Characterization of Crushed Tuff for the Evaluation of the Fate of Tracers in Transport Studies in the Unsaturated Zone

Manuscript Completed: February 1987

Date Published: March 1987

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Prepared for
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN A7150-3

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EXECUTIVE SUMMARY

Results of field-scale (caisson) transport studies under unsaturated moisture and steady and nonsteady flow conditions indicate variability and a lack of conservation of mass in solute transport. The tuff materials used in that study were analyzed for the presence of tracers and of freshly precipitated material to help explain the variability and lack of conservation of mass. Selected tuff samples were characterized by neutron activation analysis for tracer identification, by x-ray diffraction for mineral identification of freshly precipitated material, and by x-ray fluorescence analysis for identification of major and trace elements.

The results of the petrographic and x-ray diffraction analyses indicate no obvious presence of freshly precipitated material that would retard tracer movement. The nonsorbing tracers bromide and iodide were detected at some locations and not at others. Also, bromide was detected at locations where iodide was not and vice versa. The variability in the presence of nonsorbing tracers is attributed to variability in water velocity and the presence of an immobile water phase. Differences between iodide and bromide with respect to location within the caisson are attributed to differences in the dispersivities of the two nonsorbing tracers. The variability in the presence of the sorbing tracer cesium is attributed to variability in water velocity, heterogeneity of sorption sites, and possibly the transport of colloids or particulates containing the adsorbed tracer. The lack of conservation of mass in nonsorbing tracer transport is attributed to variability in water velocity and in retention of tracers in an immobile water phase.

CHARACTERIZATION OF CRUSHED TUFF FOR THE
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ABSTRACT

Results of field-scale (caisson) transport studies under unsaturated moisture and steady and nonsteady flow conditions indicate variability and a lack of conservation of mass in solute transport. The tuff materials used in that study were analyzed for the presence of tracers and of freshly precipitated material to help explain the variability and lack of conservation of mass. Selected tuff samples were characterized by neutron activation analysis for tracer identification, by x-ray diffraction for mineral identification, by petrographic analysis for identification of freshly precipitated material, and by x-ray fluorescence analysis for identification of major and trace elements.

The results of these analyses indicate no obvious presence of freshly precipitated material that would retard tracer movement. The presence of the nonsorbing tracers (bromide and iodide) suggest the retention of these tracers in immobile water. The presence of sorbing and nonsorbing tracers on the tuff at some locations (even cesium at the 415-cm depth) and not at others suggests variability in transport.

INTRODUCTION

The Los Alamos National Laboratory (Los Alamos) has conducted technical support studies to assess siting requirements mandated by the Nuclear Regulatory Commission in 10 CFR Part 61. Field-scale transport studies were conducted under unsaturated moisture conditions and under steady and nonsteady

flow conditions in large caissons located and operated in a natural (field) environment. The data obtained from those studies include moisture content, temperature, flow rate, baseline chemical, tracer influent, and tracer breakthrough data collected during tracer migration studies in Caisson B (Polzer et al. 1986). One of the objectives of those studies was to determine if stopping inflow (creating drainage condition) would have an effect on the concentration of solutes moving through the soil. The results suggest that the period of drainage (when inflow is stopped) caused an increase in tracer concentration on the soil solution at various sampling locations in the soil. Evaporation during drainage and diffusion of the tracers between immobile and mobile water are two phenomena given as possible explanations of the observed results. Fuentes et al. (1986a) found a lack of conservation of mass when comparing the breakthrough curves of solutes from one depth to another in the 3-m by 6-m field experimental caisson. That observation also suggested the presence of the solutes in the immobile water phase. The data also indicated greater variability in the transport of sorbing tracers compared with that of nonsorbing tracers. The greater variability could be due to heterogeneity of sorption sites (Polzer et al. 1986, Polzer et al. 1985, Fuentes et al. 1985, Fuentes et al. 1986b). On the other hand, the precipitation of the sorbing tracers (e.g., strontium) could also account for the variability (Springer and Fuentes 1987).

The objective of this study was to characterize the tuff material from those previous studies as to the presence of tracers and freshly precipitated material in the tuff; that presence may help to explain the variability and lack of conservation of mass in the above studies. Therefore, selected tuff samples were characterized by neutron activation analysis for tracer identification, by x-ray diffraction for mineral identification, by

petrographic analysis for indication of freshly precipitated material, and by x-ray fluorescence analysis for identification of major and trace elements.

MATERIALS AND METHODS

Crushed tuff samples were collected at four depths in Caisson B, the site of the transport studies. The depths were 36, 113, 264, and 415 cm and correspond to the locations where porous hollow fiber solution samplers were installed as discussed by Fuentes et al. (1987) for a ponding and spatial variability study conducted in 1986. Figure 1 is a schematic of the cluster of caissons that includes Caisson B. The reference coordinates and the point of origin O are also given. The surface of the tuff at the intersection of Caisson B with the access caisson is the origin of the references coordinates. The sampling locations were determined by random selection within each quadrant at each depth. Figures 2 through 6 show cross-sectional schematics of the caisson quadrants and the locations at the five depths (access ports B8, B7, B5, B3, and B2). Table I gives the x, y, and z coordinates for those locations.

A 2.0-cm-i.d. tube (King sampler) was used to core holes from the access ports. The cored tuff materials were collected in 15-cm intervals. At ports B7, B5, B3, and B2, the tuff was cored on a horizontal plane. Coring was accomplished by using a hydraulic jack (5-ton capacity) with adjustable 10- by 10-cm beams of wood between the hydraulic jack and the coring tube. The coring tube was placed on an adjustable table (Appendix) in order to maintain the desired x and y angles for coring. Each time a 15-cm interval was reached, the tube sampler was retrieved and each core segment was photographed at different light settings. A color chart and sample identification are included in the photographs (Appendix). No visual color or morphological

differences were observed among the cored samples. The core samples were then placed in tared glass jars and sealed with lids and parafilm liners. The tared glass jars and soil samples were then weighed and the wet soil weights were calculated. The samples were then stored in a laboratory refrigerator at 5°C. Core samples taken at the 113-, 264-, and 415-cm depths were collected from inside the access caisson through ports B7, B5, and B3, respectively. The tuff cores collected from the 36-cm depth were cored from the surface of the caisson. These samples were taken in 12-cm intervals to the final depth of 36 cm. Tuff samples were also collected from a hole augered at port B2 (550-cm depth).

Samples from eight of the cored locations and a sample from the augered hole were selected for characterization. A tuff sample not used in the previous studies was also analyzed for background comparisons. That background sample was preconditioned with 0.01 N CaCl_2 solution similar to the preconditioned material in the caisson. The procedure for selection of the soil samples was as follows. First, two of the quadrants from each depth were randomly chosen for sample selection. Next, the 15-cm increment nearest the end of the cored hole (sampler location) was submitted for mineralogic and elemental analyses. The adjacent 15-cm increment was then selected for neutron activation analysis. The samples selected for characterization are described by port number (B8), quadrant (Q2), sample type (core), and location (according to x and y coordinates) in Tables II and III.

For mineralogic and elemental analyses, splits of the samples were dried, mounted in rings, impregnated with epoxy, and made into 30-micron-thick, polished thin sections for petrographic and scanning electron microscopic (SEM) analysis. Petrographic analyses were performed on the samples to check for any apparent alterations. Portions of the remaining samples were ground

in a shatterbox to less than 100 microns. Splits of the ground samples were made into X-ray Fluorescence (XRF) fused discs at temperatures of 1150°C to 1180°C. The fused discs were then run on a Rigaku XRF spectrometer to analyze for major and trace element compositions. The remaining splits of the samples were ground (with acetone as a lubricant) to less than 5 microns. These samples were run on a Siemens x-ray diffractometer to determine the minerals present. Lack of mineralogic, elemental, and petrographic variations between samples alleviated the necessity to do any SEM analyses.

For neutron activation analysis, tuff samples were air dried to constant weight and ground gently with a mortar and pestle. Approximately 250 mg of samples were encapsulated in small polyethylene capsules for irradiation with either the thermal (cesium, strontium) or epithermal (bromide, iodide) neutrons. Samples were irradiated four at a time in a thermal neutron flux of $1 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$ at the Los Alamos Omega West reactor. Following three weeks' decay, these samples were counted individually for 4000 s at the face of large Ge(Li) detectors multiplexed to 4096-channel pulse-height analyzers. Gamma ray spectra were stored on Digital Equipment Corp. (DEC) RL02 discs for off-line data reduction using a DEC VAX-11/730 and GAMS spectral analysis program. The 796-keV and 514-keV lines were used for determination of cesium and strontium, activated ^{134}Cs and ^{85}Sr , respectively (Gladney et al. 1980a and Gladney et al. 1984a).

Separate aliquots of the samples were irradiated individually in a boron-filtered epithermal flux of $5 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$ at the Los Alamos Omega West reactor. Following a 10-min decay period, these samples were counted for 10 min at 5-cm distance from a large Ge(Li) detector coupled to a 4096-channel pulse height analyzer. Data were reduced manually directly on the CRT display screen of the analyzer. The 442-keV and the 617-keV lines were used for

determination of ^{128}I and ^{82}Br , respectively (Gladney and Perrin 1979 and Gladney et al. 1980b).

All activation determinations were standardized against known quantities of the elements of interest in aqueous solution. The solution was pipetted onto Whatman 41 filter papers and allowed to air dry before it was packaged in small polyethylene vials. For thermal activation, samples and standards were irradiated simultaneously. For epithermal activation, standards were interspersed at uniform intervals among the samples. For both neutron irradiation types, quality assurance was provided by concurrent analysis of NBS Standard Reference Materials 688 (basalt) and 1646 (estuarine sediment). These results compared well with NBS certified values or consensus values established in the literature (Gladney et al. 1984b and Gautier and Gladney 1986).

RESULTS AND DISCUSSION

Neutron Activation Analysis

The concentrations of tracers in the tuff samples are given in Table IV. The data indicated detectable quantities of bromide and iodide at the 36-, 246-, and 550-cm depths. However, iodide was not detected in quadrant 4 at the 36-cm depth and bromide was not detected in quadrant 3 at the 264-cm depth. Cesium was detected in samples at all depths and strontium was detected in all but two samples -- one from quadrant 4 at the 36-cm depth and one from quadrant 3 at the 264-cm depth.

Bromide and iodide are not expected to occur naturally in the Bandelier Tuff at the levels of detection of the neutron activation technique; however, naturally occurring cesium and strontium are detectable as indicated in Table V. The results of analysis from 26 background tuff samples indicate an

average concentration of $2.5 \pm 0.2 \text{ mg kg}^{-1}$ for cesium and $25 \pm 7 \text{ mg kg}^{-1}$ for strontium. The correction of the cesium results in Table IV for background indicates that cesium occurs above natural levels only at the 36-, 113-, and 415-cm (quadrant 1) depths. Greater than background levels at the 36- and 113-cm depths were expected, but not at the 264-cm depth, because of cesium's slow transport (large retardation). On the other hand, the concentrations of strontium in the soil samples, within the uncertainties of the measurement, were not greater than those of naturally occurring strontium. This conclusion is also supported by x-ray fluorescence data that will be discussed later.

The above results suggest variability in cesium transport within the soil profile. Transport of strontium may also have exhibited variability, but because of background concentrations, variability could not be detected. Several phenomena could account for the variability in the presence of sorbing tracers such as cesium. These phenomena include heterogeneity of sorption sites (Polzer et al. 1985), variability in water velocity, and movement of particulates or colloids containing adsorbed tracers. Because of the kinetics of chemical (sorptive) processes, a variability in water velocity can influence the distribution of sorbing tracers (Akratanakul et al. 1983). Modeling efforts by various investigators indicate variability in water velocity in these caisson experiments (Springer and Fuentes 1987).

The fact that bromide and iodide were detected in some of the tuff samples suggests that some of the nonsorbing tracers added to the caisson were retained in the tuff and that their retention was spatially variable. The bromide and iodide detected in the tuff samples can be assumed to be associated with the water phase and thus their concentrations can be estimated from the soil moisture content. The above assumption is based on laboratory column studies in which the breakthrough of iodide was shown to trace the

breakthrough of tritium when they are being transported through Bandelier Tuff (Essington et al. 1986). The modeling of those breakthroughs indicate similar dispersion coefficients and retardation factors (Essington et al. 1986). Tritium traces the movement of water; therefore, those similarities suggest iodide also traces the movement of water. A comparison of the modeling of bromide and iodide transport indicates similar retardation factors ($R = 1$) but slightly different dispersion coefficients (Fuentes et al. 1986). A retardation factor of 1 indicates that bromide and iodide are conservative (nonsorbing) tracers. The concentrations of bromide and iodide estimated from the moisture content are given in Table VI. The highest concentration was estimated to be 28 mg L^{-1} for iodide and 11 mg L^{-1} for bromide. Both bromide and iodide are nonsorbing tracers (retardation factor = 1) and are expected to behave similarly. However, relative differences in their concentrations in the soil suggest their transport behavior may be different. That difference may be due to differences in transport dispersivities. The variability of the presence of a nonsorbing tracer can be explained by variability in water flow. As mentioned above, modeling efforts by various investigators indicate variability in water velocity in these caisson experiments. The overall results in Table VI suggest that a significant quantity of nonsorbing tracers was retained within the tuff and that retention could possibly account for the lack of conservation of mass in the breakthrough curves from pulse additions. This conclusion is also supported by the fact that during drainage the concentrations increase to above the ambient concentrations established before drainage (Polzer et al. 1986, Essington et al. 1986); during drainage the tracers can diffuse from the immobile water phase to the mobile water phase, thus increasing their concentrations in the mobile water. This concept implies a different diffusion environment during drainage than during steady flow.

Mineralogic and Elemental Analyses

X-ray diffraction patterns are given in Figures 7 and 8 for the background and the B3 samples, respectively. Percentages of the mineralogic composition for the respective samples are given in Table VII. The results indicate that the tuff material is composed primarily of plagioclase and potassium feldspars (68% to 69%) with significant amounts of tridymite (14% to 22%) and quartz (10% to 16%). Relative differences in composition between the background and caisson samples are attributed to variability of composition and not to transport effects. The x-ray diffraction patterns as well as petrographic observations indicate no precipitation of fresh material on the tuff surface.

The x-ray fluorescence data are given in Table VIII (major elemental percentages) and in Table IX (concentrations of trace elements). Those results indicate no significant differences detected between the background tuff and the tuff from Caisson B. Those results also suggest no obvious precipitation of fresh material on the tuff surface. The strontium concentrations (Table IX) compare well with the neutron activation results (Table IV) and indicate no obvious precipitation of strontium in Caisson B.

SUMMARY AND CONCLUSIONS

Field-scale studies of nonsorbing and sorbing tracer transport under unsaturated moisture and steady and nonsteady flow conditions were conducted in Caisson B. The nonsorbing tracers were bromide and iodide and the sorbing tracers were cesium and strontium. Processes that could account for the variability and the lack of conservation of mass include precipitation of the tracers and retention of tracers in immobile water. In order to evaluate

those processes, selected tuff samples taken after tracer transport were characterized by several techniques that could signal the presence of tracers. Neutron activation was used to analyze for the tracers in the tuff; x-ray diffraction, to identify minerals; petrography, to identify freshly precipitated material; and x-ray fluorescence, to identify and quantify major and trace chemical elements.

The results of the above analyses indicate no obvious presence of freshly precipitated material that would retard tracer movement. The presence of the nonsorbing tracers bromide and iodide suggest the retention of these tracers in immobile water. The presence of sorbing and nonsorbing tracers on the tuff at some locations (even cesium at the 415-cm depth) and their absence at others suggest spatial variability in transport. The variability of the presence of nonsorbing tracers can be explained by variability in water flow. Modeling efforts by various investigators indicate variability in water velocity in these caisson experiments (Springer and Fuentes 1987). The variability in the presence of sorbing tracers could be explained by heterogeneity of sorption sites (Polzer et al. 1985), by variability in water flow, and by movement of particulates or colloids containing adsorbed tracers. Because of the kinetics of chemical (sorptive) processes, a variability in water velocity can influence the distribution of sorbing tracers (Akratanakul et al. 1983).

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TABLE I
X, Y, AND Z COORDINATES FOR PRIMARY TUFF SAMPLE
LOCATIONS IN CAISSON B

Sample ID	Sampling Coordinates (cm)		
	(x)	(y)	(z)
B8Q1	22.86	220.98	-36.0
B8Q2	-22.86	220.98	-36.0
B8Q3	-38.10	83.82	-36.0
B8Q4	22.86	83.82	-36.0
B7Q1	38.10	190.50	-113.0
B7Q2	-83.82	220.98	-113.0
B7Q3	-38.10	114.30	-113.0
B7Q4	83.82	129.54	-113.0
B5Q1	38.10	175.26	-264.0
B5Q2	-22.86	190.50	-264.0
B5Q3	-22.86	53.34	-264.0
B5Q4	68.58	114.30	-264.0
B3Q1	53.34	175.26	-415.0
B3Q2	-83.82	205.74	-415.0
B3Q3	-22.86	144.78	-415.0
B3Q4	38.10	38.10	-415.0
B2	0.00	150.00	-550.0

TABLE II
MINERALOGIC AND ELEMENTAL CHARACTERIZATION SAMPLES

Sample ID	Sample Type	Horizontal Distance from Reference Coordinate (o,o,z) to Sampling Increment Locations (cm)	Depth (z) (cm)
B8Q4	core	12-24	-36
B8Q3	core	24-36	-36
B3Q1	auger	15-25	-415

TABLE III
NEUTRON ACTIVATION CHARACTERIZATION SAMPLES

Sample ID	Sample Type	Horizontal Distance from Reference Coordinates (o,o,z) to Sampling Increment Locations (cm)	Depth (z) (cm)
B8Q4	core	12-24 ^a	-36
B8Q3	core	24-36 ^b	-36
B7Q2	core	210-225	-113
B7Q3	core	90-105	-113
B5Q2	core	165-180	-264
B5Q3	core	30-45	-264
B3Q1	core	150-165	-415
B3Q2	core	195-210	-415
B2 sand/tuff interface	auger	140-150	-550

^aVertical distance from Cartesian coordinates 22.86, 83.82, 0.00.

^bVertical distance from Cartesian coordinates -38.10, 83.82, 0.00.

TABLE IV
CONCENTRATIONS OF TRACERS IN THE BANDELIER TUFF OF CAISSON B^a

Sample ID	Concentration (mg kg ⁻¹ soil)				
	Br		I	Cs	Sr
B8Q3	0.2 ± 0.2	LT ^b	0.67 ± 0.2	4.6 ± 0.7	45 ± 17
B8Q4	1.7 ± 0.3		<0.1	4.2 ± 0.6	6 ± 18 LT
B7Q2	<0.2	LT	<0.1	6.4 ± 1.0	21 ± 13
B7Q4	<0.2	LT	<0.1	5.7 ± 0.9	15 ± 13
B5Q2	0.6 ± 0.2		1.8 ± 0.3	2.6 ± 0.4	23 ± 16
B5Q3	<0.2	LT	0.6 ± 0.2	2.5 ± 0.4	12 ± 13 LT
B3Q1	<0.2	LT	<0.1	6.6 ± 1.0	38 ± 16
B3Q2	<0.2	LT	<0.1	2.5 ± 0.4	19 ± 12
B2	6.9 ± 0.6		0.6 ± 0.1	2.2 ± 0.4	35 ± 15

^aConcentrations determined by neutron activation analysis.

^bLT = Less than detectable; ± values represent uncertainty.

TABLE V

NATURALLY OCCURRING LEVELS OF CESIUM AND
STRONTIUM IN BANDELIER TUFF OF CAISSON B^a

Sample Replication	Concentration (mg kg ⁻¹ soil)	
	Cs	Sr
1	2.7 ± 0.3	31 ± 6
2	2.4 ± 0.3	28 ± 6
3	2.5 ± 0.3	27 ± 6
4	2.4 ± 0.2	28 ± 6
5	2.5 ± 0.3	21 ± 5
6	2.3 ± 0.2	7 ± 6
7	2.9 ± 0.3	19 ± 5
8	2.6 ± 0.3	25 ± 6
9	2.6 ± 0.3	36 ± 6
10	2.4 ± 0.3	27 ± 6
11	2.3 ± 0.2	18 ± 5
12	2.4 ± 0.3	18 ± 5
13	2.4 ± 0.3	18 ± 4
14	2.8 ± 0.3	16 ± 4
15	2.6 ± 0.3	25 ± 6
16	2.5 ± 0.3	28 ± 6
17	2.2 ± 0.2	21 ± 5
18	2.6 ± 0.3	28 ± 5
19	2.8 ± 0.3	22 ± 5
20	2.6 ± 0.3	37 ± 7
21	2.6 ± 0.3	29 ± 7
22	2.4 ± 0.3	33 ± 6
23	2.5 ± 0.3	28 ± 6
24	2.5 ± 0.3	19 ± 7
25	2.3 ± 0.2	20 ± 5
26	2.3 ± 0.2	29 ± 6
Mean ± std error	2.5 ± 0.2	25 ± 7

^aConcentrations determined by neutron activation analysis.

TABLE VI

ESTIMATED CONCENTRATIONS OF BROMIDE AND IODIDE IN
THE SOIL MOISTURE OF BANDELIER TUFF OF CAISSON B

Sample ID	Soil ^a Moisture Content (%)	Concentration (mg L ⁻¹ solution)			
		Br		I	
B8Q3	13.5	1.5	LT ^b	5.0	
B8Q4		13		0.7	LT
B7Q2	15.4	1.3	LT	0.6	LT
B7Q4		1.3	LT	0.6	LT
B5Q2	16.8	3.6		11	
B5Q3		1.2	LT	3.6	
B3Q1	20.5	1.0	LT	0.5	LT
B3Q2		1.0	LT	0.5	LT
B2	25	28		2.4	

^aMoisture content estimated from average moisture readings taken 6-3-86 with neutron moisture probe.

^bLT is less than detectable (limit of detection).

TABLE VII
X-RAY DIFFRACTION DATA

Mineral	Composition (%)	
	Background	B3Q1
Quartz	10 ± 1	16 ± 1
Tridymite	22 ± 2	14 ± 1
Hematite	Trace	Trace
Feldspar (Plagioclase + Orthoclase)	68 ± 15	69 ± 13
Total	100 ± 15	99 ± 13

TABLE VIII
MAJOR ELEMENTAL COMPOSITION OF BANDELIER TUFF
DETERMINED BY X-RAY FLUORESCENCE

Composition (%)									
Element	Background		B3Q1		B8Q3		B8Q4		Uncertainty
SiO ₂	76.1	76.1	77.4	77.6	77.3	77.6	77.0	76.8	0.3
TiO ₂	0.13	0.13	0.11	0.10	0.11	0.11	0.11	0.11	0.02
Al ₂ O ₃	11.9	11.9	11.3	11.0	11.2	10.9	11.1	11.2	0.4
P ₂ O ₃	1.5	1.9	1.9	1.4	1.9	1.5	1.8	1.6	0.5
MnO	0.07	0.07	0.06	0.05	0.06	0.05	0.05	0.05	0.01
MgO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
CaO	0.38	0.37	0.31	0.31	0.34	0.34	0.41	0.39	0.06
K ₂ O	4.40	4.39	4.17	4.19	3.92	3.91	3.91	3.87	0.04
Na ₂ O	4.0	4.0	3.8	3.8	2.9	3.0	3.0	2.9	0.2
P ₂ O ₅	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Total	98.5	98.9	99.1	98.5	97.7	97.4	97.4	96.9	

TABLE IX
TRACE ELEMENT CONCENTRATIONS IN BANDELIER TUFF
DETERMINED BY X-RAY FLUORESCENCE

Concentration (mg kg ⁻¹ soil)										
Element	Background		B3Q1		B8Q3		B8Q4		LLD ^a	
Ba	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	362	
Rb	131	142	126	94	103	109	104	113	75	
Sr	27	26	11	23	33	27	27	33	25	
V	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	120	
Cr	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	<LLD	54	
Ni	<LLD	<LLD	<LLD	<LLD	133	<LLD	<LLD	<LLD	85	
Zn	72	72	74	69	52	44	58	61	37	
Y	44	48	43	34	34	41	53	56	18	
Nb	-	-	-	-	51	45	57	66	32	

^aLower limit detection.

A-F EXPERIMENT CAISSON
G INSTRUMENT AND ACCESS CAISSON

Figure 1. Plan view of the cluster of caissons showing the origin and the reference coordinate system in Caisson B. The origin of the reference coordinate system is the surface of the tuff at the point that Caisson B intersects the access caisson.

Figure 2. Cross-sectional schematic of Caisson B showing the general locations of tuff samples at the 36-cm (B8) depth. More detailed descriptions are given in Tables I, II, and III.

Figure 3. Cross-sectional schematic of Caisson B showing the general locations of tuff samples at the 113-cm (B7) depth. More detailed descriptions are given in Tables I and III.

Figure 4. Cross-sectional schematic of Caisson B showing the general locations of tuff samples at the 264-cm (B5) depth. More detailed descriptions are given in Tables I and III.

Figure 5. Cross-sectional schematic of Caisson B showing the general locations of tuff samples at the 415-cm (B3) depth. More detailed descriptions are given in Tables I, II, and III.

Figure 6. Cross-sectional schematic of Caisson B showing the general locations (solid circle) of tuff samples at the 550-cm (B2) depth. More detailed descriptions are given in Tables I and III.

Figure 7. An x-ray diffraction pattern of a background sample of Bandelier Tuff. The sample was preconditioned with 0.001 N CaCl_2 solution. The observed peaks are indicative of the minerals quartz (Q), tridymite (T), and feldspar (F). Only the major peaks of each mineral are designated.

Figure 8. An x-ray diffraction pattern of a sample of Bandelier Tuff (B3R, 15 to 25 cm). Refer to Table II for sample location. The observed peaks are indicative of the minerals quartz (Q), tridymite (T), and feldspar (F).

APPENDIX

PHOTOGRAPHS SHOWING THE CORING TABLE AND SOIL CORE SAMPLES

Figure A-1. View of coring setup and access port to Caisson B. The table was designed to adjust the coring angle to obtain samples from specific locations.

Figure A-2. View of coring setup and access port to Caisson B. The 10- by 10-cm beam provided an adjustable length between the coring tube and a hydraulic jack to obtain 15-cm increments of tuff sample.

Figure A-3. View of a cored tuff sample from Q3 of Caisson B. The sample was collected at an incremental distance of 12 to 24 cm from the tuff surface. The x and y coordinates of the sample location are given in Table I. The color chart was used to identify potential color differences between and within samples.

Figure A-4. View of a cored tuff sample from Q2 of Caisson B at port B7. The sample was collected at the incremental distance of 225 to 233.6 cm from the access port. The x, y, and z coordinates of the sample location are given in Table I. The color chart was used to identify potential color differences between and within samples.

Figure A-5. View of a cored tuff sample from Q3 of Caisson B at port B5. The sample was collected at the incremental distance of 30 to 45 cm from the access port. The x, y, and z coordinates of the sample location are given in Table I. The color chart was used to identify potential color differences between and within samples.

Figure A-6. View of a cored tuff sample from Q2 of Caisson B at port B3. The sample was collected at the incremental distance of 195 to 210 cm from the access port. The x, y, and z coordinates of the sample location are given in Table I. The color chart was used to identify potential color differences between and within samples.

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NRC FORM 335 (2-84) NRCM 1102, 3201, 3202 BIBLIOGRAPHIC DATA SHEET SEE INSTRUCTIONS ON THE REVERSE		U.S. NUCLEAR REGULATORY COMMISSION 1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any) NUREG/CR-4875 LA-10962-MS	
2 TITLE AND SUBTITLE Characterization of Crushed Tuff for the Evaluation of the Fate of Tracers in Transport Studies in the Unsaturated Zone		3 LEAVE BLANK	
5 AUTHOR(S) W. L. Polzer, H. R. Fuentes, R. Raymond, D. L. Bish, E. S. Gladney, and E. A. Lopez		4 DATE REPORT COMPLETED MONTH YEAR February 1987	
		6 DATE REPORT ISSUED MONTH YEAR March 1987	
7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Los Alamos National Laboratory Los Alamos, NM 87545		8. PROJECT/TASK/WORK UNIT NUMBER	
		9. FIN OR GRANT NUMBER A7150-3	
10 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Waste Management Office of Nuclear Material Safety and Safeguards U. S. Nuclear Regulatory Commission Washington, D. C. 20555		11a. TYPE OF REPORT Technical b. PERIOD COVERED (Inclusive dates)	
12 SUPPLEMENTARY NOTES			
13 ABSTRACT (200 words or less) <p>Results of field-scale (caisson) transport studies under unsaturated moisture and steady and nonsteady flow conditions indicate variability and a lack of conservation of mass in solute transport. The tuff materials used in that study were analyzed for the presence of tracers and of freshly precipitated material to help explain the variability and lack of conservation of mass. Selected tuff samples were characterized by neutron activation analysis for tracer identification, by x-ray diffraction for mineral identification, by petrographic analysis for identification of freshly precipitated material, and by x-ray fluorescence analysis for identification of major and trace elements.</p> <p>The results of these analyses indicate no obvious presence of freshly precipitated material that would retard tracer movement. The presence of the nonsorbing tracers (bromide and iodide) suggests the retention of these tracers in immobile water. The presence of sorbing and nonsorbing tracers on the tuff at some locations (even cesium at the 415-cm depth) and not at others suggests variability in transport.</p>			
14 DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS Tuff Tracers Solute Transport Unsaturated Zone b. IDENTIFIERS/OPEN ENDED TERMS		15 AVAILABILITY STATEMENT Unlimited 16 SECURITY CLASSIFICATION (This page) Unclassified (This report) Unclassified 17 NUMBER OF PAGES 18 PRICE	
		Field-Scale	