GEOHYDROLOGY OF ROCKS PENETRATED BY TEST WELL USW H-5, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4168

Prepared in cooperation with the
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CONVERSION TABLE

For those readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

Multiply SI units	*by*	*To obtain inch-pound units*
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
degree Celsius (°C)	1.8 °C + 32	degree Fahrenheit (°F)
degree Celsius per kilometer (°C/km)	2.9	degree Fahrenheit per mile (°F/mi)
kilogram per cubic meter (kg/m^3)	0.062	pound per cubic foot (lb/ft^3)
kilometer (km)	0.6214	mile (mi)
kilopascal (kPa)	0.1450	pound per square inch (lb/in^2)
liter per second (L/s)	15.85	gallon per minute (gal/min)
liter per minute (L/min)	0.2642	gallon per minute (gal/min)
meter (m)	3.281	foot (ft)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per second squared (m/s^2)	3.281	foot per second squared (ft/s^2)
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)
microgram per liter (µg/L)	[1]1	part per billion
microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C	1.000	micromho per centimeter at 25 degrees Celsius (µmho/cm at 25°C)
millimeters (mm)	0.03937	inch (in.)
milligram per liter (mg/L)	[1]1	part per million
pascal (Pa)	0.0001450	pound per square inch (lb/in^2)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

[1]Approximate for concentrations of dissolved solids less than about 7,000 milligrams per liter.

GEOHYDROLOGY OF ROCKS PENETRATED BY TEST WELL USW H-5, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

By J.H. Robison and R.W. Craig

ABSTRACT

This report contains the results of hydraulic testing and monitoring, geophysical logging, and water analysis of test well USW H-5, one of a group of test wells drilled in the vicinity of Yucca Mountain, Nye County, Nevada, on behalf of the U.S. Department of Energy to investigate the suitability of the area to store and isolate high-level radioactive waste. The test well was drilled to a depth of 1,219 meters; all rocks penetrated are of volcanic origin and of Tertiary age.

Depth to water in the test well was 704 meters; the hydraulic head had no measurable variation with depth below land surface; altitude of the water surface was about 774 meters above sea level.

Production during hydraulic testing of the test well was about 10 liters per second. The Bullfrog Member of the Crater Flat Tuff, which ranged in depth from 690 to 836 meters, has the most permeable zone penetrated by the test well; this zone yielded about 90 percent of the water during pumping. The Tram Member of the Crater Flat Tuff, ranging in depth from 836 to 1,040 meters, and an unnamed dacitic (?) lava, from 1,043 meters to total depth, yielded minor quantities of water. Drawdown response to pumping was consistent with two alternative conceptual models. Use of a model for an unconfined, anisotropic aquifer indicated transmissivity is about 35 meters squared per day. Use of a finite-conductivity, vertical-fracture model indicated that fracture conductivity may be large and nonradial flow responses need to be considered.

Chemical character of water from the test well was typical of that from tuffaceous rocks in southern Nevada; dissolved solids were about 200 milligrams per liter. Carbon-14 activity of the water was 21.4 percent of modern, yielding an apparent age of 12,400 years before present.

Manuscript approved for publication September 14, 1988

INTRODUCTION

The U.S. Geological Survey has been conducting investigations at Yucca Mountain, Nevada, to determine the hydrologic and geologic suitability of the site for storage of high-level nuclear waste in an underground mined repository. These investigations are part of the Yucca Mountain Project, formerly the Nevada Nuclear Waste Storage Investigations project, and are being conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802. Test drilling has been a principal method of investigation. This report presents the results of hydraulic testing of test well USW H-5.

Test well USW H-5 is in Nye County, Nev., about 140 km northwest of Las Vegas in the southern part of the State (fig. 1). The site, located at N. 233,661 m and E. 170,358 m in the Nevada State Coordinate System Central Zone (lat 36°51'22" N.; long 116°27'55" E.), is on top of the principal ridge forming Yucca Mountain. Altitude of the land surface at the well site is 1,478.5 m above sea level.

Data from the drilling, testing, and monitoring of the test well were included in a report by Bentley and others (1983). The data, repeated in part here, were analyzed and interpreted in this investigation. The test well was drilled to a total depth of 1,219 m into tuff and lava of Tertiary age. Hydraulic tests were conducted after the test well had been drilled to total depth, cased to a depth of 790 m, and perforated below 704 m; depth to water was about 704 m.

Drilling of the test well began on May 19, 1982; total depth of 1,219 m was reached on June 23, 1982, and testing was completed by August 1, 1982. The rotary-drilling fluid was air foam, consisting of air, detergent, and water. Well construction is shown in figure 2. Maximum borehole deviation from vertical was 1°45'; this deviation and the horizontal drift shown in figure 3 were derived from a gyroscopic survey. A correction factor needs to be subtracted to obtain true depths from measured depths; this factor ranges from 0.08 m near the water table to 0.14 m near total depth of the well. The test well at total depth is about 13 m southwest of the surface location.

A summary of operations and borehole conditions, part of an administrative report by Fenix & Scisson, Inc.,[1] Mercury, Nev. (consultant to the U.S. Department of Energy), September 3, 1982, is presented here:

> 762 mm (30") casing was set at 11.6 m (38') in a 914 mm (36") hole drilled to 11.6 m (38') with conventional circulation using water. The annulus was cemented to surface in 3 stages with 5.61 m^3 (198 ft^3) of cement slurry. Calculated annular volume was 2.35 m^3 (83 ft^3). 508 mm (20") hole was drilled to 94.8 m (311') using air foam. Caliper, induction and formation density logs were run 05-25-82. The average curve on the caliper log indicated hole erosion from 14.3 m (47') to 63.4 m (208') with maximum hole

[1]Use of firm or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

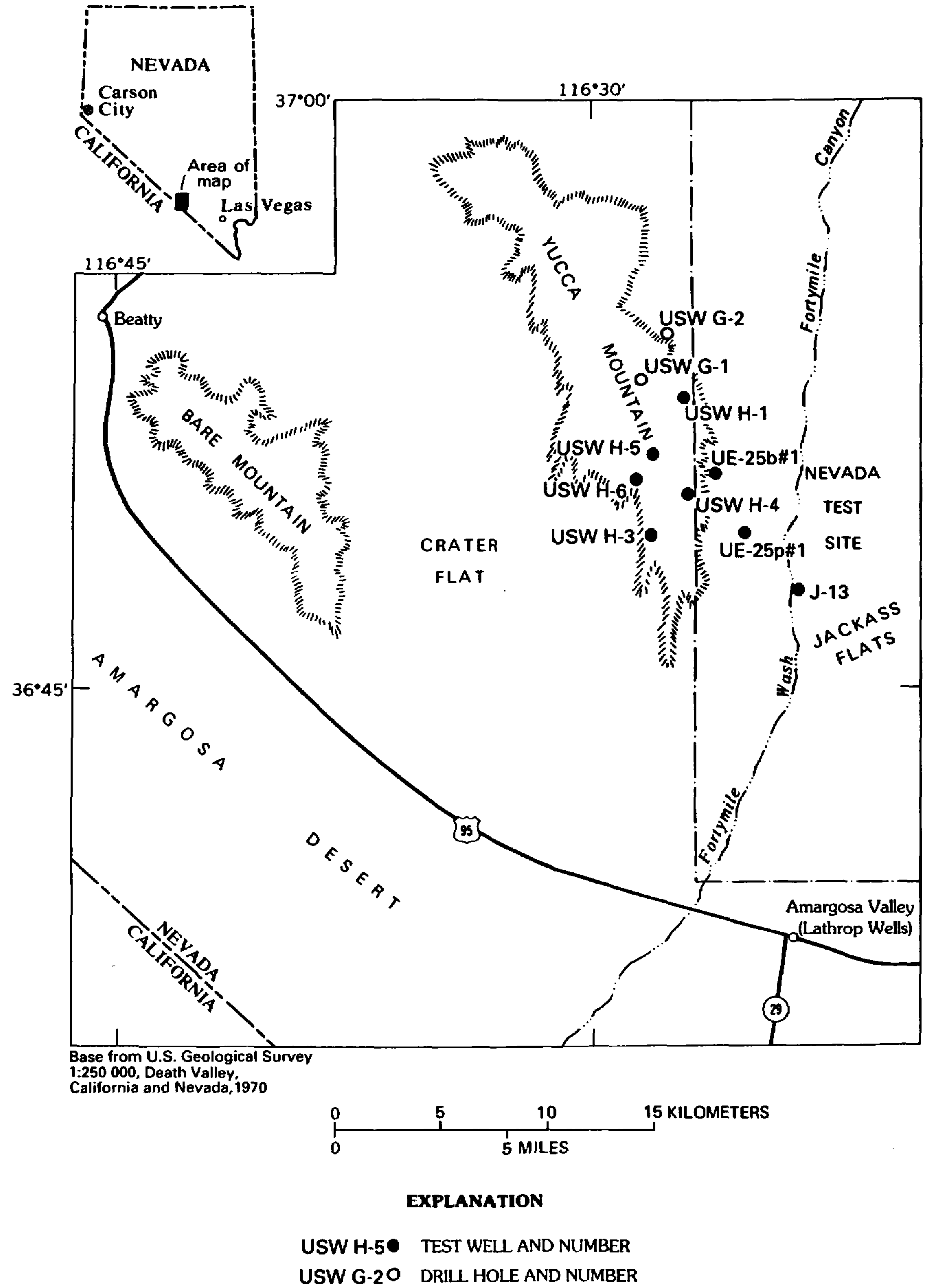

Figure 1.--Location of test well USW H-5, other test wells, drill holes, and nearby geographic features in southern Nevada.

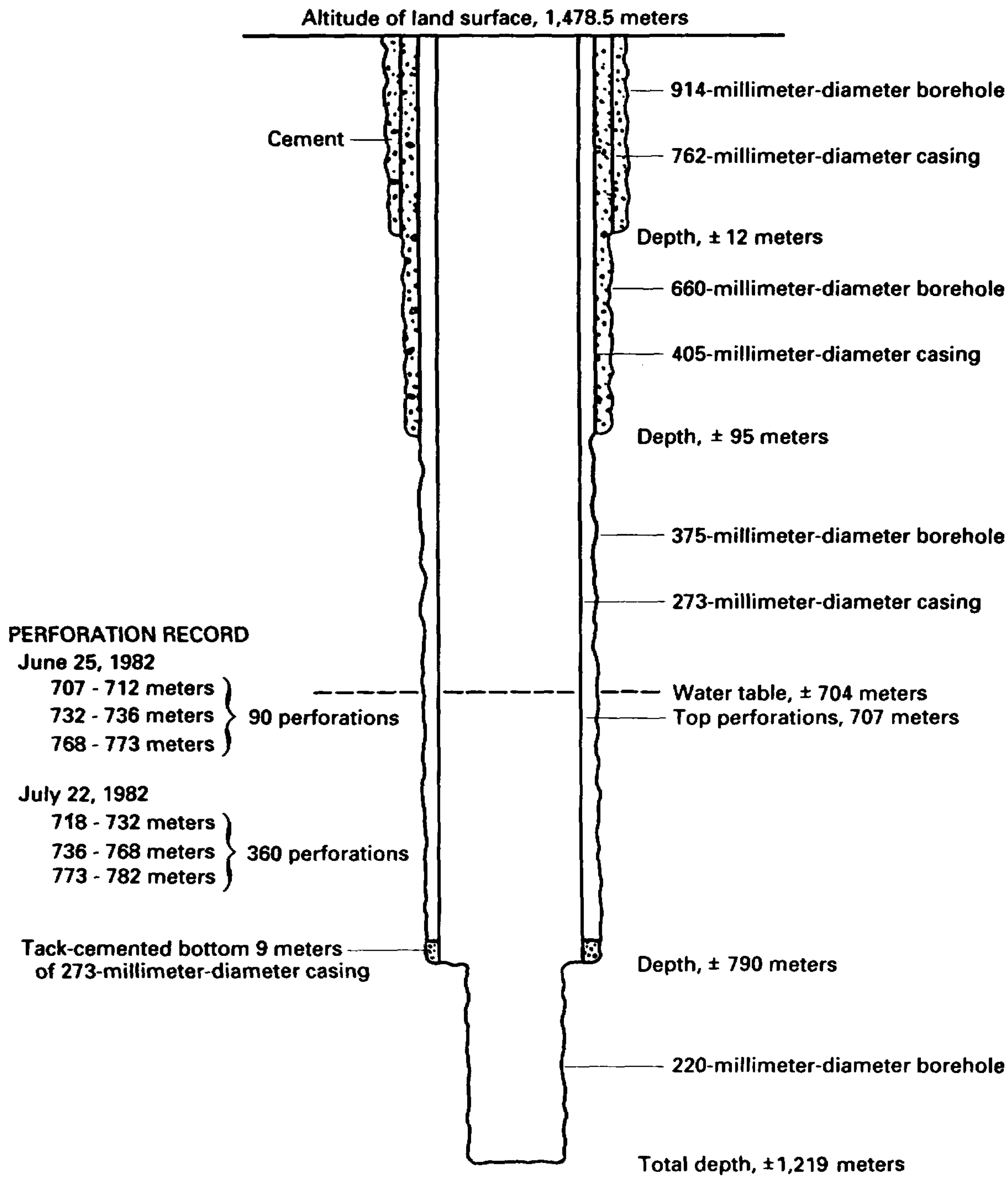

Figure 2.--Test well construction.

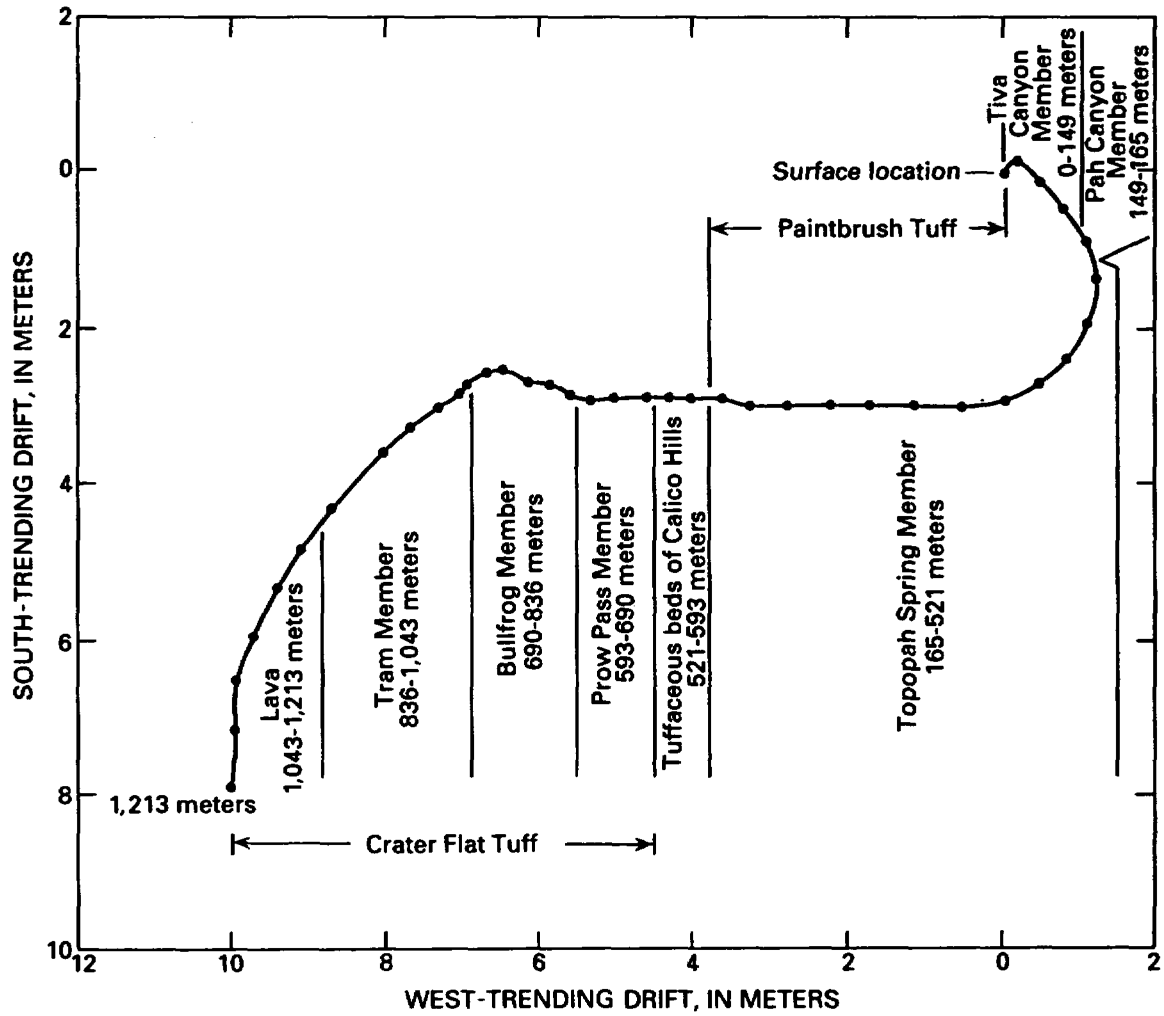

Figure 3.--Subsurface survey of borehole showing horizontal drift from surface location.

enlargement of 914 mm (36") at 29.9 m (98') and 51.2 m (168'). 406 mm (16") casing was set at 94.8 m (311') and the annulus cemented to surface in 5 stages with 30.30 m^3 (1,070 ft^3) of cement slurry. Calculated annular volume was 13.31 m^3 (470 ft^3). 375 mm (14-3/4") hole was drilled to 317.6 m (1,042') using air foam. Caliper log was run 05-30-82. The average curve on the caliper log indicated a gradual wash-out from 128.0 m (420') to 173.7 m (570') with maximum hole enlargement to 629 mm (24-3/4") thru the area from 148.1 m (486') to 166.1 mm (545'). Hole erosion was indicated between 212.8 m (698') and 235.6 m (773') with hole enlargements of 673 mm (26-1/2") at 214.0 m (702') and 838 mm (33") at 223.7 m (734'). Erosion was also indicated between 243.8 m (800') and 304.8 m (1,000') with hole enlargement to 667 mm (26-1/4") at 266.7 m (875'). 375 mm (14-3/4") hole was then drilled to 792.2 m (2,599'). Fluid density, caliper, epithermal neutron, compensated neutron, temperature logs, Vibroseis survey on 7.6 m (25') stations from 710.2 m (2,330') to 94.8 m (311') were run and sidewall samples taken between 06-09-82 and 06-13-82. The average curve on the caliper log below 304.8 m (1,000') indicated erosion between 335.3 m (1,100') and 505.4 m (1,658') with hole enlargement to 699 mm (27-1/2") at 345.6 m (1,134'). Gradual wash-out areas were indicated between 513.0 m (1,683') and 760.8 m (2,496') with hole enlargement to 660 mm (26") at 756.2 m (2,481'). 273 mm (10-3/4") casing was set 787.9 m (2,585') and the annulus cemented with 2.83 m^3 (100 ft^3) of cement slurry. Calculated top of cement in the annulus was 783.0 m (2,569'). 222 mm (8-3/4") hole was drilled to a total length of 1,219.2 m (4,000') using air foam. Gyroscopic survey, fluid density, caliper, induction lateral, compensated density, compensated acoustic-fracture, spectral logs and Vibroseis survey on 15.2 m (50') stations from 906.8 m (2,975') to 777.2 m (2,550') were run 06-23-82 and 06-24-82. The average curve on the caliper indicated hole to be nearly in gauge with maximum hole enlargement to 330 mm (13") at 868.1 m (2,848'). 273 mm (10-3/4) casing was perforated from 768.1 m (2,520') to 772.7 m (2,535'), 731.5 m (2,400') to 736.1 m (2,415') and 704.1 m (2,320') to 711.7 m (2,335') with 2 shots per foot. Hydrologic pump tests were run from 06-28-82 to 07-04-82. Hydrologic tests using a straddle packer were run from 07-13-82 to 07-19-82. 273 mm (10-3/4") was again perforated from 772.7 m (2,535') to 781.8 m (2,565'), 736.1 m (2,415') to 768.1 m (2,520') and 717.8 m (2,355') to 731.5 m (2,400') with 360 shots, 07-22-82. Caliper and temperature logs were run 07-23-82 with maximum temperature of 43.9° C (111° F) at 1,212.5 m (3,978'). The average curve on the caliper indicated additional hole enlargement of 62 mm (14-1/4") at 1,047.0 m (3,435') and 387 mm (15-1/4") at 1,098.5 m (3,604'). Hydrologic pump tests were run from 07-25-82 to 07-27-82. Hole completed 08-01-82. TV camera was run 10-25-82.

GEOHYDROLOGIC SETTING

Rocks exposed in the vicinity of the Nevada Test Site consist principally of sedimentary rocks of Precambrian and Paleozoic age, volcanic and sedimentary rocks of Tertiary age, and alluvial and playa deposits of Tertiary and Quaternary age (Winograd and Thordarson, 1975; Byers and others, 1976). Exposed rocks of Precambrian and Paleozoic age have a total thickness of about 11,000 m; they are predominantly limestone and dolomite, but include marble, quartzite, argillite, shale, and conglomerate. These rocks were intruded by granitic stocks of Mesozoic and Tertiary age and basalt dikes of Tertiary and Quaternary age. Most of the rocks of Tertiary age consist of welded, vitric, and zeolitic tuff and rhyolite flows of Miocene age that were extruded from the Timber Mountain-Oasis Valley caldera complex, centered about 20 km north of the test well (Carr and others, 1984). Alluvium of Tertiary and Quaternary age consists principally of detritus deposited in the intermontane basins, much of it as fan deposits.

The deepest rock penetrated by test well USW H-5 is dacitic (?) lava. Below the lava, more tuff of Tertiary age may occur, including the Lithic Ridge Tuff, as in other nearby test wells [test well USW H-1, 1.6 km northwest, Rush and others (1984); test well USW H-4, 2.2 km southeast, Whitfield and others (1985); test well USW H-6, 1.8 km southwest, Craig and others (1983)]. The depth and nature of pre-Tertiary rocks under test well USW H-5 are unknown, but Paleozoic rocks crop out on Bare Mountain (Cornwall and Kleinhampl, 1961, fig. 1), and Silurian dolomite was penetrated at a depth of 1,244 m in test well UE-25p#1, 5 km southeast of test well USW H-5 (Craig and Robison, 1984). A summary of major lithostratigraphic units and contacts penetrated in the test well is shown in table 1; the summary is based on a more detailed description by R.W. Spengler in the report by Bentley and others (1983).

HYDRAULIC HEADS

Measurements were made in June and July 1982, during drilling and testing, to determine hydraulic heads in various water-bearing zones, and also to determine the composite hydraulic head in the test well. Not all hydraulic-head measurements made at selected depth intervals represented complete equilibrium from the effects of drilling or testing, nevertheless the measurements had a range of less than 2.5 m; average depth to water was about 704 m, equivalent to an altitude of about 774 m above sea level (Bentley and others, 1983, p. 14). Altitudes of the hydraulic heads are comparable to those of test well USW H-6 (Craig and others, 1983), which is similar in depth and construction to test well USW H-5; however, the hydraulic heads in both test wells are about 45 m higher than those in most observation wells and test holes that are located to the east or south in the vicinity of Yucca Mountain (Robison, 1984).

Some of the stratigraphic intervals penetrated in test wells in the vicinity of Yucca Mountain for which hydraulic-head data are available have minimal permeability, particularly the lower intervals. It is believed that the short times available for measuring hydraulic heads during packer-injection-testing operations did not allow hydraulic heads to attain equilibrium, which prevented accurate determination of the direction or magnitude of vertical hydraulic gradients. To overcome that limitation, in early 1983, dual-element inflatable packers were installed near the bottom of five test wells, including test well USW H-5. The packers were installed on 73-mm-diameter open-ended tubing and positioned at locations in the boreholes that caliper surveys indicated had adequate seating for the packers. Intervals below the packer were hydraulically open to the tubing so that hydraulic heads in the lower zones might be monitored through the tubing. In test well USW H-5, the packer was set at a depth of 1,091 m, within the lava that occurs from 1,043 m to the total depth of 1,219 m. To monitor water levels of the intervals above the packers--that is, in the annulus between the borehole wall and the 73-mm-diameter tubing, 48-mm-diameter open-ended tubing was installed from land surface to slightly below the water table, and measurements of the upper zone were made inside the 48-mm-diameter tubing (fig. 4).

Table 1.--*Lithologic log*

Stratigraphy and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)[1]
Paintbrush Tuff of Tertiary age		
Tiva Canyon Member		
Tuff, ash-flow, densely welded, devitrified (probable vapor-phase crystallization from (10.7 to 12.2 meters)	12.2	12.2
Tuff, ash-flow, densely welded, devitrified (probable lithophysal zone)	51.8	64.0
Tuff, ash-flow, densely welded, devitrified	45.7	109.7
Tuff, ash-flow, moderately welded, devitrified	9.2	118.9
Tuff, ash-flow, partially welded, devitrified	6.1	124.9
Tuff, ash-flow, nonwelded, vitric	22.9	147.8
Bedded tuff (unnamed)		
Tuff, bedded, bedded ash-fall(?)	1.6	149.4
Pah Canyon Member		
Tuff, ash-flow, nonwelded, vitric	13.7	163.1
Bedded tuff (unnamed)		
Tuff bedded (?), ash-fall, vitric	2.1	165.2
Topopah Spring Member		
Tuff, ash-flow, nonwelded, vitric	7.9	173.1
Tuff, ash-flow, densely welded, (vitrophyre)	0.6	173.7
Tuff, ash-flow, densely welded, devitrified	6.1	179.8
Tuff, ash-flow, moderately welded, vapor phase	28.6	208.5
Tuff, ash-flow, densely welded, devitrified (probable lithophysal zone)	218.2	426.7
Tuff, ash-flow, densely welded, devitrified	55.5	482.2
Tuff, ash-flow, densely welded, (vitrophyre)	22.2	504.4
Tuff, ash-flow, moderately to partially welded, vitric	13.5	517.9
Bedded tuff (unnamed)		
Tuff, ash-fall, vitric; bedding planes	3.4	521.2
Tuffaceous beds of Calico Hills		
Tuff, ash-flow, nonwelded to partially welded, vitric; top of a lithic-rich zone at 528.2 meters; bedding planes	51.8	573.0
Tuff, bedded, reworked, ash-fall (?), zeolitic; bedding planes	19.8	592.8

Table 1.--*Lithologic log*--Continued

Stratigraphy and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)[1]
Crater Flat Tuff of Tertiary age		
Prow Pass Member		
Tuff, ash-flow, nonwelded, vitric----------------	7.6	600.5
Tuff, ash-flow, gray, partially welded, devitrified and vapor-phase crystallization; bedding 600.5 to 603.5 meters------------------	47.2	647.7
Tuff, ash-flow, nonwelded, zeolitized-----------	35.1	682.8
Bedded tuff (unnamed)		
Tuff, bedded, poorly sorted; bedding planes at 684.0, 684.3, and 684.9 meters-------------	7.0	689.8
Bullfrog Member		
Tuff, ash-flow, partially welded (?), vapor phase; static water level at 704 meters--------	81.3	771.1
Tuff, ash-flow, partially welded (?), devitrified------------------------------------	24.4	795.5
Tuff, ash-flow, partially to moderately welded, devitrified and zeolitic--------------	18.3	813.8
Tuff, ash-flow, moderately to densely welded, devitrified----------------------------	12.2	826.0
Tuff, ash-flow, partially welded, devitrified----	0.9	826.9
Bedded tuff (unnamed)		
Tuff, bedded, reworked, moderately indurated-----	8.8	835.8
Tram Member		
Tuff, ash-flow, moderately welded (?), devitrified------------------------------------	14.6	850.4
Tuff, ash-flow, partially welded, devitrified----	134.1	984.5
Tuff, ash-flow, partially welded, devitrified (slightly altered)----------------	27.4	1,011.9
Tuff, ash-flow, partially welded, zeolitic-------	28.1	1,040.0
Bedded tuff (unnamed)		
Tuff, bedded, reworked, zeolitic----------------	3.0	1,043.0
Lava (unnamed)		
Lava, altered to zeolites (?)-------------------	20.8	1,063.8
Lava, dacitic (?), zeolitic; 1,063.8 to 1,109.5 meters, partly glassy------------------	155.4	1,219.2
Total depth[1]		1,219.2

[1]Depth to bottom of individual interval and total depth are accurate to nearest meter, but are reported to tenths of a meter to agree with thickness of individual units.

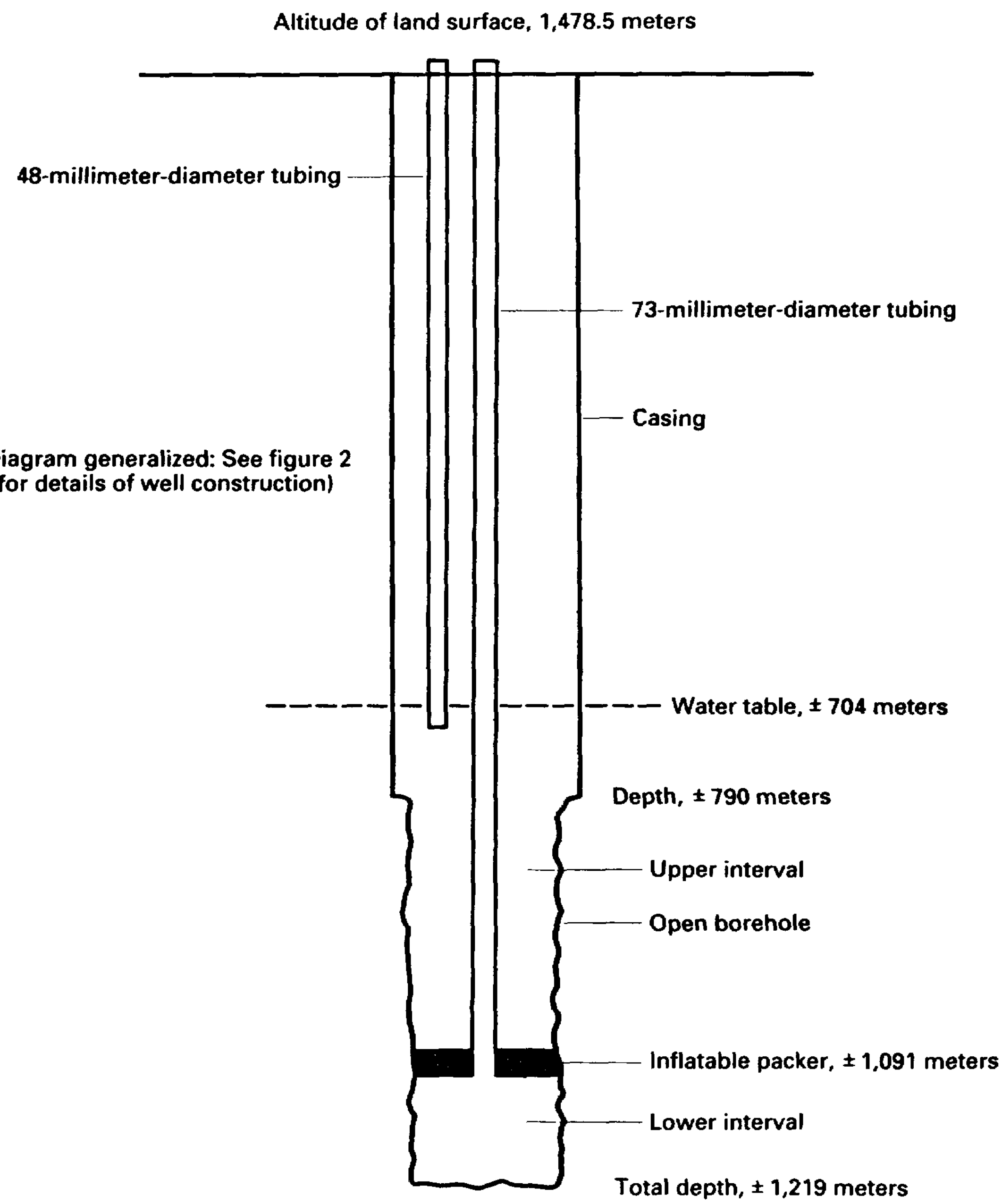

Figure 4.--Inflatable packer and tubing used for measuring hydraulic heads in two intervals.

Periodic measurements of hydraulic heads have been made of the intervals above and below the packer since March 1983. Differences in hydraulic heads above and below the packer are shown in figure 5. The graph shows that, in early 1983, the hydraulic head was 0.2 to 0.5 m lower below the packer; this difference began to decrease, and, in 1984, the hydraulic head became slightly

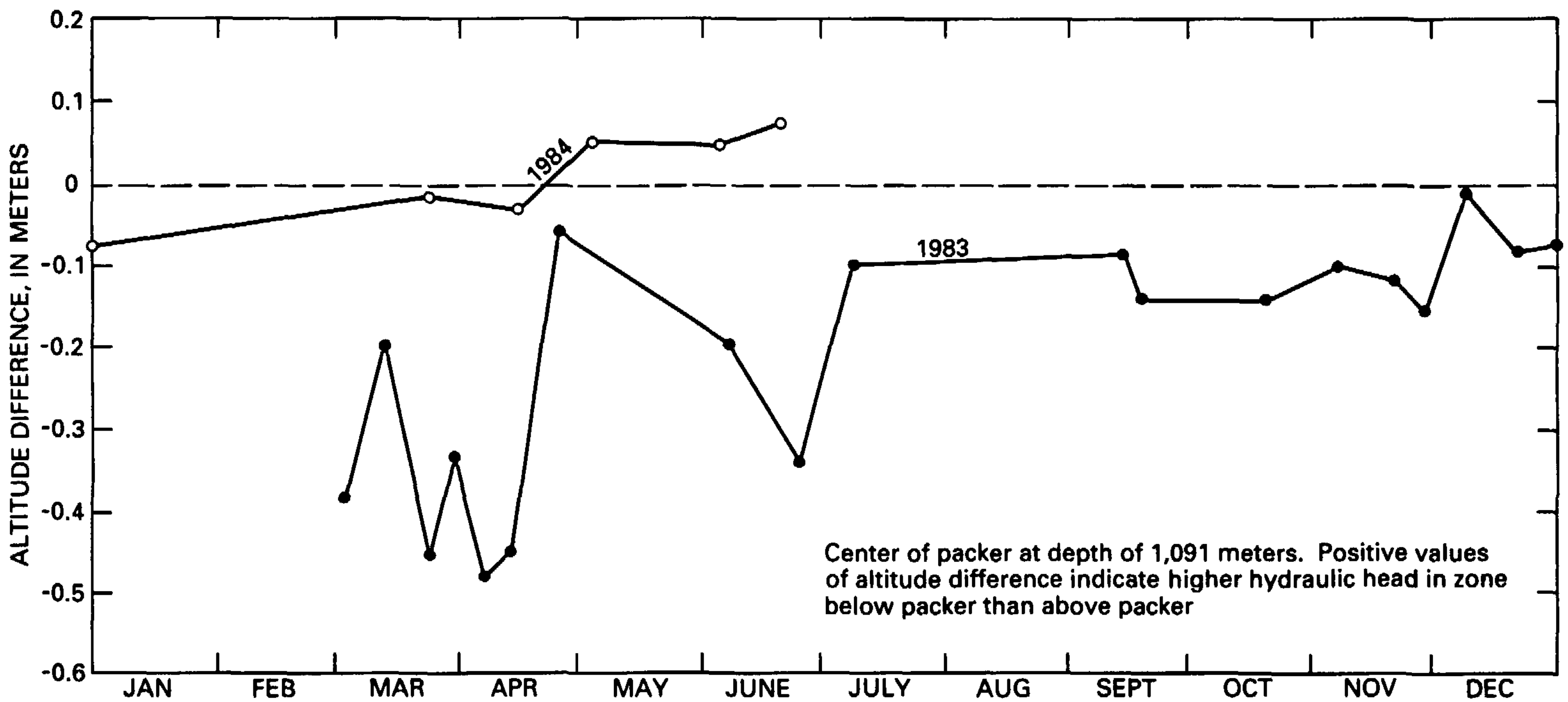

Figure 5.--Comparison of hydraulic head above and below inflatable packer.

higher relative to the upper interval. However, the recent apparent upward gradient is quite small; one explanation for the trend is that the packer, once sealed, has begun to leak.

The range in hydraulic head since measurements began is about 0.6 m in both intervals; the altitude is 774 to 775 m above sea level. Because the adjustments to periodic measurements have not been made with the precision that may be warranted, hydraulic-head altitudes are approximate.[1]

BOREHOLE-FLOW SURVEYS

Borehole-flow surveys were made to determine which intervals yielded water during pumping. The surveys were useful for appraising permeability ratios among those intervals that yield water and also for planning additional work, such as packer-injection tests.

Spot or continuous measurements were made of the vertical velocity of the water from the top of the saturated interval open to the borehole to the bottom of the borehole. In test well USW H-5, spot measurements were made using a radioactive tracer (Blankennagel, 1967, p. 15-26). An aqueous solution of iodine-131 (7½-day half-life) was ejected from a downhole tool, and movement of the radioactive slug was monitored as it passed two gamma detectors. Measured velocity was combined with the cross-sectional area determined from a caliper survey and the rate of flow, as a function of depth, was calculated.

Two surveys were made in test well USW H-5. The first survey (Bentley and others, 1983, fig. 7) was made in connection with pumping period 3, when the casing had only 90 perforations between depths of 707 and 773 m. The second survey (fig. 6) was made in connection with pumping period 4, after the casing had been perforated a second time (fig. 2), between depths of 718 and 782 m. Survey 2 shows that the lava (table 1) yielded virtually no water during pumping, but the contact zone between the lava and the overlying Tram Member of the Crater Flat Tuff yielded about 8 percent of the total. The rest of the Tram Member yielded virtually no measurable water. The Bullfrog Member of the Crater Flat Tuff yielded more than 90 percent of the total. The fact that the yield was not uniformly distributed within stratigraphic units indicates that the primary source of water may be fractures.

CONCEPTUAL MODELS

Studies of the geohydrology of rocks penetrated by other test wells in the Yucca Mountain area have used conceptual models that have attempted to

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[1]Hydraulic heads have been measured periodically by using van-mounted equipment to lower sensing devices on the end of a steel cable. To convert the hydraulic-head measurements to altitude above sea level, a number of adjustments and calculations are required. Some of the elements involved are the precise altitude of the measuring point at the test-well head, a factor for correcting apparent cable length to true length (National Bureau of Standards), and a factor for correcting apparent depth to true depth, because of borehole deviation from vertical.

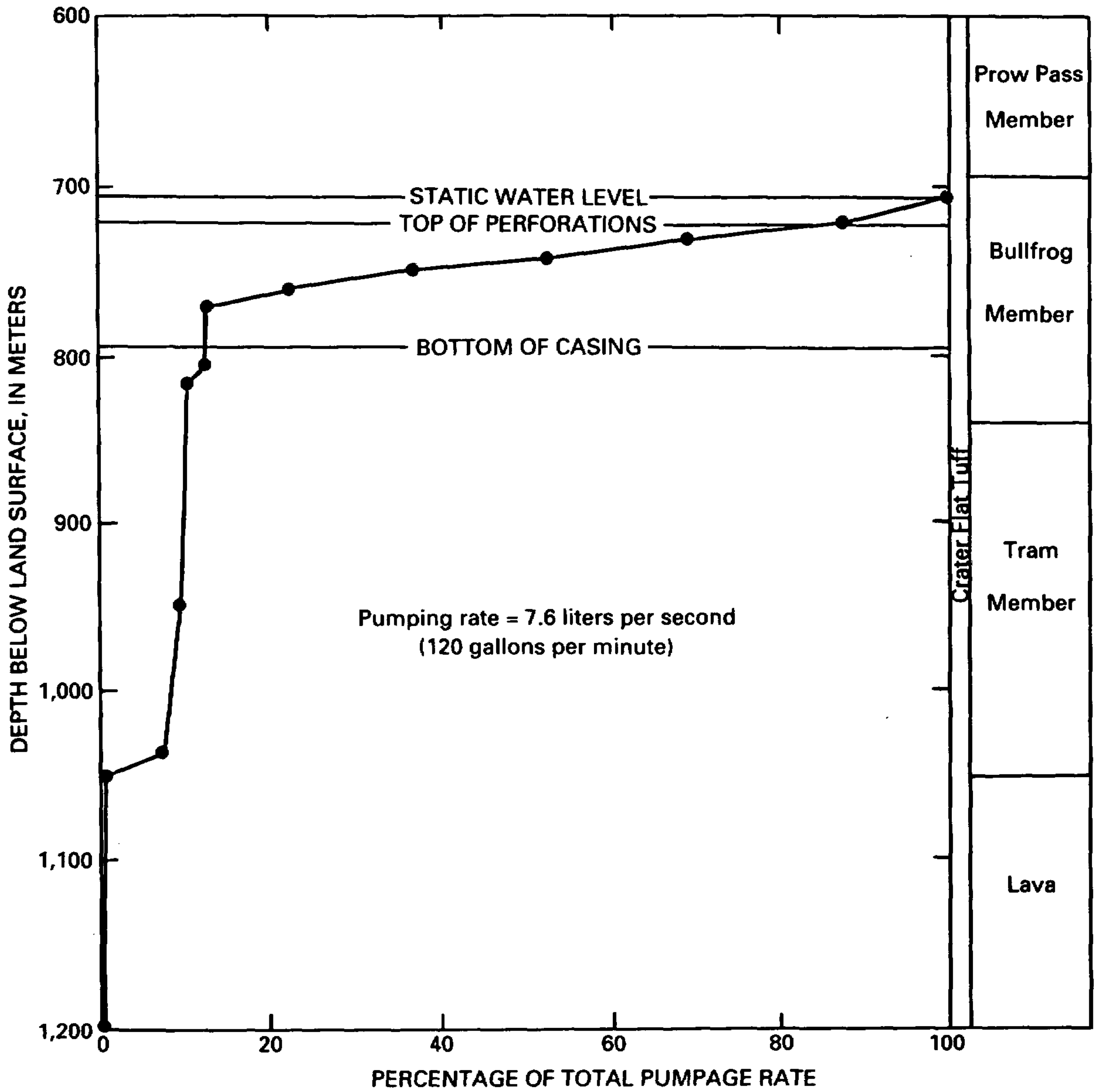


Figure 6.--Borehole-flow survey 2 showing percentage of total pumpage produced by intervals.

relate a complex heterogeneous aquifer system to a simpler, homogeneous aquifer. A dual-porosity model has been used most (Craig and Robison, 1984; Lahoud and others, 1984; Rush and others, 1984; Thordarson and others, 1985). Thordarson (1983) used a model for an unconfined, anisotropic aquifer in the study of the geohydrology of rocks penetrated by well J-13.

A characteristic common to the Yucca Mountain area is the existence of high-angle to near-vertical fractures. Existence of these fractures indicates heterogeneity and anisotropy. In addition, flow surveys in pumped test wells have consistently shown that productive zones correspond to fractured inter-als of the boreholes. In some locations, such as the site of well J-13, the primary producing zone is unconfined, whereas at others, the aquifer is most likely confined.

The process of determining a conceptual model for this study was guided by the following questions:

1. Do data appear to fit a known model?
2. Is the model consistent with what is known about the aquifer system and site characteristics?
3. Are results using the model reasonable?
4. Is there more than one model that is consistent with the data and knowledge of the aquifer system and site characteristics?

Two alternative conceptual models were chosen for this study. The first is a model for an unconfined, anisotropic aquifer (Neuman, 1975), and the second is a finite-conductivity vertical-fracture model (Cinco and Samaniego, 1981). Both models, as for those used in previous studies, contain simpli-ications of the natural system.

The conceptual model for an unconfined, anisotropic aquifer has the following elements:

1. The aquifer is unconfined.
2. The aquifer is fractured by high-angle to near-vertical fractures.
3. The aquifer is anisotropic, with vertical hydraulic conductivity several orders of magnitude greater than horizontal hydraulic conductivity, because of extensive vertical fracturing.

This model is supported by the unconfined conditions that were indicated by the location of the top of the saturated zone in the Bullfrog Member of the Crater Flat Tuff. The water surface was in a partially (?) welded zone of the Bullfrog Member about 14 m below an overlying bedded unit, indicating that confined conditions are unlikely.

The presence of fractures in the major producing zone of test well USW H-5 can only be inferred from two enlarged sections of the borehole shown by the caliper log (fig. 7). Unfortunately, logs, such as those made using an acoustical televiewer or a television camera, were not obtained for the interval that includes the main production zone. The Bullfrog Member of the Crater Flat Tuff has been studied during investigations of rocks penetrated by drill holes USW G-2 and USW G-3; these investigations determined that the Bullfrog Member is extensively fractured and that the fractures are high angle to near vertical (Maldonado and Koether, 1983; Scott and Castellanos, 1984).

Pumping-test drawdown data consistent with an unconfined, anisotropic aquifer should have a shape that is characteristic of delayed yield when plotted as drawdown versus time on a semilogarithmic plot. The curve should have a steep slope during early time, a flat or near horizontal slope during intermediate time, and a steeper slope during late time.

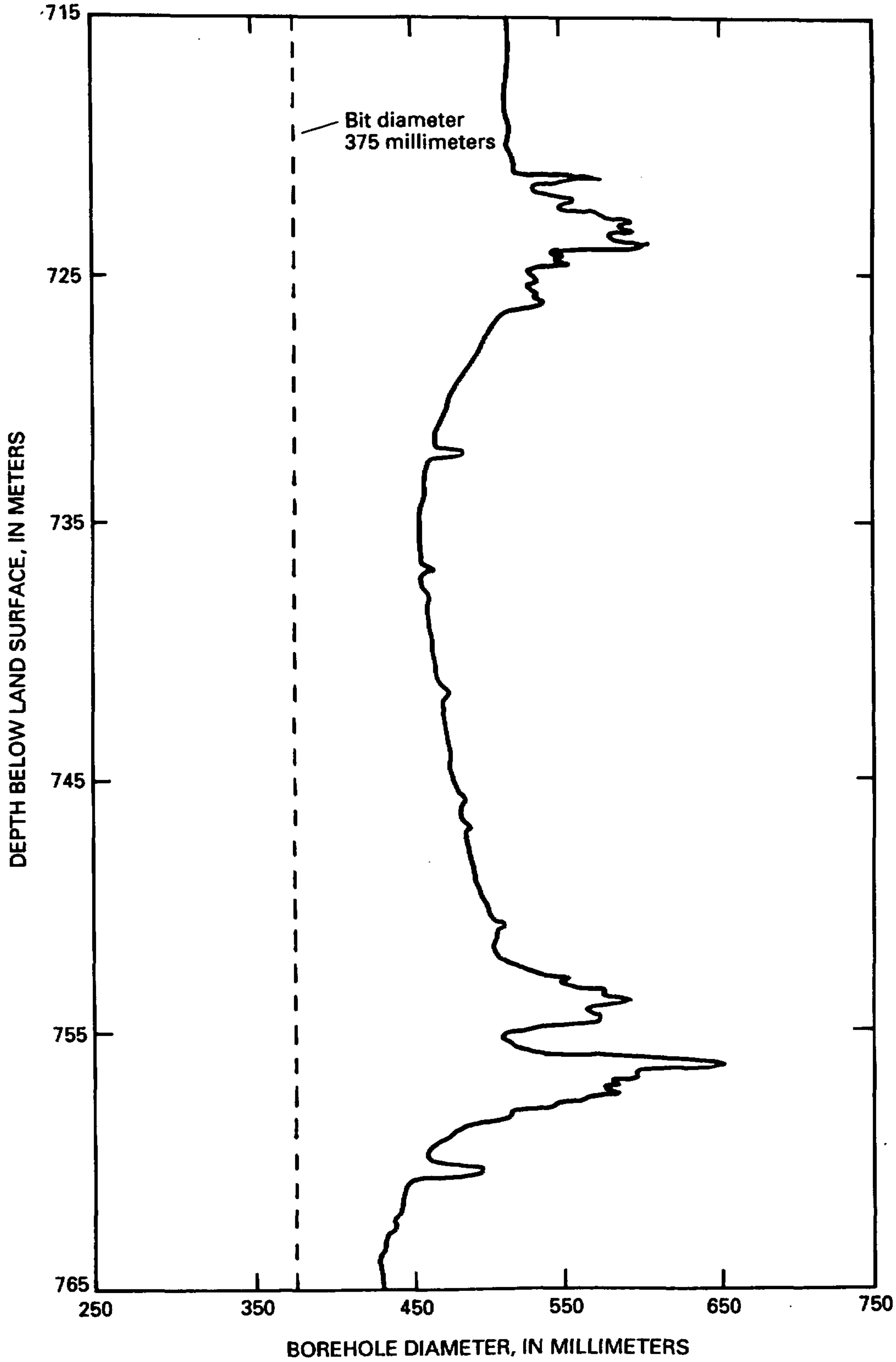


Figure 7.--Average-diameter caliper log for the depth interval from 715 to 765 meters.

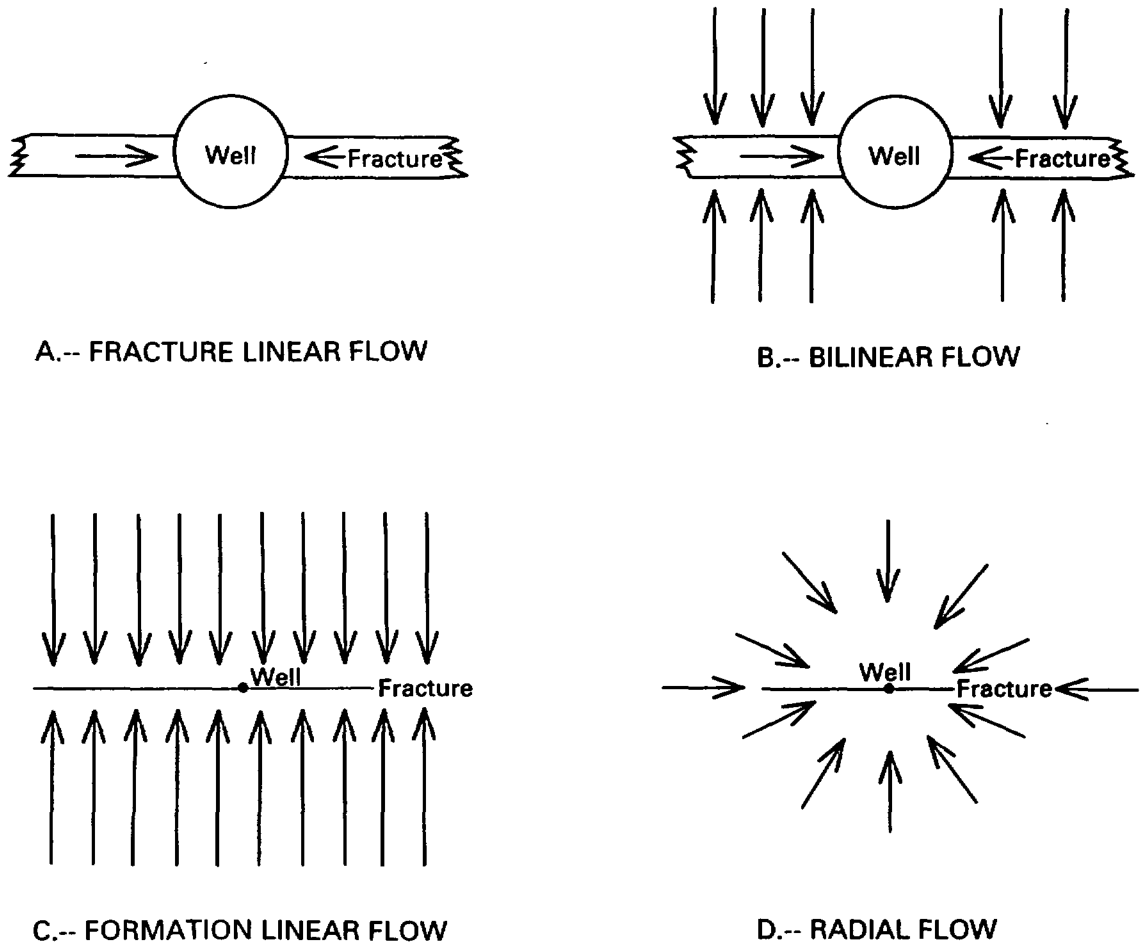
The finite-conductivity, vertical-fracture conceptual model has the following elements:

1. The well intersects a finite-conductivity vertical fracture that fully penetrates the aquifer.
2. The aquifer, with the exception of the vertical fracture, is infinite, isotropic, and homogeneous.
3. The aquifer is confined on both top and bottom.
4. Flow to the well is only through the fracture.

This model is supported by the evidence for high-angle to near-vertical fractures and by results of flow surveys in other test wells that indicate the likelihood of direct matrix contribution to the borehole is insignificant (Craig and Robison, 1984; Lahoud and others, 1984; Rush and others, 1984). In addition, pumping- and recovery-test data (presented later) indicate that the nonradial flow was occurring during testing and that a model that accounts for nonradial flow should be used.

The finite-conductivity, vertical-fracture conceptual model predicts four separate flow periods during a pumping test (fig. 8). The first is a period of fracture linear flow at an early time (fig. 8*A*). During this period, most of the water yielded by the well is from expansion of the water within the fracture, with some water produced as a result of decreased fracture-aperture during pressure drawdown. A logarithmic plot of drawdown versus time should have a straight-line segment of one-half slope. Unfortunately, this early segment is not normally useful for analysis because it is affected by the construction of the well. The second flow period is termed bilinear flow by Cinco and Samaniego (1981), because two linear types of flow occur simultaneously. Both a linear incompressible flow within the fracture and a compressible linear flow in the formation occur during the period of bilinear flow (fig. 8*B*). A logarithmic plot may have a one-quarter slope during bilinear flow depending on fracture conductivity (product of fracture permeability and fracture aperture) and fracture storage capacity. The third flow period is formation linear flow and may occur after a transition from bilinear flow (fig. 8*C*). The logarithmic plot may have a one-half slope during this period depending on fracture conductivity. The fourth flow period is conventional radial flow (fig. 8*D*), and occurs when time is sufficiently large that the well fracture combination can be treated as a line sink.

Limitations and uncertainties are associated with the use of either of the two models. The model for an unconfined, anisotropic aquifer is based on the assumption of a homogeneous aquifer system, although the natural system is probably heterogeneous on a local scale. Use of the finite-conductivity, vertical-fracture model for determining fracture properties requires that the transmissivity and the storage coefficient of the unfractured formation be known or estimated. In addition, this model also is based on the assumption of homogeneous conditions. Limitations and uncertainties associated with each model are discussed in more detail in the section on pumping and recovery tests.



(Modified from Cinco-Ley and Samaniego-V, 1981. Copyright, Society of Petroleum Engineers)

Figure 8.--Flow periods for a well intersecting a vertical fracture.

PUMPING AND RECOVERY TESTS

In this section, pumping and recovery tests conducted in test well USW H-5 are evaluated in terms of the two conceptual models. Analytical methods consistent with the model for an unconfined, anisotropic aquifer are the straight-line method (Cooper and Jacob, 1946), the Theis method (Lohman, 1972), and the method of Neuman (1975). The straight-line and Theis methods are applicable for analyzing late-time data when effects of delayed drainage are insignificant. Neuman's (1975) method is used to account for delayed drainage effects as well as late-time data. The analytical methods used with the finite-conductivity, vertical-fracture model are those described by Cinco and Samaniego (1981) for bilinear flow and transition from bilinear flow to formation linear flow. Formation linear flow is analyzed by the method of Clark (1968).

Pumping tests 1 and 2 were stopped prematurely because of generator failures after 100 and 55 minutes, respectively. As no unique data were acquired, they are not presented herein.

Pumping and Recovery Tests 3

Pumping test 3 was conducted after the test well had been completed to its total depth of 1,219 m, and the casing had been perforated between the depths of 704 and 773 m (upper part of the Bullfrog Member of the Crater Flat Tuff). Static water level prior to pumping was 705 m below the land surface. The test well was pumped at an average rate of about 10 L/s, beginning on June 29, 1982, for 5,718 minutes [incorrectly reported as 5,298 minutes in Bentley and others (1983, p. 18)], with the pump intake at a depth of 751 m.

Drawdown versus time data for pumping test 3 are shown in logarithmic form in figure 9. The data curve is similar to delayed gravity-response curves of Neuman (1975), but in view of the following evidence, analyses of pumping and recovery tests 3 are not shown. A borehole-flow survey conducted during pumping test 3 indicated that at least two-thirds of the production occurred through the perforated casing. At the time of pumping test 3, the casing had 90 perforations; the number of perforations was increased to 450 prior to pumping test 4. Comparison of the early time data for both tests indicates that well loss during pumping test 3 was substantial. If it is assumed that flow through perforations was evenly distributed during pumping test 3, the flow was at least 4 L/min per perforation, whereas during pumping test 4, the flow was about 1 L/min per perforation. Analyses of late-time data for pumping and recovery tests 3 (not shown) indicated that the calculated transmissivity is smaller, but reasonably consistent with that calculated for pumping test 4 (shown below). Data for recovery test 3, as well as pumping test 3, are shown by Bentley and others (1983, figs. 4 and 5).

Pumping and Recovery Tests 4

Pumping test 4 was conducted after additional perforating of the 273-mm-diameter casing below the water table (fig. 2); results of borehole-flow survey 1, performed during pumping test 3, indicated the possibility that the original perforations selected were faulty or at least inadequate to yield the total quantity of water that might be available from that interval of the borehole. This possibility seemed to be corroborated by the specific capacity (discharge rate/drawdown) for pumping test 4 that was about twice the specific capacity for pumping test 3. The static water level prior to pumping was 705 m below land surface. The test well was pumped at an average rate of 7.6 L/s, beginning on July 25, 1982, for 1,756 minutes, followed by a recovery-monitoring period of 720 minutes.

One difficulty with interpretation of data for pumping test 4 (fig. 10) is not uncommon among other pumping tests in the Yucca Mountain area. Drawdown during pumping is measured by a calibrated pressure transducer suspended from a wireline that transmits an output signal to a recorder on the land surface. Because drawdown is determined by the change in pressure relative to the pressure prior to the start of pumping, the initial position of the transducer is not critical as long as it is deep enough to remain

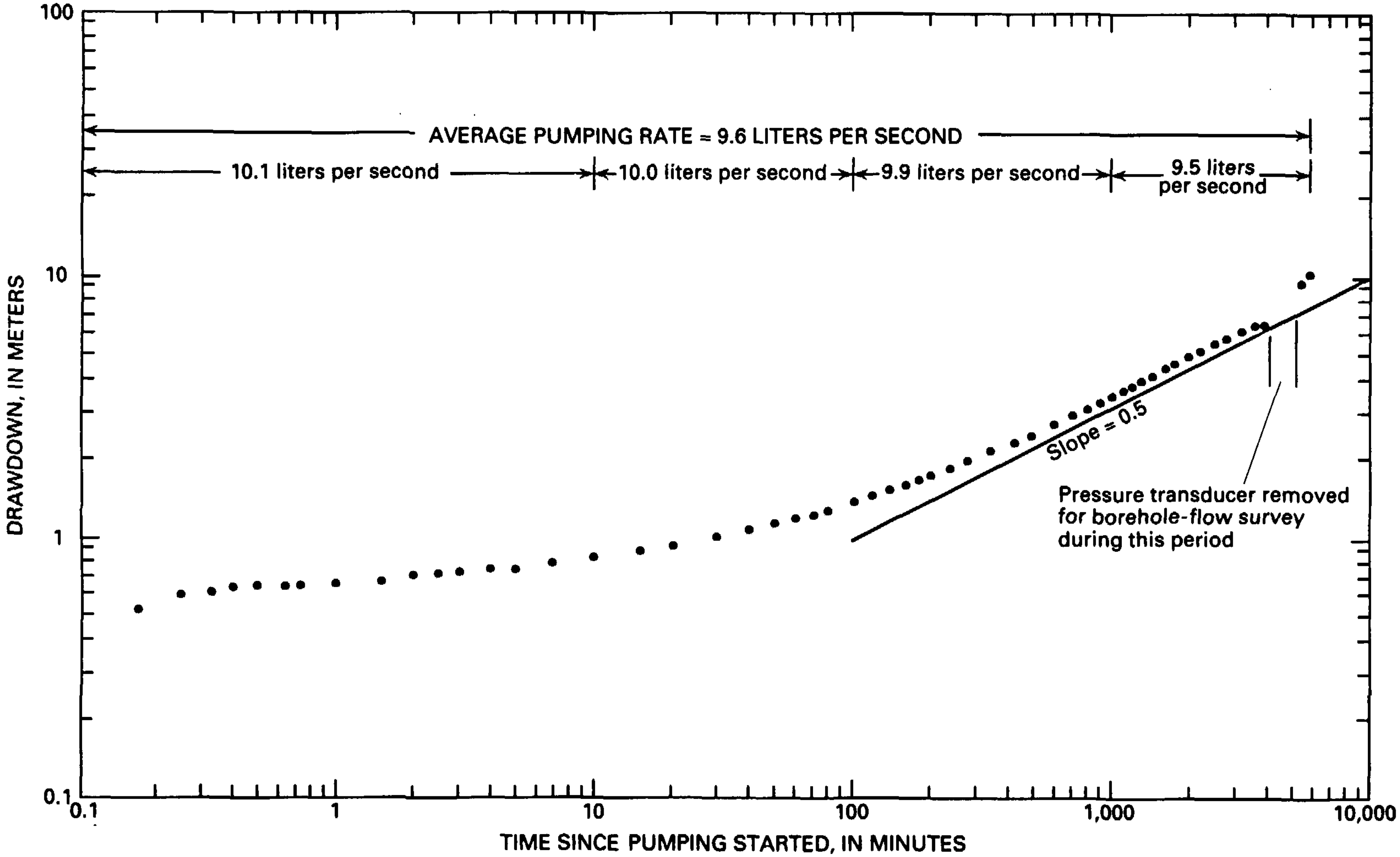


Figure 9.--Water-level drawdown, pumping test 3, depth interval from 704 to 1,219 meters.

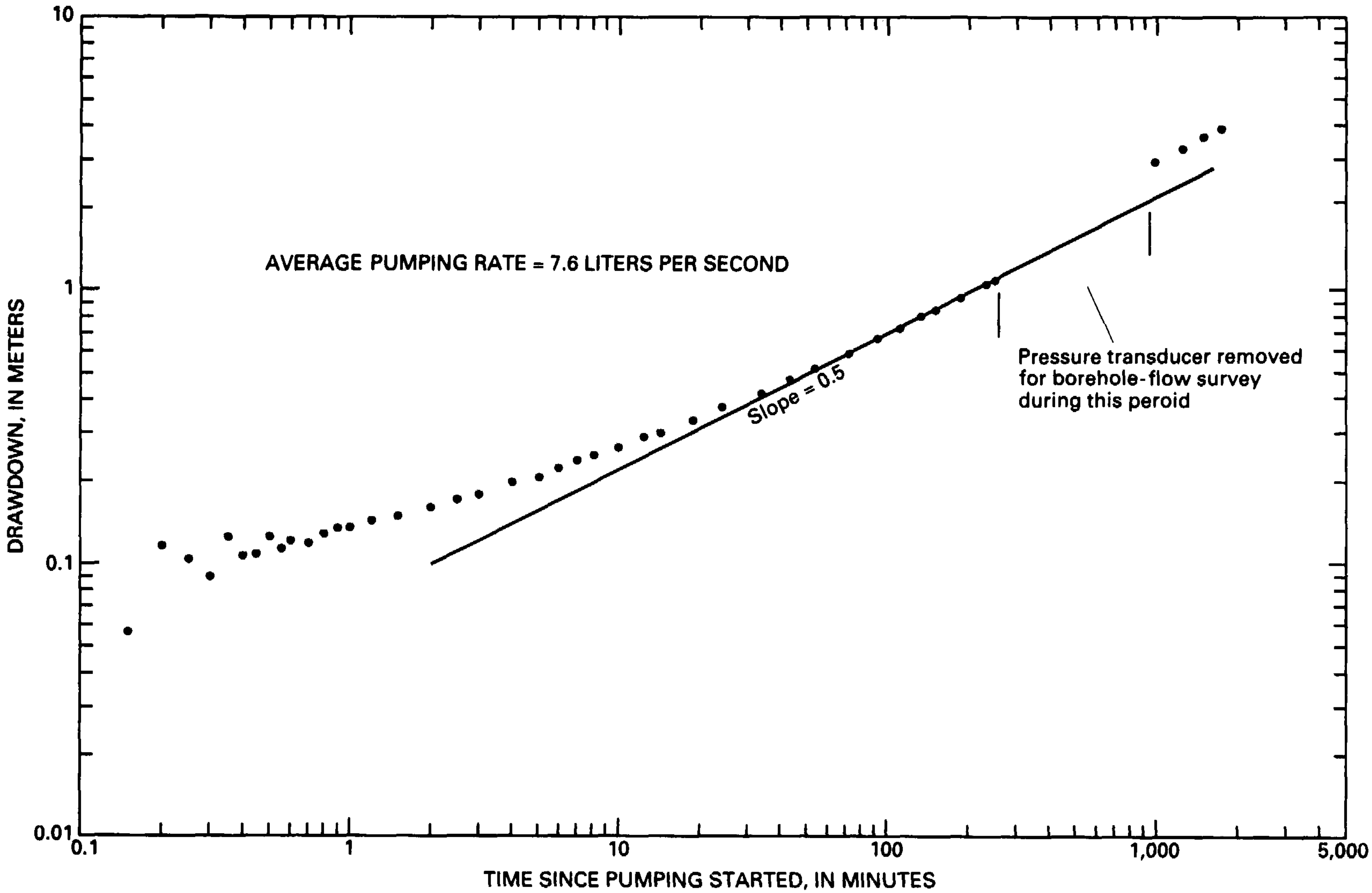


Figure 10.--Water-level drawdown, pumping test 4, depth interval from 704 to 1,219 meters.

submerged during drawdown. The problem occurs during the course of pumping when the transducer has been removed to allow access for the borehole-flow survey tool. This results in incomplete drawdown data. In addition, drawdown data for the period after the transducer has been replaced may be offset from the trend established prior to removing the transducer [for example, see Craig and others (1983), figs. 4 and 5]. Because the depth to water in test wells in the Yucca Mountain area ranges from about 300 to 750 m, a repositioning difference of only a few tenths of a percent can be significant; at a depth of 750 m, a difference of only 0.1 percent is 0.75 m.

In order to investigate the possible error in drawdown measurements after the flow survey, data for pumping and recovery tests 4 were plotted on the same figure as the log of drawdown or recovery versus the log of time since pumping started or stopped (fig. 11). Because the recovery data nearly replicate the first 254 minutes of drawdown data and because the recovery data extend to 720 minutes, drawdown data were projected to 1,000 minutes by use of a linear regression of time versus the difference of recovery and drawdown data to 254 minutes. Projected drawdown data are shown in figure 11 as that data within brackets. The result indicates that actual drawdown was about 0.7 m less than indicated after the flow survey.

A second line of reasoning also was used to assess the possible error in the late-time drawdown measurements and to determine the aquifer transmissivity based on available late-time data. It was reasoned that because transmissivity determined by the straight-line method is dependent on the relative change in drawdown with time rather than on the absolute drawdown, a transmissivity derived from late-time data would be valid whether or not the late-time drawdown measurements were in error by a constant value. Furthermore, if late-time drawdown data are in error, a match of the uncorrected data with a Theis curve should give a different result from the straight-line method, whereas a match of the corrected data should be in reasonable agreement with the straight-line method.

Drawdown versus late-time data (greater than 982 minutes) for pumping test 4 are shown in figure 12. Drawdown data have not been corrected for the re-positioning error of the transducer but have been corrected for decreased saturated thickness [Jacob (1963); Neuman (1975)]. Maximum correction for decreased saturated thickness is about 0.12 m. Transmissivity was determined by the straight-line method of Cooper and Jacob (1946); method assumptions are discussed in the cited reference. The equation for the straight-line method is:

$$T = \frac{15.8\ Q,}{\Delta s} \tag{1}$$

where T is transmissivity, in meters squared per day;
Q is discharge, in liters per second; and
Δs is change in drawdown over one log cycle of time, in meters.
Transmissivity, based on pumping test 4, is about 36 m^2/d.

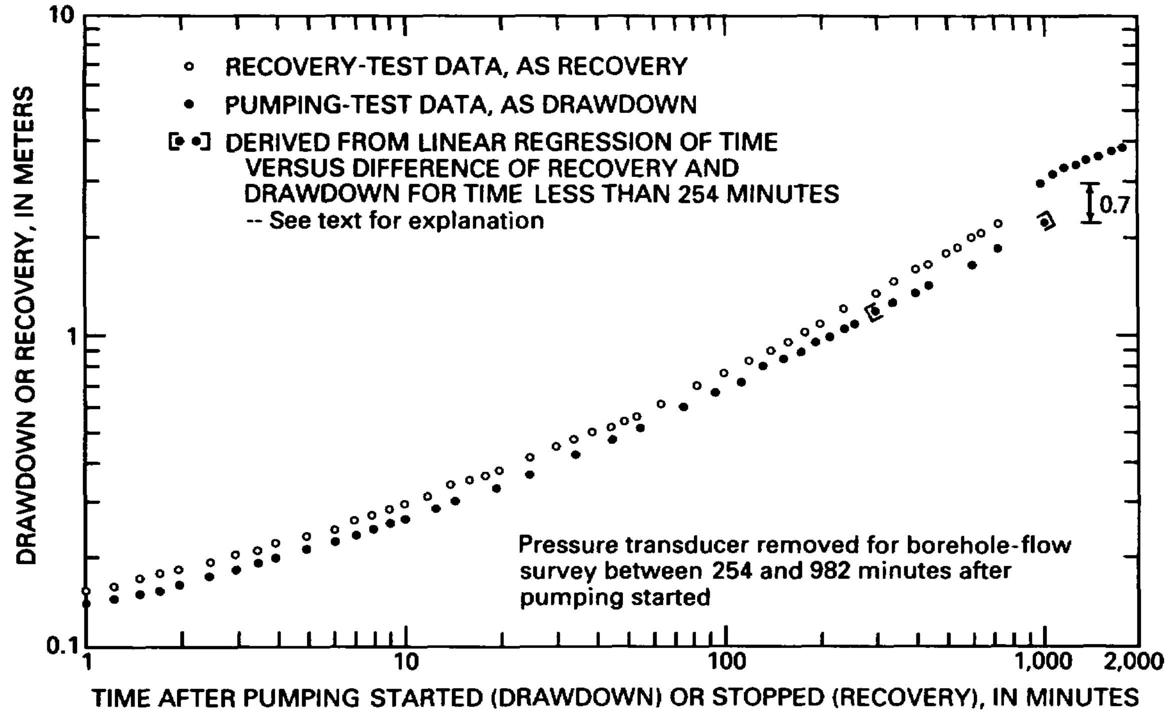


Figure 11.--Data for pumping and recovery tests 4, depth interval from 704 to 1,219 meters.

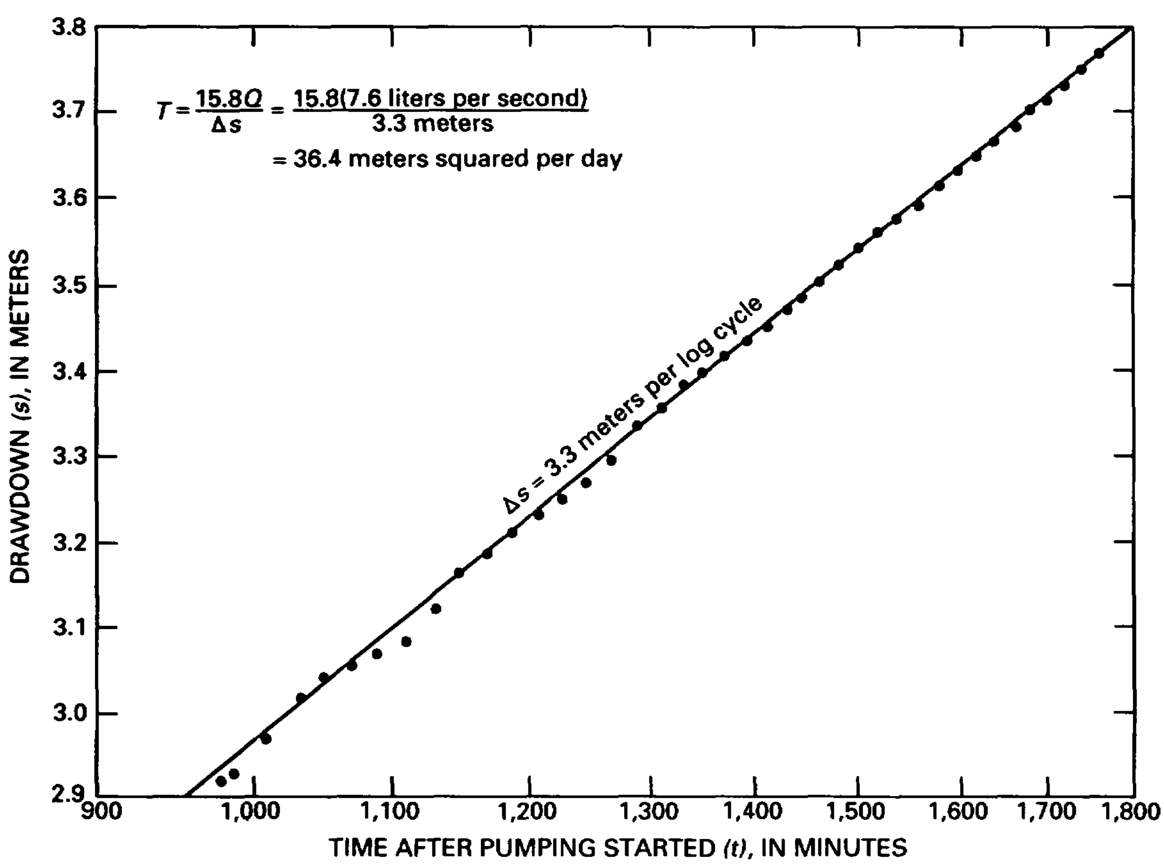


Figure 12.--Analysis of late-time data, pumping test 4, depth interval from 704 to 1,219 meters, straight-line method.

Storage coefficients determined by data from the pumped well are not usually considered reliable, but they probably are within an order of magnitude of the true value. The storage coefficient was calculated by use of the following equation (Lohman, 1972):

$$S = 2.5\, T \frac{t}{r^2} \tag{2}$$

where
- S is storage coefficient, dimensionless;
- T is transmissivity, in meters squared per day;
- t is time at projected zero drawdown, in days; and
- r is well radius, in meters.

For an unconfined aquifer, the storage coefficient should range from 0.01 to 0.4 (Freeze and Cherry, 1979). Using a value of 36 m^2/d for T, 8.8×10^{-2} days (127 minutes) for t, and 0.24 m (caliper log) for r, the calculated storage coefficient is 124. Such an unreasonably large value indicates that either the conceptual model is inappropriate or some other factor is not accounted for in the analyses.

A possible explanation for the large calculated value of storage coefficient is the value of the well radius used. It is common in the petroleum industry to use the concept of an apparent well radius derived from skin effect when appraising induced fractures for production enhancement [Earlougher (1977); Cinco and Samaniego (1981)]. The concept can be used in ground-water hydraulics to account for some well-test responses (A.F. Moench, U.S. Geological Survey, oral commun., 1985).

If an apparent well radius derived from a calculation of skin effect is used, the calculated storage coefficient appears to be reasonable. Skin effect and apparent radius were determined by use of the following equations (Earlougher, 1977, p. 8 and 185):

$$skin = 1.15129\left[\frac{s_{1hr}}{m} - \log\left(\frac{k}{\text{Ø}\rho g c {r_w}^2}\right) - 0.351378\right] \tag{3}$$

and

$$r_a = r_w e^{-skin} \tag{4}$$

where
- $skin$ is apparent skin effect, positive indicates damage and negative indicates improvement, dimensionless;
- s_{1hr} is drawdown at 1 hour projected from straight-line segment used for analysis, in meters (-1.8 m);
- m is slope of straight-line segment, in meters per log cycle of time (3.3 m);
- k is hydraulic conductivity, in meters per second (4.20×10^{-4} m^2/s/60 m or 7.0×10^{-6} m/s);
- Ø is porosity, a fraction (0.23, Lahoud and others, 1984; Rush and others, 1984);
- ρ is density, in kilograms per cubic meter (994.4 kg/m^3 at 35 °C);

g is Earth's gravitational acceleration, in meters per second squared (9.8 m/s^2);

c is compressibility of water, in pascals $^{-1}$(4.4×10^{-10}/Pa, Freeze and Cherry, 1979);

r_w is well radius, in meters (0.24 m); and

r_a is apparent well radius, in meters.

Using the above equations and values, the skin effect is -3.4 and the apparent well radius 7.0 m. Based on the apparent well radius, the storage coefficient is 0.15 for the straight-line solution of pumping test 4.

To further check both the apparent error in drawdown measurement at late time and the straight-line solution for transmissivity, an analysis of data for pumping test 4 is shown in an expanded logarithmic form in figure 13. Data shown are from about 14 minutes after pumping started to the end of pumping. Correction for apparent measurement error (0.7 m) and decreased saturated thickness for a 60-m thick aquifer have been made. Values of transmissivity and storage coefficient were determined by the Theis method. The appropriate equations are (Lohman, 1972):

$$T = \frac{6.9\ Q\ W(u)}{s}; \text{ and} \tag{5}$$

$$S = \frac{4\ Tt\ u}{r^2} \tag{6}$$

where T is transmissivity, in meters squared per day;

Q is discharge, in liters per second;

$W(u)$ is a match point, dimensionless;

s is drawdown at the match point, in meters;

S is storage coefficient, dimensionless;

t is time after pumping started at the match point, in days;

u is a match point, dimensionless; and

r is well radius, in meters.

The value of transmissivity calculated by matching the Theis curve to the corrected data for pumping test 4 is about 34 m^2/d. This value is consistent with results of the straight-line solution. The value of transmissivity based on uncorrected drawdown data is about 23 m^2/d, which indicates that the 0.7 m correction is reasonable and the true transmissivity is about 34 to 36 m^2/d. The storage coefficient calculated using a well radius of 238 mm is unreasonably large, but use of an apparent well radius of 7.0 m yields a storage coefficient of 0.28.

An analysis of pumping test 4 by Neuman's method (1975) is shown in figure 14. There is uncertainty about the applicability of Neuman's method to drawdown data from a pumped well, and this may account for the lack of a good fit for times less than 20 minutes. The calculated transmissivity is about 38 m^2/d, which agrees with previous results, as expected, because late-time data were matched to the Theis-curve part of Neuman's curves. Use of an apparent well radius of 7.0 m yields a storage coefficient of 0.25.

If the data/type-curve match in figure 14 is valid, the horizontal and vertical hydraulic conductivity can be calculated by use of the following equations (Neuman, 1975):

$$K_r = T/b; \tag{7}$$

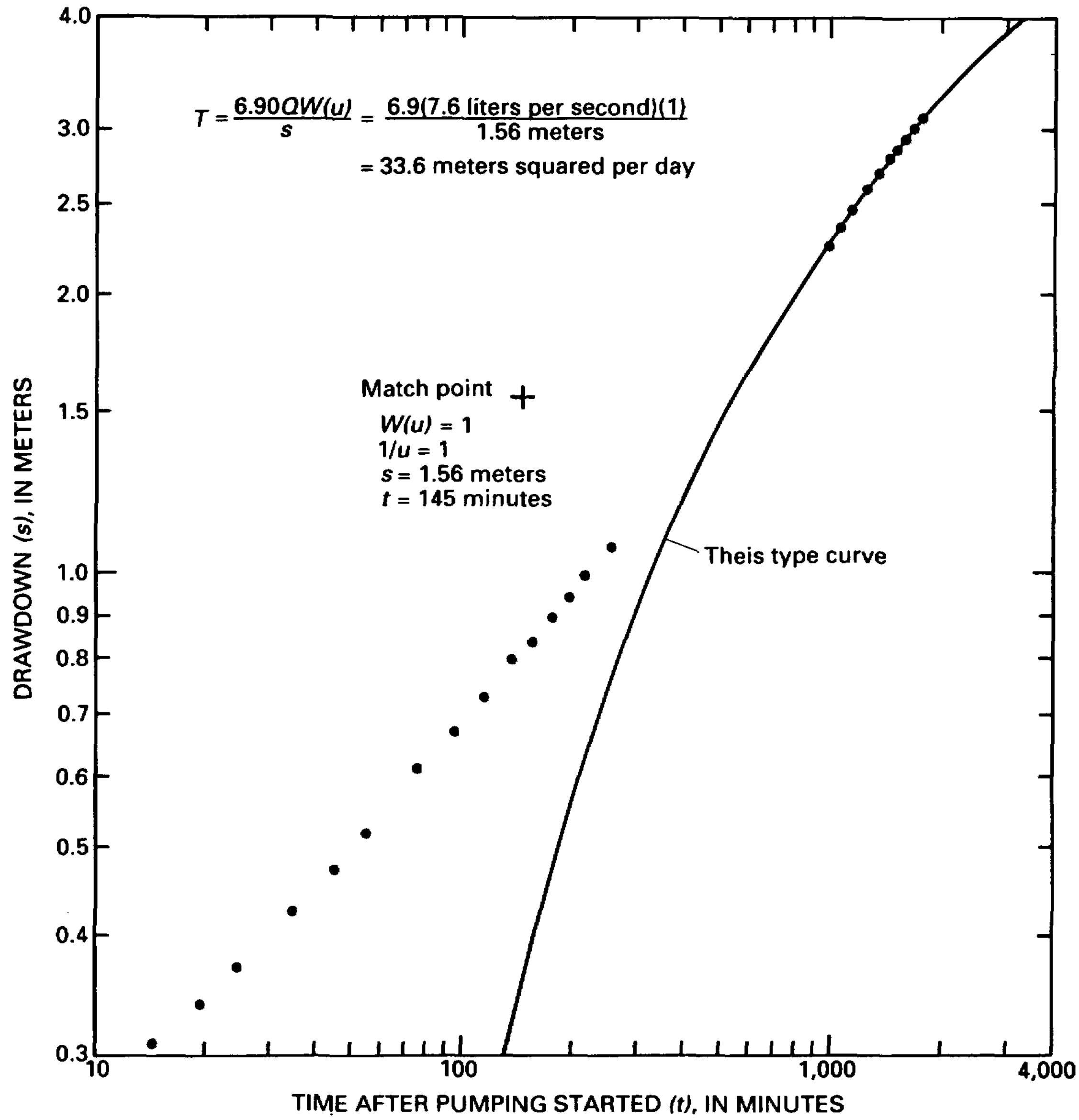


Figure 13.--Analysis of adjusted water-level drawdown, pumping test 4, depth interval from 704 to 1,219 meters, Theis method (Lohman, 1972).

$$K_D = \beta b^2/r^2; \text{ and} \quad (8)$$

$$K_z = K_D\, K_r \quad (9)$$

where K_r is horizontal hydraulic conductivity, in meters per day;

T is transmissivity, in meters squared per day;

b is initial saturated thickness of aquifer, in meters;

K_D is degree of anisotrophy, equal to K_z/K_r, dimensionless;

β is $K_D\, r^2/b^2$, dimensionless;

r is well radius, in meters; and

K_z is vertical hydraulic conductivity, in meters per day.

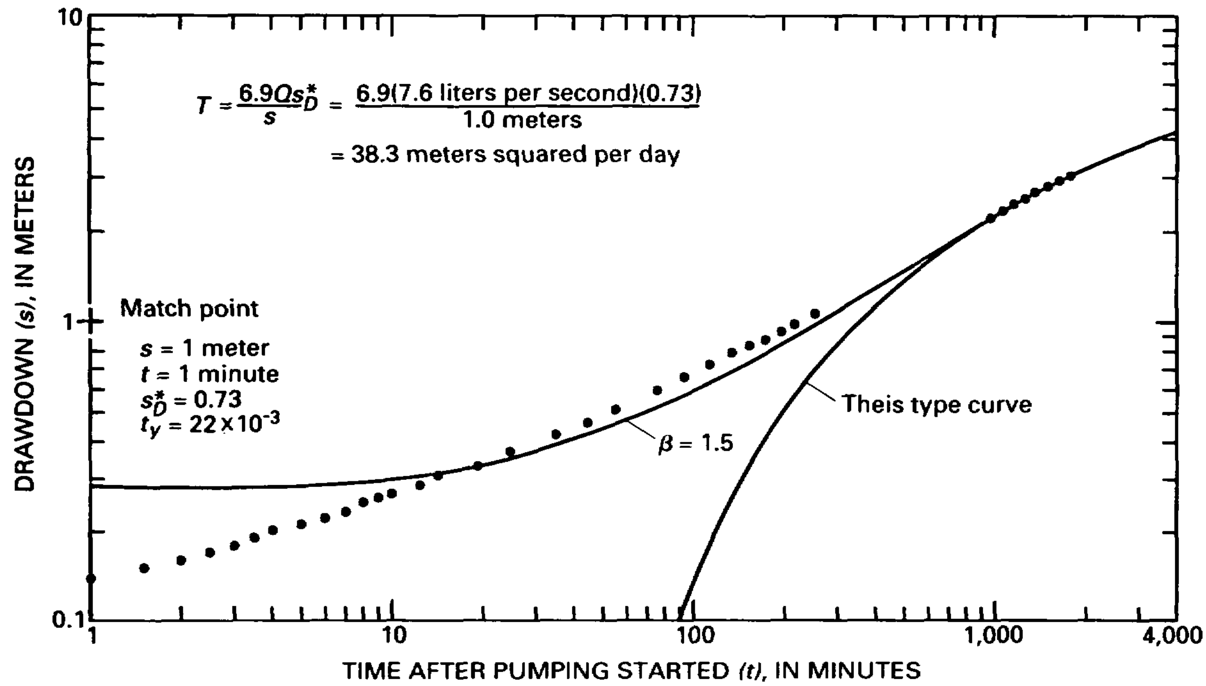


Figure 14.--Analysis of adjusted water-level drawdown, pumping test 4, depth interval from 704 to 1,219 meters, method of Neuman (1975).

Under the assumptions that T is 36 m^2/d, *b* is 60 m, β is about 1.4 from curve matching, and the well radius *r* is equal to the apparent well radius of 7.0 m then K_r is 0.6 m/d, K_D is about 103, and K_z is about 62 m/d. The degree of anisotrophy seems reasonable and probably indicates the relative magnitude of horizontal and vertical hydraulic conductivity.

According to Neuman (1975), analysis of recovery data from a pumped well is valid for his method. Data for recovery test 4 is shown as residual drawdown versus time since pumping started divided by time since pumping stopped, t/t' (fig. 15). The drawdown analysis indicates that the late-time Theis curve is not reached until after about 1,000 minutes. The recovery data ends at about 720 minutes. If later recovery data (smaller t/t') were available, Theis conditions would be reached, and the line would project to zero at t/t' equals 1. The calculated transmissivity of about 57 m^2/d is probably about 1.5 times greater than the true transmissivity.

Some background about the development and use of the finite-conductivity, vertical-fracture model will be useful for understanding the analytical methods. The model and equations were developed for the petroleum industry, where an unfractured reservoir has been tested to yield formation permeability and total compressibility. Later the reservoir is artificially fractured, sometimes resulting in a single, near vertical fracture intersecting the borehole. The reservoir is tested again to determine the effectiveness of the induced fracture. Effectiveness of the procedure is measured in terms of fracture half-length and fracture conductivity. The result is that, prior to use of the finite-conductivity, vertical-fracture model, a knowledge of formation transmissivity and storage coefficient is needed. (The relation between ground-water and petroleum terminology is presented in table 2.)

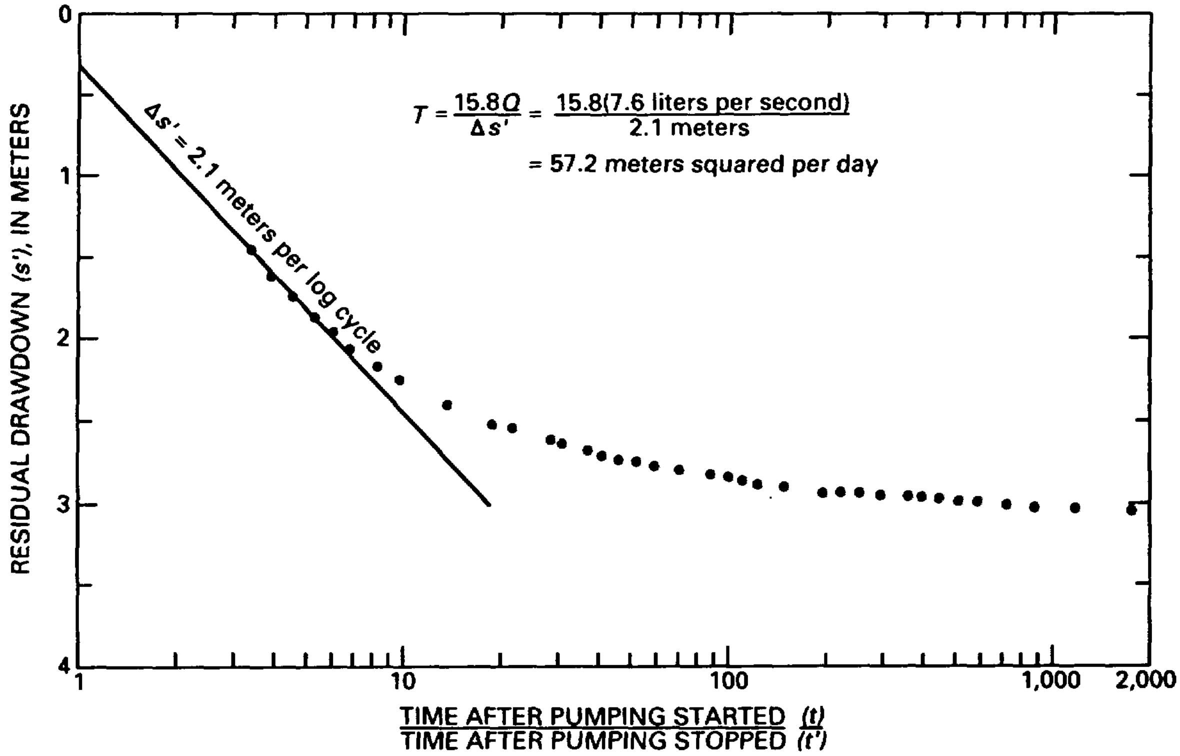


Figure 15.--Analysis of residual drawdown, recovery test 4, depth interval from 704 to 1,219 meters, straight-line method.

Table 2.--*Relation of hydraulic and petroleum terms*

[A consistent-unit system is assumed]

Hydraulic terms		Petroleum terms[1]
Transmissivity	=	$kh\rho g/\mu$
Hydraulic conductivity	=	$k\rho g/\mu$
Storage coefficient	=	$\emptyset\ c_t h\rho g$
Specific storage	=	$\emptyset\ c_t \rho g$
Drawdown	=	$\Delta p/\rho g$

[1]Definition of petroleum terms: k is permeability; h is formation thickness; ρ is fluid density; g is Earth's gravitational acceleration; μ is dynamic fluid viscosity; $\emptyset$ is formation porosity; c_t is total compressibility; and Δp is change in pressure.

Because the transmissivity and the storage coefficient are normally unknown, the usefulness of this model may be questioned. The first approach was to use values of matrix hydraulic conductivity determined by laboratory tests of core from the Bullfrog Member of the Crater Flat Tuff. A representative value for matrix hydraulic conductivity of about 7×10^{-10} m/s (Lahoud and others, 1984; Rush and others, 1984) results in an unlikely apparent fracture half-length of about several kilometers. This indicates that either the conceptual model is invalid or some substantially larger value of matrix hydraulic conductivity is appropriate.

Use of the finite-conductivity, vertical-fracture model was facilitated by a study by Moench (1984). Moench used a double-porosity model to analyze pumping-test data from test well UE-25b#1 (see fig. 1 for location). Results indicated a block conductivity of 2×10^{-6} m/s and a block specific storage of 3×10^{-4}/m. Although the result for specific storage was two or three orders of magnitude larger than published values for unfractured rock, Moench (1984, p. 84) suggested that the value was reasonable for a rock material with readily compressible microfissures. Analyses discussed below are based on the finite-conductivity, vertical-fracture model and the results of Moench (1984).

The equations used for analyses based on the finite-conductivity, vertical-fracture model follow:

Curve-matching method (Cinco and Samaniego, 1981);

$$\frac{k_f b_f}{x_f} = \frac{1842 q B \mu}{h\ (\Delta p)_M} \left[P_{wD} (k_f b_f)_D \right]_M \tag{10}$$

$$x_f = \left(\frac{k_f b_f}{x_f} \right) \left(\frac{3.6 \times 10^{-9}\ (t)_M}{\phi \mu c_t k\ \left[t_{D_{xf}}\ (k_f b_f)^2{}_D \right]_M} \right)^{1/2} \tag{11}$$

$$k_f b_f = (x_f)\ \frac{k_f b_f}{x_f}\ \text{, and} \tag{12}$$

$$(k_f b_f)\ \mathrm{D} = \frac{k_f b_f}{k x_f}\ . \tag{13}$$

Bilinear-flow method (Cinco and Samaniego, 1981);

$$k_f b_f = \left[\frac{34.97 q\ B \mu}{m_{bf} h\ (\phi \mu c_t k)^{1/2}} \right]^2 \tag{14}$$

$$x_f \geqq \left[\frac{3.6 \times 10^{-8}\ (k_f b_f)^2 t_{ebf}}{\phi\ \mu\ c_t\ k}\right]^{1/4} \tag{15}$$

$$(P_{wD})_{ebf} = \frac{kh\Delta P_{\mathrm{ebf}}}{1842\ q\mu B}\ , \text{ and} \tag{16}$$

$$(k_f b_f)_D \cong \frac{1.38}{(P_{wD})_{ebf}}\ . \tag{17}$$

Linear-flow method (Clark, 1968);

$$x_f = \frac{1.96 \times 10^{-1} q}{h\ m_{lf}} \left(\frac{\mu}{\phi c_t k}\right)^{1/2}\ . \tag{18}$$

where B is formation volume factor, in cubic meter per cubic meter;
b_f is fracture width, in meters;
c_t is total compressibility, in pascals^{-1};
h is formation thickness, in meters;
k is permeability, in micrometers squared;
$k_f b_f$ is fracture conductivity, in micrometer squared-meter;
$(k_f b_f)_D$ is dimensionless fracture conductivity;
m_{bf} is slope of straight line for bilinear flow, in kilopascals per (hour)$^{1/4}$;
m_{lf} is slope of straight line for linear flow, in kilopascals per (hour)$^{1/2}$;
P_{wD} is dimensionless pressure;
q is well flow rate, in cubic meters per day;
t is time, in hours;
t_{Dxf} is dimensionless time;
x_f is fracture half-length, in meters;
Δp is change in pressure, in kilopascals;
μ is dynamic fluid viscosity, in pascal-second; and
ϕ is porosity, a fraction.

Subscripts: bf is bilinear flow;

D is dimensionless;

e is end;

f is fracture;

lf is linear flow;

M is match point;

x_f is based on x_f; and

w is wellbore.

The formation volume factor (B) is almost 1.0 for water at the pressures in the aquifer at test well USW H-5 (Earlougher, p. 228, 1977) and so is not used in the analyses. Permeability (k) used in the analyses is $4 \times 10^{-2} (\mu m)^2$. This value gave reasonable results and is equivalent to about one-fourth of the block hydraulic conductivity determined by Moench (1984). Formation (aquifer) thickness (h) was estimated at 60 m. This value is probably within a factor or two of the true thickness. Porosity was estimated to be 0.23 based on laboratory tests of core from the Bullfrog Member of the Crater Flat Tuff in test wells UE-25b#1 and USW H-1 (Lahoud and others, 1984; Rush and others, 1984). The compressibility term, c_t, was estimated to be about 2×10^{-7}/Pa by use of the block specific storage determined by Moench (1984), and the relation for specific storage listed in table 2. The value of compressibility is subject to a large degree of uncertainty.

The assumed values are equivalent to a transmissivity of about 3 m^2/d and a storage coefficient of about 3×10^{-2}. The storage coefficient is one or two orders of magnitude larger than might be expected, but consistent with Moench's (1984) results. Assumed transmissivity is one or two orders of magnitude less than calculated at some test wells at Yucca Mountain (Craig and Robison, 1984; Lahoud and others, 1984; Rush and others, 1984) but consistent with results of testing in test well USW H-3 where transmissivity was determined to be about 1 m^2/d (Thordarson and others, 1985). Another assumption was that all production came from the formation thickness specified as 60 m. In fact, about 12 percent of the total production came from deeper in the test well.

Results of analyses using the finite-conductivity, vertical-fracture model are shown in table 3. Although the results have some scatter, the values are reasonable. The curve-match method of analysis for pumping tests 3 and 4 and recovery test 4 are shown in figures 16 to 18. The approximate start of formation linear flow shown in each figure is based on the data type-curve match. Early time data for pumping test 3 (fig. 16) show the effect of well loss determined by comparison of pumping tests 3 and 4, which were conducted before and after additional perforations were made in the test-well casing, and plot above the type curve. Fracture conductivity determined from pumping test 3 is less than that determined by pumping and recovery tests 4. This is consistent with the restrictions caused by insufficient perforations in the production zone during pumping test 3. Data for pumping test 4 match the type-curve well, with late-time data indicating a dimensionless fracture conductivity greater than 100 π (fig. 17). A better match with late-time data might have been obtained by use of a type curve for a larger fracture conductivity. Late-time data were corrected for apparent measurement error as discussed previously. Recovery test 4 also matches the type-curve well (fig. 18) and results agree with results for pumping test 4.

Table 3.--*Results of analyses using the finite-conductivity, vertical-fracture model*

[--, not determined; ≧, equal to or greater than]

Method	Ratio of fracture conductivity to fracture half-length (micrometers squared-meter per meter)	Fracture half-length (meters)	Fracture conductivity (micrometers squared-meter)	Calculated fracture conductivity (dimensionless)
		PUMPING TEST 3		
Curve match	13.9	210	2,926	111 π
Linear flow	--	205	--	--
		RECOVERY TEST 3		
Linear flow	--	133	--	--
		PUMPING TEST 4		
Curve match	19.3	292	5,638	154 π
Bilinear flow	--	≧ 434	4,128	81 π
Linear flow	--	235	--	--
		RECOVERY TEST 4		
Curve match	17.8	269	4,772	141 π
Bilinear flow	--	≧ 380	3,016	70 π
Linear flow	--	164	--	--

The analysis using the bilinear-flow method is shown for pumping and recovery tests 4 in figures 19 and 20. Points identified as approximate end of bilinear flow were selected based on when the data appeared to depart from a straight line. According to Cinco and Samaniego (1981), bilinear flow should end between two and three log cycles prior to the start of linear flow. Applying this criteria and considering the start of linear flow identified by curve matches (fig. 16 to 18), the indicated end of bilinear flow is consistent with other results.

Cinco and Samaniego (1981) suggest that data that plot as a one-half slope on a logarithmic graph also can be analyzed by the method of Clark (1968) for linear flow. An equivalent equation in hydrologic terms was developed by Jenkins and Prentice (1982). Linear-flow analyses of pumping and recovery tests 3 and 4 are shown in figures 21 to 24. Based on available

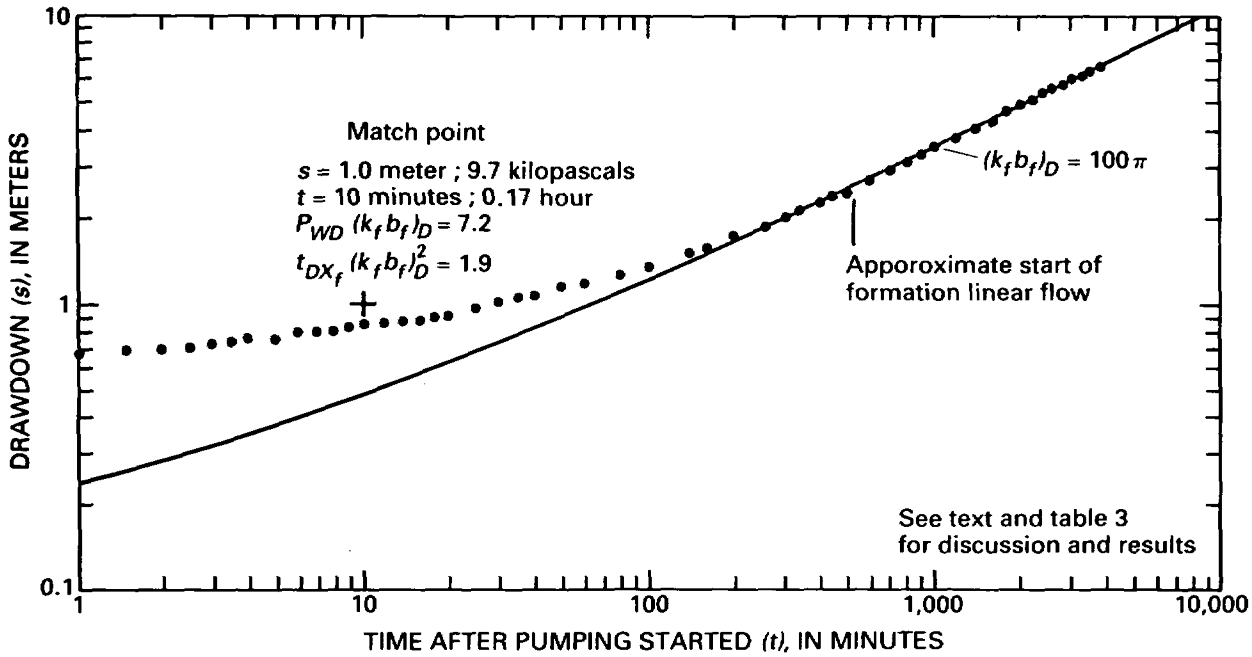


Figure 16.--Analysis of pumping test 3, depth interval from 704 to 1,219 meters, vertical-fracture model, curve-match method.

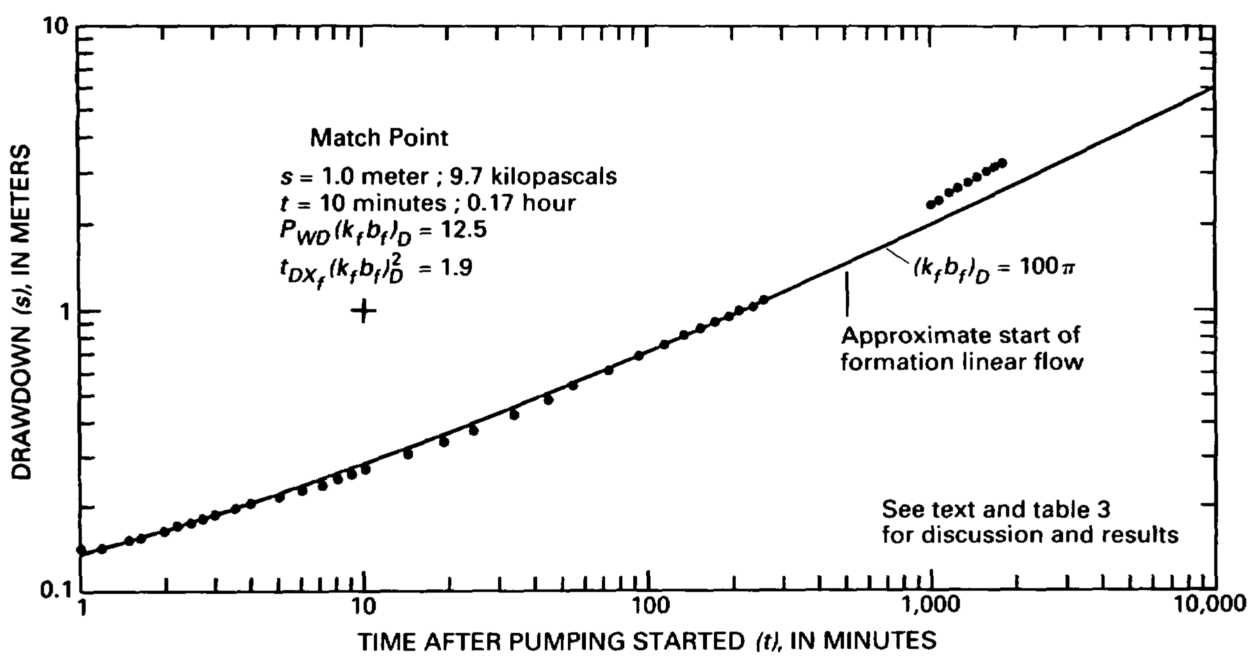


Figure 17.--Analysis of pumping test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, curve-match method.

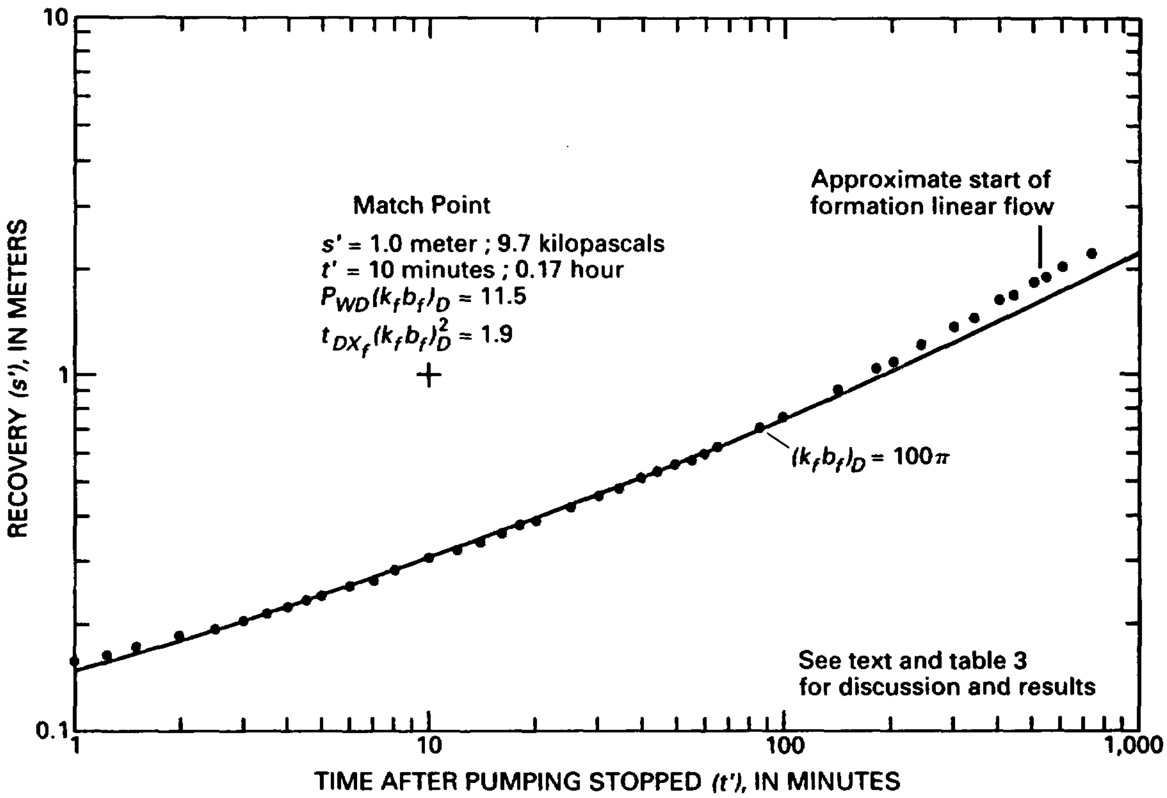


Figure 18.--Analysis of recovery test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, curve-match method.

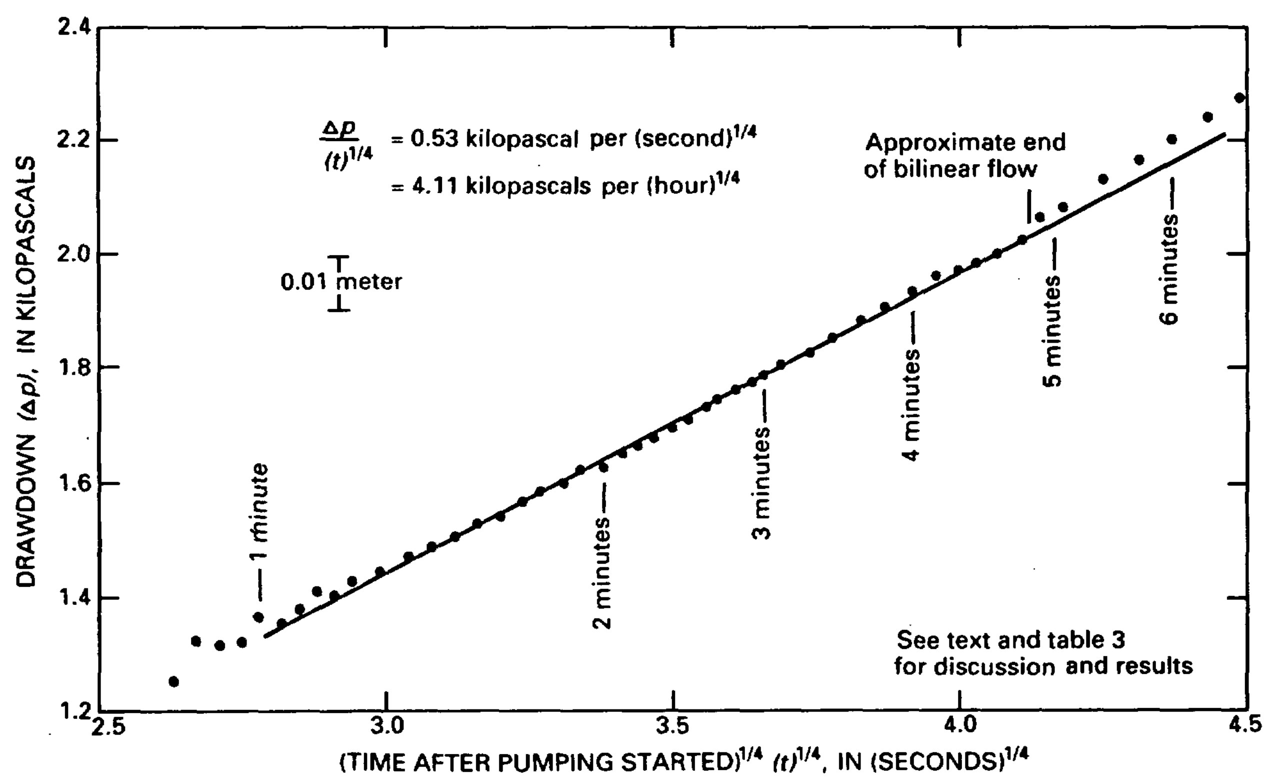


Figure 19.--Analysis of pumping test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, bilinear-flow method.

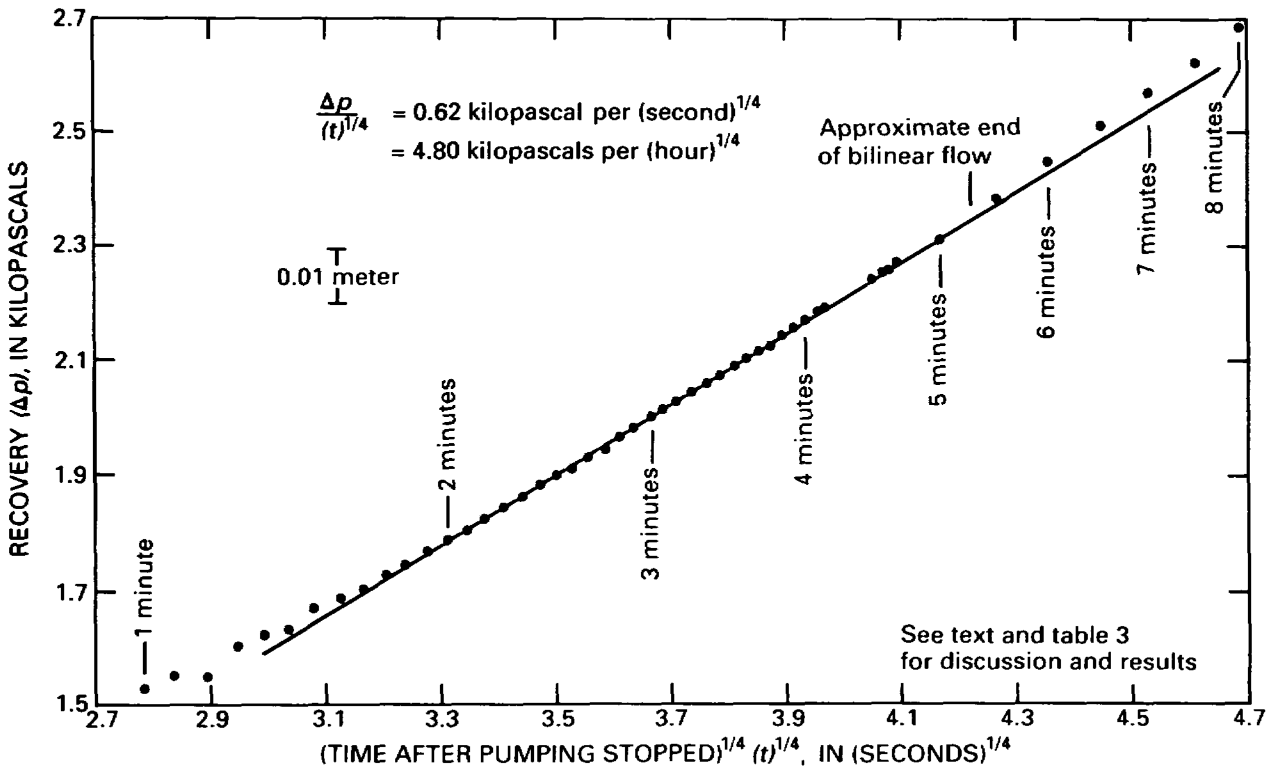


Figure 20.--Analysis of recovery test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, bilinear-flow method.

information, fracture half-lengths as determined by the linear-flow method are listed in table 3. These lengths are shorter than those calculated by the curve-match and bilinear-flow methods.

The analytical results are uncertain, but there are some important conclusions.

- Although a single discrete fracture with a length of hundreds of meters may be unlikely, analyses are consistent with a series of interconnected subparallel fractures that would, in effect, be a long continuous fracture.

- Apparently, the conductive properties of some fractures can be very large. This is not surprising considering the large fracture apertures seen by the authors in videotapes of other boreholes drilled on Yucca Mountain.

- Nonradial flow responses need to be considered when analyzing single-well, fractured-aquifer tests.

- If nonradial flow occurs during an aquifer test, it will likely be necessary to extend the duration of the test if radial-flow solutions are desired.

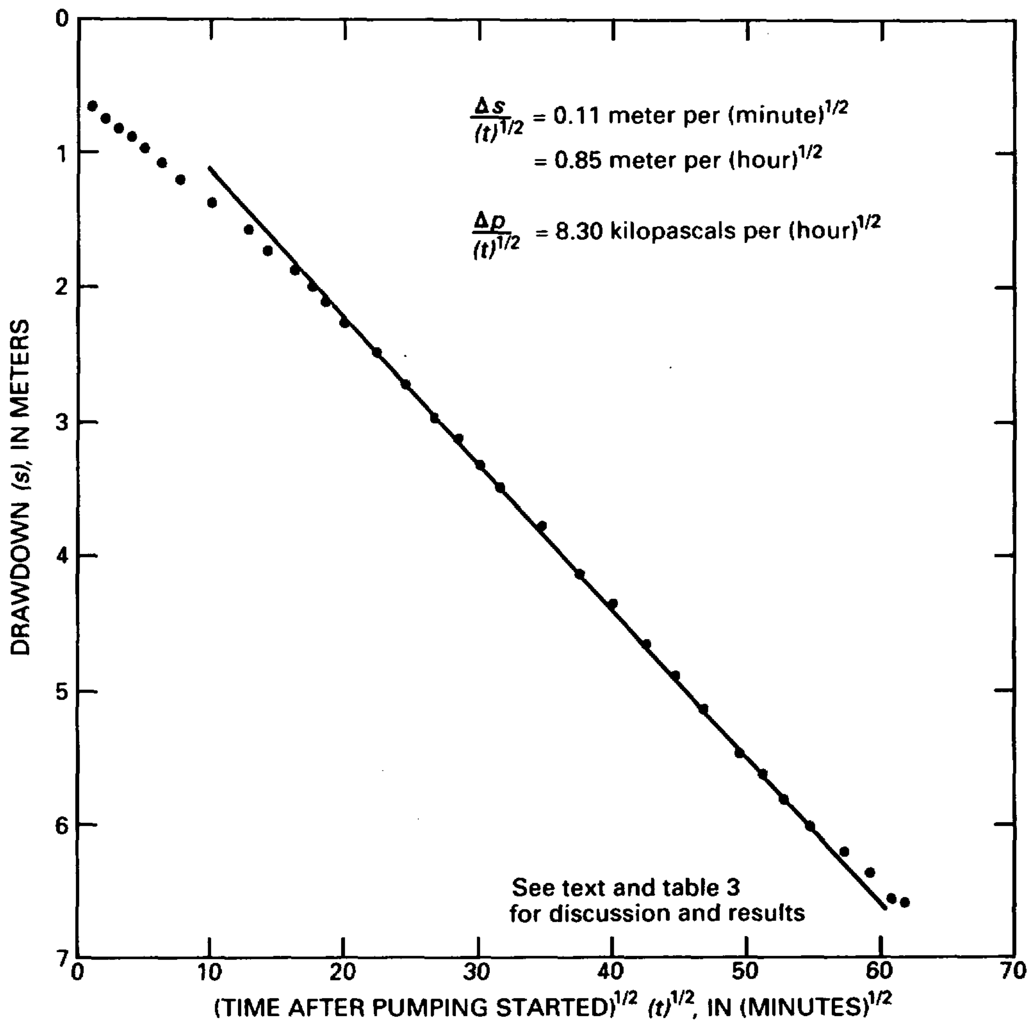


Figure 21.--Analysis of pumping test 3, depth interval from 704 to 1,219 meters, vertical-fracture model, linear-flow method.

Results of analyses based on both conceptual models are reasonable. Despite uncertainties in analyses, the vertical-fracture model probably best represents the natural system in the vicinity of the test well. Drawdown and recovery data are consistent with both models and the hypothesis that the test well intersects a fracture that is substantially more conductive than others in the rock mass. In the model for an unconfined, anisotropic aquifer, the fracture causes a negative wellbore skin, with the fracture probably extending only a short distance from the test well. In the vertical-fracture model, the fracture is assumed to be very long, and is taken explicitly into account.

PACKER-INJECTION TESTS

Packer-injection (slug) tests were conducted in various intervals of the well to obtain data on: (1) Distribution of hydraulic head in the test well; and (2) distribution of hydraulic characteristics in the test well. Tests were conducted in intervals isolated between packers, or in the interval from

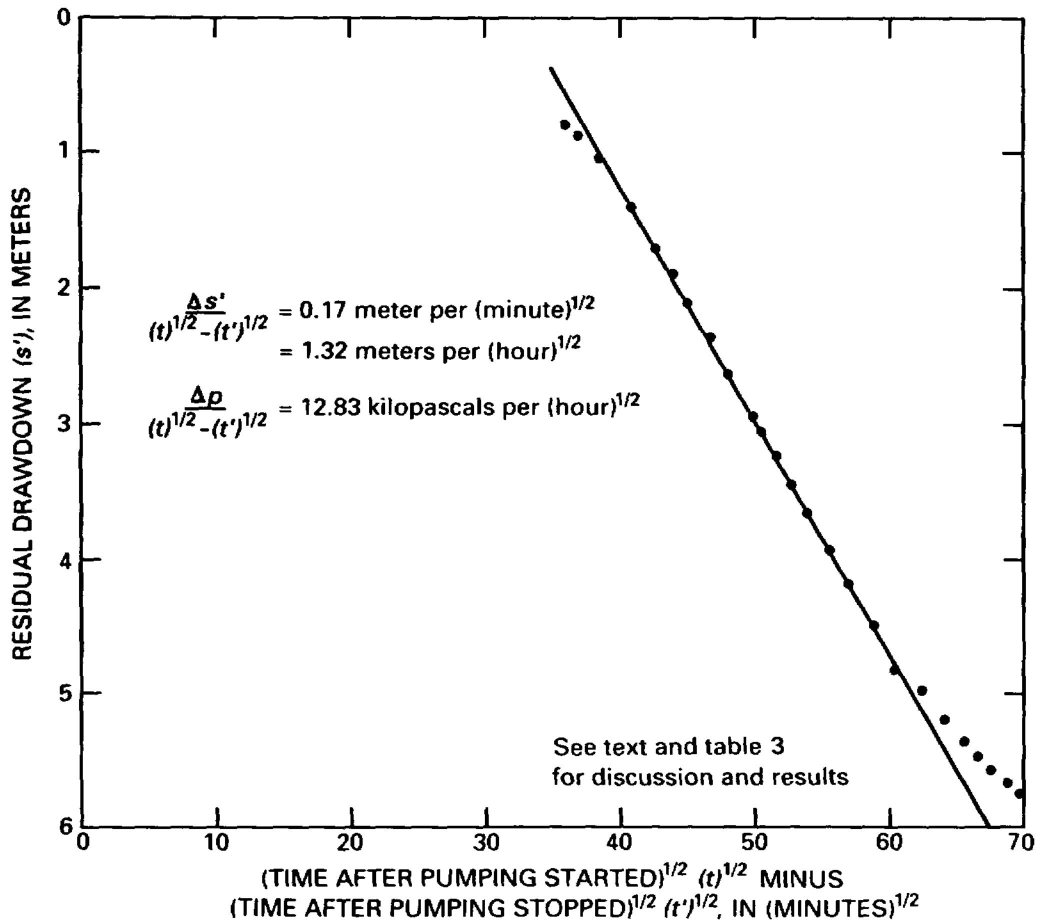


Figure 22.--Analysis of recovery test 3, depth interval from 704 to 1,219 meters, vertical-fracture model, linear-flow method.

the bottom packer to the bottom of the open hole. Water was injected by filling tubing that was connected to the packer tool and then opening the tool at the appropriate interval to allow the water to drain into the formation. The decline of hydraulic head was monitored by means of a pressure transducer suspended inside the tubing at a depth slightly below normal static level.

Each of the 11 packer-injection tests conducted in test well USW H-5 had results that were anomalous. During each of the tests, about 0.25 minute after the start of the test, the water level in the tubing, as indicated by the pressure transducer, apparently ranged from about 48 to 73 percent of the original, approximately 710-m-long, water column. The data thus indicated an unreasonably great water-level decline of about 160 to 370 m in a few seconds.

During some of the tests, in addition to the pressure-transducer signal being recorded by a digital data recorder, the transducer signal was recorded as an analog, continuous trace on a chart recorder. The signal trace for the first minute of test 4 is shown in figure 25. The first few seconds of the trace show some substantial oscillations that probably are due to pressure pulses similar to a "water hammer" effect. These high-frequency oscillations

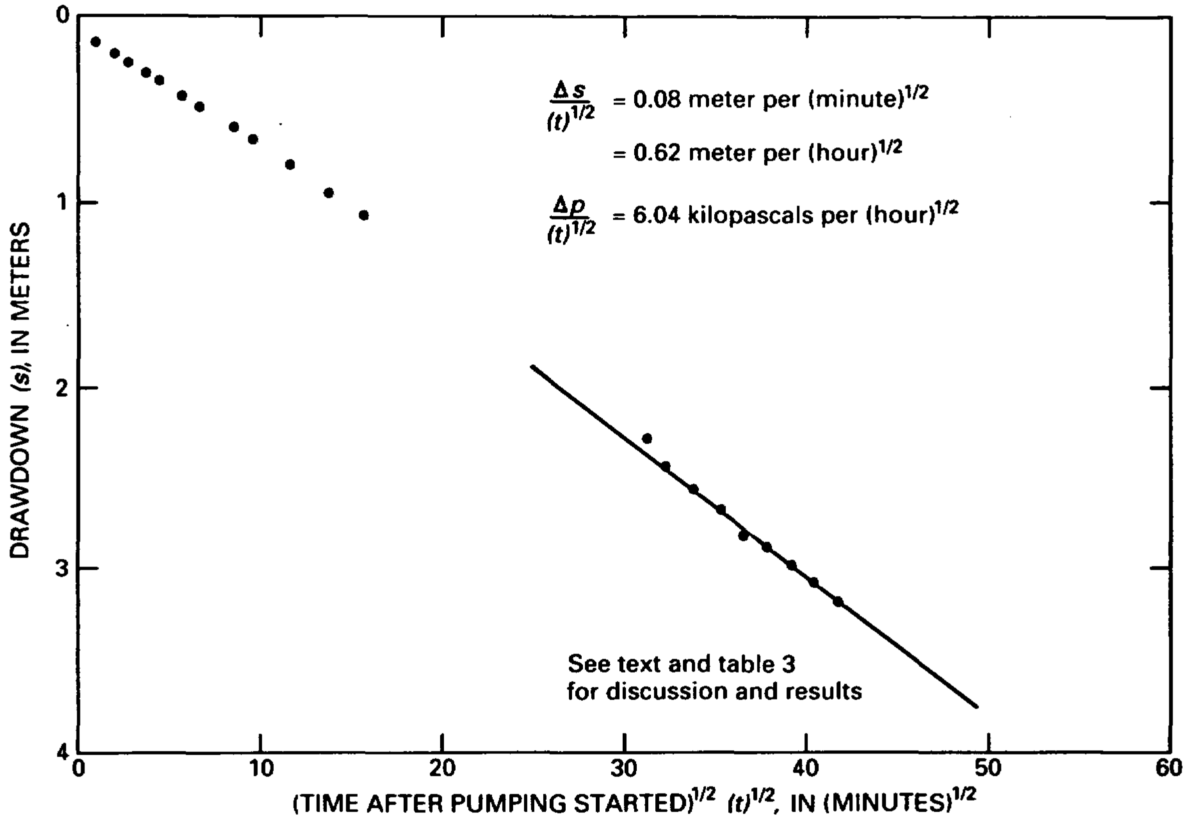


Figure 23.--Analysis of pumping test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, linear-flow method.

are related to the physical constraints of the borehole and test equipment. What is most significant is the transducer signal after the oscillations dissipated. At about 3.5 seconds after the start of the test, the transducer signal had decreased by about 23 percent (equivalent to about 160 m). Apparently factors other than true decrease in water level were involved.

In addition to the anomalous early time data, substantial deviations from expected data curves occurred during some tests. These tests resulted in data curves that were double-humped. The deviations are attributed to the high (long) initial water column that substantially overpressured the tested intervals (Thordarson and others, 1985).

Analyses of packer-injection tests performed in test well USW H-5 indicate disadvantages of using a long water column that were either not apparent or understood during previous testing of other wells near Yucca Mountain:

1. Substantial pressures induced by the long water column may temporarily increase fracture apertures and give erroneous results; this is the probable cause of the double-humped curves.

2. Velocities of water flowing past the pressure transducer in the injection tubing may be fast enough to result in erroneous water levels. This may account for some of the anomalous early time data.

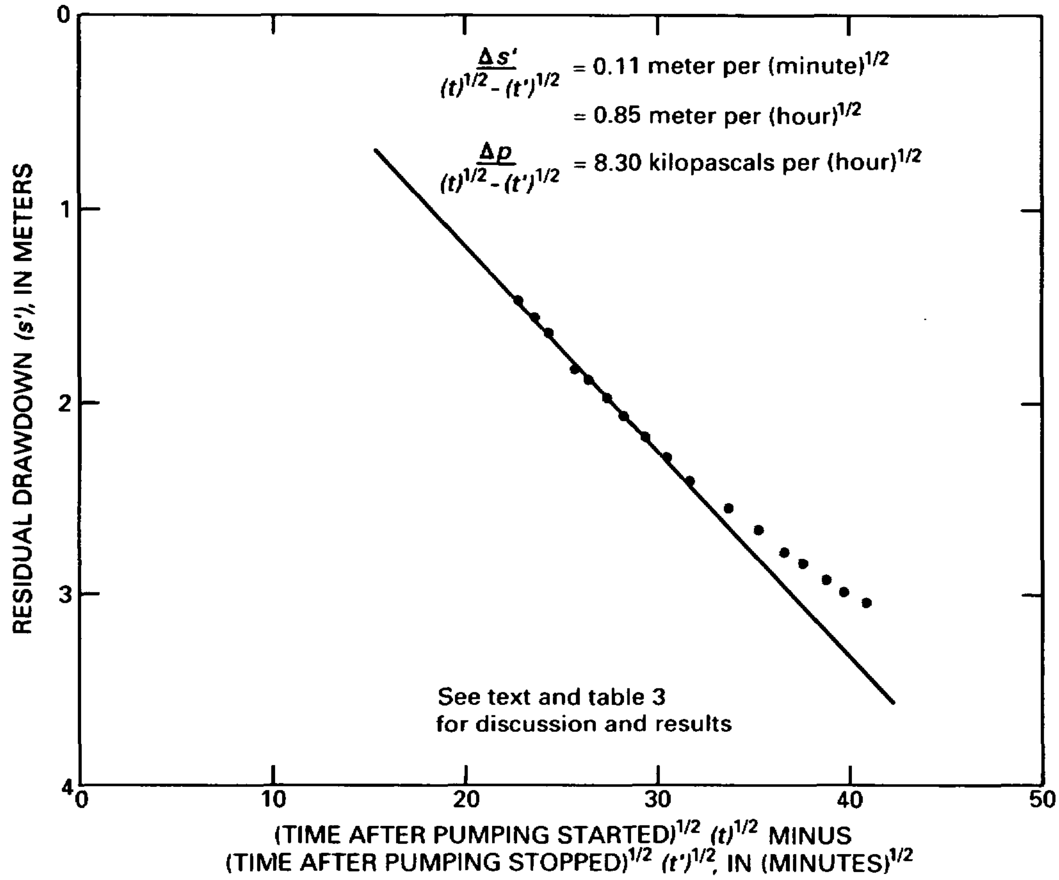


Figure 24.--Analysis of recovery test 4, depth interval from 704 to 1,219 meters, vertical-fracture model, linear-flow method.

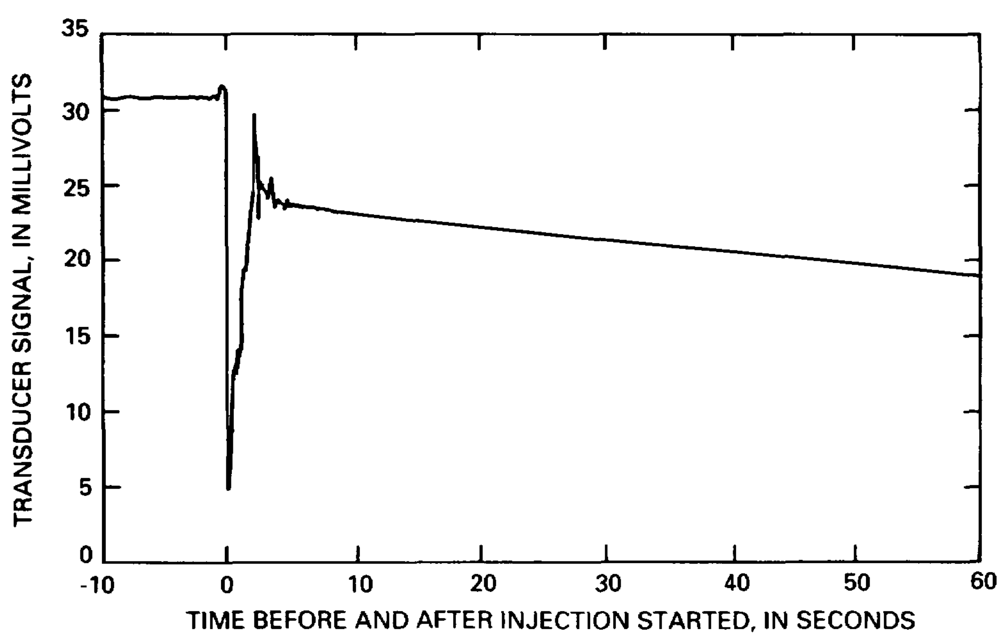


Figure 25.--Chart-recorder trace of transducer signal, packer-injection test 4, depth interval from 834 to 895 meters.

3. Inertia and friction effects probably are substantial during the early part of most tests. Where there is a fast velocity, the method of Cooper and others (1967) for analyzing packer-injection tests does not account for these effects.

Most, if not all, of the above disadvantages would be avoided by the use of much shorter water columns of about several tens of meters or less.

Because meaningful analyses of the packer-injection tests were not possible, the data are not presented herein; however, data for the packer-injection tests are presented in Bentley and others (1983).

CHEMICAL AND RELATED CHARACTERISTICS OF GROUND WATER

The chemical composition of two ground-water samples is presented in table 4. The first sample was collected on July 3, 1982, near the end of pumping test 3; the second sample was collected July 26, 1982, near the end of pumping test 4. Concentrations of most constituents and the stable isotopes were nearly identical for the two samples.

Apparent age, based on carbon-14, was 13,700 years before present for the first sample, and 12,400 years before present for the second sample. The second sample represented a greater proportion of production from the shallower zones than the first sample did (enabled by the additional perforating after test 3); a younger age for this sample was consistent with the concept that, because of sources of recharge and general ground-water movement, apparent age is likely to increase with depth.

The water from test well USW H-5 was generally similar in chemical character to other ground water in the vicinity of Yucca Mountain (Benson and others, 1983), but calcium and magnesium concentrations were less than those in most other ground water. The stable isotopes were similar to those in other local ground water, and the apparent age was consistent with that of the other deep ground water, which ranged from about 9,000 to 17,000 years before present.

The variation of temperature with depth is shown in figure 26 (J.H. Sass, A.H. Lachenbruch, F.V. Grubb, and T.H. Moses, Jr., U.S. Geological Survey, written commun., 1983). Sass and others concluded that nonconductive hydrothermal processes predominated below the water table to a depth of about 1,050 m; that, below that depth, the gradient was 28.5 °C/km; and that average gradient below the water table was 15 °C/km. The fact that the temperature gradient was almost linear below a depth of about 1,050 m, which is the contact between the Tram Member and the lava, was consistent with results of the borehole-flow surveys, which indicated insignificant water production from the lava.

Table 4.--*Results of chemical analyses of water samples, depth interval from 704 to 1,219 meters*

[Analyses by U.S. Geological Survey, Denver, Colorado; all dissolved constituents are in milligrams per liter unless otherwise indicated]

Property or dissolved constituent	Value or concentration: Sample collected 07-03-82 (pumping test 3)	Value or concentration: Sample collected 07-26-82 (pumping test 4)
Specific conductance, onsite, in microsiemens per centimeter at 25 degrees Celsius	275	278
Specific conductance, laboratory in microsiemens per centimeter at 25 degrees Celsius	273	276
pH, onsite, in standard units	7.8	7.9
pH, laboratory, in standard units	7.8	8.0
Temperature, in degrees Celsius	36.5	35.3
Calcium (Ca)	1.9	2.0
Magnesium (Mg)	0.01	0.01
Sodium (Na)	60	60
Potassium (K)	2.1	2.1
Bicarbonate (HCO_3)	124	124
Sulfate (SO_4)	16	16
Chloride (Cl)	6.1	6.6
Fluoride (F)	1.4	1.4
Silica (SiO_2)	48	48
Dissolved solids (residue on evaporation)	220	206
Lithium (Li), in micrograms per liter	62	71
Strontium (Sr), in micrograms per liter	9	4
Tritium, in picocuries per liter	200	200
Oxygen-18/oxygen-16 (δ ^{18}O)[1]	-13.6	-13.6
Deuterium/hydrogen (δ ^{2}H)[2]	-102	-101
Carbon-13/carbon-12 (δ ^{13}C)[3]	-10.3	-10.3
Carbon-14, percent of modern standard	18.2	21.4
Carbon-14, apparent age, years before present	13,700	12,400

[1]Deviation of oxygen-18/oxygen-16 ratio of sample from standard mean ocean water (SMOW), relative to SMOW, in parts per thousand.

[2]Deviation of deuterium/hydrogen ratio of sample from standard mean ocean water (SMOW), relative to SMOW, in parts per thousand.

[3]Deviation of carbon-13/carbon-12 ratio of sample per PeeDee belemnite standard (PBD) relative to PDB, in parts per thousand.

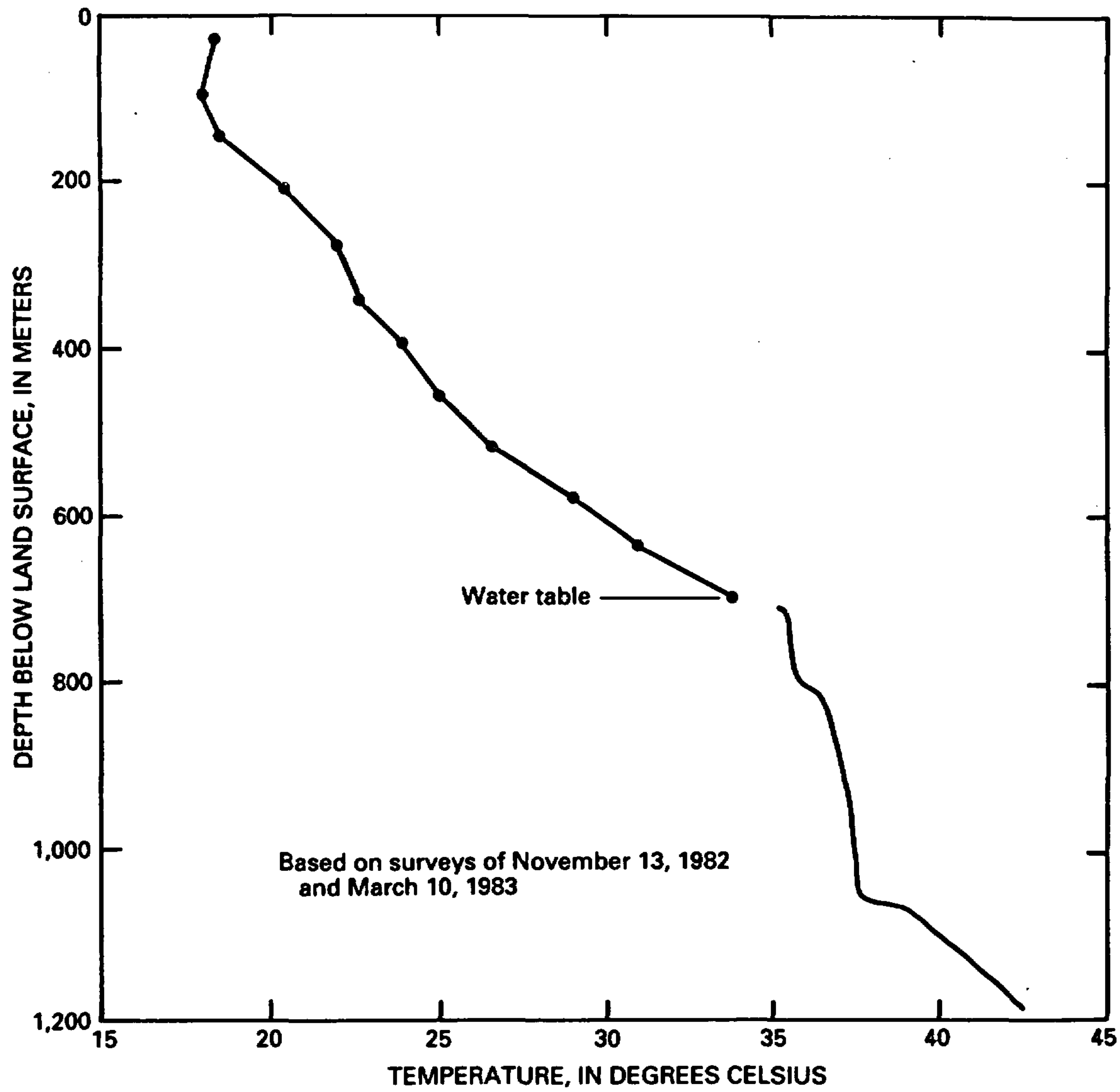


Figure 26.--Variation of temperature with depth (modified from J.H. Sass, A.H. Lachenbruch, F.V. Grubb, and T.H. Moses, Jr., U.S. Geological Survey, written commun., 1983)

SUMMARY AND CONCLUSIONS

Test well USW H-5 was drilled to a depth of 1,219 m, penetrating volcanic rocks of Tertiary age. Depth to water in the test well was 704 m, equal to an altitude of 775 m above sea level.

A borehole-flow survey made in the test well, while pumping at about 10 L/s, indicated that about 90 percent of the total yield was from the Bullfrog Member of the Crater Flat Tuff, and most of that probably was from the upper part near the water table. The Tram Member of the Crater Flat Tuff and an unnamed dacitic (?) lava contributed the remainder of the production, mostly from near the contact between these two units.

Two alternative conceptual models are consistent with data obtained during pumping and recovery tests. The first model is for an unconfined, anisotropic aquifer. This model is based on the assumptions of an unconfined aquifer that is fractured by high-angle to near vertical fractures. The fractures cause anisotropic conditions, with the vertical hydraulic conductivity being several orders of magnitude greater than horizontal hydraulic conductivity. The second model is a finite-conductivity, vertical-fracture model. This model is based on the assumptions of an infinite, isotropic, homogeneous confined aquifer that is fractured by a finite-conductivity vertical fracture. The test well intersects the vertical fracture and flow to the well is only through the fracture.

Based on the first model, pumping tests indicated a transmissivity of about 35 m^2/d. Storage coeffîcents based on actual well radius were too large and an apparent well radius of 7.0 m was assumed that results in a reasonable storage coefficient of about 0.2.

Analytical methods associated with the finite-conductivity, vertical-fracture model do not allow determination of values of transmissivity and storage coefficient but allow determination of values of fracture conductivity and fracture length. Lack of reliable formation parameters that necessitated estimates and assumptions that limited the usefulness of the analytical methods but did indicate that fracture conductivity may be substantial and that nonradial flow responses need to be considered. Calculated fracture conductivity ranged from about 3,000 to 5,600 $(\mu m)^2$-m and fracture half-lengths ranged from about 130 m to equal or greater than about 430 m.

Results of packer-injection tests were inconclusive but did establish that much shorter water columns, tens of meters or less, should have been used during testing to provide better results.

The chemical character of water from the well was typical of that from tuffaceous rocks in southern Nevada, with sodium the principal cation and bicarbonate the principal anion; dissolved-solids concentrations were a little more than 200 mg/L. Carbon-14 activities of two samples indicated apparent ages of 13,700 and 12,400 years before present; apparent ages of other nearby ground water from Tertiary rocks range from about 9,000 to 17,000 years before present.

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