lithology can be found at http://www.nyecounty.com/ewdpmain.htm. The tracer tests at Site 22 had the primary objectives of (1) obtaining estimates of ambient ground-water velocity in the alluvium, (2) assessing whether a single- or a dual-porosity conceptual solute transport model is more appropriate for the alluvium, and (3) evaluating sorbing solute transport and colloid transport in the alluvium. This paper describes the test methods, test results, and analysis results.

II. TEST METHODS

Two single-well injection-withdrawal tracer tests were conducted in the saturated alluvium at Site 22 in December 2004 and January 2005. In each of these tests, two nonsorbing solute tracers with different diffusion coefficients were simultaneously injected (a fluorinated benzoate, or FBA, and iodide). Tracer solutions were prepared by dissolving tracers in ground water that had been withdrawn from the test interval of 22S prior to any of the tests. Tracer concentrations were kept low to minimize density contrasts between the injection and chase solutions and the ground water. The two tests were conducted in exactly the same manner except for the time that was allowed to elapse between the end of tracer and "chase" water injection (untraced water injected immediately after the tracer solution) and the initiation of pumping; i.e., the so-called "rest" or "shut-in" period.

35842

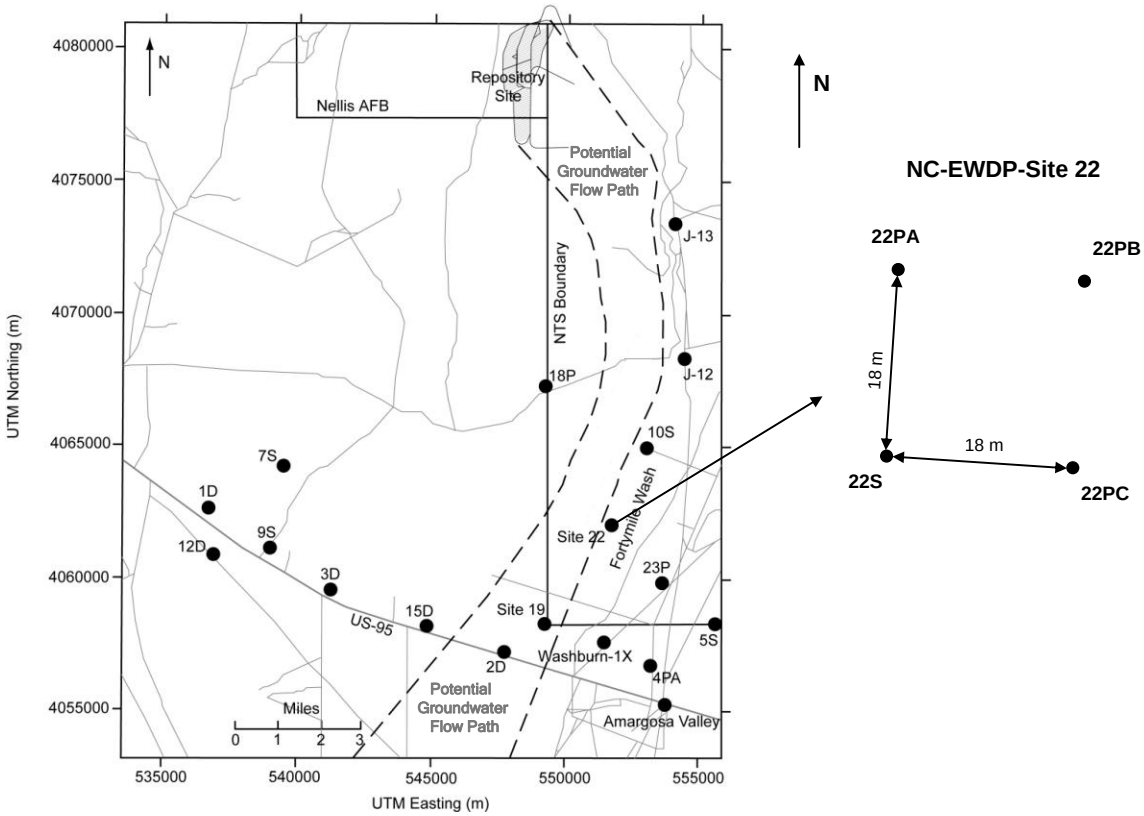

Figure 1. Location and surface layout of Nye County EWDP Site 22 relative to the proposed Yucca Mountain repository. Black circles are well locations.

The rest periods in the tests were ~3 days and ~30 days, to vary the time allowed for the tracers to migrate with the ambient ground-water flow and for them to tracers in the same test and (2) the responses of similar tracers in the different tests. "Response" here refers to tracer concentrations normalized to injection mass as a function of time or volume pumped (i.e., normalized breakthrough curves). Differences in the responses of the two tracers injected in the same test provide information on diffusion into stagnant water in the system[1], whereas differences in the responses of tracers injected in different tests (after accounting for the effects of diffusion) provide information on ground-water drift velocity during the rest periods of the tests.[2]

The two single-well tests were conducted in the second screened interval below the water table in well 22S, which ranges from approximately 57 to 87 m below the water table (gravel pack from approximately 55 to 90 m below the water table). The static water table is approximately 144 m below land surface at this location. The tracer solution volume injected in each test was approximately 5,700 liters, and the volume of chase water was approximately 76,000 liters. The chase water was intended to push the tracers into the formation to minimize the influence of the well bore and gravel pack on the test results. Each tracer and chase water injection took about 18 hours.

diffuse into stagnant water in the flow system. Test interpretations were based on *comparing* (1) the responses of different

The two single-well tracer tests were followed by two cross-hole forced-gradient tracer tests in which tracers were injected into one or more of the piezometer wells while well 22S was pumped at approximately 180 L/min. The first cross-hole test was initiated in January 2005 during pumping to recover tracers from the second single-well tracer test. The cross-hole test involved injections into the second screened interval from the surface in both 22PA and 22PC (completed at essentially the same depth as the production interval in 22S). The nonsorbing tracers 2,4,5 trifluorobenzoate (TFBA) and bromide were injected simultaneously with a weakly-sorbing cation tracer (lithium ion) into 22PA, and 2,6 difluorobenzoate (DFBA) was injected into 22PC. The injection volumes were approximately 1000 L each. A small volume of chase water (just enough to flush tracers out of the tubing string) followed both tracer injections. The test was concluded in late March 2005 when pumping of 22S ceased.

The second cross-hole tracer test involved the simultaneous injection of sodium iodide and sodium perrhenate into the second screened interval of 22PA. This test was initiated in late August 2005, and it was conducted in a manner identical to the first cross-hole

tracer test between 22PA and 22S (same volumes and pump rates), although the total dissolved tracer concentration was much lower than in the first test, resulting in a significantly less dense tracer solution. The test was concluded in mid-October 2005 with the cessation of pumping of 22S.

Perrhenate ion was used as a surrogate for pertechnetate ion in the second cross-hole test. Pertechnetate is the predominant technetium species predicted to be in solution in oxidizing groundwaters at Yucca Mountain, and ^{99}Tc is one of the radionuclides that have been identified as potentially contributing significantly to future offsite doses[3] because of its high solubility and weak sorption behavior. However, both pertechnetate and perrhenate are predicted to be reduced to species of much lower solubility and significant sorption under reducing groundwater conditions. Thus, if perrhenate were significantly retarded relative to a nonsorbing tracer (e.g., iodide), it would suggest that local reducing conditions may exist in the alluvium that would also be capable of retarding pertechnetate.

III. TEST RESULTS

Figure 2 shows the normalized tracer responses (tracer concentrations divided by injection mass) for the two single-well tracer tests conducted in NC-EWDP-22S. The lack of separation between the response of the iodide and the FBAs in each test suggests that there was very little diffusion into stagnant water in both tests. If diffusion into stagnant water had been significant, there would have been noticeable differences in the responses of these tracers because the diffusion coefficients differ by about a factor of three (with the iodide diffusion coefficient being larger). Note that the offset between the iodide and PFBA in the tail of the 3-day test is suspected of being an analytical artifact because an offset was not observed in the 30-day test, where there should have been more diffusion. This possibility will be explored further as the data are reviewed and quality assured.

Figure 3 shows the normalized tracer responses in the first cross-hole tracer test. For interpretation purposes, the bromide curve was adjusted upward so that the bromide recovery matched the 2,4,5 TFBA recovery. This adjustment was made because the TFBA recovery was ~10% higher than the bromide recovery when the tracer concentrations were normalized by dividing by their injection masses. This sort of difference for nonsorbing tracers with different diffusion coefficients is not unusual if there is a significant amount of diffusion into stagnant water in the flow system, but if diffusion were responsible for the different recoveries, the tails of the two tracer curves would have had different slopes over time and would cross over at some point to conserve tracer mass. The tails of the bromide and TFBA curves in Figure 3 are essentially parallel throughout the test, which

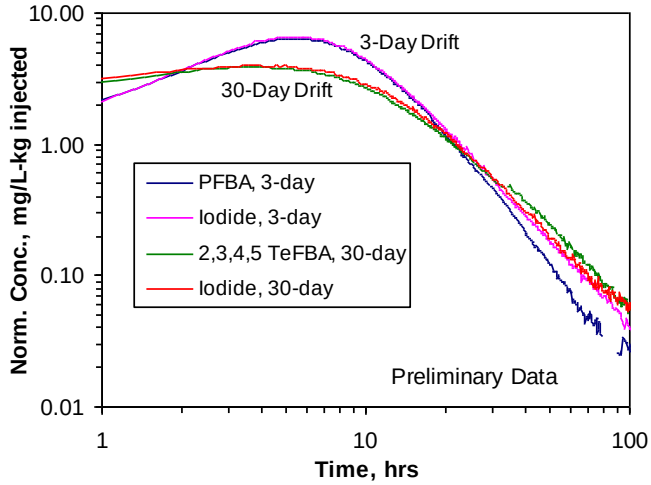

Figure 2. Normalized tracer breakthrough curves in the two single-well tracer tests. Rest periods are indicated in the legend (PFBA = pentafluorobenzoate, TeFBA = tetrafluorobenzoate).

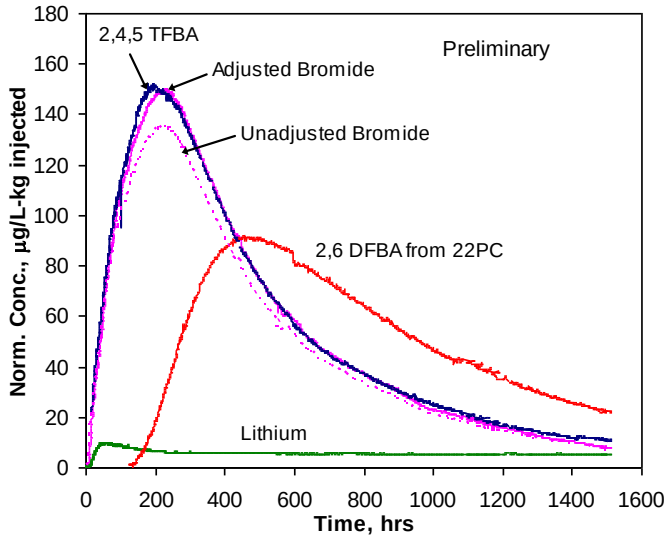

Figure 3. Normalized tracer breakthrough curves for tracers injected in the first cross-hole tracer test. All tracers except 2,6 DFBA were injected into well 22PA.

suggests that there was very little diffusion occurring - certainly not enough to account for the difference in recoveries. Laboratory batch sorption tests conducted prior to the tracer test indicated that neither bromide nor TFBA sorbed to alluvium from the test interval, so sorption is ruled out as an explanation for the difference in tracer recoveries. Because we believe that the recovery discrepancy is inconsistent with the shapes of the breakthrough curves and with mass balance constraints, we consider it justified to raise the bromide curve to match the TFBA recovery.

Several qualitative conclusions can be drawn from the breakthrough curves of Figure 3 (quantitative results are discussed in subsequent sections):

- The slight delay in the peak arrival time of the bromide relative to the TFBA suggests a small amount of diffusive mass transfer between flowing and stagnant water in the flow system.
- The lithium response relative to the bromide and TFBA indicates that the alluvium can significantly attenuate cation-exchanging solutes. The fact that a small fraction of lithium broke through at about the same time as the nonsorbing solutes was probably due to the extremely high concentration of lithium in the injection solution. This high concentration would have resulted in lithium saturation of cation-exchange sites on the alluvium along flow pathways, thus leading to conservative transport of a fraction of the lithium.
- The response of the 2,6 DFBA from well 22PC relative to the 2,4,5 TFBA response suggests that there is horizontal flow anisotropy in the alluvium at Site 22, with a greater north-south hydraulic conductivity (parallel to inferred flow direction) than east-west conductivity (transverse to flow direction).

Figure 4 shows the responses of iodide and perrhenate in the second cross-hole tracer test, along with semi-analytical model fits to the tracer responses, which are discussed later. Despite the fact that these tracers were injected in the same volume of water as in the first cross-hole test, and the pumping rate at 22S was the same as in the first test, these responses are significantly different than the bromide and TFBA responses of Figure 3. The first arrival of bromide and TFBA was ~10 hours after injection compared to ~16 hours for iodide and perrhenate in the second test, and the peak normalized concentration was significantly higher and tail concentrations lower in the second test relative to the first test. The most likely explanation for these differences is that the tracer solution in the first test was much more dense (calculated to be 1.133 g/ml) than in the second test (calculated to be 1.005 g/ml), resulting in density-driven flow of the first solution near the injection zone, whereas the second solution was too dilute to experience density-driven flow. The density-driven flow could have caused the tracers to access flow pathways in the first test that were not accessed in the second test (or to access pathways in different mass proportions in each test).

Perhaps the most significant result from the second cross-hole tracer test is that the tracer breakthrough curves bear the hallmarks of diffusion into stagnant water in the flow system. The lower peak concentration and higher tail concentration of the perrhenate relative to the iodide is consistent with the perrhenate experiencing more diffusion into stagnant water than the iodide. However, the free-water diffusion coefficients of these tracers are

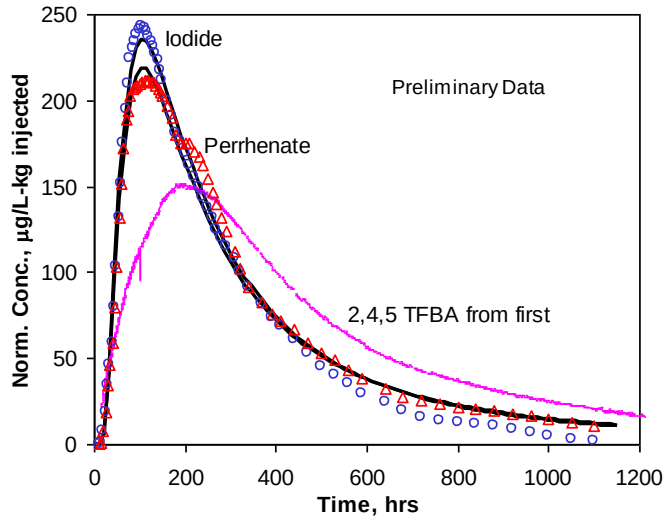

Figure 4. Iodide and perrhenate breakthrough curves in the second cross-hole tracer test between 22PA and 22S and RELAP model fits to the data (solid black lines). The 2,4,5 TFBA curve from the first cross-hole test (Figure 3) is shown for comparison.

2.04×10^{-5} cm^2/s for iodide[4] and 1.46×10^{-5} cm^2/s for perrhenate[5], so if the ratio of free-water diffusion coefficients reflects the ratio of pore-water diffusion coefficients (as has typically been observed[6]), the only way that perrhenate could have experienced what appears to be more matrix diffusion than iodide would be for it to sorb to surfaces in the stagnant pore spaces. This possibility is discussed later. The possibility that perrhenate sorption occurred in the flowing porosity can be ruled out because this would have resulted in a significant time delay in the perrhenate response relative to the iodide, which was not observed.

IV. ANALYSIS

Given that there was very little, if any, evidence of diffusion into stagnant water in the single-well tracer tests, the differences in the responses of the tracers in the two tests (Figure 2) can be attributed to different amounts of tracer "drift" with the natural groundwater flow during the different rest periods in the two tests. Specific discharge in the test interval was estimated from the tracer responses using the "peak" and "tail" arrival time methods of Reimus et al.[2] These methods use the *differences* in the tracer peak arrival times and the arrival times associated with a high fractional recovery in the tails of the breakthrough curves, respectively, to estimate the distance that the tracers moved under the influence of the natural gradient during the time *difference* in the rest periods of the two tests. This distance divided by the time difference provides an estimate of the water flow velocity.

The arrival time used in the "tail" analysis was the time associated with a 94% tracer recovery, which was the recovery at the end of the 30-day rest period test (the lower overall recovery of the two single-well tests). The times associated with a 94% recovery were 117.4 hours for the 30-day test and 42.5 hours for the test with the 3-day rest period. The peak arrival times were approximately 3.9 and 5.6 hours in the 30-day and 3-day tests, respectively. The fact that the peak arrival time was shorter in the longer-duration test suggests that a significant fraction of the injected tracer mass moved upgradient during the injection and chase phases of both tests and then drifted back toward the well during the rest periods. The flow porosities assumed in the analyses were the flow porosity estimates from the two cross-hole tracer tests conducted between 22PA and 22S and the estimate from the cross-hole test conducted between 22PC and 22S (discussed later).

The nonsorbing tracer responses in the cross-hole tracer tests were interpreted using the RELAP (REactive transport LAPlace transport inversion) model, which is described in detail elsewhere.[7] The interpretation procedure is summarized as follows:

- The normalized iodide and perrhenate breakthrough curves in the second cross-hole test were analyzed assuming that the diffusion coefficient of perrhenate was 0.7 times that of iodide (based on the ratio of their free-water diffusion coefficients). Thus, to fit the perrhenate breakthrough curve (which has a lower peak concentration), it was necessary to assume that perrhenate was sorbing in the stagnant porosity of the flow system (i.e., the retardation factor in the stagnant porosity was varied to obtain a fit).
- The flow pathway corresponding to the iodide and perrhenate responses was assumed to be contributing to the tracer responses in the first cross-hole tracer test. However, to account for the earlier tracer arrival time and the longer tailing in the first test, it was necessary to also assume that there was a fast-flow pathway and a slow-flow pathway in the first cross-hole test that were not present in the second test (presumably because they were accessed by density-driven flow that did not occur in the second test).
- The mean tracer residence time, longitudinal dispersivity, and diffusion parameters obtained from fitting the iodide and perrhenate responses were used to account for the "middle" portion of the bromide and TFBA responses in the first test. The diffusion coefficient of bromide was assumed to be the same as for iodide, and the diffusion coefficient of TFBA was assumed to be a factor of 3 less than that of bromide (corresponding to the ratio of their free-water diffusion coefficients). The tracer mass fraction associated with this flow pathway was adjusted so that the calculated TFBA and bromide breakthrough curves fell below the actual breakthrough curves of these tracers and resulted in early- and late-time residuals that resembled tracer breakthrough curves.
- RELAP was used to obtain estimates of mean tracer residence times, dispersivities, and diffusion parameters yielding good fits to the early- and late-time residuals for the bromide and TFBA responses.
- The resulting "fits" to the three pathways comprising the bromide and TFBA responses were mathematically pieced together to obtain a composite "fit" that was compared to the actual normalized breakthrough curves of the tracers.
- Adjustments were made as necessary to the mass fraction of tracers associated with the intermediate flow pathway, and the early- and late-time residuals were then refitted to obtain the best possible "fit" to the overall bromide and TFBA breakthrough curves.
- Finally, the 2,6 DFBA response from well 22PC was fitted with RELAP assuming a single flow pathway with no diffusion into stagnant water (only the mean residence time, dispersivity, and mass fraction of tracer participating in the test were allowed to vary as adjustable parameters).

V. ANALYSIS RESULTS

Estimates of the groundwater specific discharge in the test interval based on the "peak" and "tail" arrival time analyses of the single-well tracer tests are listed in Table 1. Table 1 also provides estimates of specific discharge based on estimates of the natural hydraulic gradient at Site 22 (ranging from 0.0007 to 0.0028 m/m) and the hydraulic conductivity obtained from cross-hole pump testing in the 22S test interval.[8] The range of specific discharge estimates from the hydraulic gradient and conductivity estimates reflects the uncertainty in the natural gradient, which is very flat in this area and is based on water elevations in 22S and in two wells that are several km distant from 22S (10S and 19D). The specific discharge estimates from the peak and tail arrival time analyses of the single-well tracer tests are at the low end of the range obtained from the hydraulic gradient and conductivity estimates.

Table 1. Alluvium specific discharge estimates (m/yr) at Site 22 as a function of flow porosity from the peak and tail analysis methods and from estimates of the natural gradient and hydraulic conductivity at the site.

Flow Porosity[a]	0.076	0.118	0.27
Peak Analysis	0.55	0.68	1.04
Tail Analysis	2.5	3.1	4.7
Nat. Grad. Analysis		3.1 - 12.7	

[(a)]The three flow porosity values are from the two cross-hole tracer tests between 22PA and 22S (first two columns), and the cross-hole tracer test between 22PC and 22S (last column).

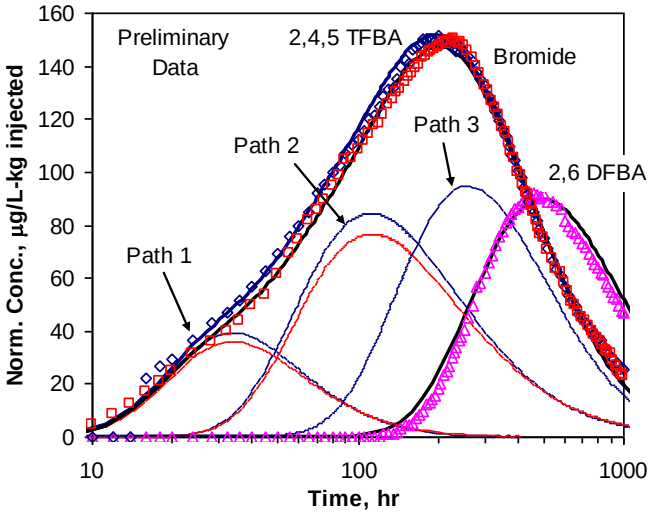

Figure 5. RELAP model fits to the tracer breakthrough curves in the first cross-hole tracer test. The fits to the 2,4,5 TFBA and bromide responses are composed of three separate pathways, with Path 2 corresponding to the pathway that fit the iodide and perrhenate responses between 22PA and 22S. The dark blue lines for Paths 1 and 2 are for TFBA and the red lines are for bromide. Note the log time scale for the x axis.

RELAP model fits to the iodide and perrhenate responses in the second cross-hole tracer test are shown in Figure 4, and fits to the bromide, TFBA, and 2,6 DFBA responses in the first cross-hole test are shown in Figure 5. Figure 5 also shows the contributions of the individual simulated pathways between 22PA and 22S that sum to the bromide and TFBA responses. The transport parameter estimates associated with the RELAP fits are listed in Table 2.

A key constraint in the interpretations of the two cross-hole tracer tests was that they be consistent in explaining the different nonsorbing tracer responses in the two tests. This constraint was honored by assuming that the flow pathway(s) contributing to the responses in the second cross-hole test also contributed to the responses in the first test – an assumption that required that there be additional flow pathways in the first test to account for the early and late portions of the tracer breakthrough curves in that test. These additional pathways can logically be attributed to the high density of the tracer injection solution in the first test and the resulting density-driven flow that would have occurred near the injection interval, which could have caused tracers to enter pathways that they otherwise would have missed.

However, even without the benefit of knowing the iodide and perrhenate responses in the second cross-hole test, a multiple-pathway interpretation would have been deduced for the first test because it was simply not possible to obtain a good single-pathway fit to the bromide and TFBA responses in the this test. The shape of the breakthrough curves of these tracers, and in particularly the very large ratio of the peak arrival times to first arrival times, simply does not conform to a single-pathway solution of the advection-dispersion equation. Furthermore, a derivative analysis of the rising limbs of the breakthrough curves of the bromide and TFBA indicated that there were three separate tracer arrivals corresponding to three flow pathways for these tracers.[9] Thus, the multiple-flow-pathway interpretation of the first cross-hole test can be deduced and justified even without knowing the tracer responses in the second test; and, in fact, the iodide and perrhenate responses can be viewed as lending additional support and providing additional constraints for such an interpretation.

The flow porosity estimates of Table 2 were calculated assuming a confined aquifer using the equation $\phi = Q\tau/\pi b R^2$, where ϕ = flow porosity; Q = production flow rate, m^3/hr; τ = mean tracer residence time in pathway (assuming radial flow), hr; b = flow interval thickness, m; and R = distance between wells, m. For each flow pathway, a flow interval thickness of 30 m and a production rate of 180 L/min (10.8 m^3/hr) were assumed in this equation. Given that only ~3% of the tracer mass in the first cross-hole test participated in the fastest flow pathway between 22PA and 22S in this test, it is tempting to say that the volumetric flow rate associated with this pathway was only 5.4 L/min (3% of 180 L/min), which would result in an extremely low flow porosity. However, if we assume that the production flow rate is distributed among the flow pathways in proportion to tracer mass fractions, then we should also apportion the total interval thickness between the flow pathways. The most objective way of doing this would be to assign thicknesses in proportion to mass fractions, which would cancel the effect of apportioning of the production flow rate according to mass fractions. Thus, we simply use the total production flow rate and the total interval thickness to calculate flow porosities associated with each pathway. The mass-weighted average of the flow porosities in the three flow pathways between 22PA and 22S in the first cross-hole test is 0.118, which is slightly larger than the flow porosity for the single pathway between these two wells for the second cross-hole test (0.076).

VI. DISCUSSION

The tracer test results provide valuable information about the flow and transport characteristics of the alluvium at Nye County Site 22. The range of specific discharge estimates from the single-well tracer tests are in relatively good agreement with the specific discharges calculated from estimates of the natural gradient and hydraulic conductivity at Site 22 (Table 1), which lends confidence to the single-well interpretive analysis. The slightly lower estimates obtained from the single-well test

Table 2. Tracer transport parameter estimates from the cross-hole tracer tests at Site 22.

-------- First 22PA-to-22S Test --------

Parameter	Path 1	Path 2	Path 3	2nd 22PA-to-22S	22PC-to-22S
Tracer mass fraction[a]	0.03	0.32	0.58	0.98	1.0
Tracer mean residence time[b], hr	44	215	415	215	770
Longitudinal dispersivity[b], m	5.3	3.6	5.3	3.6	5.9
Halide $\frac{\phi_m}{b}\sqrt{D_m}$ [c], $sec^{-1/2}$	0.00032	0.00032	0	0.00032	0
Effective Flow Porosity	0.016	0.076	0.147	0.076	0.27
Ratio of stagnant to flowing water volume	1.9	1.9	0	1.9	0

(a) Determined by trial-and-error for first 22PA-to-22S test.

(b) Tracer mean residence time and longitudinal dispersivity based on radial flow in a confined aquifer of 30 m thickness.

(c) Diffusive mass transfer lumped parameter: ϕ_m = stagnant water porosity, b = half-width of flowing porosity (cm), D_m = diffusion coefficient in stagnant porosity (cm^2/sec)

interpretations indicate that Site 22 may be in a region of locally shallow gradient relative to the large-scale hydraulic gradient. It should be noted that specific discharge estimates obtained from single-well tracer tests at the NC-EWDP-19D location, located about 4.5 km southwest of 22S (Figure 1), ranged from 1.2 to 9.4 m/yr.[2] These estimates are also in good agreement with the specific discharges of Table 1. Specific discharge estimates from the Yucca Mountain site-scale flow model range from 1.9 to 3.2 m/y at the 19D location.[3]

The high tracer mass participation (Table 2) associated with each cross-hole tracer response (over 90%) suggests that there was good hydraulic communication between the injection and production wells. By contrast, the tracer mass participation in cross-hole tracer testsconducted in fractured volcanic tuffs at the C-wells complex near Yucca Mountain never exceeded about 70%.[1] These results suggest that the flow heterogeneity and tortuosity in the fractured tuffs was considerably greater than in the alluvium, which is a reasonable expectation.

The flow porosity estimates of Table 2 fall within the range of alluvium flow porosities developed in Yucca Mountain flow and transport models (0 to 0.3).[3] However, the fastest-arriving pathway in the first cross-hole tracer test has an estimated flow porosity (0.016) that is at the extreme lower end of the distribution used in the models, suggesting that there may be some flow channels in the alluvium that can result in relatively rapid transport.

The mean tracer residence times and flow porosities derived from the iodide and perrhenate responses between 22PA and 22S and from the 2,6 DFBA response between 22PC and 22S suggest a horizontal flow anisotropy ratio (the ratio of hydraulic conductivities) in the alluvium of approximately 3.5:1, with a greater hydraulic conductivity in the north-south direction than in the east-west direction. If the mass-weighted average of the mean residence times and flow porosities of the bromide and TFBA responses between 22PA and 22S are compared to the 2,6 DFBA response, the estimate of anisotropy ratio becomes approximately 2.3:1 in the north-south direction. Either way, the cross-hole test results suggest a greater hydraulic conductivity in the north-south direction.

Although the single-well tracer test results indicated insignificant diffusion between flowing and stagnant water in the flow system at Site 22, both cross-hole tracer tests between 22PA and 22S indicated a small amount of diffusion in the flow system. The cross-hole test results are given more weight because a greater volume of the aquifer was interrogated in these tests than in the single-well tests. Assuming a flow porosity of 0.076 (from the iodide and perrhenate cross-hole responses) and a homogeneous, isotropic flow system, the tracer penetration distance into the aquifer in the single-well tests would have been about 3.5 m (or about 6 m in the north-south direction if a 3:1 flow anisotropy is assumed), compared to 18 m of transport distance in the cross-hole tests.

The ratio of stagnant water volume to flowing water volume deduced from the cross-hole tracer test results is 1.9. This ratio plus one (i.e., 2.9) can be considered an estimate of the effective retardation factor that nonsorbing solutes will experience as a result of diffusion into stagnant water in the alluvium. This estimate times the estimated flow porosity yields an estimate of the total porosity in the alluvium of 0.22. The total porosity in the alluvium, based on other lines of evidence, is generally considered to be between 0.2 and 0.3, so the flow porosity and the stagnant-to-flowing water volume ratio deduced from the cross-hole test interpretations are consistent with total porosity estimates.

The apparent sorption of perrhenate in the stagnant porosity of the flow system, as deduced from the second cross-hole tracer test, is potentially one of the most important results from the tracer tests because it implies significant retardation of perrhenate, and by inference

pertechnetate, over large time and distance scales in the alluvium. Given that the mass recovery of perrhenate and iodide were nearly the same at the end of the tracer test, we conclude that if sorption was occurring, it had to be fully reversible over the time scale of the test. Unfortunately, a sorption or retardation mechanism cannot be inferred directly from the field test results. The groundwater at Site 22 contains dissolved oxygen and therefore should not be capable of reducing perrhenate, but the possibility of locally reducing conditions in the stagnant porosity of the flow system cannot be ruled out. However, if reduction of perrhenate occurred, it would have to be followed quickly by oxidation for reversible sorption behavior to be observed.

VII. CONCLUSIONS

The two single-well tracer tests conducted at Nye County Site 22 yielded estimates of specific discharge in the alluvium of 0.55 to 4.7 m/yr, compared to a range of specific discharge estimates of 3.1 to 12.7 m/yr based on natural gradient and hydraulic conductivity estimates at Site 22. Although the single-well tracer tests showed no evidence of tracer diffusion into stagnant water in the alluvium, the cross-hole tracer tests indicated a small amount of diffusion, yielding an estimate of the ratio of stagnant to flowing water volumes of 1.9:1, which would result in an effective retardation factor of 2.9 for nonsorbing tracers over long time and distance scales in the alluvium. The cross-hole tracer tests also yielded flow porosity estimates ranging from 0.076 to 0.118 for the north-south flow direction and 0.27 for the east-west flow direction at Site 22. However, a small fraction of tracer mass (0.03) in the north-south direction in the first cross-hole tracer test had a response that was consistent with an effective flow porosity of 0.016, suggesting that fast flow channels may exist in the alluvium. The tracer mean residence times and effective flow porosities estimated from the cross-hole tracer responses from 22PA to 22S and 22PC to 22S suggest a horizontal flow anisotropy ratio ranging from 2.3:1 to 3.5:1, oriented in the north-south direction.

The iodide and perrhenate responses in the second cross-hole tracer test are consistent with reversible sorption of perrhenate in the stagnant porosity of the flow system. Perrhenate sorption is invoked as a process because the perrhenate response had a lower peak concentration and longer tail than the iodide (consistent with greater diffusion of perrhenate) despite the fact the diffusion coefficient of perrhenate is supposed to be less than that of iodide. The only way this contradiction can be reconciled is by allowing reversible sorption of perrhenate in the stagnant porosity. The implication is that pertechnetate may also exhibit sorbing behavior in the alluvium and may therefore be significantly retarded over large time and distance scales.

ACKNOWLEDGMENTS

This work was supported by the Yucca Mountain Project Office, U.S. Department of Energy, Office of Civilian Radioactive Waste Management. The tracer tests were conducted by the Nye County Early Warning Drilling Program, which will perform its own independent interpretation of the test results.

REFERENCES

1. Reimus P. W., M. J. Haga, A. I. Adams, T. J. Callahan, H. J. Turin, and D. A. Counce. 2003. Testing and parameterizing a conceptual solute transport model in saturated fractured tuff using sorbing and nonsorbing tracers in cross-hole tracer tests, *J. Contaminant Hydrology*, *62-63*, pp. 613-626.
2. Reimus, P., M.J. Umari, R. Roback, J. Earle, J. Darnell, and I. Farnham. 2003. Estimates of Ambient Ground-Water Velocity in the Alluvium South of Yucca Mountain, Nye County, Nevada, from Single-Well Tracer Tests**,** *Proceedings of the 10th International High-Level Radioactive Waste Management Conference*, American Nuclear Society, pp. 102-113.
3. Bechtel-SAIC. 2005. Saturated zone flow and transport model abstraction, *MDL-NBS-HS-000021, Rev. 03*, Bechtel-SAIC Company, Las Vegas, NV.
4. Newman, J. 1973. *Electrochemical Systems.* Prentice-Hall, Englewood Cliffs, New Jersey.
5. Lide, D.R. (ed.) 2000. *CRC Handbook of Chemistry and Physics*. 81st ed. CRC Press, Boca Raton, FL.
6. Reimus, P.W., Haga, M.J., Humphrey, A.R., Counce, D.A., Callahan, T.J., and Ware, S.D. 2002. Diffusion cell and fracture transport experiments to support interpretations of the BULLION forced-gradient experiment. *LA-UR-02-6884*, Los Alamos National Laboratory, Los Alamos, NM.
7. Reimus, P. W., G. Pohll, T. Mihevc, J. Chapman, M. Haga, B. Lyles, S. Kosinski, R. Niswonger, and P. Sanders. 2003. Testing and parameterizing a conceptual model for solute transport in fractured granite using multiple tracers in a forced-gradient test, *Water Resour. Res.*, *39*(12), 14-1,15, doi:10.1029/2002WR001597.
8. NWRPO. 2004. Analysis of Aquifer Pump Tests in Individual Well Zones at Site 22 near Yucca Mountain, Nevada., *NWRPO-2004-02*, Nye County Department of Natural Resources and Federal Facilities, Nuclear Waste Repository Project Office, Pahrump, NV.
9. Umari, M.J., Earle, J.D. and Fahy, M.F. 2006. *Analysis of single-hole and cross-hole tracer tests conducted by Nye County, Nevada, at the Nye County Early Warning Drilling Program well complex, NC-EWDP-22*. This volume.