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Physical properties of and movement of water in the Bandelier Tuff, Los Alamos and Santa Fe Counties, New Mexico

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Abstract

Radioactive wastes from the Los Alamos Scientific Laboratory near Los Alamos on the Pajarito Plateau in north-central New Mexico are released onto the surface and in the subsurface within the area. In the 1940's liquid wastes were processed for the removal of some radionuclides but the quantity of radioactivity discharged into open infiltration pits on the plateau or into natural drainage in deep canyons were not recorded. After waste treatment plants were built in 1951, supernatant liquids, separated from sludges containing most of the radioactivity, were treated to below off-site tolerances and discharged. The sludges are buried on the plateau after being mixed with concrete or vermiculite and placed in metal barrels.

The Pajarito Plateau is part of the Jemez Mountains volcanic complex. The altitude of the plateau ranges from about 7,800 feet at the base of the Sierra de los Valles on the west to about 6,200 feet at an escarpment overlooking the Rio Grande on the east. The plateau has been dissected by east-west trending canyons as much as 1,000 feet deep.

The plateau is capped by the Bandelier Tuff of Pleistocene age that is at least 1,000 feet thick near the western margin of the plateau and thins eastward to less than 100 feet near White Rock Canyon. The Bandelier Tuff is divided, in ascending order, into the Guaje, Otowi, and Tshirege Members. In much of the plateau, the Tshirege comprises about three-fourths of the thickness of the Bandelier Tuff.

The Santa Fe Group of middle (?) Miocene and Pleistocene (?) age underlies the Bandelier Tuff and forms the main aquifer in the Los Alamos area.

Disposal of radioactivity wastes have been, for the most part, on the surface of or buried in the Tshirege Member. Most of the studies described in this report are with the Tshirege Member of the Bandelier Tuff, and reference to tuff in this report are to the Tshirege unless the Guaje and Otowi Members are mentioned specifically.

The Tshirege Member of the Bandelier Tuff contains sub-units that probably are individual beds of tuff. Water moving through the tuff is temporarily perched by variations in vertical permeability. The permeability varies from one bed to another, from one member to another, and from the Bandelier Tuff to underlying beds of the Santa Fe Group.

Joints are common throughout the Tshirege Member. The joints which are not filled with sediments or alteration products may interconnect across the contacts of sub-units and may provide paths for rapid movement of water which negate the effects of differences in the rock permeability. Nuclides in water moving through open joints would have a relatively limited opportunity to be absorbed into the tuff, as compared to nuclides in water that moved through the pores of the tuff.

Most of the gross alpha (plutonium) activity discharged into disposal pits was retained in tuff at a depth less than 15 or 20 feet beneath the bottom of disposal pits, except for isolated areas where water carried the activity through joints to greater depth. There was an inverse relationship between gross alpha activity and the pH of water percolating through the tuff. (Christensen, Thomas, 1961)

The porosity of the tuff ranges from about 20 percent to about 60 percent. The porosity is inversely related to the moisture content at one-third atmospheric tension, which is roughly the average field capacity of the tuff. About 20 to 25 percent of the total pore space transmits most of the water which moves through the tuff. The average permeability is low--about ½ to 6 gallons per day per square foot.

The moisture content after 99 days of infiltration into a pit that ~~penetrated a~~ above one-half foot of a 5-foot thick soil zone over ~~under~~lying tuff ranged from about 39 percent by volume in the soil zone to less than 4 percent within a foot below the top of the underlying tuff. Soil cover reduces the amount of water that would infiltrate the tuff

The moisture content ranged from less than 1 percent by volume in undisturbed tuff to about 26 percent in tuff that was disturbed by man ~~after intermittent infiltration and drainage~~ or nature. The average moisture content of the undisturbed tuff was less than 5 percent.

The moisture content during percolation of water through parts of the tuff that contained few joints or density gradients was in the 25 to 35 percent range. This range is slightly above the median of field capacity and porosity of the tuff. The rate of movement directly into dry tuff averaged about 2 feet per day during the first day, half a foot per day during the next 11 days, and about a tenth of a foot per day during the next 56 days. The moisture content of the tuff during upward capillary movement of water was less than the effective porosity. The temperature of the water, due to seasonal changes, apparently affected the rate of infiltration at the water-tuff interface to the extent that the rate of percolation exceeded the rate of infiltration when the water was near freezing.

Introduction

The Los Alamos area is on the Pajarito Plateau in north-central New Mexico, approximately 25 miles northwest of Santa Fe (fig. 1).

Figure 1.--Index map of New Mexico showing Los Alamos County.

It is mostly in Los Alamos County, but it extends a short distance into Santa Fe County. The area comprises about 30 square miles.

The Pajarito Plateau is part of the Jemez Mountains volcanic complex (fig. 2). The plateau slopes eastward from the Sierra de

Figure 2.--Map of the Los Alamos area showing the locations of sites for studies of the physical properties and water movement in the Bandelier Tuff.

los Valles, which forms the east rim of the Jemez Mountains caldera. The altitude of the plateau ranges from about 7,800 feet on the west side to about 6,200 feet on the east side at the escarpment overlooking the Rio Grande. The plateau has been dissected by deep canyons cut by streams flowing eastward from the Sierra de los Valles to the southward flowing Rio Grande. The canyons are 200 to 400 feet deep in the central and western parts of the plateau but are as much as 800 to 1,000 feet deep at the east side of the plateau where they join White Rock Canyon of the Rio Grande. The canyons are floored by volcanic rocks in the western part of the plateau. In the middle and eastern part of the plateau the canyons are floored by alluvium, in places as much as 80 feet thick. Nearly flat finger-like mesas extend east-southeastward between the canyons. The mesas are narrow, many a half mile wide or less. They have a soil cover as much as 9 feet thick. The soil cover thins eastward as the canyons become wider and the mesas become narrower.

The plateau is mostly forested by Ponderosa pine, Pinon, and Juniper. A clump grass is common in the clearings.

The average annual precipitation is 20 to 25 inches on the western part of the plateau and 12 to 15 inches on the eastern part near the Rio Grande. Precipitation in the central part is 17 to 18 inches. Most of the precipitation occurs during summer thundershowers, when several inches of rain may fall during as many hours. About a quarter of the precipitation occurs during the winter. Some precipitation percolates into the rock on the mesas or into the alluvium in the canyon floors. Some runoff from storms and from snowmelt reaches the Rio Grande.

The Pajarito Plateau is capped by the Bandelier Tuff of Pleistocene age (Griggs, 196_, Water-Supply Paper 1753, in press). The stratigraphic relations of the Bandelier and the rocks underlying the Bandelier are shown diagrammatically on figure 5. The Bandelier

Figure 5.--Diagrammatic cross-section showing generalized stratigraphic relations of the Bandelier Tuff and older rocks in the Los Alamos area.

is about 1,000 feet thick along the western margin of the plateau. The formation laps onto the Tschicoma Formation to the west and thins abruptly; it thins also to the east and is less than 100 feet thick on the east side of the plateau.

The Bandelier Tuff is divided into the Guaje, Otowi, and Tshirege Members, in ascending order. (Griggs, 196_, Water-supply Paper 1753, in press). The Guaje Member consists chiefly of rounded fragments of white, gray, and tan pumice in a glassy matrix; the Otowi Member consists of light-gray, pinkish-tan welded tuff and tuff breccia and beds of pumice fragments; the Tshirege Member is the caprock on the plateau and consists of welded tuff and tuff breccia. The Tshirege Member in much of the plateau comprises at least three-fourths of the thickness of the Bandelier Tuff.

The main ground-water body and aquifer in the Los Alamos area is in the Tschicoma Formation and the Santa Fe Group of middle (?) Miocene to Pleistocene (?) age (fig. 3). The depth to the top of this aquifer is about 1,200 feet beneath the surface in the western part of the Pajarito Plateau, about 1,000 feet beneath the surface near Los Alamos ~~in the middle part of the plateau~~, and 300 to 900 feet below the canyon floors. The piezometric surface of the main aquifer slopes east-southeastward at about 60 to 80 feet per mile. The water in this aquifer moves east-southeastward to ~~its~~ natural discharge points along the Rio Grande valley.

The Bandelier Tuff is above the main aquifer (fig. 3), but ~~in~~ at places the Bandelier ~~it~~ contains perched water (Griggs, 196_, Water-supply Paper 1753, in press). Perched water occurs also in the alluvium in the canyons cut into the Bandelier.

Radioactive wastes from the laboratories near Los Alamos are ~~disposed of to~~ released on the surface and in the subsurface subsurface within the area. The solid wastes, which consist mostly of materials such as metal objects, glassware, and garments, are buried in shallow pits on the mesas. Sludge wastes, obtained by concentrating liquid wastes, also are buried on the mesas after being mixed with concrete or vermiculite and placed in metal barrels. Liquid wastes are supernatant liquids that have been separated from the sludges. The liquid wastes are treated to below off-site tolerance limits and discharged into open infiltration pits on the mesas or into natural drainage channels in the canyons. From the early 1940's until the waste-treatment plants were built about 1951, liquid wastes were not treated, although some were processed for removal of certain nuclides, ~~and~~ the quantities of radioactivity discharged prior to 1951 were not recorded.

Water seeping into the rocks from precipitation and snowmelt could become contaminated with radionuclides from liquid waste in the infiltration pits, ~~and~~ in stream channels on canyon floors, and from buried solid wastes. If this contaminated water reached the main aquifer, the contamination would spread beyond the Los Alamos area. Ground water of the Los Alamos area does not remain stationary, but moves downgradient and becomes a part of the surface and ground water of the Rio Grande valley.

Water percolating into the ground and down toward the main aquifer in the Los Alamos area must pass through the Bandelier Tuff, and that formation probably offers the greatest resistance to water movement of any formation between land surface and the main aquifer. Because the Bandelier is particularly resistant to water movement, the present study was concerned with the hydraulic properties and radionuclide retention characteristics of that formation. Reference to tuff in this report will mean the Tshirege Member unless the Guaje and Otowi Members are mentioned specifically.

The investigation was made by the United States Geological Survey in cooperation with the United States Atomic Energy Commission and the University of California, Los Angeles Scientific Laboratory, to determine the direction and rate of movement of water and radioactive wastes from infiltration pits and the capacity of the surrounding rocks to retain radionuclides. Field studies were made by the Survey during 1958-61. The moisture movement and nuclide retention studies at Site 6 was a cooperative investigation with the Health Division (H-7) of the Los Alamos Scientific Laboratory. Moisture and density measuring equipment were provided and maintained by the Los Alamos Scientific Laboratory. Mr. William D. Purtymun, U. S. Geological Survey, participated in the construction and data collection at most of the sites that were studied.

Physical properties of the Bandelier Tuff

The site numbers, locations, and pertinent information about the study sites are summarized in table 1. The average values of the physical properties of the Bandelier Tuff including some for the Guaje and Otowi Members are summarized in table 1-A. The data contained in table 1 was obtained from physical analysis of samples collected from the various sites. The approximate number of samples collected were:

100 samples from Site 6
80 samples from Site 5 (79 were moisture measurements only)
40 samples from Site 2
32 samples from Site 7 (7 tests made on each sample)
12 samples from Site 8
7 samples from Site 9
6 samples from Site 3
6 samples from Site 1
1 or 2 samples from each of the other sites

Data from Site 6 are used predominantly in the discussion on water retention in the tuff because of the comparatively large number of analyses made and the corresponding statistical control possible. Results of studies at the other sites commonly were parallel to those from Site 6, but generally they were not mathematically significant because of the small number of samples that were collected or because the samples were widely scattered.

Table 1.-Sites investigated

Site No.	1/ Location	Name of Site	Position in stratigraphic column	Description of site	Operation at site
1	NW¼NE¼ sec. 14, T. 19 N., R. 6 E.	Tshirege Tuff boulder in Pueblo Canyon	Tshirege Member of Bandelier Tuff. Stratigraphic position not known	Access holes in boulder embedded in alluvium, with water ponded against base of boulder.	Core samples of tuff collected; neutron meter moisture measurements made during capillary rise of water in boulder.
2	SE¼SE¼ sec. 18, T. 19 N., R. 7 E.	Road cut in lower part of Pueblo Canyon	Lower part of Tshirege Member	Core holes in northeast-facing wall of road cut.	Core samples of tuff collected.
3	NW¼SW¼ sec. 14, T. 19 N., R. 6 E.	Laundry pit	Middle part of Tshirege Member	Several access holes as much as 60 feet deep at different angles beneath a pit used occasionally for disposal of liquid radioactive wastes. Pit partly backfilled with gravel.	Samples of tuff collected and neutron meter moisture measurements made in access hole. Some water from precipitation and possible overflow from other pits.
4	NE¼SW¼ sec. 22, T. 19 N., R. 6 E.	Soil study	Middle part of Tshirege Member	Two infiltration pits about 2 feet in diameter and half a foot deep in soil about 5 feet thick overlying tuff. Five access tubes 3 to 5 feet deep in and around one pit. One access tube 28 feet deep in other.	Unconsolidated samples of tuff collected and neutron meter moisture measurement made in access tubes. Constant head of water in one pit during infiltration studies.
5	E½SW¼ sec. 31, T. 19 N., R. 7 E.	Southeast Mesita del Buey	Lower part of Tshirege Member	Eight access tubes to depths of about 40 feet around an infiltration pit adjacent to the south wall of a 29-foot deep disposal pit.	Unconsolidated samples of tuff collected and neutron meter moisture measurements made. Water into pit metered. Pool three-quarters of a foot deep maintained.
6	NE¼SE¼ sec. 14, T. 19 N., R. 6 E.	DP-West	Middle part of Tshirege Member	Horizontal and slanting access tubes beneath disposal pit backfilled with gravel. Slant holes 75 to 99 feet deep.	Core samples of tuff collected from horizontal holes. Unconsolidated samples of tuff collected from slant holes. Neutron meter moisture measurements made and sample of liquid wastes collected during and after infiltration of raw wastes and of tap water.
7	NW¼ sec. 3 and NE¼ sec. 4, T. 18 N., R. 6 E.	TA-49	Depth from 0 - 90 feet upper part of Tshirege Member. Depth from 90 - 275 feet middle part of Tshirege	Numerous holes in area about half mile in diameter. Most of the holes (commonly 6 feet in diameter) were less than 100 feet deep, but some small-diameter holes were as much as 275 feet deep.	Many core samples of tuff collected. Fractures in walls of hole were mapped.
8	NW¼NW¼ sec. 36, T. 19 N., R. 6 E.	Northwest Mesita del Buey	Lower part of Tshirege Member	One hole 6 feet in diameter and about 60 feet deep.	Some chunk samples of tuff collected and walls of hole inspected
9	Near cen. S½S½ sec. 23, T. 19 N., R. 6 E.	Beta hole	Middle part of Tshirege Member	One hole 6 feet in diameter and about 40 feet deep.	Some chunk samples of tuff collected.

10	$NW\frac{1}{4}SW\frac{1}{4}$ sec. 22, T. 19 N., R. 6 E.	TA-50	Middle part of Tshirege Member	Rectangular pits up to 20 feet deep for construction of building.	One chunk sample of tuff collected.
11	$SW\frac{1}{4}SE\frac{1}{4}$ sec. 9 and $N\frac{1}{2}N\frac{1}{2}$ sec. 16, T. 19 N., R. 6 E.	Acid Canyon	Middle part of Tshirege Member	Canyon floor and walls.	Three sets of core samples of tuff collected
12	$SW\frac{1}{4}SE\frac{1}{4}$ sec. 13, T. 18 N., R. 6 E.	TA-33	Lower part of Tshirege Member	Small pit into which small quantities of radioactive waste had been discharged.	Unconsolidated samples of tuff collected to depth of 12 feet beneath pit.
13	$NE\frac{1}{4}NE\frac{1}{4}$ sec. 20, T. 19 N., R 6 E.	Near Administration building	Upper part of Tshirege Member	Bore holes for foundation investigation.	Core samples of tuff collected by contractor.
14	$SE\frac{1}{4}NE\frac{1}{4}$ sec. 17, T. 19 N., R. 6 E.	Beneath bridge on Diamond Drive	Middle part of Tshirege Member	North wall of Los Alamos Canyon	Two core samples of tuff collected.
15	$SE\frac{1}{4}SE\frac{1}{4}$ sec. 9, T. 19 N., R. 6 E.	Lower part Acid Canyon	Alluvium on Otowi Member of Bandelier Tuff	Seep area downstream from contact of Tshirege and Otowi Members	Visited site numerous times to observe seep.
16	$NW\frac{1}{4}NW\frac{1}{4}$ sec. 20, T. 19 N., R. 7 E.	Otowi	Middle part of Otowi Member	South wall of Pueblo Canyon	One core sample of tuff collected.
17	$SW\frac{1}{4}NW\frac{1}{4}$ sec. 18, T. 19 N., R. 7 E.	Pueblo Canyon Site A	Contact of Guaje Member of Bandelier Tuff and Puye Conglomerate	In dry streambed	Two samples of tuff collected from Guaje Member near base and two samples of tuff collected from Puye Conglomerate near top.
18	$NW\frac{1}{4}SE\frac{1}{4}$ sec. 19, T. 19 N., R. 7 E.	Pueblo Canyon Site B	Contact of Guaje Member and Puye Conglomerate	In dry streambed	Two samples of tuff collected from Guaje Member near base and two samples of tuff collected from Puye Conglomerate near top.
19	$SW\frac{1}{4}NW\frac{1}{4}$ sec. 18, T. 19 N., R. 7 E.	Pueblo Canyon Site C	Contact of silt bed and underlying alluvium on canyon floor	Intermittent flow in streambed	Samples collected at base of silt and in underlying alluvium.

1/ Site numbers and locations shown on figure 2.

Table 1-A.--Physical properties of Bandelier Tuff collected at 18 sites

and alluvium at one site on the Pajarito Plateau.

(Values given are average for each site.)

Site No.	Site name	Moisture content, in percent by volume	Dry Unit weight, in gm per cc	Specific gravity, rounded to nearest hundredth	Moisture content at one-third atmosphere tension in percent by volume	Specific retention in percent by volume	Total porosity ~~(avg)~~	Specific yield in percent by volume	Coefficient of permeability (gal per day per foot/ per foot) vertical	Coefficient of permeability (gal per day per foot/ per foot) horizontal
1	Tshirege Tuff boulder in Pueblo Canyon	5.4	1.63	-	23.9	-	a/ 35.8	-	-	-
2	Road cut in lower part of Pueblo Canyon	4.3	1.28	2.55	21.2	7.1	49.8	42.4	9.0	11.0
3	Laundry pit	24.9	1.44	2.56	21.0	12.6	43.7	32.9	1.7	.7
4	Soil Study	<1.0	-	-	b/ 14.5	-	-	-	-	-
5	Southeast Mesita del Bucy	1.0	1.30	2.55	b/ 14.7	-	49.0	-	-	-
6	DP-West	23.1	1.47	2.56	20.6	16.7	42.1	25.8	2.6	6.5
7	TA-49 Depth, 0-90 feet	2.1	1.34	2.57	33.4	19.0	48.7	29.0	2.8	3.4
7	Depth, 90-275 feet c/	1.2	1.84	2.55	-	16.7	27.9	-	.4	-

Table 1-A.--Physical properties of Bandelier Tuff collected at 18 sites and alluvium at one site on the Pajarito Plateau. (Continued)

Site No.	Site name	Moisture content, in percent by volume	Dry Unit weight, in gm per cc	Specific gravity, rounded to nearest hundredth	Moisture content at one-third atmosphere tension in percent by volume	Specific retention in percent by volume	Total porosity	Specific yield in percent by volume	Coefficient of permeability (gal per day per foot/ per foot) vertical	Coefficient of permeability (gal per day per foot/ per foot) horizontal
8	Northwest Mesita del Buey	-	1.50	2.55	14.4	12.5	d/ 41.3	28.8	3.8	-
9	Beta hole depth 0-20 feet	0.6	1.44	2.56	14.5	12.0	43.6	31.6	4.0	-
9	Beta hole depth 20-40 feet	.4	1.31	2.56	24.3	11.6	49.1	37.5	21.0	-
10	TA-50	-	1.57	2.56	-	-	38.7	27.1	2.0	-
11	Acid Canyon depth 0-1 feet below floor	7.4	-	-	-	-	-	-	-	-
11	Acid Canyon 5 feet below rim	7.6	-	-	-	-	-	-	-	-
11	Acid Canyon 0-5 feet below rim	12.7	-	-	-	-	-	-	-	-

Table 1-A.--Physical properties of Bandelier Tuff collected at 18 sites and alluvium at one site on the Pajarito Plateau. (Continued)

Site No.	Site name	Moisture content, in percent by volume	Dry Unit weight, in gm per cc	Specific gravity, rounded to nearest hundredth	Moisture content at one-third atmosphere tension *in percent by volume*	Specific retention in percent by volume	Total porosity	Specific yield in percent by volume	Coefficient of permeability (gal per day per foot/ per foot)	
									vertical	horizontal
12	TA-33 depth 0-7 feet	16.0	-	-	-	-	-	-	-	-
12	Depth 7-12 feet	5.3	-	-	-	-	-	-	-	-
13	Near Administration building;[e] depth 0-10 feet	16.5	-	-	-	-	-	-	-	-
13	Near Administration building;[e] depth 10-20 feet	10.4	-	-	-	-	-	-	-	-
14	Beneath bridge across upper Los Alamos Canyon	-	-	-	-	-	59.3	-	5.3	-

Table 1-A.--Physical properties of Bandelier Tuff collected at 18 sites and alluvium at one site on the Pajarito Plateau. (Continued)

Site No.	Site name	Moisture content, in percent by volume	Dry Unit weight, in gm per cc	Specific gravity, rounded to nearest hundredth	Moisture content at one-third atmosphere tension in percent by volume	Specific retention in percent by volume	Total porosity	Specific yield in percent by volume	Coefficient of permeability (gal per day per foot per foot)	
									vertical	horizontal
15	Lower part Acid Canyon (observations only)	-	-	-	-	-	-	-	-	-
16	[f] Otowi	-	1.19	2.42	-	-	50.8	-	-	-
17	Pueblo Canyon site A-Base of Guaje	60.8	-	-	-	-	-	-	-	-
17	Pueblo Canyon site A-Top of Puye	34.2	-	-	-	-	-	-	-	-
18	Pueblo Canyon site B-Base of Guaje	30.6	-	-	-	-	-	-	-	-
18	Pueblo Canyon site B-Top of Puye	16.0	-	-	-	-	-	-	-	-

Table 1-A.--Physical properties of Bandelier Tuff collected at 18 sites

and alluvium at one site on the Pajarito Plateau. (Continued)

Site No.	Site name	Moisture content, in percent by volume	Dry Unit weight, in gm per cc	Specific gravity, rounded to nearest hundredth	Moisture content at one-third atmosphere tension in percent by volume	Specific retention in percent by volume	Total porosity	Specific yield in percent by volume	Coefficient of permeability (gal per day per foot/ per foot) ver-tical	hori-zontal
19	Pueblo Canyon site C-Base of silt bed	22	-	-	-	-	-	-	-	-
19	Pueblo Canyon site C-Alluvium below silt bed	12	-	-	-	-	-	-	-	-

a/ Effective porosity 32.7 percent
b/ Repacked-bulk
c/ Most samples from 200-275 foot intervals
d/ Effective porosity 39.4 percent
e/ Values of contractors
f/ Otowi Member of Bandelier Tuff

Porosity

Porosity is the ratio of the volume of the void spaces to the total volume of the rock or aggregate sample. The porosity of the Tshirege Member is as much as 60 percent in some zones, which is within the upper porosity range of fine clays. Such high porosity is unusual for consolidated sediment; however, samples of tuff collected ~~from the Tshirege~~ only a short distance vertically from zones of high porosity had porosities as low as 20 percent, which is within the range of many consolidated materials. The average porosities at study sites where three or more samples were collected ranged from 27.9 to 49.8 percent. An analysis of the variance of the porosity values indicates that the four different average groups of percentages, 27.9, 35.8, 42.1, and 43.7, and 48.7, and 49.8 (table 1-A) are significantly different at the 1 percent level. There is a difference of about 6 to 8 percent between groups, which may be of no significance.

The standard deviations (Snedecor, 1946, p. 36) show that the range of porosity values of the samples collected at most sites was relatively small. The ~~maximum~~ range of porosities was 36.2 to 48.0 percent for 38 porosity determinations at Site 6, but most porosity determinations were 42.1 percent, plus or minus 2.6 percent (table 2), probably because the area at Site 6 is relatively small. The high standard deviations of samples collected from the 0 to 90 and the 90 to 275 foot intervals at Site 7 are due to the relatively small number of samples representing a thick section of the Tshirege Member. The different average porosities of the 0-20 foot interval and the 20-40 foot interval at Site 9 and the small standard deviation of each indicate that the physical properties that control porosity of the tuff are different in the two intervals.

The porosity values shown in table 1-A are calculated total porosity and are slightly higher than the values of the measured effective porosity. Effective porosity is the ratio of the volume of the void spaces that will yield or transmit water to the total volume of the rock or aggregate sample. Total porosity includes all the pore space in the tuff, some of which water cannot move through because interconnection between pores is lacking, whereas effective porosity includes only the interconnected pore space and water can move between adjoining pores.

Table 2.--Standard deviation and deviation from means of the percent porosity at seven sites in the Los Alamos area.

Site No.	Average porosity (from table 1)	Standard deviation	Deviation from means
1	35.8	2.2	0.7
2	49.8	1.4	.3
3	43.7	1.9	.8
6	42.1	2.6	.4
7 (0-90 ft below surface)	49.4	4.0	1.0
(90-275 ft below surface)	27.9	6.2	2.3
8	41.3	2.5	.9
9 (0-20 ft below surface)	43.6	1.0	.8
(20-40 ft below surface)	49.1	1.1	.6

Moisture content

The moisture content of rock or soil is the ratio of the weight of water contained in the sample to the oven-dry sample, expressed as a percentage.

The moisture content of approximately 280 samples of tuff collected at or just below the surface of the plateau ranged from less than 1 percent by volume in samples from undisturbed areas (natural conditions) to about 26 percent by volume in samples from disturbed areas (any change from natural conditions). The moisture content of tuff from disturbed areas was generally less than 10 percent and commonly less than 5 percent by volume.

At most sites where the moisture content of near surface was relatively high, the moisture content decreased with depth to less than about 5 percent by volume. An example is Site 12, where the moisture content beneath the pit decreased to about 5 percent below 12 feet (table 1-A).

A curve denoting the relative position of the three known moisture values, oven-dry, air-dry, and one-third atmosphere moisture tension, of the tuff at several sites can be drawn to illustrate the energy relationships of moisture in the tuff. The curve (fig. 5)

Figure 5.--Energy relationship with moisture content of the Bandelier Tuff at Site 6.

shows that the air dry moisture content of the Tshirege Tuff is approximately 5 percent at Site 6. The moisture content at the 15 atmospheres moisture-tension point is about 8 percent (moisture tension is the attraction of rock or soil for water, Baver, 1956, p. 227-234), and is the moisture-tension point at which plants can no longer obtain water by capillary movement. The moisture content at the one-third atmosphere moisture-tension point (approximate field capacity, Colman, 1947, p. 380) is about 23 percent. At atmosphere pressures at altitudes over 5,000 feet above mean sea level the one-third atmosphere moisture-tension point is close to one-half atmosphere moisture tension. The approximate 15 percent moisture-content difference between the 15 atmosphere moisture-tension point and the approximate field capacity point is redistributed at depth and the moisture content of the tuff theoretically would eventually approach the 15 atmosphere moisture-tension point if aided by the influence of plant roots or movement of air through the rock. The moisture content of surrounding rocks, the amount of porosity, the size of the pores, and the temperature gradient all affect the length of time required for redistribution to take place. The saturated moisture content of the tuff is shown to be about 41 percent.

The placement of the curve for Bandelier Tuff (fig. 5) shows that the tuff at Site 6 is between those for a sandy loam and sand, which places the tuff in a range similar to sandy silt.

The negative correlation coefficient of the moisture content at the one-third atmosphere tension and porosity for sites 6 and 8, significant at the 1 percent level (chances 1 out of 100), that figure is not an average of random figures is an indication that a larger volume of water will drain from the turf as the porosity increases. The reason for the lack of correlation between the moisture content at the one-third tension values and the porosity at sites 2 and 7 is not clear, except possibly for the small number of samples involved at these sites (table 3). Data in table 3 show also that the one-third atmosphere tensions do not correlate with any other physical properties at site 2 although the four sets of non-significant correlations are given to show the trend and the degree of correlation.

Table 3.--Correlation coefficient of physical properties of samples from Sites 2, 6, 7, and 8

Site No.	Properties	Level of significance	Number of pairs of samples	Correlation coefficient	Approximate minimum coefficient necessary for significance at the 5 percent level
2	Moisture content at one-third atmosphere tension correlated with porosity	a/ NS	10	0.04	0.63
2	Moisture content at one-third atmosphere tension correlated with specific retention	a/ NS	9	.32	.67
2	Moisture content at one-third atmosphere tension correlated with dry unit weight	a/ NS	9	.53	.67
2	Specific retention of moisture correlated with porosity	a/ NS	9	.59	.67
6	Moisture content at one-third atmosphere tension correlated with porosity	c/ 0.01	59	-.65	-
6	Moisture content at one-third atmosphere tension correlated with undisturbed moisture content.	b/ .05	59	.54	-

Table 3.--Continued

Site No.	Properties	Level of significance	Number of pairs of samples	Correlation coefficient	Approximate minimum coefficient necessary for significance at the 5 percent level
6	Moisture content at one-third atmosphere tension correlated with specific retention	[c] 0.01	9	0.81	-
6	Moisture content correlated with dry unit weight	[c] .01	84	.39	-
6	Moisture content at one-third atmosphere tension correlated with dry unit weight	[a] NS	39	.26	0.32
7	Moisture content at one-third atmosphere tension correlated with porosity	[a] NS	-	-	-
7	Moisture content at one-third atmosphere tension correlated with specific retention	[b] .05	12	.65	-
8	Moisture content at one-third atmosphere tension correlated with porosity	[c] .01	12	-.95	-
8	Moisture content at one-third atmosphere tension correlated with dry unit weight	[c] .01	12	.99	-

a/ Not significant
b/ 5 percent [illegible]

Samples of the Bandelier Tuff that were tested for moisture content at one-third atmosphere tension fell into two general groups. The average moisture content of samples collected at sites 2, 3, 6, and from a depth of 20 to 40 feet at site 9 were 21.2, 21.0, 20.6, and 24.5 percent respectively, which is about 91 percent of the 24 percent average of moisture content of the tuff at sites 3 and 6 where water had been added to the tuff intermittently for years. The averages of samples collected at sites 4, 5, 8, and from a depth of 0 to 20 feet at site 9 were 14.5, 14.7, 14.4, and 14.5 respectively, which is about 55 percent of the 24 percent average of the wetted tuff at sites 3 and 6. The porosity of the samples seems unrelated to these differences of moisture contents, but the size of the pores in the tuff may be related to the differences.

Specific gravity

The specific gravity of the Bandelier Tuff on the Pajarito Plateau ranges from about 2.54 to 2.58, and most values range from about 2.56 to 2.57. These values are about the specific gravity of the major constituents of the tuff, which are quartz, 2.5 to 2.8, and orthoclase feldspar, 2.5 to 2.6 (Baver, 1956, p. 57). The specific gravity of particles in the 1- to 2-micron range, which are slightly smaller than the median size of tuff particles, is 2.56.

A decrease in specific gravity with depth similar to that which occurs at site 7 may indicate differences in vertical composition of the Tshirege Member (table 4-A). The specific gravity of the tuff may decrease from west to east across the plateau as indicated in table 4-B. This apparent decrease in specific gravity may indicate slight changes in the composition of the tuff or slight differences in the concentration of constituents of the tuff.

The decrease downward at site 7 and the apparent decrease eastward of the specific gravity of the tuff might indicate that the upper part of the Tshirege contains a larger percentage of feldspar than does the lower part, or it could indicate that the lower part contains less heavy minerals.

Table 4-A --Standard deviation, deviation from mean, and range of specific gravity at site 7

Interval	Ave/	Standard deviation	Deviation from mean	Range
0 - 90 ft.	2.568	0.015	0.003	2.555 - 2.581
90 -275 ft.	2.550	0.008	0.001	2.542 - 2.560

Table 4-B.--Comparison of specific gravity of the Tshirege Tuff from west to east across the Pajarito Plateau.

North line	-	2.560 (Site 3)	2.555 (Site 6)	-	-	2.550 (Site 2)	-
South line	2.560 (Site 10)	-	-	2.558 (Site 9)	2.552 (Site 8)	-	2.550 (Site 5)

Dry unit weight

Dry unit weight is the weight in air of a given volume of oven-dry material. The dry unit weight of any material may be calculated from the formula $Y_d = \frac{W_d}{V}$ where Y_d = the dry unit weight of the sample, W_d = the oven-dry weight of the sample in grams, and V = the volume of the sample in cubic centimeters.

A statistical analysis of the dry unit weight of samples of tuff shows four significantly different groups of values: 1.84, 1.63, 1.44 and 1.47, 1.28, and 1.34, similar but opposite to those of porosity (table 1-A). Each group (for example, 1.44 and 1.47) is different significantly from each other at the 1 percent level. [~~(chances are 99 out of 100 that figures are not an average of random values)~~.]

The dry unit weight of different samples of a material vary inversely to the porosities of unit volumes of the samples. A difference in dry unit weight and porosity between two samples indicates a difference in composition. Evidence of vertical changes in the composition of the tuff is shown by the difference of the dry unit weight and the porosity in samples from Site 2. A statistical analysis of 28 cores collected from two holes drilled into the wall of the road cut indicates that the average dry unit weight is 1.28 (table 1-A). The average dry unit weight of samples from the upper hole is higher significantly than those in the hole about 3 feet stratigraphically lower in the tuff:

Location	Dry unit weight (gm per cc)	Porosity (percent)
Upper hole	a/ 1.30	b/ 49.2
Lower hole	a/ 1.26	b/ 50.4

a/ 1 percent level: chances are 99 out of 100 that figure is not an average of random values.

b/ 5 percent level: chances are 19 out of 20 that figure is not an average of random values.

The area involved is small, and the difference in average dry unit weights, though significant, is also small.

Moisture-tension relationship

Moisture-tension as used in this report is a contracted form of reference to the moisture content-moisture tension relationship. Moisture content has been described previously. Moisture tension is the equivalent negative gage pressure, or suction, in the soil moisture. Soil-moisture tension is equal to the equivalent negative or gauge pressure to which water must be subjected in order to be in hydraulic equilibrium, through a porous permeable wall or membrane, with the water in the soil. Moisture tension is a measure of the attractive force that rock or soil has for water. Tension is expressed in this report in centimeters of water or in units of atmospheric pressure. Tension of one-third atmosphere, or 344 centimeters of water, is comparable to field capacity (Colman, 1947, p. 280). This value of tension is used frequently in the report.

Many of the accepted concepts of flow of water below the water table cannot be applied directly to movement of water above the water table where pressure on the suspended or moving water is always less than one atmosphere. This pressure deficit is directly connected with the surface tension and the curvature existing on liquid and gas interfaces within the porous medium (Miller and Miller, 1956, p. 324). Much of the flow in the zone of aeration at moisture contents of less than field capacity is in thin films where resistance to flow is great (Kemper, 1961, p. 257). Capillary conductivity above field capacity is through thick films of water on the particles comprising the porous medium, whereas all the effective pore space in the zone of saturation or in laboratory studies of permeability is filled with water under pressure, and flow is predominantly through the middle of the flow channels.

Pore size

Equivalent pore size and moisture-tension relationship are related in the manner shown in the following table. (From capillary equation $h = \frac{2\gamma \cos\alpha}{r \rho_w g}$)

r = radius
ρ_w = den. of water
g = accel. of grav.
γ = surf. tens.
α = contact ∠

Pore diameter (mm)	Tension (cm of water)
0.20	15
.10	30
.05	60
.02	150

The non-capillary porosity (pore size sufficiently large that capillary rise of water is negligible) and the rate of percolation through soils vary directly with each other (Smith and others, 1944, p. 208), thus water will drain more rapidly from tuff containing a higher percentage of large pores spaces than from tuff containing few large pores even if the porosity is the same.

Little or no water can be withdrawn from a sand with nearly equal particles and pore sizes until a certain minimum tension value is reached (Youngs, 1960, p. 4027), and then only small additional tension is needed to empty many pores, whereas in the Bandelier Tuff pores of different size are randomly distributed throughout each sample and the large pores are interconnected by narrow necks so that each addition of tension increases the volume of water extracted. A tension of 1 cm (centimeter) of water applied to some samples, desaturated only a few large pores and increased tension drained progressively smaller pore spaces. Moisture measurements were made at tensions of 15 cm, 30 cm, 60 cm, 150 cm, and 344 cm tension on all samples. This system of tension measurements duplicated conditions of continuity of the sample similar to tuff in place.

The water content of various size pores at various tensions are shown in figures 6A-6F for samples of material from Sites 1, 2, 3, 6, and 7. An average curve for each group of samples is shown on the figures and represents a curve calculated from an estimated effective porosity and is used for comparison with curves from other sites. Most of the curves are similar but each curve has some characteristic that distinguishes it from the curves for samples from other sites. Table 5 summarizes some of the physical properties of the tuff and shows the estimated percentage of pores drained using estimated effective porosity values. The field capacities and porosities given in table 5 are slightly different from those given in table 1-A because all the data was not used in preparing table 5, and values for percentage of pores drained are rounded because the effective porosity is estimated.

Table 5.--Comparison of water drained from rock samples at one-third atmosphere tension with porosity.

Site No.	Location of sample	Porosity: Average total (percent)	Porosity: Estimated effective (percent)	Water drained from saturated material: Percent by volume at one-third atmosphere tension, or field capacity	Water drained from saturated material: Percent of total from pores larger than 0.1 mm [a]	Water drained from saturated material: Percent of total from pores larger than 0.2 mm [a]	Corresponding figure numbers
1	In boulder	36.1	32.8	23.9	2	25	6-A
7	At depths of 40, 60, and 104 feet beneath surface.	43.5	40.0	36.6	5	15	6-D
7	At depths of 30, 55, and 64 feet beneath surface.	46.6	43.0	-	0	10	6-D
3	Beneath laundry pit	[illegible]	[illegible]	[illegible]	20	[illegible]	[illegible]-B
6	Upper half of caisson hole.	47.0	43.0	22.0	20	50	6-C
7	At depths of 67 and 82 feet beneath surface	51.2	47.0	22.6	20	50	6-D
2	Side of road cut	[illegible].8	45.0	20.8	5	[illegible]	-F
6	Beneath a pit	43.9	41.0	17.1	2	55	-F
6	Lower half of caisson hole	45.0	42.0	20.1	1	55	6-C

a/ Corrected to approximate effective porosity.

A comparison of the one-third atmosphere tension values of drill cuttings and cores collected at site 6 showed that the values were reasonably close but that the dry unit weight, porosity, and permeability values were significantly different. The following are averages of analyses on samples collected at two depths:

Sample	Moisture content at one-third atmosphere tension in percent by volume	Dry unit weight	Porosity in percent	Coefficient of permeability (gpd per sq ft)
core	13.3	1.45	43.0	2.0
bulk	15.0	1.35	47.4	7.0

The results indicate that the laboratory analyses of samples of drill cuttings cannot be used for accurate interpretation of these physical properties, although values for the moisture content at one-third atmosphere tension were reasonably similar.

Coefficient of permeability

The average values of the permeability of the tuff (field coefficient of permeability is the number of gallons per day that flows through a cross section of 1 square foot under a unit hydraulic gradient, or through a section 1 foot high and 1 mile wide under a gradient of 1 foot per mile at prevailing conditions of water temperature. Laboratory determinations of the coefficient of permeability ~~are~~ (corrected to a temperature of 60°F) ranged from 0.4 gpd per sq ft (gallons per day per square foot) in the 90 to 275 foot zone at Site 7 to 10 gpd per sq ft at Site 2, but the range at each site was sufficiently narrow to assign a general value. The lowest average values of permeability coincided with the lowest porosity, and the highest values of permeability coincided with approximately the highest porosity (table 1-A). This indicates a gross relation which may not be true at individual sites. The relation between permeability and porosity, except for the extremes, appears to be random and cluster within 1.7 to 4.0 gpd per sq ft for the permeability and 38.7 and 49.8 percent for the porosity. The difference between vertical and horizontal permeability in the tuff is small. In general the horizontal permeability is larger than the vertical permeability and is probably related to density gradients within the flows, or to bedding.

Joints have increased the permeability of the Tshirege Member. Near the surface of the meses joints are filled with clay, but at depth the joints are free of sediment. The width of joints ranges from 0 to as much as 3 inches. Most of the joints are vertical and extend to great depth in the Tshirege. At places, joints probably are open and interconnected through the Tshirege and form avenues through which water can move readily to depth. *

Joint spacing is irregular but widespread. The average density near site 9 is about one joint per square yard.

The Tshirege Member of the Bandelier Tuff contains sub-units that probably are individual beds of tuff. Water moving through the tuff is temporarily perched by variations in vertical permeability. The permeability varies from one bed to another, from one member to another, and from the Bandelier Tuff to underlying beds of the Santa Fe Group.

Movement of water in Bandelier Tuff

Site 1 - Tshirege tuff boulder in Pueblo Canyon

A boulder of Tshirege tuff embedded in alluvium in Pueblo Canyon was used for the study of capillary movement of water from a ponded surface. Six holes 3 inches in diameter and a maximum of 6 feet deep were drilled and cored into the boulder perpendicular to the steep west-facing slope of the boulder, and three pair of access tubes were installed during the fall of 1960 (fig. 9). Water was

Figure 9.--Sketch showing isohydral lines of ~~equal~~ moisture content, in percent by volume, and moisture content during capillary rise of water in boulder at Site 1.

ponded against the lower part of the boulder on the east and north sides to provide a constant supply of water in direct contact with the boulder at a controlled distance below the bottom of the access tubes.

The pond was filled and a constant head was established on September 18, 1960. Nine days later on September 27 the moisture content in the boulder was about 10 percent about 3 feet above and west of the pond (fig. 9), and was approximately 30 percent near the level of the land surface which is approximately half a foot above pond level. On October 6, after 18 days, the 10 percent isohydral line had moved upward another 2 to 3 feet; the 15, 20, and 25 percent isohydral lines were unevenly spaced beneath the 10 percent line. The maximum moisture content measured in the boulder was about 30 percent on Dec. 8, the 81st day after the constant head in the pond had been established. The capillary movement through the boulder was not a sharp "front" as commonly takes place in the downward movement of moisture but was uneven.

The pattern formed by the isohydral lines on figure 9 indicates that the water moved laterally, ~~in~~ nearly saturating that part of the boulder beneath the land surface for several feet before it moved vertically. [~~This suggests that the boulder was saturated for several feet from the pond.~~] However, evaporation from the east face of the boulder may have about the same effect, on the isohydral lines.

During the winter of 1960-61, the pond was frozen over or empty, and the decrease in moisture content in the boulder was not recorded. In 1961, the pond was refilled, and a second study of capillary movement in the boulder was made. A maximum moisture content of about 30 percent was measured on May 11, 1961, the 49th day following the start of the second study. The faster movement of water in the boulder, recorded in the second study, suggests that the boulder was still moist from the first study, and that the rate of capillary rise is faster in wetted material than in dry material.

The effective porosity of the tuff in the boulder, from core analysis, was 32.8 (table 1A). Thus, the approximate 3 percent difference between the maximum moisture content reached in the boulder and the effective porosity may indicate that the capillary fringe was not completely saturated under conditions of the study. A slight density gradient in the boulder may have had some effect on the movement of water. The density apparently is higher near the center and may indicate weathering of the outer layers of the boulder.

Site 3 - laundry pit

The study at Site 3 was to determine the possibility of using the site for a long-term infiltration experiment. Since about 1945, liquid radioactive wastes from contaminated laundry had been discharged into pit 1; overflow ~~passed~~ was piped to the lower pits 2 and 3 ~~through buried pipes~~ (fig. 11). The quantity reaching pit 3 was not determined

Figure 11.--Moisture content of the tuff beneath the disposal pit at Site 3.

but is believed to have been small, thus, most of the moisture in the tuff beneath the pit probably is from precipitation.

The moisture content of samples collected at depths of 3 and 4 feet beneath the south side of pit 3 (at letter "A" on figure 11) decreased with depth from 29 percent to 18 percent, and the permeability decreased from 0.3 gpd per sq ft to 0.006 gpd per sq ft. The decrease in permeability is not readily explained by the pore-size distribution curve (fig. 6B) because the percent of large pores for samples of tuff collected beneath the pit at letter "A" was moderately high (table 5), and the difference in total porosity was small. The low permeability may have been caused in part by clogged pores rather than by the physical properties of the tuff, as indicated by the clay, roots, and rootlets associated with the samples collected. A bulk sample collected at a depth of about ~~seven~~ 7 feet in hole 2 had a moisture content of 30 percent and became hard when it was dried in the oven. ~~which indicates weathering tuff.~~

Moisture contents as high as 30 percent in holes 1 and 2 beneath the zone of low permeability possibly represent water that moved laterally from the gravel fill near the center of the pit. This is indicated, too, by the moisture content in hole 2 near the gravel fill, which was generally higher than at hole 1. The high moisture content between depths of 15 and 25 feet in hole 2 and the sharp decrease at a depth of about 25 feet suggest the presence of semi-permeable layers that perch the water. The high moisture content of about 30 percent in hole 1 apparently represents another perching layer below 33 feet. The density of the tuff at 30 to 33 feet is almost 6 pounds per square foot less than above or below that interval. Decreasing moisture content above 25 feet at hole 1 on October 12, 1961, when the moisture content between 32 and 33 feet at hole 2 increased, indicates vertical as well as lateral movement beneath the pit.

Discharge to the pits was to be discontinued in late 1961, therefore additional experiments at this site were not ~~further~~ considered.

Site 4 - soil study

The studies at Site 4 were intended to ascertain the effect that a soil cover and the transition zone will have on the quantity of water that moves into the underlying tuff. The vertical and horizontal movement of water in the soil was also studied. The site was near the middle of a finger mesa, which sloped southeastward at about 1 to 2 percent. Cores for natural moisture-content determinations were collected at the site on Oct. 10, 1958.

Infiltration tests were made in 1958 and 1959, (Abrahams and others, 1961, p. D-144). Installations consisted of two shallow infiltration pits slightly less than 2 feet in diameter, one or more access tubes in each pit, and a supply of water. The tests during 1958 were made in the soil zone beneath pit A, and the tests during 1959 were made in the soil zone in the underlying tuff at pit B. The water supply at pit A was intermittent; at pit B the head was constant during the period of the test.

At pit A lateral movement is indicated by a higher moisture content in access tube 1, downgradient from the pit (fig. 12-A, profile I).

Figure 12-A.--Isohydral lines of moisture content, in percent by volume, beneath pit A at Site 4 during intermittent infiltration and drainage, 1958.

Moisture penetration was less than ~~three~~ 3 feet in holes 2 and 3, but probably more than ~~four~~ 4 feet in hole 1 after ~~four~~ 4 feet of water had infiltrated into pit A in 6 hours following 14 days of drainage. The rapidly increasing moisture content at the 1-foot depth in hole 1 indicates some lateral movement (fig. 12-B, profile I).

Figure 12-B.--Moisture content beneath infiltration pit A at Site 4 during intermittent infiltration and drainage, 1958.

The rate of percolation, after 19 days of drainage, averaged about one-half foot per day during the first 3 days of infiltration (fig. 12-A, profile II). The front became diffused during further infiltration and the rate of percolation could not be determined.

The maximum moisture content after 23 days of infiltration at pit A was about 37 percent at hole 1 (fig. 12-B, profiles II and III); the moisture content of the soil moved downward at approximately the same percent of saturation. The total porosity of the soil at a depth of about 1 foot was approximately 51 percent, and at 2 feet was approximately 49 percent, which indicated that the moisture content of 37 percent probably was well above field capacity but did not represent saturated conditions.

The rate of infiltration at pit B during the 99 day study decreased approximately logarithmically throughout most of the period as follows:

1gpd/ft² = .07 in/hr.

1st and 2d days - 20 gpd per sq ft

4th to 18th days - 10 gpd per sq ft

18th to 31st days - 5 gpd per sq ft

31st to 51st days - 2 gpd per sq ft

51st to 69th days - less than 1 gpd per sq ft

Evapotranspiration was relatively constant. The infiltrating water followed two courses; (1) some went downward; and (2) some went to support evapotranspiration. As downward rates slowed, and a constant rate to evaporation was maintained, the ratio of between the two changed.

The wetted front moved to a depth of about 5 feet during the first 2 days of infiltration at pit B (fig. 13) and to a depth of

Figure 13.--Moisture content in the soil and tuff beneath pit B at Site 4 during 99 days of continuous infiltration and subsequent drainage for 21 months.

about 6½ feet within about 99 days. The decrease in the rate of movement of the front ~~decrease~~ was logarithmic~~ly~~. The moisture content decreased with depth from a maximum of about 39 percent in the soil to less than 4 percent about 1 foot below the top of the tuff. After 8 months of drainage the moisture content was about the same as before infiltration started.

The high moisture content beneath the pit before infiltration started was due in part to heavy rains in August 1959 and the relatively poor drainage in the sandy surface soil. The May 19, 1961 measurements were high because of snowmelt, and the Oct. 2, 1961 measurements were low because of low precipitation.

The water use per square foot during this study was equivalent to about 40 or 50 years of precipitation on the Pajarito Plateau; however, natural conditions were not duplicated because the seasonal distribution of alternating percolation and drainage could not be duplicated. The fact that water did not penetrate the dense transition zone between the soil and tuff during the study or in the following year, indicates that the soil cover will impede vertical movement into the underlying tuff. Capillary rise, evaporation, and transpiration were perhaps the principal reasons that the water did not penetrate the underlying tuff, rather than the low permeability of the transition zone.

Site 5 - Mesita del Buey

Site 5 is adjacent to the south wall of a solid-waste disposal pit 29 feet deep (fig. 14), near the eastern end of Mesita del Buey,

Figure 14.--Wetted areas on south wall of the disposal pit at Site 5 resulting from seepage from the infiltration pit 10 feet back of the wall. deleted

a finger mesa. The study at this site was to investigate movement of water and nuclides during continuous infiltration.

An infiltration pit, access tubes, and a water-storage tank were installed near the edge of the vertical wall of the disposal pit (fig. 15).

Figure 15.--Sketch showing relation of infiltration pit and access tubes to the disposal pit at Site 5.

The center of the infiltration pit was 10 feet south of the south edge of the waste disposal pit. The upper 2 feet of the infiltration pit was shored with wood planks within the soil and fill material, and the lower 1 foot was dug into the unweathered tuff. Water entered the pit through a 3/4-inch pipe connected to a value box adjacent to a 3,000-gallon storage tank. A float valve in the infiltration pit maintained a constant head of water of about three-fourths foot. Eight holes 40 feet deep lined with plastic tubing were installed in and near the infiltration pit (fig. 15).

Periodic measurements of water losses from the storage tank were made to determine the volume of water moving to the infilration pit.

The infiltration experiment started when water was put into the pit October 8, 1959. Between December 29, 1959 and January 6, 1960 the water line froze and the pit dried up. The infiltration phase of the experiment was suspended until April 20, 1960 and then restarted. About December 9, 1960 the water line froze again and the infiltration phase of the experiment was stopped, but moisture measurements were made in access tubes for several months to observe drainage patterns.

Photographic evidence that water moved into the tuff from the infiltration pit was a wet patch (fig. 16) that developed on the wall

Figure 16.--Wetted areas on south wall of the disposal pit at Site 5 resulting from seepage from the infiltration pit 10 feet back of the wall.

of the disposal pit 10 feet to the north. Evaporation from the wall discharged water that would have moved deeper in the tuff.

The rate of infiltration of water through the pit at Site 5 is shown graphically on figure 17. The slope of the log curve of

Figure 17.--Rate of infiltration from infiltration pit at Site 5, 1959-60.

The rate of infiltration for the 1959 study shows that the rate of infiltration decreased from about 0.75 gph per sq ft (gallons per hour per square foot) to about 0.2 gph per sq ft.

Significant seasonal changes in the log curve of the rate of infiltration for the 1960 study occur during the months of April and September. The steeper parts of the curve show a relatively rapid decrease in the rate of infiltration with time during the months in which the average temperature is less than about 50 degrees. The flatter part of the curve shows the rate of infiltration during months in which the average temperature is above 50 degrees. In these months the rate of infiltration decreased from about 0.4 gph per sq ft to about 0.2 gph per sq ft. The range of the temperature of the water in the pit, from near freezing during the winter to about 80 degrees in the summer, was enough to cause seasonal differences in the rate of infiltration into the tuff due to changes in viscosity (Horton, 1940, p. 417) In addition, seasonal temperature variances in the tuff beneath the infiltration pit may have been sufficient to cause some small differences in the rate of percolation.

The flatter part of the log curve of infiltration includes the time of the growing season at Los Alamos, and it is possible that evapotranspiration of tumbleweed on the soil and fill pad consumed small amount of water moving from the pit. However, when most of the plants were removed no measurable effect on the rate of infiltration took place. Several plants growing with their tap roots along the side of access tubes were kept in place. The moisture content of the upper 2 feet of material (table 7) was reduced at access tubes 2 and 3 where the tumbleweeds were growing; the moisture content increased after the plants were removed September 1. The moisture content at all the other tubes remained high throughout the growing season.

Table 7.--Effects of transpiration by Tumbleweed plants on the moisture content of tuff at Site 5, 1960.

Hole No.	Remarks	1960 May 18	June 2	July 1	July 29	Sept. 1	Dec. 6
		Moisture content, in percent by volume					
3	Tumbleweed at side of access tube.	22.5	16.5	12.5	8	6	20
2	Tumbleweed at side of access tube.	27.5	27.5	23.5	19	14	21
4	No Tumbleweed nearby.	26	26	27.5	25.5	24	26
6	No Tumbleweed nearby.	27.5	29	27.5	27	27.5	29
8	Tumbleweed removed from near access tube.	20	19.5	19	19.5	15	18

Table 6.--Particle-size distribution of samples of tuff from sites 2, 3, and 6, in percent by weight.

Sample Location	Number of Samples	Clay		Silt		Total, silt and clay		Sand		Gravel	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
2, side of ad cut.	2	-	4.2-6.9	-	34.2-38.5	-	38.4-45.4	-	54.6-61.6	-	-
3, beneath undry sposal pit.	8	11.8	8.0-14.4	39.8	36.6-43.2	50.6	44.6-57.6	48.3	42.4-55.4	1.1	0.2-1.6
6, caisson le.	2	-	6.2-7.0	-	29.2-30.4	-	36.2-36.6	-	62.3-62.6	-	1.1-1.2
6, beneath sposal pit.	4	-	-	-	-	38.4	21.3-49.3	60.1	50.0-78.3	1.5	0.4-4.2

The two moisture-tension curves on figure 6-A were constructed

Figure 6-A.--Moisture-tension relationship and pore size in the tuff at Site 1.

from the same set of moisture-tension values and from laboratory determinations of total porosity and effective porosity. Curves prepared using data from samples taken from most other places on the Pajarito Plateau have the same general parallel relationship. The curve prepared using effective porosity data indicates 2 percent of the pores 0.20 mm (millimeter) in diameter and larger drain when the tension increases from zero (complete saturation) to 15 cm of water; about 25 percent of the pore spaces drain at one-third atmosphere tension (344 cm of water); and that about 75 percent of the pores are smaller than about 0.01 mm in diameter.

Samples for which moisture-tension curves type A were prepared in figures 6-B to 6-D have similar drainage properties. The position of those curves indicates that in these samples approximately 20 percent of the pores are larger than 0.20 mm in diameter and 40 to 50 percent are larger than 0.01 mm. Initial drainage from those groups of samples is relatively rapid because of the high percentage of large diameter pores and moderately high porosity, and approximately half the water in a saturated sample drains by gravity. The nearly horizontal trend of the moisture-~~tens in~~ Tension curve on figure 6-C below 90 cm and the nearly vertical trend above 90 cm shows that about 40 percent of the pore space are relatively large and 60 percent are relatively small and that there are few intermediate size pores. This is similar to a typical field sand. The type A curves on figures 6-B and D indicate there is a relatively constant decrease in the size of the pores.

Figure 6-B.--~~Curve showing relation of water content at several tensions to the size of pores~~ Moisture-tension relationship and pore size in the tuff at Site 3.

Figure 6-C.--~~Curves showing relation of water content at several tensions to the size of pores~~ Moisture-tension relationship and pore size in the tuff in the caisson area at Site 6.

Figure 6-D.--~~Curves showing relation of water content at several tensions to the size of pores~~ Moisture-tension relationship and pore size in the tuff at Site 7.

The steep slopes of type B and C curves on figure 6-D for samples of the Tshirege Member at site 7 indicate that the pores in these samples are almost entirely small. The type B curve indicates that about 85 percent of the pores are smaller than 0.01 mm in diameter and do not drain by gravity, and the type C curve indicates that few pores are larger than 0.05 mm. These samples could represent a part of the Tshirege that would be relatively impermeable to vertical movement of water and wastes.

The type B curve on figure 6-C and the type A curves on figures 6-E and F indicate that only a small percentage of pores 0.20 mm in diameter drain initially and that more than half of the total pore space drains by gravity. The curves for samples collected at site 6 fall into two groups with the sandy material represented by the type A curve on figure 6-C. The curves of samples at depth adjacent to the disposal pit (type B curve on fig. 6-C) and at depth beneath the pit (type A curve on 6-E) are nearly parallel but the steeper slope beneath the flex point on figure 6-E may indicate that waste water moving through the tuff beneath the pit intermittently over a period of years has caused ~~some changes~~ a slight decrease in the size of the pores. The flat curve (fig. 6-F) indicating an even distribution of pores does not readily explain the comparatively low specific retention values of samples of the Tshirege Member from site 2.

Figure 6-E.--~~Curve showing relation of water content at several tensions to the size of pores in~~ Moisture-tension relationship and pore size in the tuff at site 6, beneath disposal pit.

Figure 6-F.--~~Curve showing relation of water content at several tensions to the size of pores~~ Moisture-tension relationship and pore size in the tuff at site 2.

The values listed below show the general relationship between pore size and percolation rate (Nelson and Baver, 1940, p. 73) and indicate that the rate of percolation through the 0.23-mm pore spaces is more than 60 times that through 0.02-mm pores. ~~If these values are used,~~ The calculated rate of percolation through tuff having about 20 percent pore

Pore size (mm)	Percolation rate (cc per 10 minutes)
0.230	723
0.151	335
0.122	285
0.067	133
0.020	12

space 0.20 mm or more in diameter and about 50 percent pore space 0.01 mm or more in diameter and high in porosity (table 5, site 6, upper half of caisson hole), is more than 100 times faster than the rate of movement through the boulder (table ~~6~~ 5, Site 1).

Hysteresis

Data obtained about the moisture-tension relationship during the draining or drying and wetting of a rock sample when plotted on graph paper produces two curves that join at two points to form a loop. There is marked hysteresis between the two curves, and the loop is commonly referred to as the "hysteresis loop".

The hysteresis loop (fig. 7) for a particular rigid porous

Figure 7.--Hysteresis curve showing the relation between moisture tension and moisture content of a sample of the Bandelier Tuff at Site 6.

medium is unique and its results are reproducible (Puri, 1949, p. 428). Hysteresis is due in part to the resistance of water adhesion within the small pore spaces during both the wetting and drying cycle. The moisture content on the drying cycle of the hysteresis loop at the one-third atmosphere tension in figure 7 is about 22 percent by volume and the moisture content at the same point on the wetting cycle is approximately 14 percent. These percentages are approximately the average for samples from Site 6. The maximum difference in moisture content on the two curves occurs between about 210 cm of water and 344 cm of water or one-third atmosphere tension.

Particle-size distribution

The particle size distribution of samples of tuff from four sites is listed in table 6. Many of the particles in the samples tested consisted in part of shards or glassy cementing material; thus the values in the table may be misleading, because some of the variations in the sizes of the particles may be due to the method of collecting the samples, which was by augering. The averages of 46 percent of ~~fines~~ clay and silt and 53 percent sand from table 6 is descriptive of a sandy silt.

The size of the particles in a porous medium have a direct effect on the movement of water because their arrangement and degree of packing determine the porosity and the pore sizes. Waldron and others (1961, p. 206) using glass beads 51 to 203 microns in diameter showed that open packing resulted in a porosity of 47.6 percent and that close packing resulted in a porosity of 26.0 percent. Lutz and Leamer (1940, p. 28) showed that permeability increases exponentially with the size of the particles and therefore with the size of pores, as follows: silt, 0.8 cc per min (cubic centimeters per minute); very fine sand, 3.7 cc per min; fine sand, 14.3 cc per min; and medium sand, 47.8 cc per min.

No evidence was found that water moved through the soil and fill pad and evaporated from the surface in quantities sufficient to affect the rate of infiltration in the pit. The moisture content of the upper foot of the soil ranged between 5 and 10 percent by volume, which generally is too low to transmit much water. The sandy material tends to form a barrier that reduces evaporation (Willis, 1960, p. 241).

The rate of infiltration during the warmer months (5 to ~~10~~ 12 gpd per sq ft) was within or somewhat above the range of permeability determined from cores in the Laboratory. The field permeability (rate of percolation) in the zone of aeration cannot be directly compared to the saturated permeability (laboratory measurement) because water in the infiltration pit not only moved downward but also moved laterally as much as 8.5 feet from the edge of the infiltration pit (fig. 14). Thus, the rate of percolation, particularily from a small source of water located in a layered medium, is substantially less than the saturated permeability, because the water is subject to forces not involved in saturated flow.

The wetting front moving into the unsaturated tuff was sharpest in the early part of the 1959 study, but it became thicker and more diffuse as infiltration continued (fig. 18, profile I). Energy barriers

Figure 18.--Moisture content and density of tuff in access tube 1 at Site 5, ~~1959-60~~.

at the front retard the movement until the moisture content behind the front is raised to a maximum or optimum value (Bodman and Colman, 1944, p. 117-118). The thickness of the zone of transmission, the area between the unwetted tuff and the maximum moisture content attained during the vertical movement, ~~apparently~~ probably was a function of layering in the tuff. The average rate of movement of the part of the front containing a moisture content of 25 to 28 percent by volume was about 2 feet during the first day, about half a foot per day during the next 11 days, and about a tenth of a foot per day during the next 56 days, with additional movement in the lower moisture range to a total depth of about 18 feet. The rate of movement of the front in 1960 was higher (fig. 19, profile II) than in 1959 probably because the rock was wetted and fewer energy barriers existed to reduce the rate of movement and less water was needed to reach field capacity. (See ~~also~~ fig. 19 and 20.).

The moisture content of 25 to 28 percent apparently was the maximum attained away from the pit (fig. 18, profiles II and III) at Site 5. This moisture content is several percent above field capacity but is considerably less than saturation. The maximum moisture content 1 foot beneath the infiltration pit was about 40 percent, which is 6 to 7 percent less than the estimated effective porosity. The 6 to 7 percent ~~figure~~ probably represents the large pore spaces from which water drained into the underlying material, although it may also represent entrapped air. However, entrapped air should not be a problem in this study because of the large volume of porous medium involved and the probability that entrapped air beneath the infiltrating water would escape and not be surrounded or compressed (Free and Palmer, 1940, p. 395).

The moisture content of the tuff decreased steadily above an apparent bulk density change at about 25 feet beneath the infiltration pit to a range of 5 to 16 percent after about 9½ months drainage (fig. 18, profile IV). The moisture content below the apparent density change slowly increased during drainage and after about 2 months, reached a moisture content of about 8 percent. The 8 percent saturation extended below the bottom of the access tube.

The movement of water during the 1960 study at Site 5, and subsequent drainage, is shown on figures 19 and 20 by the changing

Figure 19-A.--Isohydral lines of moisture content of the tuff, in percent by volume, along an east-west section at Site 5 on Apr. 20, 1960, after about 3½ months of drainage.

19-B.--Isohydral lines of moisture content of the tuff, in percent by volume, along an east-west section at Site 5 on June 2, 1960, after 43 days of infiltration.

19-C.--Isohydral lines of moisture content of the tuff, in percent by volume, along an east-west section at Site 5 on July 28, 1960, after 99 days of infiltration.

19-D.--Isohydral lines of moisture content of the tuff, in percent by volume, along an east-west section at Site 5 on Dec. 6, 1960, after 230 days of infiltration.

19-E.--Isohydral lines of moisture content of the tuff, in percent by volume, along an east-west section at Site 5 on Mar. 1, 1961, after about 3 months of drainage.

patterns of isohydral line of moisture content.

Figure 20-A.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on Apr. 20, 1960, after about 5½ months of drainage.

20-B.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on June 2, 1960, after 42 days of infiltration.

20-C.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on July 28, 1960, after 99 days of infiltration.

20-D.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on Sept. 1, 1960, after 134 days of infiltration.

20-E.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on Dec. 6, 1960, after 230 days of infiltration.

20-F.--Isohydral lines of moisture content of the tuff, in percent by volume, along a north-south section at Site 5 on Mar. 1, 1961, after about 3 months drainage.

Isohydral lines are shown on both figures for the day infiltration was restarted (April 20, 1960); after 42, 99, and 230 days of infiltration; and about 3 months after infiltration of water from the pit ceased. In addition, isohydral lines 134 days after infiltration started are shown on figure 20. The effect of density gradients in the tuff is reflected in the moisture pattern changes in figure 19. The effect of evaporation from the wall of the adjacent disposal pit is reflected prominently in the moisture patterns in figure 20. The expanding wet area on the wall of the disposal pit as outlined in figure 14 correlates to some degree with the moisture patterns in figure 20.

The positions of the isohydral lines on the day infiltration started, after 42, 99, and 230 days of infiltration, and after about 3 months drainage with no infiltration of water from the pit are shown in figures 19 and 20. The position after 134 days of infiltration is also included in figure 20. The effect of the density gradients in the tuff and evaporation from the disposal pit wall are reflected in the moisture patterns in figure 19. The effect of evaporation from the wall of the disposal pit on the movement of water in the tuff is shown by the moisture patterns. This sequence can be followed to some degree by the changes in the patch of wet area on the south wall of the disposal pit outlined on figure 16.

Water was retained in the tuff to near field capacity between the depths of 8 and 14 feet beneath the bottom of the pit approximately $3\frac{1}{2}$ months after the infiltration phase of the experiment was suspended in January 1960 (figs. 19-A and 20-A). The slight bunching of the 10, 15, and 20 percent isohydral lines to the east in figures 19 A-E may indicate movement down dip in the tuff, or because of density changes at access tubes 4 and 5. The effects of density gradients were prominent on the east-west section at holes 4 and 5 and were beginning to show at a depth of about 20 to 25 feet at hole 2. Moisture content with respect to depth below the infiltration pit was greater to the south in figure 20. The moisture content gradient in the tuff north of the infiltration pit indicates that water moved toward the wall of the disposal pit under the influence of forces resulting from evaporation of water from the wall of the disposal pit. The apparent increasing rate of evaporation from the wall, with the approach of longer and warmer days, is evident on the north-south section. Little or no increase in moisture was apparent at depth at holes 6 and 7. Figures 19B and 20B show approximately the position and maximum extent of the tuff that contained a moisture content of 20 percent or more.

The closing of the 25 percent isohydral line and the constriction of the 20 percent isohydral line on 19-C and 20-C probably indicate that water evaporated from the wall of the disposal pit faster than it moved into the tuff from the infiltration pit. The 25 percent isohydral line closed late in June after 60 to 65 days of infiltration. The 10 and 15-percent isohydral lines did not advance significantly in any direction from the positions shown on figures 19-D and 20-C, except possibly at hole 1, although the rate of infiltration decreased only a small amount. The 2-percent isohydral line on figure 19-D showed a tendency to flatten, probably because of a density gradient at a depth of about 25 feet at hole 1. The lower moisture content at the upper part of holes 2 and 3 was due to evapotranspiration by the tumbleweeds growing there. Figure 20-D shows a continuing decrease of the area within the 25-percent isohydral line and almost total closure of the 20-percent lines beneath the infiltration pit.

Moisture measurements, made on December 6 after 230 days of infiltration, (figs. 19-D and 20-E) show a decrease in the moisture content of the tuff from that of previous measurements. Although the rate of evaporation from the disposal pit wall decreased steadily during the fall, because of the decreasing temperature, the rate of infiltration probably also decreased because of the greater viscosity of the water. The rate of infiltration at the near-freezing temperatures in the pit in December was probably only about half that during the middle of summer (Mavis and Wilsey, 1936, p. 17). Water in the pit probably froze during extremely cold nights late in November and early in December before the permanent freeze, thus completely stopping infiltration for periods of several hours. The rate of percolation exceeded the rate of infiltration from the pit when the water was near freezing.

On March 1, 1961, after about three months of drainage (figs. 19-E and 20-F), the isohydral lines assumed about the same positions and shapes as of April 20, 1960, except in the lower moisture range directly beneath the infiltration pit where a low moisture content column 3 or 4 feet in diameter formed below a depth of about 30 feet.

A total of about 11,100 gallons of water moved through the infiltration pit during the 230 days of the study, most of which infiltrated during the summer months. A water budget cannot be calculated, however, because of the unknown quantities lost by evaporation.

Site 6 -- DP-West

Site DP-West is within one of the original disposal areas at Los Alamos technical area DP-West, and lies between the axis and the north rim of a finger-mesa.

The disposal area consists of four pits about 20 feet wide, 100 feet long, and 5 feet deep that were dug into the tuff and backfilled with layers of sand and gravel, and connected in pairs by buried pipes. Plutonium wastes dissolved in hydrofluoric acid were discharged into the pits between 1943 and 1952. The pits were not roofed and ~~Some water derived from~~ precipitation contributed water to the pits. The objectives of the present study were to determine if and where ~~were to study the movement of~~ water moved beneath a disposal pit and to ascertain if waste products moved with the water. Samples of water, extracted with porous cups placed beneath the pit, were analyzed for chemical and radiochemical quality. The moisture content beneath the pit was measured in horizontal access tubes, and in tubes placed at an angle beneath the pit to a depth of about 100 feet.

A caisson 30 feet deep, 6 feet wide and 12 feet long was excavated about 6 feet north-northeast of the eastern quarter of pit 1 (fig. 21). The caisson was shored with planks and

Figure 21.--Diagrammatic sketches of installations and caisson pit at Site 6.

reinforced with timbers and contained three platforms 6 feet apart vertically. [~~A vacuum system capable of about one atmosphere was installed.~~]

Twelve pairs of holes 3 inches in diameter and 8 to 12 feet long and dipping downward at about ½-inch per foot were drilled at 2-foot intervals through the south wall of the caisson into the tuff beneath the pit (fig. 21). The uppermost hole was about 6 feet below the berm and less than half a foot beneath the bottom of the pit. A plastic tube approximately 2 inches in diameter was installed in one hole of each pair for moisture measurements. The annular space between the access tube and the wall of the drilled hole was not backfilled. The other hole of the pair contained a porous cup placed at the back of the hole and connected to ~~the~~ a vacuum system that was capable of about one atmosphere. The holes were backfilled around the vacuum tubes with crushed tuff emplaced with compressed air.

Six holes 4 to 6 inches in diameter and 75 to 99 feet in depth were drilled near the edge of the pit. Four of these holes were slanted to penetrate the tuff beneath the pit. The holes were lined with plastic access tubes approximately two inches in diameter and the annular space between the tubes and the walls of the holes was backfilled with crushed tuff.

Conditions before infiltration

Several facies in the tuff exposed during the construction of the caisson created special problems of data interpretation (sketch D on fig. 21). These facies types were an upper tuffaceous sand that was slightly consolidated and partly weathered and contained numerous roots and rootlets (bed A, fig. 21 and table 8); a pumiceous tuff that appeared to pinch out several feet south of the caisson (bed B, fig. 21); and an underlying welded tuff that was weathered, especially along joint faces along which wastes may have moved (bed C, fig. 21). A clay zone 6 to 12 inches thick overlies the welded tuff.

Table 8.--Description of material

in caisson pit at Site 6.

Position on figure 21	Description [a]
A	Sand, light orange-brown, weathered yellowish; consists of subround to subangular silt to coarse grains of quartz, sanidine, pumice, and minor amounts of mafic minerals, some grains pitted.
B	Tuff, light orange-gray, weathered throughout; much clay present.
C	Tuff, light gray, weathered yellowish around devitrified pumice fragments and adjacent to joints, locally weathered into clay, weathering more intense in bottom of pit; consists of ash and some mafic minerals.

a/ by William D. Purtymun

The banding effect of the one-third atmosphere tension moisture values (fig. 22-A) parallel to the clay development (sketch C, fig. 21)

Figure 22-A.--Section through Site 6 showing banding effect of the moisture content at one-third atmosphere tension.

suggests that waste-water movement may have changed some of the physical properties of the tuff, such as pore and particle sizes. Some of the wastes discharged in the east end of the disposal pit may have moved laterally through the sandy material (Bed A on sketch C and D, fig. 21) along the sloping top of the tuff and then vertically into the tuff. The lower moisture values (fig. 22-A) seem to coincide with areas of tuff in which the greatest amount of staining had occurred. The stained areas may indicate a different stage of weathering than that at the clay layer due to alternate wetting and drying cycles. A trend towards banding in the tuff is indicated also by the dry unit weight, specific retention, porosity values, and by the pattern (fig. 22-B) formed by plotting the gross alpha count on the section through the study area.

The moisture content and gross alpha activity of the cores collected in the study area decreased significantly from east to west and with depth (table 9), which indicates that much of the liquid discharged into the pit moved only a short distance laterally through the sandy material before infiltrating the tuff. The average moisture c ontent of the third horizontal group was significantly lower at the one percent level than that of the two upper groups, but not significantly less than that of the fourth group.

Table 9.--Averages of moisture content and gross alpha counts of tuff cores collected at site 6.

Group of holes by depth	Depth (feet)	Moisture content (in percent by volume)	Difference from lowest moisture content (18.4)	Least significant difference	Gross alpha counts per minute per dry gram[a]
First	0, 2, and 4	29.6	11.2	9.0	1,817
Second	6, 8, and 10	26.0	7.6	7.2	901
Third	12, 14, and 16	18.4	-	-	238
Fourth	18, 20, and 22	21.3	2.9	-	148
East	0, 6, 12, and 18	25.0	-	-	1,188
Middle	2, 8, 14, and 20	23.6	-	-	563
West	4, 10, 16, and 22	20.9	-	-	482

a/ Analysis by Los Alamos Scientific Laboratory.

The tuff is extensively jointed (fig. 21), and the tendency for liquid to move through the joints is indicated by higher gross alpha activity in local areas as shown by the gross alpha count of 1,000 per minute per dry gram at the 20 foot depth on figure 22-B.

Figure 22-B.--Section through Site 6 showing gross alpha activity.

In the east group of holes (fig. 21) the joints become more numerous with increasing depth. Several open joints on the south wall of the caisson were found below a depth of 25 feet. Waste water had penetrated the fineline joints to depths of at least 22 feet and subsequently altered the tuff adjacent to the joint as much as one-quarter to one-half inch. Clays developed locally and impeded drainage so that the joints retained water to the extent that the moisture content of the tuff was locally as much as 35 percent (fig. 23, profile I).

Figure 23.--Isohydral lines of moisture content of tuff constructed from moisture readings in horizontal access tubes at 2, 8, 14, and 20 feet below the bottom of disposal pit 1 at Site 6.

The isohydral lines of the June 30 measurements (fig. 23, profile II) show a lateral movement of moisture from the disposal pit towards the caisson area before infiltration began. This increase in moisture content of the tuff probably was caused by infiltration of snowmelt and by the above normal precipitation in June (3.40 inches).

The moisture content of chunk samples collected at various depths during excavation of the caisson in October 1959 indicate that water from the disposal pit had moved northward only a short distance. Some water had moved through the sandy materials above the clay layer as indicated by moisture contents of 19 and 16 percent, respectively, at the 6 and 4 foot levels. Little or no water had reached the 12 and 14 foot levels although some had moved laterally at the 18 and 22 foot depth.

Infiltration studies, 1960 and 1961

The flow of water into the disposal pit was continuous for two months in both 1960 and 1961. Both studies were during the summer months when the temperature of the water, and other conditions, probably were comparable. The dates and approximate rates of flow of wastes and tap water into the pit are shown below (Christenson and Thomas, 1962, p. 261).

	Raw waste discharge		Tap water discharge	
1960	July 6-July 31	approximately 8,000 gallons per day	Aug. 1-Sept. 7	approximately 6,500 gallons per day
1961	June 30-Aug. 1	approximately 6,400 gallons per day	Aug. 2-Aug. 26	approximately 7,100 gallons per day

The moisture content of the tuff during continuous infiltration ranged from less than 30 to more than 35 percent (fig. 23, profile III). Isolated areas having a moisture content of 35 to 40 percent developed locally during August, suggesting movement through open joints. Drainage in the 10 to 15 foot zone below the pit was relatively slow after infiltration stopped (fig. 23, profile IV) probably because the caisson acted as a barrier to the lateral movement of water.

The moisture content before the 1961 study after almost $9\frac{1}{2}$ months of drainage (fig. 23, profile V) was about the same or slightly lower than before the 1960 study, probably because of less rainfall. The moisture content through July 1961 also was about the same as during the 1960 study (fig. 23, profile VI), but during August the moisture content of the tuff increased (fig. 23, profile VII). The high moisture content of 45 percent at a depth of 8 feet indicates that water drained from a joint directly into the annular space around the access tube and that water may have been standing in the hole. Drainage from this area was relatively rapid (fig. 23, profile VIII), again suggesting movement through open joints.

Gross alpha activity in water samples from the 8 foot depth averaged several times higher than the activity in samples from other depths (Christenson and Thomas, 1962). Samples from other depths also c ontained relatively high alpha activity, which indicated movement through joints. There was an inverse relationship between gross alpha activity and the pH of the solution. Total hardness and total solids increased with depth, suggesting solution and resolution of previously deposited materials.

~~Deep~~ access tubes (fig. 25) were installed in deep holes drilled

Figure 25.--Plan view showing locations of deep access tubes, sections through disposal pit, and moisture content of deep access tubes at site 6.

~~without water (except DPW-1A)~~ in February 1961. Pre-test moisture content or gross alpha counts were not determined. High gross alpha activity of drill cuttings at a depth of about 30 feet in hole DPW-2 as listed below probably was due to a zone of free water perched on the facies change noted in the walls of the caisson pit.

Hole number	1	1A	2	3	4	5
Gross alpha counts per minute per dry gram	2	24	698	3	1½	3

The moisture content during March and April ranged between 20 and 35 percent around the upper part of the tubes, due in part to snowmelt and impeded drainage and was about 10 percent or less around the bottom of all the access tubes except DPW-1A. The moisture at the bottom of access tube DPW-1A may have been due to drilling water; drilling water was not used in the construction of other holes. At depth below about 20 or 30 feet the moisture content was highest around tubes near the northeast part of the disposal pit.

Most of the water discharged into the disposal pit infiltrated the tuff and percolated downward within a roughly 1,000 square foot area at the east end of the disposal pit near the caisson (fig. 25). Outside the oval shaped area of maximum infiltration (fig. 25), particularily to the north, is a fringe zone about 20 feet wide and about 60 feet deep where percolating water maintains the moisture content of the tuff slightly above field capacity.

The moisture content at most depths approached the pre-infiltration level about 2½ months after discharge of water into the pit was stopped. The moisture content of the tuff at DPW-3 and 4, adjacent to the western half of the disposal pit, increased only in the upper 20 to 30 feet after almost 2 months of infiltration, whereas the moisture content at the east side of the pit increased to depths of more than 92 feet. The irregularities in the curves of moisture content for access tubes DPW-1, 1A, and 2 probably are due to changes in permeability. The increases in moisture from depths of about 45 to 60 feet at DPW-1 and at 10 to 40 feet at DPW-2 probably is caused by water reaching these intervals through joints.

The effects of joints and contacts between subunits of the tuff on water movement

Water moves through the tuff in two ways--by capillary movement through the pores of the tuff, and by movement through open interconnected joints. Water entering open interconnected joints might move rapidly, downward, through the joints; however, if the joints are not continuous through contacts between subunits of the tuff the water might be perched above the contact and would tend to move laterally.

Liquid wastes are discharged periodically from a treatment plant onto the Tshirege Member in the floor of Acid Canyon. The point of discharge is about a quarter of a mile above a seep flowing several gallons per minute at the contact of the Tshirege and Otowi Members in Acid Canyon (fig. 26). The liquid wastes are discharged from the plant in

Figure 26.--Sketch of Acid Canyon showing possible movement of water through joints in the Tshirege Member of the Bandelier Tuff and the location of a seep area in Acid Canyon at Site 15.

slugs and cause intermittent surface flow on the canyon floor for periods of as much as one hour. Between intermittent flows the floor of the canyon normally is dry between the treatment plant and the seep; flow in the canyon is perennial below the seep.

The only known source of water emerging in the seep area is the liquid waste discharged from the treatment plant. Study of the area indicates that liquid waste percolates through joints in the Tshirege Member to the top of the massive Otowi Member where it is perched and then moves laterally along the contact to the seep area.

Liquid may also be moving along the subsurface contact of the two members to other points of discharge which have not as yet been found. The attitude of the contact is unknown; if it is relatively level water could be moving underground in all directions from the point of recharge.

Perched water occurs also at the contact between the Guaje Member and the underlying Puye Conglomerate. Moisture measurements of samples from Sites 17 and 18 from two holes drilled through the Guaje into the Puye indicated that the contact between the units forms a perching surface for percolating water. At both sites holes were drilled in the streambed in small canyons tributary to Pueblo Canyon and several yards upstream from the contact between the two units of the tuff.

The moisture contents above and below the Guaje-Puye contact were significantly different at both sites (table 11). The 60.8 percent average moisture content in the Guaje at Site 17 probably represents saturation or near saturation and the 34.2 percent in the clayey top of the Puye probably represents about field capacity or less. Apparently water infiltrates slowly across the contact and ~~percolates through~~ infiltrates the Puye after field capacity or above is attained in the Guaje. At Site 18, where less water is available because of a small drainage area, the average moisture content in the Guaje was 30.6 percent, or about half that at Site 17. The moisture content of the Puye at Site 18 was correspondingly low.

Samples were collected at the base of and below a compacted silt layer about 13 feet thick in the upper part of the Puye Conglomerate, and which perches the stream in part of Pueblo Canyon (Site 19). Moisture content of the samples show that little or no water infiltrates the silt layer. The moisture content at the bottom of the silt layer was about 22 percent by volume; the moisture content of the sandy sediments immediately beneath the layer was about 12 percent by volume.

Table 10.--Moisture content, in percent by volume, near the contact of the Guaje Member of the Bandelier Tuff and the Puye Conglomerate at Sites 17 and 18.

Site No.	Distance above or below contact (feet)	Moisture content (in percent by volume)	Stratigraphic Unit
17	1-2	61.0	Guaje Member
	0-1	60.7	Guaje Member
	0-1	34.2	Puye Conglomerate
18	2-4	29.9	Guaje Member
	0-2	31.4	Guaje Member
	0-2	15.9	Puye Conglomerate
	2-4	17.1	Puye Conglomerate

Summary and conclusions

The Bandelier Tuff is divided into three members--the Guaje Member at the base, the Otowi Member in the middle, and the Tshirege Member on top. Vertical density gradients in the Tshirege Member are caused by changes in the physical properties of the tuff. The specific gravity of the Bandelier Tuff decreases slightly with depth and also from west to east across the Pajarito Plateau.

The porosity of the tuff ranged from about 20 percent to about 60 percent and the deviation from the mean at any particular study area was generally only a few percent. The higher porosity values are within the upper parts of the units and within the upper few feet of the sub-units. The porosity is inversely related to the dry unit weight; the dry unit weight near the base of the units and sub-units is relatively high and the porosity relatively low. The porosity is also inversely related to the moisture content at one-third atmosphere tension, which was found to be roughly the average field capacity of the tuff. Pore-size distribution curves show that about 20 to 25 percent of the total pore space transmits most of the water which moves through the tuff, and that the water in the smaller pores moves mostly by the slower processes of capillarity and diffusion, and contributes little to the bulk of the movement. The average permeability is low--about ½ to 6 gallons per day per square foot.

Jointing is common throughout the Tshirege Member. They are narrow and filled with sediments for a few feet below the land surface, but are sediment-free at depth. Joints interconnected to depth in the Tshirege could provide paths for rapid downward movement of water. In places, the movement of water through joints would negate the effect that a bed of low permeability would have caused had water movement been only through pores in the tuff. Nuclides in water moving through open joints would have a relatively limited opportunity to be absorbed onto the tuff, as compared to nuclides in water that moved through the pores of the tuff.

The moisture content during percolation of water through parts of the tuff that contain few joints or density gradients was in the 25 to 35 percent range. This range is slightly above midway between field capacity and porosity of the tuff. Slight changes in the physical properties of the tuff apparently caused local areas to become nearly saturated, but generally the moisture content during percolation through the bulk of the tuff was substantially less than saturation. Beneath restricting layers, water continued to move in the lower moisture range. The temperature of the water, due to seasonal changes, apparently affected the rate of infiltration at the water-tuff interface. The rate of percolation exceeded the rate of infiltration when the water was near freezing.

The rate of percolation in dry soil decreased from about half a foot per day during the first day to less than a quarter of a foot per day during the third day. In a wetted soil the wetted front moved to a depth of almost 5 feet during 2 days of infiltration. The maximum moisture content after 99 days of infiltration was about 39 percent in the soil zone and decreased to less than 4 percent within a foot of the top of the underlying tuff. The rate of movement directly into dry tuff averaged about 2 feet per day during the first day, half a foot per day during the next 11 days, and about a tenth of a foot per day during the next 56 days.

Water movement was monitored by moisture meter readings to a depth of about 90 feet below a disposal pit. Water in the low moisture range apparently moved to depths greater than 90 feet. Water in unknown quantities moves through open joints or joints enlarged by solvents in the wastes.

Alternate wetting and drying of the tuff due to intermittent or 'slug' discharge of wastes may cause different patterns of uptake of ions than continuous discharge. After the tuff has once been wetted and drained, the moisture content remains in the 10 to 20 percent range for a period of several months due to hysteresis, much of the movement being in the lower moisture range. Subsequent movement of water through the tuff is more rapid because the tuff is already wetted and an energy barrier is not created at the wetted front.

The effective and total porosity, pores sizes, pore size distribution, and the particle size each affect the movement of water in the Bandelier Tuff. Their individual and collective effects can be evaluated relative to various standard methods of studying water movement in a porous material, such as moisture content, tensions at different specific conductance and specific yield, and permeability. The water retention and water transmission properties of the tuff are functions of the porosity and the percent of large pore spaces, which in turn are related to the dry unit weight and particle size distribution.

Most of the gross alpha activity found beneath an infiltration pit was within tuff a short distance beneath the pit. Below a depth of about 15 to 20 feet the alpha activity was low, except for local areas of high alpha activity where water carried the activity along joints. Rapid movement of water through joints was substantiated during infiltration studies. The relationship between gross alpha activity and the pH of the solution was inverse. Total hardness and total solids increased with depth, suggesting solution and resolution of previously deposited materials.

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