LA-11511-MS

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Cover Photo: *Constant head device used at site 2.*

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LA-11511-MS

UC-702
Issued: August 1989

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by

W. D. Purtymun, E. A. Enyart, and S. G. McLin

ABSTRACT

Injection wells were used to determine some of the bydrologic transmitting characteristics of the unsaturated Bandelier Tuff. At site 1, a 60-ft injection well with a 5-ft injection zone was used to conduct four tests. These preliminary tests were made in order to design an injection-well monitoring system that could track the movement of fluids in the tuff.

At site 2, a second injection well with a 10-ft injection zone and seven observation holes was used to monitor the movement of 335 000 gal. of water injected into the tuff. The initial injection rate at site 2 was 5.8 gallons per minute (gpm), but that rate gradually declined to 0.4 gpm after 89 days of the test; 289 days after the test ended, the pear-shaped nephol (the shape of moisture injected into the tuff) reached a maximum depth of 210 ft and had a diameter of about 120 ft.

A second test at site 2 indicated that intermittent use of an injection system would allow for short periods of higher injection rates, thereby extending the life of the system. Finally, a third test at site 2 was made using a 50-ft injection zone, which resulted in an injection rate of 15.8 gpm, or about 3 times the initial rate achieved when a 10-ft injection zone was used.

I. INTRODUCTION

The U.S. Geological Survey, in cooperation with the U.S. Atomic Energy Commission (now the U.S. Department of Energy) and the Los Alamos Scientific Laboratory (now the Los Alamos National Laboratory), began a study in 1964 to determine the hydrologic characteristics of the unsaturated Bandelier Tuff with reference to use of injection wells. This report is an interpretation and documentation of the field data from this study.

The Pajarito Plateau, located near Los Alamos, New Mexico, forms an apron around the eastern flanks of the Sierra de los Valles. The plateau is composed of Bandelier Tuff, which ranges in thickness from about 1000 ft along the western edge of the plateau to less than 50 ft eastward along the canyon cut by the Rio Grande. The tuff that forms the plateau contains no perched water and is above the upper surface of the main aquifer (Purtymun 1984). The study of the hydrologic characteristics of the unsaturated tuff indicated that liquids injected into the tuff could be retained or suspended in the tuff above the main aquifer.

Information was collected from two test areas where different amounts of water were injected into the tuff at different depths and pressures. The purpose of the study was (1) to investigate the rates and conditions at which the unsaturated tuff would accept water so that an injection system could be designed, and (2) to monitor the movement of fluids from the injection zone into the adjacent tuff.

A. Definition of Terms

Several terms not generally used to describe the injection and movement of water into the tuff are defined as follows:

Injection zone is the outside portion of a cased or uncased wellbore that is hydraulically connected to the surrounding porous media so that injected fluids can freely move between the wellbore and media when a fluid pressure differential exists. Actually, it is more precise to say "a fluid piezometric head differential," which is simply the sum of the pressure head and the elevation head above some arbitrary reference datum. However, for the purposes of this report, the term pressure head will suffice. The interested reader may see any groundwater hydrology text for a more complete discussion (for example, Bouwer 1978).

Wellhead pressure refers to the hydraulic pressure of injection well fluids; it is measured as the vertical distance from the center of the injection-zone interval upward to the free surface of the injection fluids. This vertical distance, or head, is typically measured by a pressure gauge reading relative to atmospheric pressure; it has units of pounds per square inch, gauge (psig or, more simply, psi). Injection fluids are held in a storage reservoir that is connected to the injection well via surface piping; the fluids are either gravity fed or pumped to the wellbore for injection. Hence, wellhead pressure consists of the vertical distance from the injection-zone interval to the top of the wellbore (converted to a pressure), plus the feed-line pressure from the injection-fluid reservoir measured at the top of the wellbore.

Injection-zone pressure refers to the hydraulic pressure in the injection interval; it can be measured in the injection zone by a monitoring tube that is strapped to the injection pipe and inserted into the injection borehole. Hence, it would be measured as the vertical distance in the monitoring tube from the center of the injection-zone interval upward to the fluid surface. Wellhead pressure in the injection pipe is always greater than injection-zone pressure because of friction losses associated with fluid flow through the porous media from the injection zone.

Nephol (Greek for cloud) refers to the body of moisture formed by water injected into the unsaturated tuff; it may consist of both saturated and partially saturated porous media.

Capillaries best describe the system of interconnected pore space in the porous media; these pore spaces are generally less than 1 mm in diameter. In unsaturated porous media, capillary forces have a significant effect on the simultaneous movement of water and air, so this interconnected network is generally referred to as the capillary system.

Voids describe pore spaces that are larger in size than those in the capillary system; void space may also describe joint or fracture openings in the porous media.

Porosity is the total pore space per unit volume of porous media, expressed as a percent. Effective porosity is the interconnected pore space that can transmit a fluid such as water when it is subjected to a hydraulic gradient. Effective porosity is always less than the porosity because dead-end pores that do not transmit fluids are not taken into consideration.

Specific retention, or field capacity, is the ratio of the volume of liquid that the saturated porous media will retain against the pull of gravity to a unit volume of porous media.

Specific yield is the ratio of the volume of liquid that the saturated porous media will yield under the pull of gravity to a unit volume of porous media.

B. The Application of Injection Wells

The original intent of the study was to determine if shallow injection wells could be used for the safe disposal of small volumes of low-level radioactive liquid effluent into the unsaturated near-surface tuff. The method was never developed or used at Los Alamos and, under current federal and state regulations, the injection of liquid wastes into the unsaturated tuff would never be considered. The data that were collected for this study, however, have become important to other waste-management technologies. For example, this information can be used to evaluate seepage potential from existing or newly proposed surface impoundments and solid-waste landfills that may be located on or near the plateau's surface. The major potential contaminant pathway to the main aquifer from these near-surface disposal areas would be associated with the movement of contaminated fluids through unsaturated tuff.

A few factors recognized in the early 1960s that are related to the safe injection and disposal of liquid radioactive wastes are present in the geologic and hydrologic setting at Los Alamos (LeGrande 1962). The injection of such wastes now would never be considered, but the same factors governing the movement of injection fluids through the tuff can also be used to control the movement of intercepted precipitation infiltration from surface impoundments and landfills. These factors must be characterized so that existing and future waste-disposal operations can be safely engineered to prevent excessive subsurface contaminant migration. These factors in the Los Alamos area include the following:

- *Depth to Water.* The water table (main aquifer) is from 600 to 1200 ft below the surface of the plateau. This thickness of unsaturated tuff can contain a large, but presently unknown, volume of fluids, with little danger of these fluids ever reaching the top of the main aquifer.
- *Low Hydraulic Conductivity of the Arresting Medium.* The hydraulic conductivity of saturated tuff ranges from 0.1 to 6 gallons per day per square foot (gpd/ft^2); the hydraulic conductivity of the unsaturated tuff is a function of moisture content and is typically two to five orders of magnitude smaller than values for saturated tuff. Low hydraulic conductivity is consistent with low fluid velocity and a reduced contaminant migration hazard.
- *High Accessible Porosity of Arresting Medium.* The effective porosities of the tuff range from 18 to 52%; specific retention values range from 18 to 38%.

II. GEOLOGIC AND HYDROLOGIC CHARACTERISTICS OF THE TEST AREAS

The site used for the test area (injection wells and observation holes) is on a narrow mesa near the center of the Pajarito Plateau, just east of Laboratory Technical Area 50 (liquid-waste treatment plant). This location was chosen because of available electricity and proximity to a water supply and because the area is underlain by a thick section of unsaturated tuff.

A. Geology

The surface of the mesa at the test area is underlain by Bandelier Tuff, which is composed of three members. In ascending order they are

1. The lower Guaje Member, an air-fall-deposited lump pumice about 50 ft thick;
2. The overlying Otowi Member, a massive nonwelded ash flow about 300 ft thick; and
3. The upper Tshirege Member, a series of nonwelded-to-welded ash flows about 525 ft thick (Griggs 1964).

The Bandelier Tuff is underlain by the Puye Conglomerate, which is composed of mixed gravels and boulders in a matrix of sand. The top of the main aquifer is defined by the presence of a continuous water table located in the lower part of the Puye Conglomerate beneath the plateau. There is little, if any, recharge to the main aquifer through the unsaturated tuff and sediments that form the plateau (Abrahams 1961 and Cushman 1965). The recharge area to the main aquifer is located approximately 8 to 10 miles west of the study area in the Sierra de los Valles.

This study is concerned with the Bandelier Tuff. It focuses on the upper Tshirege Member, which is composed of a series of nonwelded-to-welded ash flows (Purtymun 1971) exposed at the surface of the study area. All of these ash flows have the same general composition, although the size of mineral and rock fragments and the degree of welding in the ash matrix vary from ash flow to ash flow. The tuff is composed of quartz, sanidine crystals and crystal fragments, minor amounts of mafic minerals, and rock fragments of pumice, dense rhyolite, and latite in a matrix of fine ash.

The injection wells and observation holes were completed in the Tshirege Member. The test area consisted of two sites that are adjacent to each other (Fig. 1). The injection wells and observation holes varied in diameter and depth (Table I). The deep observation wells at site 2 penetrated four separate ash flows, each with varying degrees of welding. These ash flows, in descending order, were moderately welded tuff, welded tuff, moderately welded tuff, and nonwelded tuff (Table II).

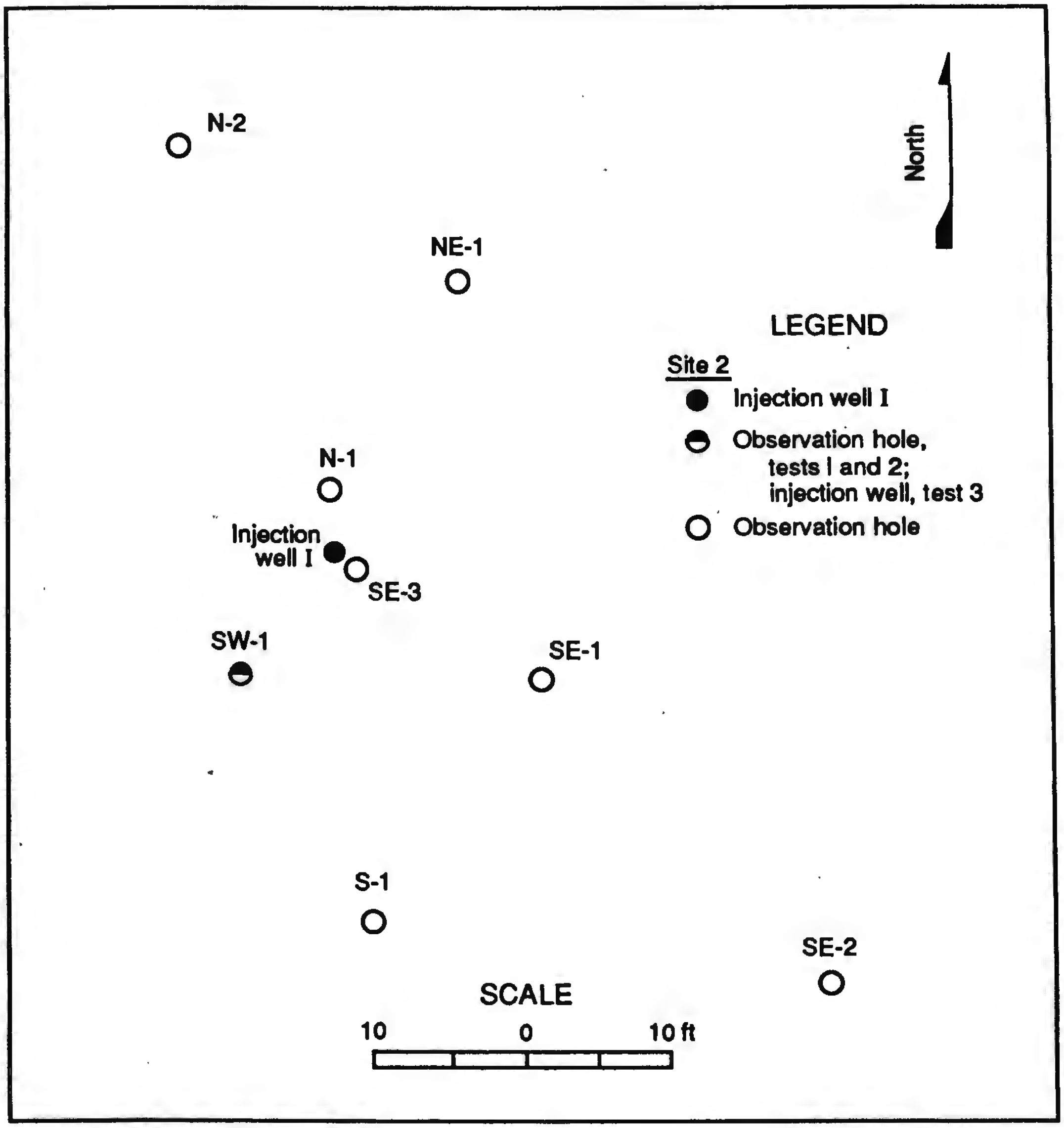

Fig. 1. Location of injection wells and observation holes at site 2. (Not shown in the figure is the injection well at site 1, located 300 ft to the southeast.)

B. Hydrologic Characteristics of the Tuff

Variations in the degree of welding produce different hydrologic transmitting characteristics in the tuff. The estimated total and effective porosities of the ash flows underlying the test sites show that both total and effective porosities in nonwelded tuffs are greater than those in welded tuffs (Table II). Variations in hydrologic transmitting characteristics in a given area of nonwelded-to-welded tuff underlying the mesa at the sites occurred because of differential cooling rates within a single ash flow. The degree of welding (as reflected in density variations) of a given ash flow generally increases with depth. As a result, the larger porosities and hydraulic conductivities occur near the top of a given ash flow and decrease with depth (Table III).

A large portion of hydrologic data typically determined in the laboratory is not directly applicable to the field conditions that exist on Pajarito Plateau. Laboratory data are normally determined under idealized

Table I. Injection Well and Observation Hole Construction Data.

Hole or Well Designation	Diameter (in.)	Depth (ft)	Remarks
Site 1			
1	5	60	Injection well
Site 2			
N-2	5	112	Observation hole
NE-1	5	118	Observation hole
N-1	5	97	Observation hole
I	5	65	Injection well[a]
SE-3	4	295	Observation hole
SW-1	5	95	Observation hole and injection well[b]
SE-1	5	97	Observation hole
S-1	4	295	Observation hole
SE-2	4	112	Observation hole

[a]Injection well, tests 1 and 2.
[b]Observation hole, tests 1 and 2; injection well, test 3.

Note: Observation holes had a surface casing to 1 ft; open holes, to total depth. Holes were augered except for SE-3 and S-1, which were drilled by an air rotary method. Logs recording neutron moisture and density were run in open observation holes.

saturated conditions. However, field conditions indicated that the tuff is not fully saturated. Instead, it generally has a moisture content of less than 4% by volume. Even with recent developments and improvements in laboratory equipment and test procedures, hydrologists have difficulty achieving accuracy at these low moisture contents.

It has been determined that a moderately welded tuff (upper ash flow at sites 1 and 2) with an effective porosity of about 38% by volume has an energy relationship of moisture movement in four different forms:

1. At a moisture content below 6% by volume, there is no movement of water or moisture.
2. From 6%–~12% moisture, fluid movement is governed by diffusion.
3. From ~13%–~24% moisture, movement is mainly controlled by capillary forces in the

Table II. Statigraphic Units and Porosities of Tshirege Member of the Bandelier Tuff at Sites 1 and 2.

	Thickness (ft)	Depth Below Land Surface (ft)	Effective Porosity[a] (% by volume)	Porosity[a] (% by volume)
Tshirege Member				
Moderately welded tuff	110	110	38	46
Welded tuff	120	230	33	37
Moderately welded tuff	20	250	38	46
Nonwelded tuff	45+	295+	54	60

[a]Estimated from logging of moisture and density at site 2.

Table III. Hydrologic Characteristics of a Moderately Welded Ash Flow.

	Unit	Height Above Base of Ash Flow 47 ft	20 ft	12 ft
Porosity	% by volume	54	47	38
Specific yield	% by volume	38	27	18
Specific retention	% by volume	16	20	20
Hydraulic conductivity of saturated tuff	gpd/ft^2	6	2	0.9

lower moisture content ranges and is also supplemented by gravity in the upper moisture content ranges.

4. From a moisture content of ~24%–~38%, moisture movement is gravity-dominated (Abrahams 1963).

For the moderately welded tuffs at the injection well test sites 1 and 2, native moisture contents were supplemented with water additions during the test procedures. The data collected from these tests indicate that injection will cause all four types of movement to take place. The tuff immediately adjacent to the wellbore injection zone will be at or near saturation; however, farther away from the injection-zone perimeter, the migration of moisture in the unsaturated tuff will be controlled by diffusion or capillary forces.

At still more radially distant points, the moisture contents will approach their native values and moisture movement will be severely restricted. Hence, a gradual transition from gravity-dominated, saturated flow conditions to capillary-dominated, unsaturated flow conditions will be established radially away from the injection zone. The unsaturated zone will be considerably larger than the saturated zone, so that the primary mechanisms for water movement will be in the moisture range dominated by the capillary-size pores. When injection ceases, the saturated zone will slowly dissipate until the entire nephol is dominated by unsaturated flow. Eventually, this nephol will slowly expand until it stabilizes and no further movement occurs.

III. TESTS AT SITE 1

The injection well at site 1 was drilled to a depth of 60 ft with a diameter of 5 in. Two 0.75-in.-diam plastic tubes were installed to the bottom of the wellbore. The bottom 5 ft of each tube were perforated with 0.125-in.-diam holes. The bottom 5 ft of the wellbore annulus were filled with 0.25-in.-diam gravel. A 7-ft-thick cement plug was poured on top of the gravel using a drop line to prevent bridging of the cement above the gravel. The rest of the borehole annulus was filled with drill cuttings.

One of the two plastic tubes in the injection zone was used to inject water, while the other was used to monitor the pressure in the injection zone. Four separate tests were made at site 1. The flow rates of water injected into the well, wellhead pressures, and pressures in the injection zone were monitored during each of the tests.

The tests at site 1 were not designed to monitor the movement of moisture into the tuff. They were conducted instead to determine the best test design for monitoring the movement of moisture into the tuff under controlled conditions. Each of these four tests is described below.

A. Test 1

Test 1 was a gravity-flow test, with 3613 gal. of water injected into the tuff during the period May 11–13, 1965. Water was injected from an 800-gal. constant head reservoir at the wellhead. A constant wellhead pressure of 26 psi was maintained throughout the test; however, because of water loss into the tuff, the pressure in the injection zone never reached 26 psi.

The 5-ft injection zone in the tuff received water at a rate of about 2.5 gpm during the first 2.5 h of the test. At the end of this period, the injection-zone pressure

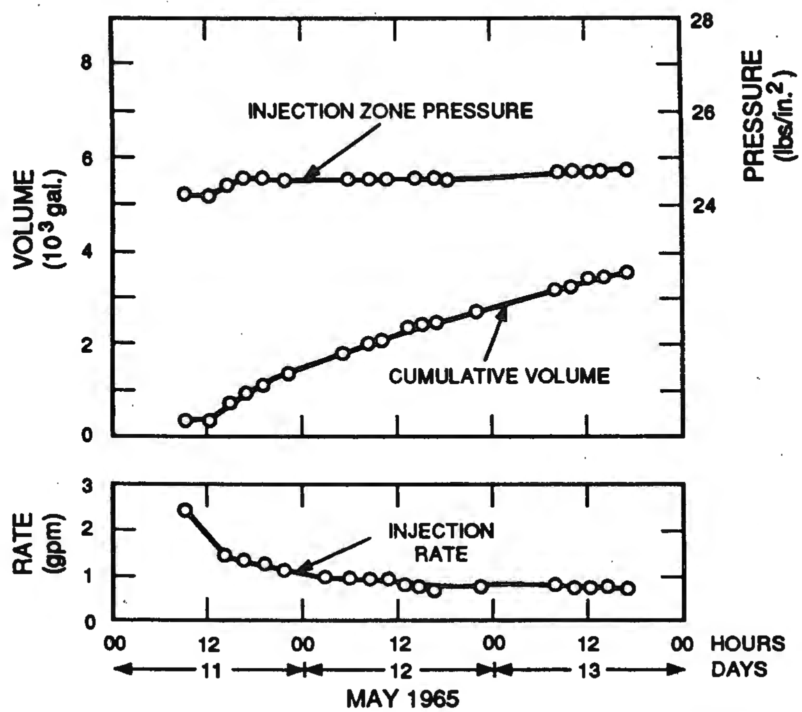

Fig. 2. Injection rate, injection-zone pressure, and cumulative volume of water injected into tuff during test 1 at site 1, May 11–13, 1965.

was 24.3 psi (Fig. 2). The injection rate gradually decreased to 1.0 gpm at the end of 24 h, while the pressure in the injection zone gradually increased to 24.6 psi. At the end of the 72.5-h test, the injection rate had further decreased to 0.8 gpm and the pressure in the injection zone had increased to 24.7 gpm.

Throughout the test, the injection-zone pressure increased while the injection rate declined. If the pressure in the injection zone had ever reached the full injection pressure of 26 psi during the test, then hydraulic equilibrium conditions would have been achieved and gravity flow would have stopped.

B. Test 2

In test 2, the injection tube was connected directly to the waterline. A flowmeter and gate valve were also installed between the waterline and injection tube. The gate valve was used to control the flow rate and, hence, the injection pressure. The pressure in the injection zone therefore equaled the wellhead pressure plus the line pressure.

The initial injection rate was about 1.8 gpm, with a corresponding injection-zone pressure of 36 psi (a constant wellhead pressure of 26 psi plus a line pressure of 10 psi). After about 3.5 days, the injection rate had gradually decreased to a constant rate of about 1.3 gpm, where it remained until the end of the test. At the same time that the injection rate had decreased, the corresponding pressure in the injection zone had gradually increased from 36 to 38 psi; it then increased from 38 to 41 psi when the test ended on May 19 (Fig. 3). An injection-zone pressure of 41 psi (a constant wellhead pressure of 26 psi plus a line pressure of 15 psi) is theoretically equivalent to a hydrostatic water column 94.6 ft high.

A total of 10 785 gal. of water was injected into the tuff during test 2, May 13–19, 1965. A cumulative total of 14 398 gal. of water was injected into the tuff during tests 1 and 2.

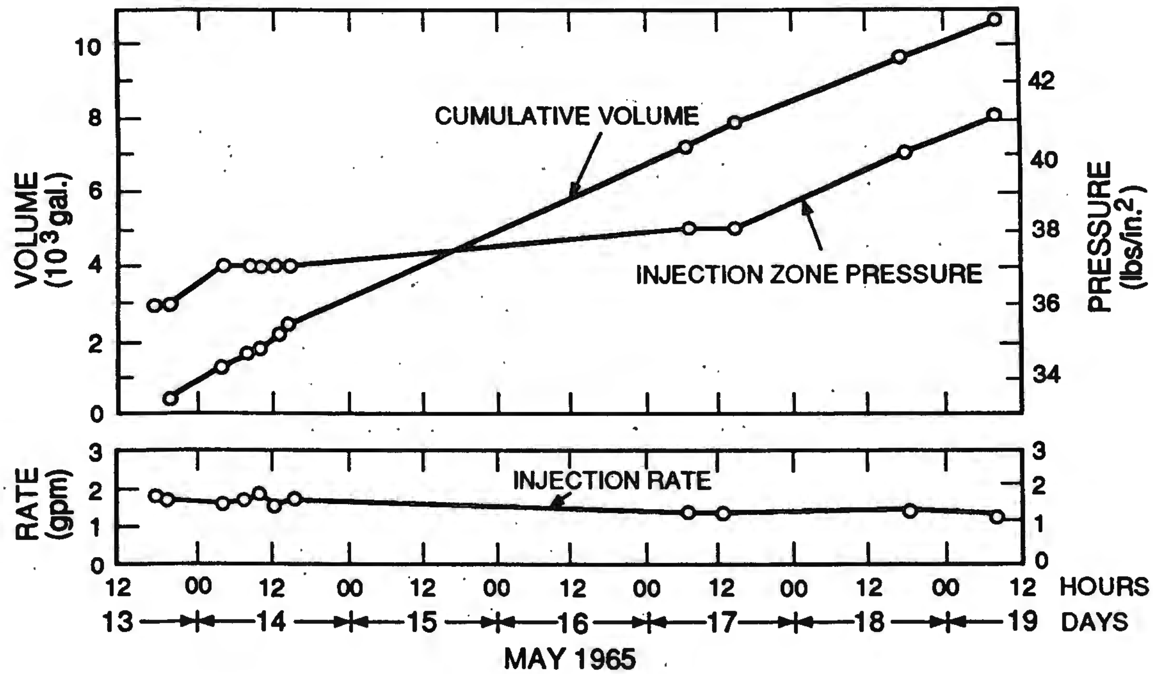

Fig. 3. Injection rate, injection-zone pressure, and cumulative volume of water injected into tuff during test 2 at site 1, May 13–19, 1965.

C. Test 3

The gate valve on the waterline was opened, and the pressure on the injection zone was equal to the waterline pressure plus the constant wellhead pressure. During test 3, waterline pressures fluctuated noticeably because of increased or decreased water use at TA-50; hence, the injection-zone pressure also fluctuated.

At the start of the test, the injection rate and injection-zone pressure were 2.5 gpm and 51 psi, respectively; 48 h later they were 3.3 gpm and 59 psi. The injection pressures decreased during the afternoon of May 19 because of a drop in waterline pressure (Fig. 4). The decrease in pressure in the injection zone was accompanied by a decrease in the injection rate. Injection rates and pressures continued to fluctuate throughout the test. The final injection-zone pressure of 59 psi (a constant wellhead pressure of 26 psi and a line pressure of 33 psi) is theoretically equivalent to a hydrostatic water column 136.2 ft high.

A total of 7330 gal. of water was injected into the tuff during test 3, May 19–21, 1965. A cumulative total of 21 728 gal. of water was injected into the tuff during tests 1, 2, and 3.

D. Test 4

At the end of test 3, the waterline pressure was reduced. For test 4, the initial injection rate was about 1.8 gpm, with an injection-zone pressure of 31 psi (a constant wellhead pressure of 26 psi and a line pressure of 5 psi). Near the end of the test, the injection rate had gradually declined to about 1.0 gpm, while the injection-zone pressure had increased to 40 psi (Fig. 5). An injection-zone pressure of 40 psi is theoretically equivalent to a hydrostatic water column 92.3 ft high.

To determine if the injection rate could be increased by a wetting agent, 2 lbs of sodium phosphate were introduced into the injection zone between the hours of 1600 and 1700 on May 24. The addition of this amount of wetting agent had no effect on the injection rate.

The pressure on the injection zone was increased to about 48 psi (a constant wellhead pressure of 26 psi and

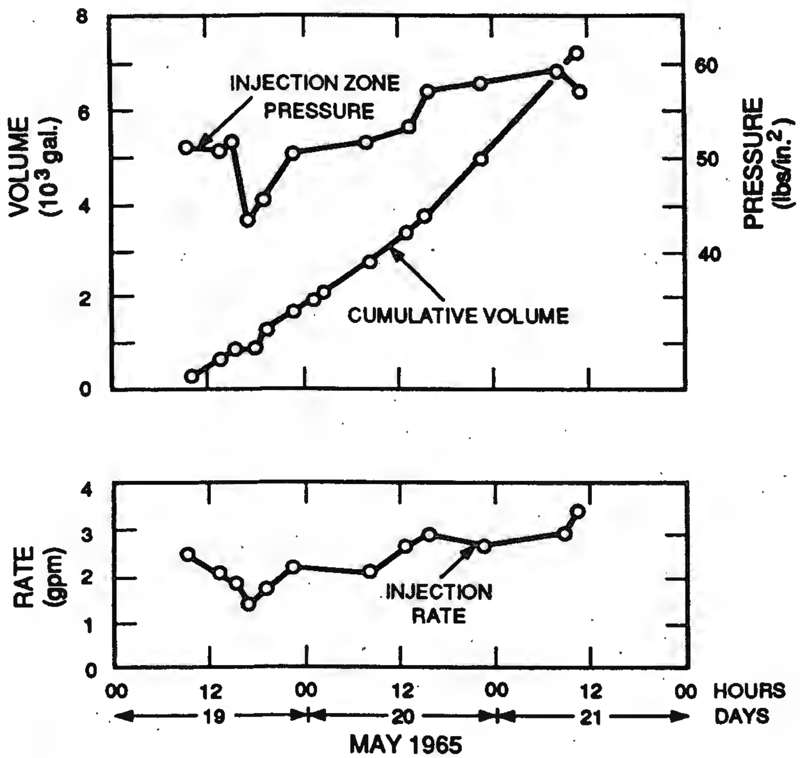

Fig. 4. Injection rate, injection-zone pressure, and cumulative volume of water injected into tuff during test 3 at site 1, May 19–21, 1965.

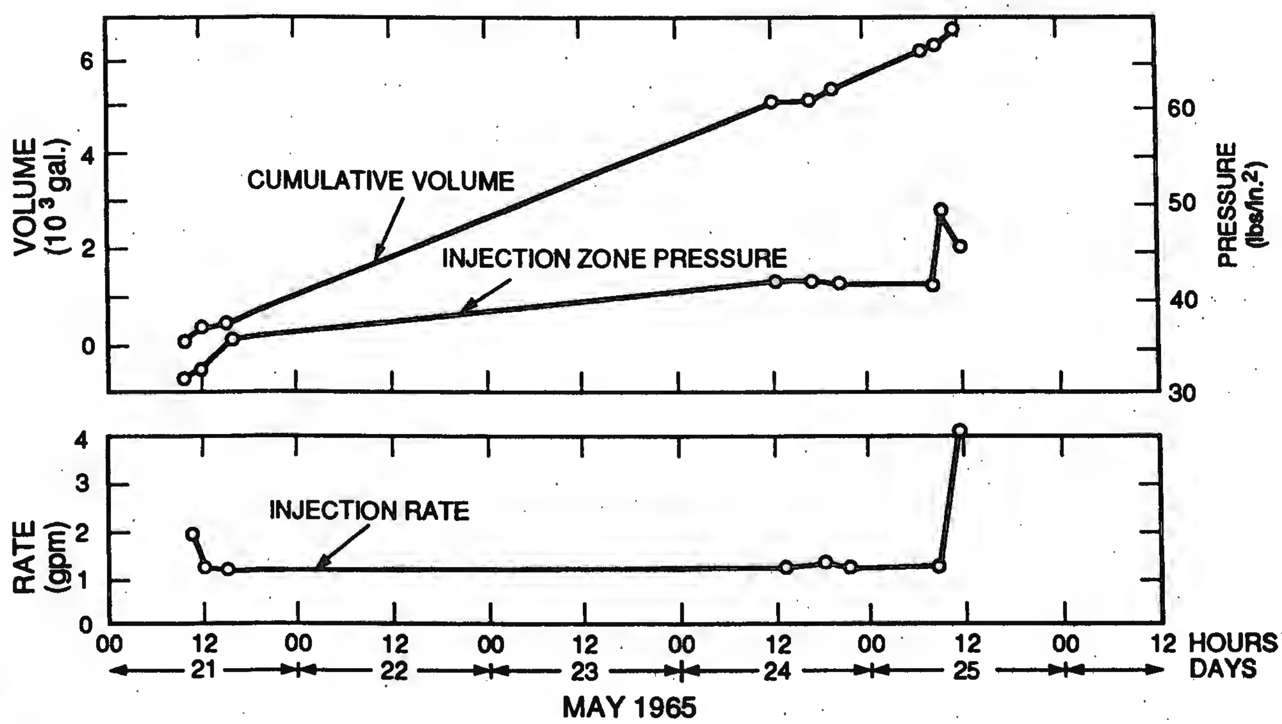

Fig. 5. Injection rate, injection-zone pressure, and cumulative volume of water injected into tuff during test 4 at site 1, May 21–25, 1965.

a line pressure of 22 psi) at an injection rate of about 4 gpm on May 25 at 1000 h. The injection rate began to gradually increase, and, after 2 h, water began to leak from the earthen fill at the top of the injection wellbore annulus (Fig. 5). The concrete plug on top of the injection zone apparently had failed and begun leaking; the experiment was therefore discontinued.

A total of 6677 gal. of water was injected into the tuff during test 4, May 21–25, 1965. A cumulative total of about 28 405 gal. of water was injected into the tuff during tests 1, 2, 3, and 4.

E. Site 1 Summary and Conclusions

A total of 28 405 gal. of water was injected into a 5-ft zone located at a depth of 55 to 60 ft in an injection well completed in a moderately welded tuff. Four separate tests were conducted over a 14-day period. During these tests, the injection pressures were varied; the pressure variations resulted in injection rate variations.

Test 1 was conducted using a constant head storage reservoir and gravity feed yielding a wellhead pressure of 26 psi (an equivalent pressure head of 60 ft); however, the injection-zone pressure was less than 26 psi because of water loss into the tuff. The initial injection rate gradually declined from 2.5 gpm at the beginning of the test to 0.8 gpm at the end of the 51-h test. The corresponding pressure in the injection zone gradually increased from 24.3 to 24.7 psi (Table IV). The 24.7-psi value is theoretically equivalent to a hydrostatic water column 57.0 ft high.

Test 2 was conducted with an initial injection-zone pressure of 36 psi (a constant wellhead pressure of 26 psi and a line pressure of 10 psi). The injection-zone pressure increased from an initial value of 36 to 41 psi at the end of the 136-h test. During this period, the injection rate gradually declined from 1.8 to 1.2 gpm (Table IV). At end of the test, the injection-zone pressure was theoretically equivalent to a hydrostatic water column 94.6 ft high.

Table IV. Summary of Tests at Site 1.

	Test 1[a]	Test 2	Test 3	Test 4
Length of Test (h)	51	136	50	94
Injection-Zone Pressures (psi)				
Initial	24.3	36.0	51.0	31.0
Final	24.7	41.0	59.0	40.0
Equivalent to the Injection-Zone Pressures (ft)				
Initial	56.1	83.1	117.7	71.5
Final	57.0	94.6	136.2	92.3
Injection Rates (gpm)				
Initial	2.5	1.8	2.5	1.8
Final	0.8	1.2	3.3	1.0
Volume of Injected Water (gal.)				
Each test	3 613	10 785	7 330	6 677
Cumulative	3 613	14 398	21 728	28 405

[a]Gravity flow; wellhead pressure, 26 psi.

Test 3 was conducted with an initial injection-zone pressure of 51 psi (a constant wellhead pressure of 26 psi and a line pressure of 25 psi). This pressure increased to 59 psi at the end of the 50-h test, while the corresponding injection rate increased from 2.5 to 3.3 gpm over the same period. This is the only test conducted at site 1 where both the injection pressure and injection rate simultaneously increased. This occurrence was probably due to our inability to accurately control large line-pressure fluctuations during the test while the gate valve remained fully open.

Test 4 was conducted with an initial injection-zone pressure of 31 psi (a constant wellhead pressure of 26 psi and a line pressure of 5 psi). This pressure gradually increased to 40 psi at the end of the 94-h test. The corresponding injection rates gradually decreased from 1.8 to 1.0 gpm at the end of the test. An injection-zone pressure of 40 psi is theoretically equivalent to a hydrostatic water column 92.3 ft high.

During tests 1, 2, and 4, the pressures in the injection zone gradually increased while the corresponding injection rates declined. The low injection rates produced by the moderately increasing heads during each of these three tests are compatible with the inferred hydraulic conductivity of the low-saturation tuff. The general decrease in the injection rate with time and the corresponding increase in injection-zone pressure were expected because the resistance to flow increases as the water moisture plume gradually expands to occupy an ever-increasing volume of unsaturated tuff.

Test 3 did not follow the pattern of the other three tests; instead, there was an increase in injection rate over time with a corresponding increase of injection-zone pressure. The fluctuations in injection rates caused by uncontrolled waterline pressure variations yielded the anomaly of test 3 when compared with the other three tests.

The results of the tests at site 1 indicated that monitoring the movement of water from the injection zone into the tuff should be designed to use a gravity-flow system with a constant head reservoir at the surface. To facilitate more accurate injection-rate measurements, the length of the injection zone in subsequent tests was modified to 10 ft at a depth of 60 ft. An alternate approach would be to increase the wellbore diameter; however, this is generally less cost effective and was not done.

IV. TESTS AT SITE 2

Three tests were performed at site 2. Tests 1 and 2 used injection well I (Fig. 1); test 3 used injection well SW-1 (Fig. 1).

Injection well I is 5 in. in diameter and was completed at a depth of 65 ft. It was equipped with a 1.25-in. injection pipe with a 5-ft drive point attached to the bottom. Thirty holes, each 0.25 in. in diameter, were drilled into the pipe and drive point to ensure adequate release of water into the injection zone. A second 1.25-in.-diam pipe was used to monitor the pressure in the injection zone. The lower 5 ft of this pipe were also perforated with thirty 0.25-in.-diam holes. The injection and monitoring pipes were strapped together and lowered into the same borehole; both pipes were set at a depth of 60 ft. The injection zone, located between 55 and 65 ft, was filled with 0.25-in.-diam gravel. The wellbore immediately above the gravel-packed injection zone was filled with cement up to the land surface.

Test 3 at site 2 used observation hole SW-1 for the injection well (Fig. 1). SW-1 was drilled to a depth of 95 ft and is 5 in. in diameter. For test 3, the injection tube and the pressure-monitoring tube were both installed to a depth of about 70 ft, with sections of both tubes perforated between 60 and 70 ft. The hole was then backfilled with 0.25-in.-diam gravel to a depth of 45 ft; the 50-ft gravel-packed interval filled the wellbore from 45 to 95 ft. The hole above this gravel pack was filled with a light cement slurry.

The movement of water in the tuff during these three tests was reflected by changes in the moisture contents that were measured in the surrounding observation holes (Fig. 1). These moisture contents were observed to fluctuate between 4% by volume (the natural moisture content) and 34% (the saturation-induced moisture content). All moisture measurements were made using neutron-logging equipment. This equipment was calibrated against a γ-ray logging tool to establish a calibration curve. The neutron source probe was lowered into each observation hole, and multiple readings at varying depths were recorded at the surface to determine the moisture content in percent by volume.

A. Test 1

During test 1, water from the municipal water supply was metered into a volume-calibrated 500-gal. tank. This large tank discharged into a smaller tank equipped with a float valve so that a constant head of water was maintained in the injection well. This constant head device (Fig. 6) maintained a wellhead pressure of 26 psi (an equivalent pressure head of 60 ft) in the injection well. The pressure in the injection zone was determined from the water level in the pressure-monitoring tube located adjacent to the injection tube. The pressure in the injection zone during the test was less than the wellhead pressure because water moved into the tuff.

About 335 000 gal. of water were injected into the tuff through injection well I between 0830 h on June 17 and 1530 h on September 14, 1965. The initial injection rate was 5.8 gpm on June 17, but that rate gradually decreased to 1.4 gpm on June 25, gradually increased back to 5.8 gpm on July 15 and 16, and then gradually declined from the peak reading of 5.8 gpm on July 14 to about 0.4 gpm on September 14 when the test ended (Fig. 7). The injection-zone pressure was generally inversely correlated to the injection rate.

The pressure in the injection zone increased from 23.2 psi during the first day to 25.4 psi on June 24, declined to 21.3 psi by July 8, and then fluctuated between 21.0 and 21.6 psi during the rest of the test (Fig. 7). The pressure in the injection zone was less than the wellhead pressure of 26 psi maintained by the constant head device.

Slight changes in the injection rate and injection-zone pressure occurred during the test. The exact causes of these small changes could not be precisely

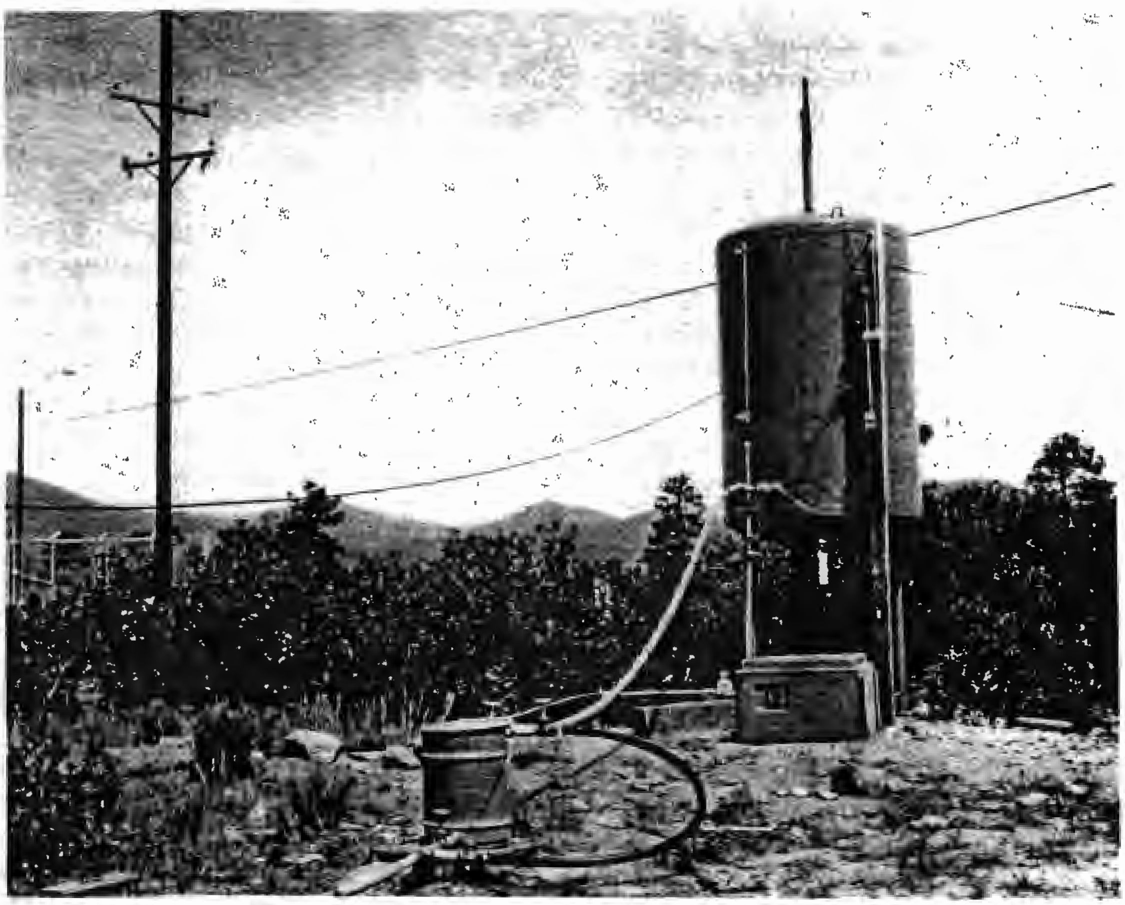

Fig. 6. Storage tank and constant head device.