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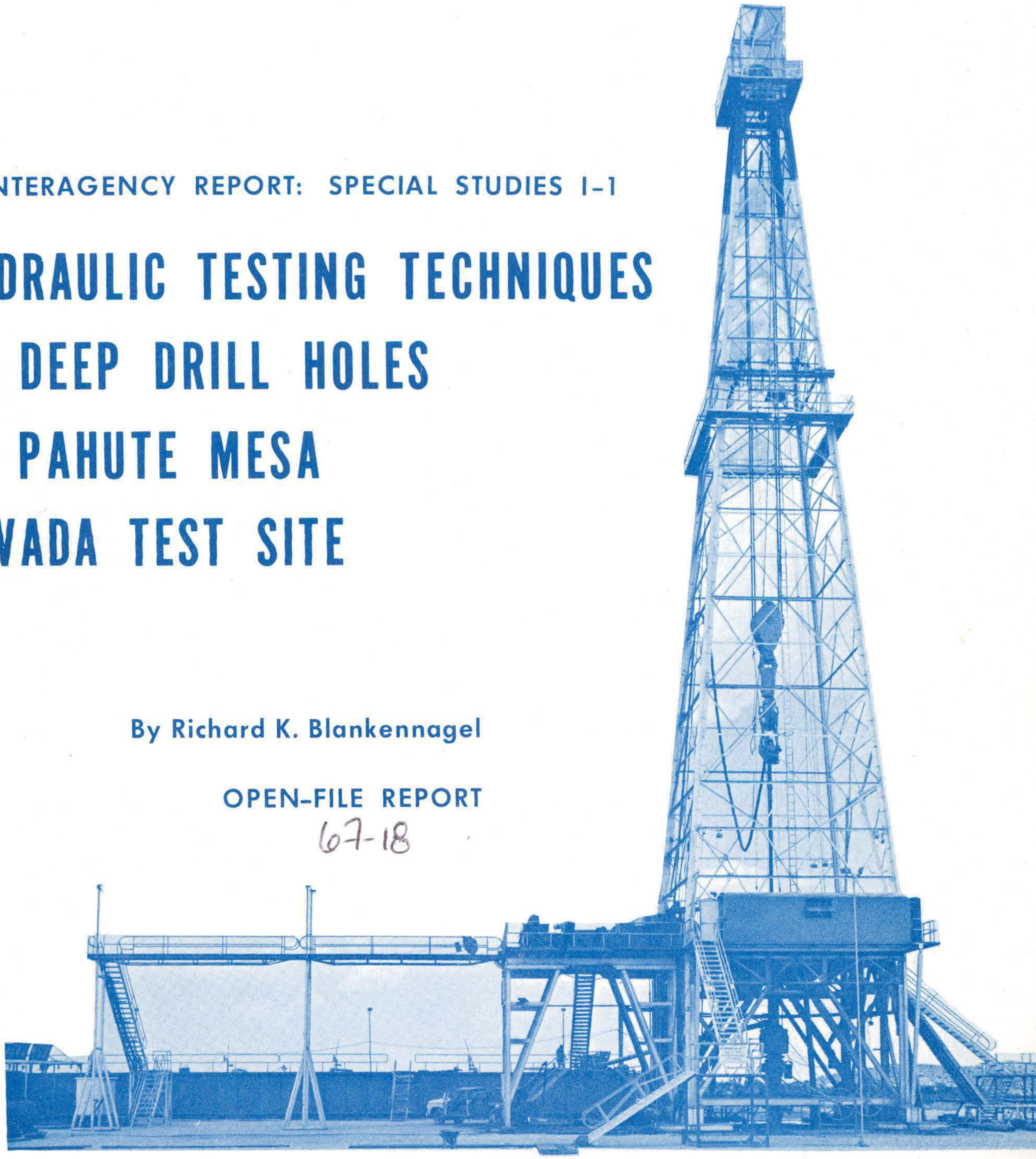
HYDRAULIC TESTING TECHNIQUES OF DEEP DRILL HOLES AT PAHUTE MESA NEVADA TEST SITE

By Richard K. Blankennagel

OPEN-FILE REPORT
67-18



This report is preliminary and has not been edited for conformity with Geological Survey format and nomenclature.

PREPARED IN COOPERATION WITH THE ATOMIC ENERGY COMMISSION

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CONTENTS

Page

ILLUSTRATIONS

TABLES

HYDRAULIC TESTING TECHNIQUES OF DEEP DRILL HOLES AT PAHUTE MESA, NEVADA TEST SITE

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ABSTRACT

This report describes the testing techniques used by the U.S. Geological Survey to obtain hydrologic data in deep holes drilled in volcanic rocks at Pahute Mesa, Nevada Test Site. The testing program in each hole includes geophysical logging, pumping, and injecting and swabbing between straddle packers.

Rock lithologies and qualitative data on hydrologic conditions in the borehole are obtained from electric, caliper, temperature, and fluid resistivity logs. Quantitative data on major water-yielding intervals in the borehole are obtained from radioactive tracer and spinner surveys.

Pumping tests are made to measure the combined yield of the various aquifers. Injection and swabbing tests are made by adding known volumes of water to, or withdrawing known volumes of water from, straddle-packed intervals and observing the rate of decline or rise in water level resulting from this injection or withdrawal of water. The yield of tested intervals is stated as relative specific capacity, in units of gallons per minute per foot of drawdown.

INTRODUCTION

This report is a review of the geophysical logging tools, mechanical devices, and techniques used during hydraulic testing of deep holes drilled at Pahute Mesa, Nevada Test Site. The methods and techniques are representative of the experience that the U.S. Geological Survey has gained during 6 years of hydraulic testing of deep-drilled holes at the Nevada Test Site on behalf of the U.S. Atomic Energy Commission. The testing program, which is reasonably standardized for use on the mesa, may be applicable with or without modifications in other areas. The techniques of testing are presented in great detail for the benefit of those who may be faced with deep-well testing for the first time.

The Pahute Mesa area lies about 130 miles northwest of Las Vegas, Nevada, in the northwestern part of the U.S. Atomic Energy Commission's Nevada Test Site (fig. 1). It is an elevated plateau with relatively gentle relief and includes an area of about 200 square miles; elevation ranges from 5,500 to more than 7,000 ft above mean sea level. Pahute Mesa overlies a deep structural basin containing more than 13,600 ft of volcanic tuff beds and intercalated lava flows. The volcanic rocks are displaced by regional faults that strike N. 20° W. to N. 20° E.; vertical displacements along faults average less than 100 ft, but range from a few feet to 600 feet. Static water levels under the mesa range from about 1,000 to more than 2,300 ft below land surface.

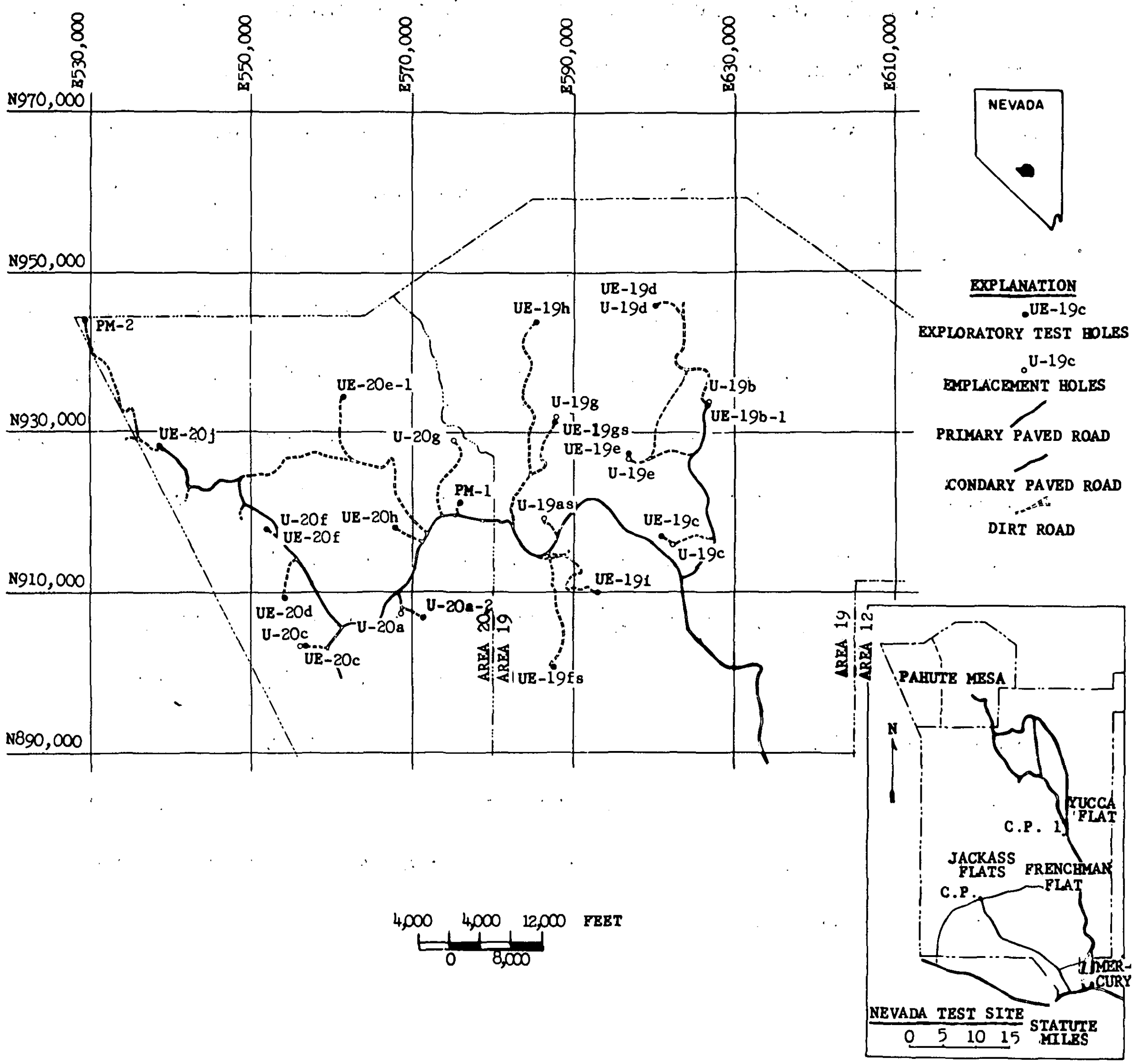


Figure 1.--Location of exploratory and large diameter emplacement holes drilled at Pahute Mesa, Nevada Test Site, Nye Co., Nevada.

The yield of water to wells penetrating the volcanic rocks underlying Pahute Mesa ranges widely. Some of the bedded tuff units are relatively watertight. Rhyolitic lava flows and densely welded tuff have a wide range in water yield potential. Some parts of these rocks are virtually watertight, whereas other parts, particularly the highly fractured zones or the brecciated zones, may yield as much as 50 gpm (gallons per minute) per foot of drawdown.

Underground testing of nuclear devices at Pahute Mesa involves emplacement of devices within the zone of saturation in the volcanic rocks. Many of the proposed tests require chambers at the emplacement depth and these chambers must be constructed in intervals of rock having specific capacities less than 0.04 gpm per ft.

Purpose, scope, and methods of hydraulic testing

The immediate objective of the hydraulic testing program was to determine the water-yielding potential of the volcanic rock strata in each test hole, and, in particular, those strata that have the lowest water yield and are favorable for construction of chambers in emplacement holes.

Hydraulic tests were made in 17 exploratory test holes drilled at Pahute Mesa. Most hole depths ranged from 4,500 to 8,000 ft; one exploratory hole was drilled to 13,686 ft. In emplacement holes where mining of chambers in the zone of saturation is scheduled, drilling of the 72-in diameter holes is interrupted several hundred feet above the interval to be mined. Casing with an outer diameter of $10\frac{3}{4}$-in is tack-cemented at this depth, and a $9\frac{7}{8}$-in hole is drilled and cored through the critical interval to permit geophysical logging and hydraulic testing. Hydraulic tests were made in five of these center-punched, large-diameter holes.

Commonly, hydraulic tests are made in the exploratory holes after the hole has been drilled to a depth somewhat deeper than the proposed emplacement depth. Another suite of tests is made if the hole is drilled to a greater depth. The hydraulic testing schedule followed in the Pahute Mesa exploration program usually starts with geophysical logging. These logs provide detailed information on lithologic changes, potential water yield, and hole size needed for selection of intervals to be isolated by straddle packers and tested by injection or swabbing techniques.

After completion of geophysical logging, a pumping test is made to measure the combined yield of the various aquifers. The pumping test data are analyzed for transmissibility following standard methods described in the literature; see, for example, Ferris and others (1962). During the pumping, radioactive tracer and temperature surveys are made to locate the zones of entry of water into the hole. The principal use of this phase of the hydraulic tests is to identify the large water-yielding zones and to obtain some relative transmissibilities. After practically all the fluids injected during the drilling have been removed, during the first part of the pumping test, the composite formation water can be sampled.

After the pump has been pulled out of the hole, selected intervals in the drill hole are subject to a series of injection or swabbing tests. Injection and swabbing tests are made by adding known volumes of water to, or withdrawing known volumes of water from, straddle-packed intervals and observing the rate of decline or rise in water level resulting from this injection or withdrawal of water. From the rate of change of water levels in time, the yield of the various intervals tested can be computed. The yield of the tested interval is stated as relative specific capacity, in units of gallons per minute per foot of drawdown. The water-level measurements obtained during the slug injection tests may also be utilized to determine the transmissibility of the aquifer immediately adjacent to the bore as described by Cooper and others (1967); however, the value of relative specific capacity alone usually sufficed to pinpoint intervals with transmissibility suitable for chambering. The maximum interval that may be straddled between packers is 198 ft; however, the interval may be considerably less since lithology and hole size are governing factors. Standard oilfield pressure gauges are used above and below the packers to obtain information on leakage around the packers. In most tests, the packer seats have been satisfactory; but in some holes the conditions have been so bad that effective packer seats could not be found and, hence, a test of that particular part of the hole could not be made.

Oilfield drill-stem testing procedures--such as those described by Dolan and others (1957) and Ammann (1960)--were not utilized in the testing program on Pahute Mesa; however, they have been used elsewhere at the test site. The economic requirement of testing several thousands of feet of open hole in one sweep after completion of the drilling and the known several orders of magnitude difference in the transmissibility of the zones to be tested favored use of the inflatable packers and the slug injection method. In addition, the inflatable packers could be run with significantly greater hole clearance than the hard rubber packers utilized on standard drill-stem testing tools; they also provided a seal more than twice as long in time as the hard rubber packers.

In a companion report to this report, Garber and Koopman (in press) describe various instruments used to measure deep water levels at the test site and the relative and absolute errors of each method.

Acknowledgments

Various departments of the U.S. Atomic Energy Commission cooperated in the hydraulic testing of exploratory holes at the Nevada Test Site. U.S. Atomic Energy Commission contractors such as Reynolds Electrical and Engineering Company, Fenix and Scisson, Inc., and various drilling companies expedited the obtention, transportation, and manipulation of testing equipment. Charles Ingram of Lynes, Inc., Houston, Texas, and Elwood Bennett, formerly a field representative for Lynes, Inc., assisted and advised on the operation of inflatable packers. J. M. Bird and R. D. Clarke of Birdwell, Division of Seismograph Service Corporation, rendered outstanding contributions to the geophysical logging program. Their interest in the application of geophysical logs to hydrologic investigations resulted in modifications and improvements on standard oilfield logging tools for this purpose. Several members of the U.S. Geological Survey assisted with office and field support. Of these, I. J. Winograd, R. A. Young, and J. E. Weir, Jr. deserve special recognition.

GEOPHYSICAL LOGGING

The application of various geophysical logs to hydrologic investigations has been published in reports such as those by Bennett and Patten (1960 and 1963), and in some journal articles. Interpretations of logs and logging techniques, however, are governed by rock characteristics in a particular area, drilling methods, and the objectives of the hydrologic investigations. For example, there is little or no information available for interpretation of basic logs made in holes drilled in volcanic rock types. Stemming from experience gained on Pahute Mesa, some qualitative data on rock lithologies and hydrologic conditions in the borehole may be determined from electric, caliper, temperature, and fluid resistivity logs. Quantitative data on the major water-yielding intervals in the borehole are obtained from radioactive-tracer or spinner surveys.

Electric, caliper, and temperature logging operations need only be monitored occasionally by the geologist or hydrologist so that the desired logging speed (at Pahute Mesa a logging speed of approximately 30 ft per minute is most efficient and effective) is maintained by the logging engineer, proper calibration data are noted on the log, repeat curves of a short interval in the hole are recorded, and the desired horizontal scales are obtained. Direct supervision is necessary during preparations before and during logging of the fluid-resistivity (salinometer), radioactive-tracer, and flowmeter (spinner) logs.

A brief discussion of the application of electric, caliper, and temperature logs to the hydraulic testing program follows. Fluid resistivity, radioactive-tracer, and flowmeter surveys require a geologist's supervision at the well site; hence, logging techniques are given for these surveys.

Electric log

The electric log is used for the determination of the lithologic character of the rocks; hence, it is valuable for correlation purposes and identification of potential water-yielding zones. Most ground-water movement under Pahute Mesa occurs along open fractures in relatively competent welded tuff and rhyolite. Fractures in the less competent zeolitized tuff units are usually resealed by weight of overburden. The normal and lateral resistivity curves are excellent indicators of rock types. Borehole fluid resistivities at Pahute Mesa are such that the apparent resistivity of the 16-inch normal curve can be taken as the true resistivity of the formation at apparent resistivities less than 1,000 ohm-meters. Apparent resistivities of relatively impermeable zeolitized tuff units are usually less than 100 ohm-meters on the short normal curve of the log; apparent resistivities of highly welded tuff, vitrophyre, and rhyolite exceed 225 ohm-meters. Examples of electric logs in typical lithologies at Pahute Mesa are shown in figures 2 and 3. In holes drilled at Pahute Mesa, the major water-yielding zones usually occur in the upper 2,000 ft of saturation in rock types with resistivities greater than 225 ohm-meters.

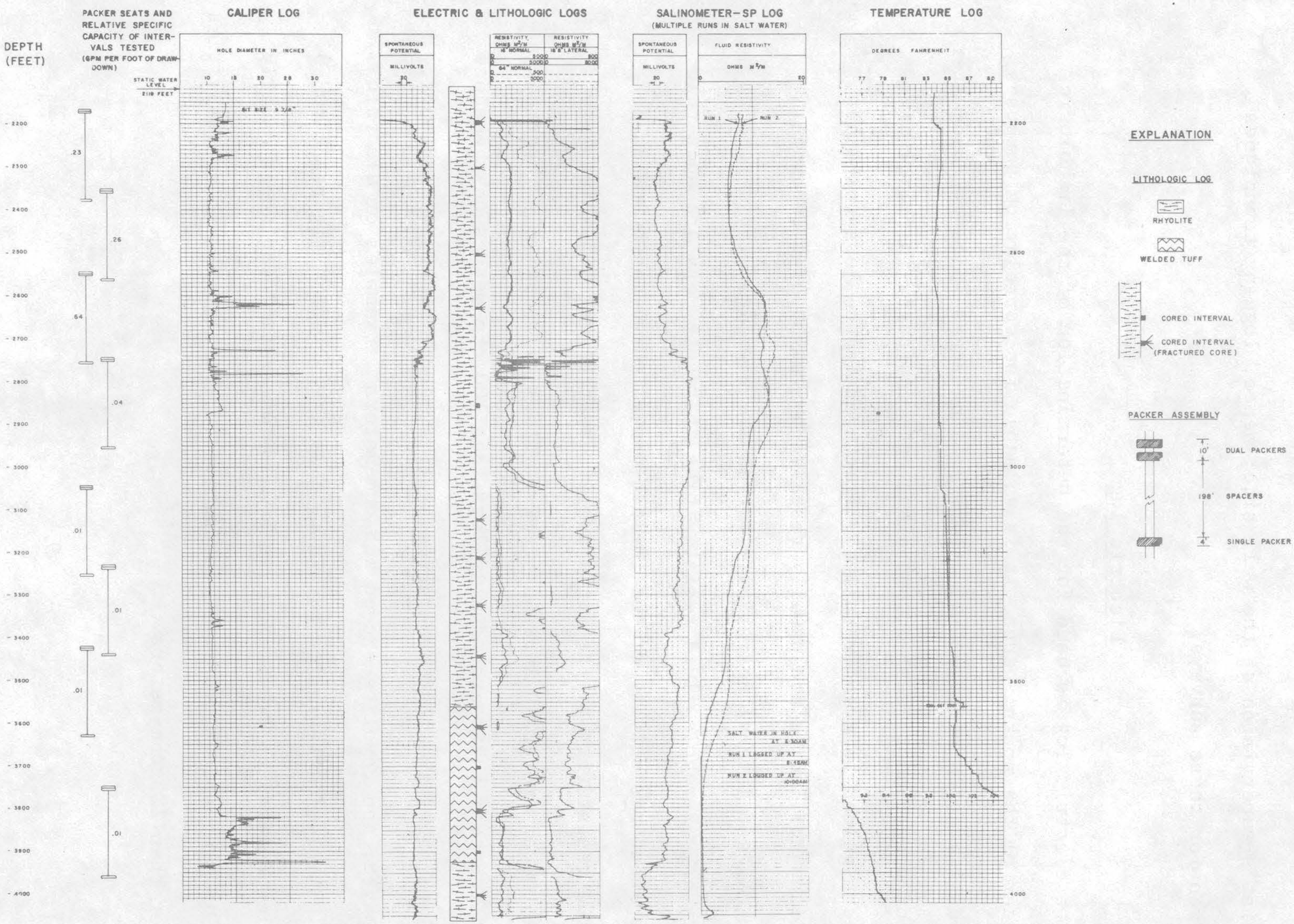


Figure 2.--Lithologic and geophysical logs of hydraulic testing program in exploratory hole Ue19b1 at Pahute Mesa, Nevada Test Site, Nye Co., Nevada

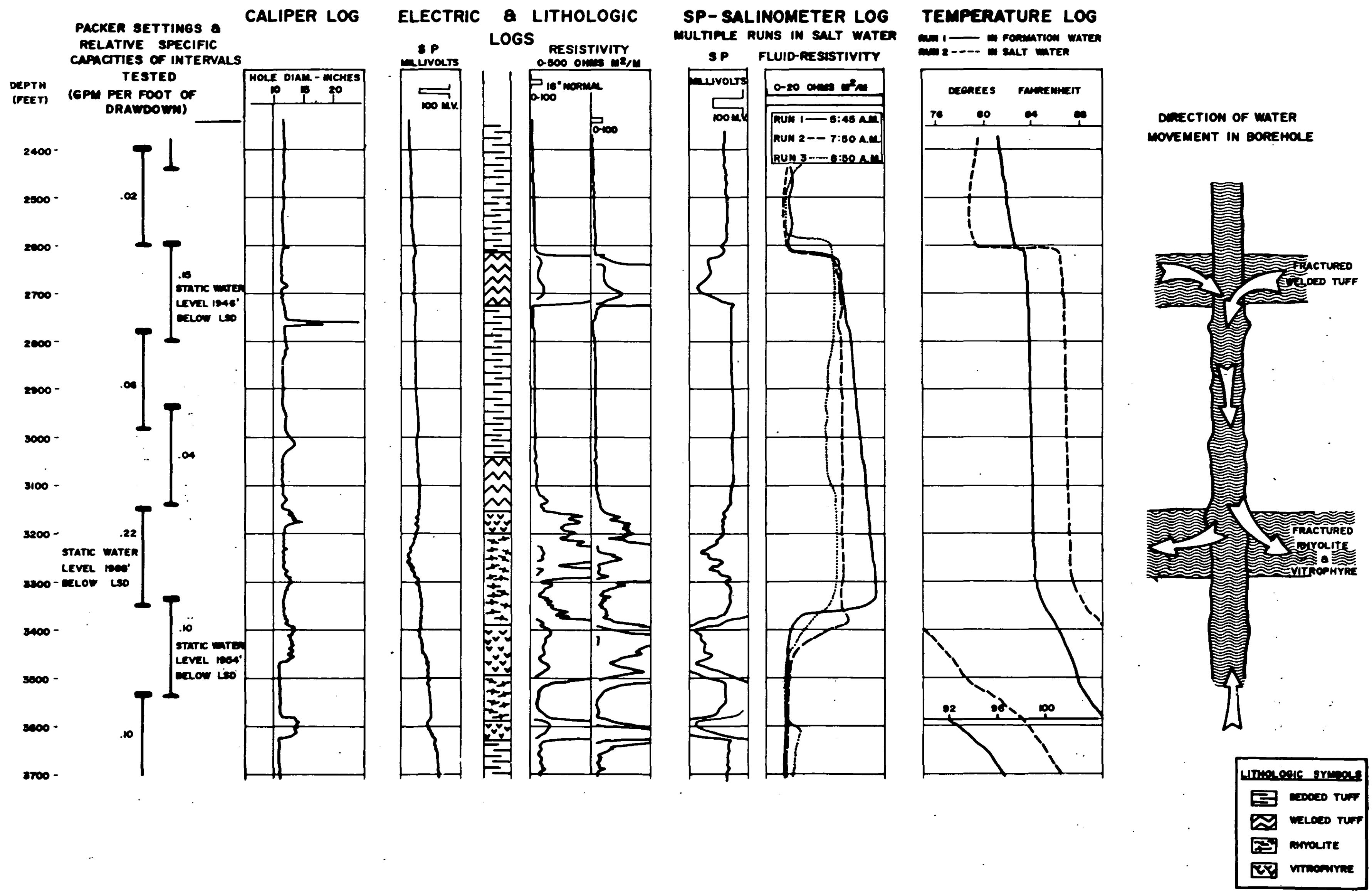


Figure 3.--Lithologic and geophysical logs of hydraulic testing program in exploratory hole Ue20f at Pahute Mesa, Nevada Test Site, Nye Co., Nevada.

During drilling operations using air and water, fluids in the borehole and rock formations are similar. Lack of contrast between these fluids usually results in a flat and featureless spontaneous potential curve.

Streaming potential, probably the result of interaquifer circulation and pressure differentials (Patten and Bennett, 1963) is illustrated on the spontaneous potential curve in figure 3; the streaming potential occurs in the interval between 3,200 to 3,500 ft, and also may be noted at 3,600 ft.

Caliper log

Knowledge of borehole diameters is essential to selection of packer seats, radioactive tracer survey computations, and interpretations of various geophysical logs. The caliper tool with three independently operating arms that are extended and retracted from the surface may detect variations as small as a quarter of an inch in average hole diameter.

The caliper log often indicates rock type and highly fractured intervals, and thus yields information related to porosity and permeability. On Pahute Mesa the caliper curve is usually smooth and the diameter of the borehole is in gauge with the drill-bit size through sections of competent, non-fractured welded tuff and rhyolite; borehole rugosity and angular caved zones are indicated on the log in highly fractured intervals. Prominent ledges and abrupt "washed-out" zones often occur at the contact of competent and incompetent rock types. Intervals of zeolitized tuff are usually indicated on the caliper curve by large "washed-out" or caved intervals; hole size is generally greater than drill-bit size.

Temperature log

Temperature logs in conjunction with other logs yield valuable information on intervals of water entry and movement of fluids in the borehole (Bird, 1954). Termination of a consistent increase in the thermal gradient with depth may indicate a zone of water entry or a permeable interval that is accepting water from an aquifer at greater depth. Interaquifer circulation is indicated where there is no change in temperature with depth. Below or above the interval of crossflow--where there is little or no movement of fluids--the temperature gradient increases or decreases to adjust to the temperature normal for the subsurface depth. The temperature logs made in exploratory hole Ue20f (fig. 3) clearly indicate that the crossflow between aquifers occurs in the depth interval 2,600 to 3,300 ft. Formation water from the upper aquifer at about 2,600 to 2,700 ft circulates downward displacing warmer fluids in the borehole and enters the more permeable aquifer at 3,300 ft. Below 3,300 ft--where there is little or no movement of fluids--there is rapid increase in the temperature gradient. Data obtained from straddle packer tests (permeabilities and head changes) confirm the direction of water movement in the borehole. Direction of movement of fluids in the borehole may be determined from an examination of some temperature logs, but confirmation from other geophysical logs or testing methods is usually required.

Temperature logs made during pumping are useful for identifying the major water-yielding intervals. On figure 4, two contributing aquifers in exploratory hole Ue19c may be detected on the temperature log made during pumping at a constant rate of 66 gpm. The lower aquifer, a minor contributor, lies at a depth of about 3,160 ft. In the interval 3,160 to 3,090 ft there is little or no change in the temperature gradient; this condition indicates upward movement of water from the lower aquifer. Cooler water enters the borehole from the major aquifer in the interval 3,090 to 3,070 ft and reduces the temperature of the water from the lower aquifer. Upward movement of fluids with no additional contributing zones is again indicated above 3,070 ft by little or no change in the temperature gradient. A radioactive tracer survey, made in Ue19c shortly after the temperature log, indicated no measurable movement of fluids below a depth of 3,200 ft.

<u>Fluid resistivity (salinometer) log</u>

The fluid resistivity tool contains electrodes spaced so that the tool will measure the resistivity of the borehole fluid only and will not be affected by formation resistivities. For successful application of the log to hydrologic investigations at the test site, the drilling and circulating media should be air or water. The use of detergents during drilling is acceptable.

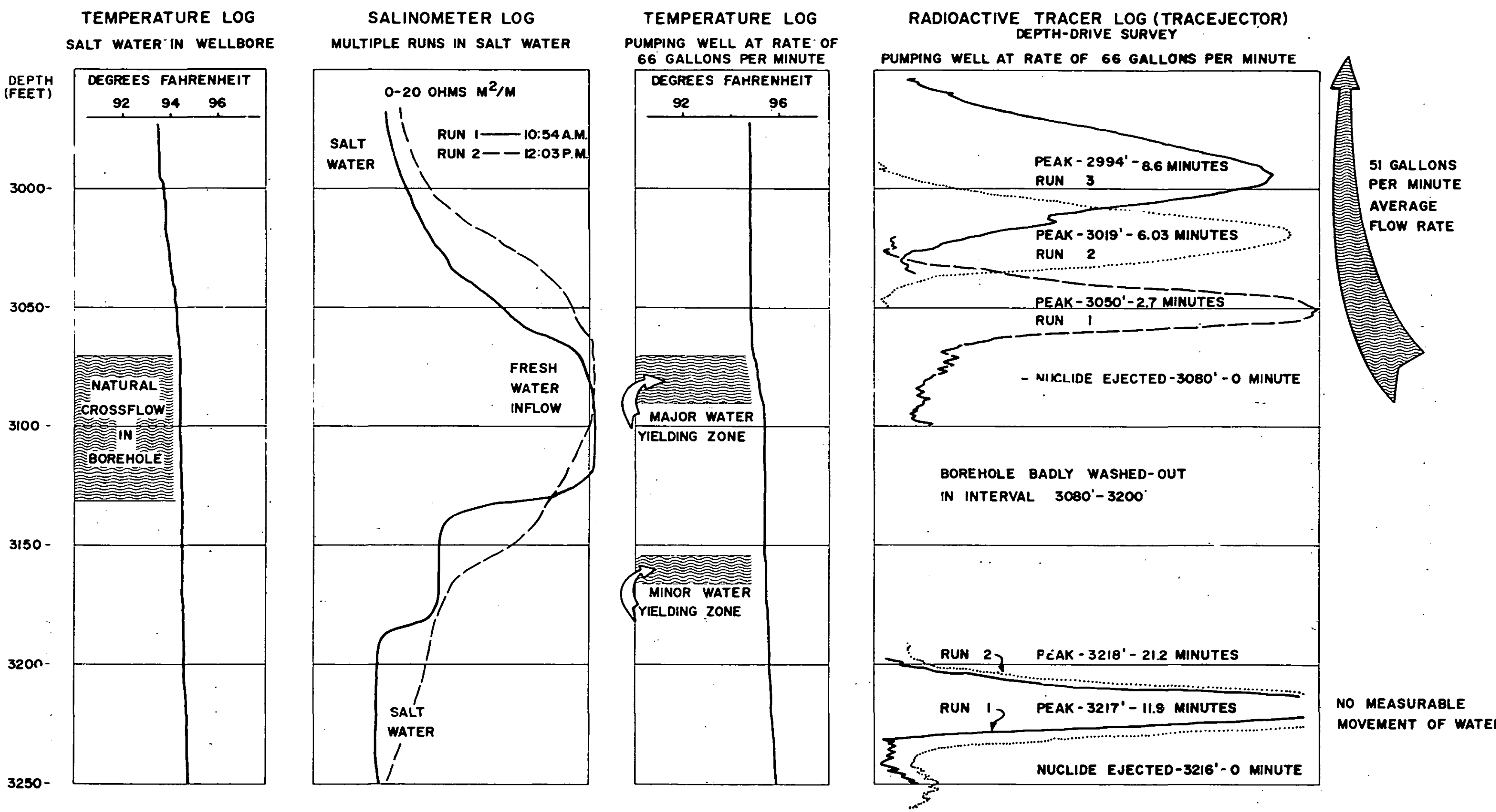


Figure 4.--Geophysical logs illustrating movement of fluids in exploratory hole Ue19c at Pahute Mesa, Nevada Test Site, Nye Co., Nevada.

The fluid resistivity survey is made in holes at the Nevada Test Site after the natural fluid in the borehole has been replaced by a low resistivity brine solution. Contrasts in the resistivity of the fluid in the borehole occur at the depths of water entry and circulation. Multiple surveys, each recording a single resistivity curve in a range from 0 to 20 ohm-meters, indicate zones of fresh-water entry by a marked increase in resistivity (figs. 2, 3, & 4). Direction of water movement sometimes may be deduced from an examination of the fresh- and salt-water interfaces. When water from the contributing zone is circulating in the borehole at low velocities, the fresh- and salt-water interfaces may be noted at different depths in the direction of movement during the multiple log recordings. Usually this interface is more diffused.

In exploratory hole Ue20f (fig. 3) circulation of formation water in the borehole is indicated on the fluid resistivity (salinometer) log between the depths ranging from about 2,600 to 3,350 ft. The circulatory pattern was established before the multiple logs were made; hence, the direction of fluid movement cannot be determined from the fluid resistivity log alone. The fresh- and salt-water interfaces, however, are reasonably well defined. The anomalous increase in salinity with increase in time through the zone of circulation cannot be explained. In exploratory hole Ue19b1 (fig. 2), the principal zones of water entry are not well defined on the fluid resistivity (salinometer) log. Radioactive-tracer surveys indicate a major water-yielding zone at depths ranging from about 2,610 to 2,640 ft. Circulation of fluid in the borehole from this contributing zone is primarily lateral, but there is some minor downward movement.

A spontaneous potential curve is made concurrently with the fluid resistivity curve. The contrast in ion content between the borehole fluid and formation waters causes significant deflections of the spontaneous potential curve. In the volcanic section, negative deflections occur opposite the fractured, fresh-water-yielding formations and high resistivity formations (fig. 3).

Testing techniques

Salting of the fluid in the borehole and logging with the salinometer tool is done after all other geophysical logging has been completed. Techniques are as follows:

The amount of fluid necessary to displace the fluid in the drill pipe when the drill pipe is lowered, open-ended, to total depth is calculated (fluid in pipe from static water level to total depth of hole).

A brine solution in the amount calculated to displace the fluid in the drill pipe is prepared by dissolving 100 to 300 lb of sodium chloride crystals in water in a tank at the well site. Resistivity of the prepared brine solution should be less than 1 ohm-meter.

Open-ended drill pipe is lowered into the borehole to total depth, and, using the mud pump and hose on the rig, the salt solution is pumped into the drill pipe.

The drill pipe is "chain-pulled" from total depth to the static water level. This method reduces turbulence and introduces the brine solution into the borehole as evenly as possible. The pipe remaining in the borehole above the static water level is rotated out of the hole.

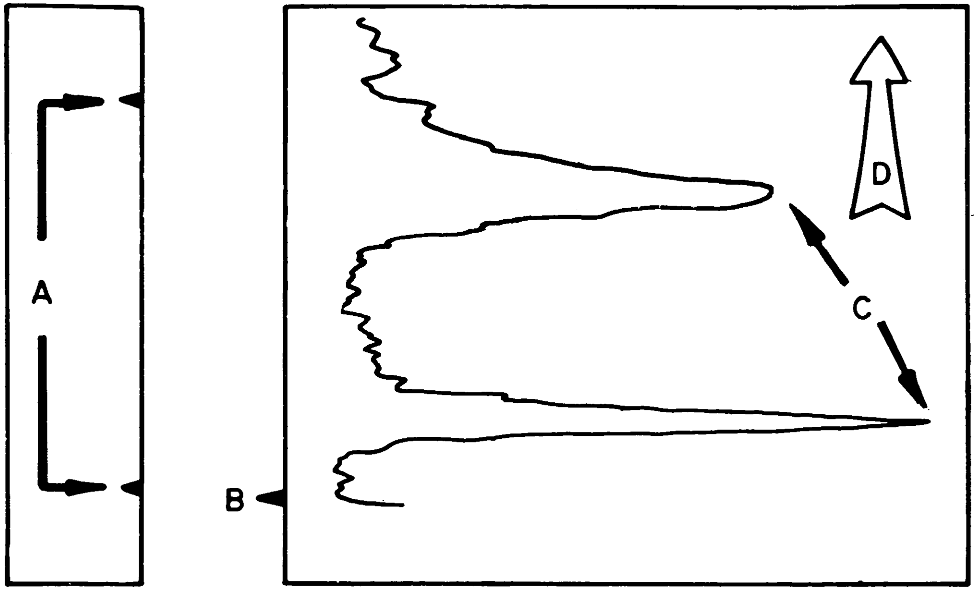
The logging engineer makes the initial run through the fluid in the borehole as soon as the last stand of drill pipe has been removed. At least three logging runs are made in the hole. Logging always is recorded in the same direction, and there is a delay of at least half an hour between logging runs. A paper recorder, rather than a photographic film recorder, is preferable since multiple runs can be recorded on the same logging strip and penciled notations can be made on the log. The hour and the minute at the start and end of each logging run are noted on the log.

Radioactive tracer log

Several tools bearing different trade names but similar in operation have been used for tracer surveys in exploratory holes on the mesa. The tools were developed for oilfield use where the major application is the determination of quantitative injection profiles in water-flood projects (Bird and Dempsey, 1955; Johnson and others, 1964). The outer diameter of the tools ranges from $1\frac{1}{4}$ to $1\frac{5}{8}$ inch. These diameters permit entry of the tool through 2-inch inner-diameter access tubing during pumping operations. Length of the tools ranges from 8 to 15 feet. An aqueous solution of radioactive iodine-131 with a concentration of 1 millicurie per milliliter, and preferably dyed red for visual detection of spillage, is injected into a chamber in the tool. The chambers range in volume from 7 to 20 cubic centimeters.

A positive displacement pump in the tool, electrically actuated from the surface, ejects a small volume of the iodine-131 solution into the fluid in the borehole. The rate of movement or location of the slug is determined with one or two scintillation gamma detectors built into the tool. When the slug reaches the detector, a recorder at the surface registers an increase in gamma activity. The arrival times of the slug and the average hole size determined from the caliper log are used for computing flow rates.

Two tracer-logging techniques have been used in exploratory holes on Pahute Mesa. During pumping or injecting water at a constant rate in excess of 10 gpm, the time-drive technique in which the tool is in a stationary position is used. If fluid movement is less than 10 gpm, the depth-drive technique in which the tool is moved through the slug of iodine-131 is used. The waiting time for the slug to pass detectors, when flow rates are low, makes the time-drive technique inefficient. Brief discussions of time-drive and depth-drive techniques and computations are given in figures 5 and 6. When the recorder is in time-drive and flow rates are greater than 10 gpm, computations based upon the time between recorded peaks are similar to those based upon the time between the center of masses as the iodine-131 slug passes the recorders. Computations based on the first arrival break proved to be less accurate; hence, this method was not used. When the recorder is in depth-drive, stopwatch time is recorded at each peak or maximum amplitude. The peaks become diffused as a result of moving the tool through the iodine-131 slug, and stopwatch time may be recorded prematurely or too late. Therefore, adjustment of recorded times must be made before final calculations, and, if peaks are not distinct, calculations based upon the center of mass may be preferable.



LOG RECORDED FROM DUAL DETECTOR TOOL

TOOL STATIONARY IN BOREHOLE WHEN NUCLIDE IS EJECTED- RECORDER IN LOGGING TRUCK SET AT CONSTANT SPEED IN TIME-DRIVE. TIME-DRIVE TECHNIQUE USED WHEN FLOW RATE EXCEEDS 10 GPM IN 6 TO 12 INCH DIAMETER BOREHOLE.

A. recorded minute markers
B. point of ejection of nuclide
C. peaks recorded on single channel as nuclide moves past detectors
D. direction of fluid movement

COMPUTATIONS

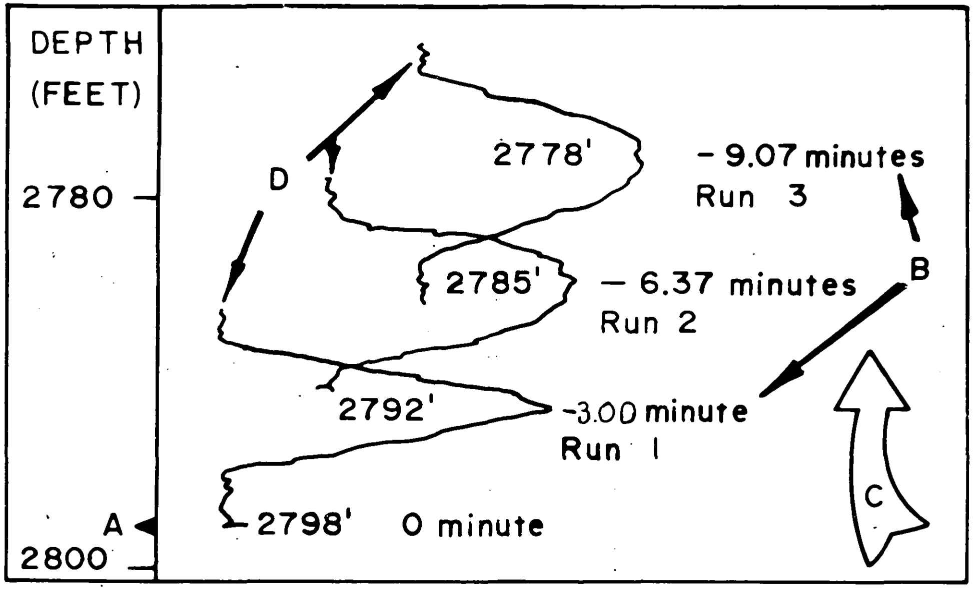
1 $\dfrac{\text{Distance in teet between dual detectors of tool}}{\bullet\ \text{Time in minutes between recorded peaks}} = \text{Velocity in feet/minute}$

2 $\left(\text{Velocity in feet/minute}\right) \overset{*}{\left(\text{Volume in gallons/linear foot}\right)} = \text{Flow rate in gallons per minute}$

• Time between peaks measured directly from log

* Average hole size between detectors computed from caliper log

Figure 5.--Radioactive-tracer survey (time-drive).



LOG RECORDED FROM SINGLE DETECTOR TOOL

SUCCESSIVE RUNS MADE THROUGH NUCLIDE RECORDER IN LOGGING TRUCK SET IN DEPTH-DRIVE TO RECORD FOOTAGE LOGGING OF PEAKS ALWAYS DONE IN SAME DIRECTION. DEPTH-DRIVE IS PREFERRED TECHNIQUE WHEN FLOW RATE IS LESS THAN 10 GPM IN 6 TO 12 INCH DIAMETER BOREHOLE.

A. Point of ejection of nuclide

B. Peaks recorded as detector is moved through nuclide. Run numbers and stopwatch time marked on log by observer in truck.

C. Direction of fluid movement

D. Scale shifted after each recorded peak for clarity

COMPUTATIONS

Computations are similar to those used for time-drive

Data recorded on log differs from time-drive data as follows:

1. Time between peaks measured by stopwatch – not directly from log
2. Distance between peaks measured directly from log

Figure 6.--Radioactive-tracer survey (depth-drive).

Conversions of hole size to volume per linear foot and seconds to minutes are shown in tables 1 and 2. Figure 7 is a standard form for recording radioactive-tracer-survey data.

Testing techniques

Techniques for making surveys during pumping, during constant-rate injection, and under static or natural crossflow in the borehole vary. During pumping, the techniques used at the mesa are as follows:

Two-in. ID access tubing is banded to the pump column. The bottom of the access tubing is approximately 10 ft below the pump motor, and care is exercised to prevent warping of the access tubing between the pump unit and the pipe column.

The pumping rate is stabilized (radioactive surveys usually are made after a standard 24-hour pumping test and 12-hour recovery test).

A temperature log is run after pumping at least half an hour. The horizontal scale should be one that will cause a minimum number of scale changes; however, it must yield good definition of all anomalies. A scale of 1^{o} per inch is usually satisfactory in this area.

If there is a possibility that hole conditions have changed since the caliper log was run, the geologist requests a rerun of the log made with a $1\frac{5}{8}$-in OD caliper tool.

The radioactive-tracer tool is made up with the ejector at the base of the tool and two scintillation detectors above the ejector. Spacing of the detectors is determined by the type of tool used; however, careful measurements are made of the distance in feet between the ejector port and the first detector, and between the first and second detectors.

Table 1.--Conversion of hole size to volume per linear foot

Diameter of borehole (in)	Volume per linear foot (gal)	Diameter of borehole (in)	Volume per linear foot (gal)
8	2.61	13	6.90
8-1/4	2.78	13-1/4	7.17
8-1/2	2.95	13-1/2	7.44
8-3/4	3.12	13-3/4	7.72
9	3.30	14	8.00
9-1/4	3.49	14-1/4	8.29
9-1/2	3.68	14-1/2	8.58
9-3/4	3.88	14-3/4	8.88
10	4.08	15	9.18
10-1/4	4.29	15-1/4	9.49
10-1/2	4.50	15-1/2	9.80
10-3/4	4.72	15-3/4	10.12
11	4.94	16	10.44
11-1/4	5.16	16-1/4	10.78
11-1/2	5.40	16-1/2	11.12
11-3/4	5.63	16-3/4	11.46
12	5.88	17	11.79
12-1/4	6.13	17-1/4	12.14
12-1/2	6.38	17-1/2	12.50
12-3/4	6.64	17-3/4	12.86
		18	13.22

Table 2.--Conversion of seconds to minutes

Seconds	Minutes	Seconds	Minutes	Seconds	Minutes
1	0.017	21	0.350	41	0.683
2	.033	22	.367	42	.700
3	.050	23	.383	43	.717
4	.067	24	.400	44	.733
5	.083	25	.417	45	.750
6	.100	26	.433	46	.767
7	.117	27	.450	47	.783
8	.133	28	.467	48	.800
9	.150	29	.483	49	.817
10	.167	30	.500	50	.833
11	.183	31	.517	51	.850
12	.200	32	.533	52	.867
13	.217	33	.550	53	.883
14	.233	34	.567	54	.900
15	.250	35	.583	55	.917
16	.267	36	.600	56	.933
17	.283	37	.617	57	.950
18	.300	38	.633	58	.967
19	.317	39	.650	59	.983
20	.333	40	.667	60	1.000

Radioactive tracer survey form

Sheet no._____of_____

Pumping rate:____________________

Test hole:________________ Geologist/Engineer________________________________

Injection rate:__________________

Date:_____________________ Logging company:__________________________________ Static survey:___________________

Run no.	Type of drive	Depth (ft)	Diam. of hole (in)	Vertical dis- tance (ft)	Time (in min)	Velocity (ft/min)	Volume per lin. foot (gal)	Flow (gpm)	Mean flow (gpm)	Remarks

Figure 7.--Radioactive-tracer-survey form.

The chamber in the tool is loaded with iodine-131 (at the Nevada Test Site this operation is supervised by RadSafe personnel) and the tool is lowered into the hole.

After the tool is lowered below the access tubing, the logging engineer activates the ejector switch a few times. Usually it is necessary to press the switch several times before the radioactive material will eject out of the port.

With the recorder in time-drive, a stopwatch is used to check the minute marker for accuracy. A vertical scale of 15 to 20 divisions per minute (30 to 40 ft) on the logging paper is preferable.

If the hole is cased below the bottom of the access tubing, several calibration runs are made in the cased portion. Measured flow rate in the casing in gallons per minute should be within 10 to 15 percent of discharge rate measured on the surface.

The iodine-131 is ejected from top to bottom of the hole so that the slug will be moving away from the next measuring point. At some point in the hole, movement of fluid may be downward. At that point, measurements are made from bottom to top. If fluid movement is less than 10 gpm, it may be necessary to change to depth-drive; if it is greater than 10 gpm, the time-drive technique is used after removing the tool and placing the ejector above the detectors.

After a gross survey to establish major water-contributing zones, a detailed survey is made to determine exact depths to various contributing intervals. Zones of relatively constant hole diameter over the interval to be tested are selected, and hole diameters over the interval are averaged. If the borehole has not been washed out to diameters in excess of 13 in, the permeable zones can be delineated to an accuracy within a few feet. Considerable dispersion of the iodine-131 slug occurs in intervals where the average hole size is greater than 13 in; hence, peaks are often not clearly defined. The pumping rate is measured during the entire test. If it does not remain constant, the flow-rate computations will be erratic.

If a pump is not available, the time-drive technique is used while water is injected at a constant rate into the borehole. No tubing is required; hence, the survey can be made without the necessity of a rig on the hole. The mud pump and the hose on the rig, or gravity flow from a 500-barrel water tank, are used to inject water into the borehole at rates of 100 gpm or more. Either way, maintaining a constant flow rate is a serious problem. When using mud pump equipment, the cyclic rate of the pump is adjusted to obtain the desired flow rate. A check is made of the cyclic rate at periodic intervals throughout the test. When using gravity flow from a water tank, a flow-meter and gate valve are attached to the flow line.

Procedures for the time-drive technique during constant rate injection of water are similar to those described under testing techniques during pumping. However, the ejector is placed above the detectors, and, to avoid running through old slugs, the iodine-131 is ejected from the bottom to the top of the hole.

The depth-drive technique is preferable when measuring natural crossflow in the borehole or when the flow rate is less than 10 gpm. Testing techniques for the depth-drive survey are as follows:

Temperature and caliper logs, if required, are made.

A single-detector tool is used. If the tool has two detectors, one can be cut out during the recording operation.

The ejector is placed below the detector and no sinker bar is attached to the tool. Since the tool must be moved through the slug several times, a shorter tool will cause less dispersion of the nuclide.

The recorder is set in depth-drive so that accurate footage is recorded. Depth is recorded from the ejector port.

With the tool in the hole, a slug is ejected into the fluid in the borehole. A stopwatch is started the instant that the logging engineer pushes the ejector switch. The tool is held stationary for approximately 3 minutes; and then if the slug has not passed the detector, the tool is lowered through the slug. Stopwatch time and footage moved are recorded as near as possible to the peak of the curve recorded on the log. After the tool has passed through the slug, the tool is pulled up through the slug without recording on the log. Logging is done in the same direction. If peaks are recorded in both directions, an error of a few feet in depth may occur. This error may be due to a time constant that is common to most radiation tools and to stretch in the cable and slack in the gears of the recorder.

Several passes are made through the slug in the manner described in the preceding discussion. The time interval between passes is determined at the well site since it depends on the flow rate and dispersion of the iodine-131. Peaks generally are distinct and relatively easy to pick during the first and second passes through the slug. After the nuclide has been disturbed, the curves become broad and the peaks less distinct.

Flowmeter (spinner) log

A modified spinner-type tool has been used for only one survey in a 20-in hole on Pahute Mesa. The tool was inaccurate for quantitative measurement of flow rates; however, results were so encouraging that consideration is being given to enlarge and adapt a standard oilfield flowmeter tool for use in holes with diameters ranging from 9 to 24 in. The tool, if built, will consist of calibrated impeller units positioned within an inflatable packer. When expanded against the borehole wall, the packer insures that all fluid flow at that level is directed against the impeller. The impeller will be calibrated in terms of revolutions versus flow, and appropriate curves will be recorded on the surface. Flow rates ranging from 1 to 100 gallons per minute should be measurable with a one-impeller setup. A motor in the tool, electrically activated at the surface, will draw fluid from the borehole to inflate the packer. The packer will be of a size that will seal off holes ranging from 9 to 20 in. in diameter.

The spinner tool gives a reasonably accurate measurement of the water level in the borehole during constant-rate water injection. A sharp break on the log occurs when the spinner is pulled out of the water. Hence, an estimate of the specific capacity of the hole, based on the injection rate and the water-level rise, also can be obtained during the spinner survey.

SWABBING TESTS

Swabbing an entire hole may be justified if a review of the geophysical logs and drilling history indicates that the hole may not yield sufficient water to sustain pumping for 12 or more hours at rates in excess of 30 to 40 gpm. Swabbing a hole capable of yielding more than this quantity of water is usually not justified since no measurable drawdown will be detected.

At times mud and other materials are added to holes during drilling to combat loss of circulation. Swabbing or bailing is usually required to clean these holes before testing with packers.

Swabbing between packers sometimes is done as a check on water-injection test results in critical intervals where mining operations are scheduled. Swabbing between packers also is done to collect water samples from specific intervals in the hole.

Equipment

Equipment and materials used for swabbing tests include the following:

Sufficient drill pipe or tubing to lower the string to a depth generally ranging from 200 to 500 ft below the static water table.

A basket-type, or equivalent, swab unit consisting of a hollow supporting mandrel with upward opening valve, rubber cups, and sinker bar (Uren, 1946). A note of caution that cannot be overstressed is the obtention of a sufficient quantity of rubber cups, having the proper outer diameter for the tubing or drill pipe to be used, well in advance of the swabbing date. The swabbing unit should be equipped with the equivalent of a vertical check valve and a pop safety valve to eliminate the possibility of trapping more fluid than the swab is designed to lift.

Proper connections and tubing on the surface to install a discharge line and an "oil saver" to prevent escape of fluid under pressure yet permitting free movement of the drilling cable.

Motor-driven reel and line. For rigs equipped with a sand reel and sand-line, lowering and pulling of the swab unit can be accomplished smoothly and rapidly. Unfortunately, this equipment has been eliminated from most rigs; and a motor-driven reel and line must be imported. The unit is usually set up beyond the pipe rack, and the cable passes through sheaves on the derrick floor and the top of the derrick to the swab. Because of the distance of the unit from the well head and the dual sheaves through which the cable must pass, the driller or operator of the unit cannot "feel" the swab hit the fluid in the hole; nor can he lower and pull the swab smoothly and rapidly.

Mud tank capable of holding 2,000 to 7,000 gallons of fluid.

Water-level-measuring device (iron horse), stopwatches, tape measure, conductivity meter, quick-drying spray paint for marking sandline, and miscellaneous materials to record data and repair basic equipment.

Testing techniques

Testing techniques vary considerably depending upon the experience of the crew and supervisors, the objectives of swabbing, and the time that can be allotted to the operation. General procedures are as follows:

A basket connection is screwed into the open-ended pipe to catch equipment that may fall into the hole. The drill pipe or the tubing is lowered into the hole. The necessary surface connections for the swab unit and the discharge line are made, and the discharge line is directed into the mud tank.

Dimensions of the mud tank are measured and the number of gallons of fluid for each foot of rise in the tank is determined.

The swab is attached to the sandline or the cable and is then lowered slowly through the drill pipe or tubing. Below the water level, the fluid in the hole lifts the check valve, passes up through the inner tube, and enters the space above. At a depth approximately 500 ft below the static water level, the swab is pulled out of the hole. The check valve prevents the fluid from again passing through the swab. The weight of the fluid flattens the rubber cups and expands the diameter of the cups until they press firmly against the pipe. This prevents leakage of fluid around the swab and the pipe, and the fluid is lifted to the surface. Several experimental runs with the swab are made before the test. The drill pipe or tubing is usually not free of blisters, rust, and dirt; and one or more sets of rubber cups is usually destroyed before the pipe is clean and smooth.

After experimental swabbing, the swab is lowered to the fluid level in the hole. The sandline is marked at selected depths with quick-drying spray paint. Marking the sandline aids the driller and also aids in rough estimation of drawdown during the operations. In addition to a mark at the fluid level, the line is usually marked when the swab is at depths of 50, 100, 200, and 500 ft below the fluid level. Several colors of paint may be used, or the length of the markings are varied to distinguish the various depths.

Clock time is noted beginning with the first pull of the swab and the amount of fluid discharged into the mud tank at the end of each swab is measured. Each lowering and pulling of the swab is done as smoothly and rapidly as possible. The number of swabs pulled and the total swabbing time depend upon factors already discussed. The rate in gallons per minute produced by swabbing depends upon the depth to the fluid level and the efficiency of the operation. Water samples are collected periodically for measurements of specific conductance and for chemical analysis. The temperature of the water is measured after each swab; figure 8 is a standard form for recording swabbing-bailing data.

Before the final swab, the drilling crew is advised that the swab is to be pulled completely out of the hole and that all connections are to be broken as quickly as possible so that the water-level-measuring device can be lowered into the drill pipe and the fluid level in the hole can be measured.

Swabbing-bailing test form ______ Hole ______ Area

Observed by: ______________________________ Date: ______________

Hole depth ______________ diameter ______ in Cased interval ______

Perforated intervals ____________ Tested interval ____________

Water levels measured with ________________

Measuring point is ____________ which is ________ ft below / above land surface.

Static water level ______________ ft below measuring point.

BAILING TESTS

Type of bailer ____________ length ________ diameter (ID) ________

capacity

SWABBING TESTS

Method of measurement (barrel, tank, etc.) ____________

Tank dimensions (ft): Width ________ length ________ height ________

Capacity: 1 ft = _____ gal 0.1 ft = _____ gal 0.01 ft = _____ gal

Measuring point ____

____

Depth tubing set __________ Depth swabbing from ________________

Weight of fluid at end of cleanout ________ lbs/gal ________ lbs/cu ft

Time	Bailer or swab trip no.	Water removed (gal)	Depth to water below MP (ft)	t', time since discharge stopped	Remarks (temperature, color, specific conductance, etc. of sample)

Figure 8.--Swabbing-bailing-test form.

When the final swab is pulled upward from the bottom, a stopwatch that has been previously strapped on the "iron horse" is started. The water-level-measuring device is lowered into the hole as soon as the surface connections are broken. A record is made of the time to reach the fluid level and of the depth to the fluid level. Thereafter, recovery measurements are made at standard intervals of time. If swabbing operations are relatively efficient and if there is appreciable drawdown, then a rough estimate of specific capacity and transmissibility of the aquifer or aquifers can be calculated.

If detergent was added to water during drilling of the hole, suds may build up in the drill pipe or in the tubing during the swabbing. Prolonged swabbing will not remove all the suds; therefore, if suds cause erratic action of the millivoltmeter on the measuring device, a liquid antifoaming agent is poured into the pipe.

To prevent serious accidents, personnel stand clear of the sandline when the swab is lowered into the hole.

PUMPING TESTS

The high cost of rig time has been a decisive factor in limiting the time allotted to pumping tests and recovery periods after pumping tests on Pahute Mesa. Generally, surging the hole for development precedes the pumping test. After several hours of alternately surging and awaiting recovery, the well is pumped for no less than 24 hours. During the subsequent recovery period, water levels are measured for at least 12 hours.

Reda or Byron Jackson submersible pumps have been used in all wells that have been pumped on Pahute Mesa. A positive displacement check valve was placed immediately above the pump in all tests. Pumping rates ranged from 50 to 220 gallons per minute.

Equipment

Equipment for a pumping test at the well site includes the submersible pump and the following accessory equipment: electric cable, generators, transformers, and panels; 2-in ID access tubing and 3-in or $2\frac{7}{8}$-in ID tubing for pump column; dual slips and elevators designed for the tubing and pump column; subs or "pup joints" in 2-, 4-, 6-, 8-, and 10-ft lengths; connections for pump and pump column; banding equipment, surface connections, and tubing for discharge line; and Sparling water meter, gate or ball valve to adjust flow, 2,000- or 7,000-gallon tank, weir or Parshall flume, and two empty 55-gallon barrels.

Testing techniques

Testing techniques for a pumping test are as follows:

Two-inch access tubing is banded to the pump unit and column. Caution to be taken during banding was noted under preparations for radioactive-tracer surveys.

The pump is lowered into the hole so that the pump intake is at least 50 to 100 feet below the estimated drawdown level. The driller's tally of the tubing for the pump column is checked by the geologist or hydrologist at the well site. A large margin of safety is given in estimating drawdown levels, and the capacities and limitations of the pump are taken into consideration. Whenever an excess amount of foam or soap suds occurs in the hole, a length of 3-in diameter hose is attached to the end of the discharge line. The catline is hooked midway along the length of the hose and a U-bend is made along the hose by raising the catline several feet. This creates back pressure on the water meter and improves the accuracy of flow-rate readings.

Before the pump test, the well is surged for a 6-hour period. During surging, the well is alternately pumped for 30 minutes and then shut down for 15 minutes to allow recovery or partial recovery. During each pumping period, drawdown is recorded at 0.5-minute intervals for the first 4 minutes, 1-minute intervals for the next 6 minutes, 2-minute intervals for the next 10 minutes, and 5-minute intervals for the next 10 minutes. The same general timing schedule for water-level-recovery measurements is followed.

During surging, the discharge rate is checked and adjusted to the desired rate. Flow-meter readings are checked by timing the flow into a 55-gallon barrel or a large capacity tank. Water temperature is recorded at the beginning and the end of each pumping period. To gain additional control on the discharge rate, a weir or Parshall flume may be set into a trench between the discharge line and the reservoir.

A 24-hour pumping test is started at the completion of surging and after full recovery to the static water level. The same time schedule listed in the paragraph describing surging operations to record drawdown measurements made with the "iron horse" is used. After 40 minutes, measurements are made at 10-minute intervals for the next 60 minutes, at 20-minute intervals for the next 100 minutes, at 50-minute intervals for the next 200 minutes, and at 100-minute intervals for the remainder of the test. Discharge rates are checked at hourly intervals after the rate has stabilized. Temperature readings are made at hourly intervals; and before the test is concluded, water samples are collected for chemical analysis. Specific conductance measurements are usually made at 2-hour intervals. Water samples are collected and treated in the manner specified by the USGS Water Resources Division chemical laboratory.

During detailed measurements with the water-level-measuring device, many problems may be experienced. When readings are made in tenths and hundredths, masking tape strips are used to mark the steel cable of the device after each reading. Accuracy to 0.02 foot can be obtained only when using this and other procedures listed by Garber and Koopman (1968). Also, the tape on the cable is an essential control point when mechanical failure in the device necessitates removing the probe from the hole temporarily for repairs and cleaning. After several hours' use friction or other things may cause the steel cable of the device to adhere to the walls of the access tubing and prohibit lowering of the probe. When this happens, the probe is raised 100 or 200 ft above the depth below which the probe would not descend, and then the probe is lowered into the hole as rapidly as possible. Care must be taken during this procedure to insure that the cable does not slip off the sheave of the water-level-measuring device.

A 12-hour period of recovery is measured after the pumping test. A time schedule similar to that for all measurements during the recovery period is used. Figure 9 is a standard form for recording pumping-test data.

Pumping test form

Sheet____of____

Hole no._________ Test no.__________ Pump setting______________________ft; Geologist/Engineer_______________________

Cased interval_________________ft; Perforated interval_____________; Open hole_____________ Diameter________ in ____

Iron horse no.__________; Cable correction____________ft/ft; Measuring point is_____________________________________

Date 19___	Hour (Military)	Elapsed time (minutes)		Water-level measurement (feet)				Discharge (gpm)	Temp (°F)	Comments
		Pumping (t)	Recovery (t')	D/W Below MP	I.H. Cable correction	D/W Below LSD	Drawdown			

Figure 9.--Pumping-test form.

WATER INJECTION AND SWABBING BETWEEN PACKERS

Water injection and swabbing tests between straddle packers are singularly important for determination of the water-yielding potential of specific intervals in the borehole. Data collected during these tests have been used to evaluate the intervals as excellent, marginal, or unfavorable for construction of underground chambers. In addition, static water levels (formation pressures) of selected intervals are obtained. Injection tests are made in the final stage of the hydraulic testing program.

Equipment

In addition to the standard equipment on the rig, the following equipment must be at the well site.

A quantity of $2\frac{7}{8}$-in or 3-in ID tubing equal to the total depth of the hole. The 3-in tubing is preferable since the probe and cable are less likely to adhere to the walls of the larger diameter tubing.

Slips and elevators to handle the tubing.

Subs or "pup joints" for $2\frac{7}{8}$-in or 3-in ID tubing in lengths of 2, 4, 6, 8, and 10 ft.

Lynes inflatable open-hole straddle packer. On the mesa, 9-in dual-seal elements are the most practical size for use in holes drilled with a $9\frac{7}{8}$-in bit; $7\frac{3}{8}$-in elements must be used in holes drilled with an $8\frac{7}{8}$-in bit. By-pass is more common around upper packer elements; hence, two packers are usually placed in tandem above and a single packer is placed below the spacers. At least one spare packer element is at the well site to replace one that may become damaged or ruptured.

Spacer tubing, 200 ft.

Three pressure gauges whose ranges are compatible with the depths to be tested.

Water tank, 500-barrel capacity.

Testing techniques

The techniques used in water injection testing are as follows:

The length of spacing used between packers is governed principally by hole conditions and lithology. The most effective and practical spacing is decided after a thorough study of geophysical logs and other available data. In an ideal situation, intervals with similar rock lithologies would be isolated by the packers and tested progressively downhole without having to come out of the hole to change the length of the spacers. In actual practice, this rarely occurs; for even if the lithologies were uniformly distributed, the hole may be washed out and too large for packer seats in many critical areas. Hence, the spacing that most closely approaches the ideal situation is selected. Although the length of spacing may need to be changed occasionally, this procedure is too time consuming and costly to become common practice. In planning the packer setting, the dimensions of the various units of the straddle packer assembly are considered. The upper packers and connections are 10 ft in length; the lower packer is 4 ft in length. Spaces between packers--the interval into which water will be injected--generally range from 38 to 198 ft.

Standard oilfield pressure gauges, equipped with clocks and pressure ranges compatible with the length of testing time and the depths to be tested, are installed above the upper packers and below the lower packer. The pressure charts yield information on leakage around the packers. Any leakage around the packers would, of course, give apparent higher yield results than the actual yield.

A careful tally of each joint of tubing is made before connecting and going downhole. A small error often will place one of the packers into a washed-out section of hole, and, during inflation, the packer may be ruptured. A "rabbit" (plug) is run through each joint of tubing to check for any obstructions. Little or no pipe dope is used on the threads of the pipe when adding joints to avoid plugging the probe of the water-level-measuring device.

After the packers have been lowered to the depth desired, the tubing on the surface should not project more than 34 in above the rotary table; hence, the necessity for the subs or "pup joints." If the tubing projects in excess of 34 in above the rotary table, the water-level-measuring device (iron horse) is set on wooden blocks so that the probe can be lowered into the tubing.

The Lynes inflatable packer element is made of a heavy outer layer of rubber backed with a braided metal sheath. A rubber inner tube backs up the metal sheath and retains the inflating fluids. A mandrel extends through the sealing element. Water is pumped through a standard rig-type hose into the tubing at the surface, enters the space between the inner tube and the outer diameter of the mandrel, and is trapped. The element expands and seals against the borehole. The tubing filled with water to the surface shows that the elements are sealed against the borehole and that no leaks exist in the tubing string. Since the entire length of tubing is dry on the first trip, despite the fact that the first setting may be several hundreds of feet below the static water level, the length of time needed to load the tubing is considerably greater than it is on subsequent packer settings.

Testing is started after the tubing has been filled with water and most of the entrapped air has been released by bubbles rising to the surface. The water-level-measuring device is checked and ready to be moved into position on the rotary table over the tubing; the drilling crew is alerted to duties concerning removal and replacement of slips and breaking and removing the elevator from the tubing. Slight pulling and rotation of the tubing raises the mandrel of the straddle packer into the open-between position (fig. 10). With the ports between the packers open to the formation, the water, under hydrostatic pressure, enters the formation. A sound audible at the surface accompanies the opening of the ports, and the water in the tubing drops at a rate determined by the permeability of the formation being tested. A stopwatch previously strapped to the "iron horse" is started the instant the ports are opened, or as soon as the sound is heard at the surface. As rapidly as possible, tension on the pipe is released, the slips are reset, and the elevator is removed from the tubing and raised up the mast. The "iron horse" is placed over the hole, zeroed at the top of the tubing, and the water-level depths are measured with the probe. Readings are recorded at 0.5-minute intervals for 4 minutes, 1-minute intervals for the next 6 minutes, 2-minute intervals for the next 10 minutes, and 5-minute intervals for the next 20 minutes. If the interval being tested is relatively impermeable and it is necessary to continue measurements for an hour or more, the time schedule for water-level measurements is similar to that used during pumping tests. Figure 11 is the standard form for documenting water injection test data. The water in the tubing may drop 2,000 ft from the surface in a matter of minutes during testing of a highly permeable zone on the mesa. In an impermeable zone, the water level may drop only several hundreds of feet below the surface after more than 30 minutes. In the latter case, many hours or even days would be required to attain a static level; hence, the water-level measurements may be abandoned after a trend has been established and usually no longer than 1 hour.

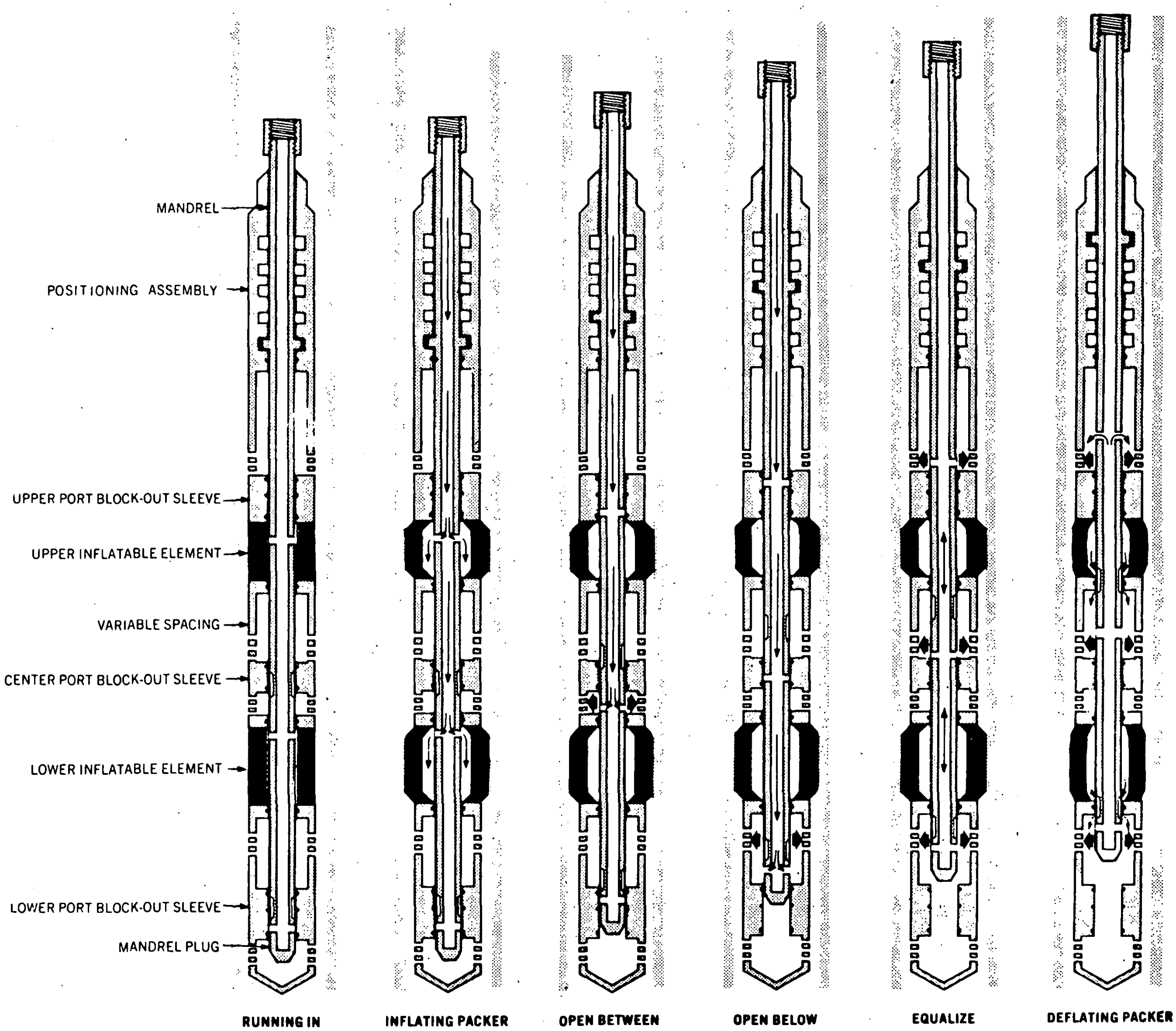


Figure 10.--Inflatable straddle packer used in open hole or casing. (Courtesy of Lynes, Inc., Houston, Texas.)

Injection-test form

Test hole_______________ Test no._______________ Date_______________

Geologist/Engineer_______________ Contractor representative___________

Hole depth_________ft Diameter____________in Cased interval___________

Tested interval__________________________

Packer type_______________ Diameter___________in Spacing____________

Ports opened between___________Below__________Above_______________

Water levels measured with I.H. no._____ I.H. Correction____________ft/ft

Rotary table____________________ft above land surface

Measuring point___________which is__________ft above rotary table

Static water level__________________________ft below measuring point

Remarks:

Military clock time	Time since ports opened (t) (min)	Depth to water below M.P. (ft)	Remarks

Figure 11.--Injection-test form.

Plotting water-level measurement data on 2- or 3-cycle logarithmic paper often will indicate that the packers had been well seated or that leakage occurred around the packers. If there is any question of leakage, the packers are reseated a few feet in either direction, and the test is rerun. Definite evidence of leakage can be obtained from charts recorded in the pressure gauges, but only after the tools have been removed from the hole. Hence, rerunning questionable tests before moving on to the next setting saves much time. A sudden change in the rate of drop of a water level from only a few tens of feet per minute for 10 to 20 minutes to several hundreds of feet per minute indicates bypass around the packer or packer failure.

After a test has been concluded and the water-level-measuring device has been removed and placed beyond the rotary table, the mandrel of the straddle packer is moved to the equalize position. When static conditions have been renewed in the borehole, additional joints are added to the string and the packer is moved to the next setting. The tool can be moved and reset many times without coming out of the hole. Occasionally, however, too much weight may be applied in pulling the tubing from one position to another, and the tool may be positioned into the "come-out" position. If that happens, the tool must be lifted out of the hole and adjusted.

A bridge or poor-hole conditions may prevent testing the lower part of a hole between straddle packers. In these circumstances, the tool is opened below the lower packer and an injection test is made of the entire interval.

Computations

From the rate of change of water levels in time, a yield rate of the various sections tested is computed. The yield of the tested interval is stated as relative specific capacity in units of gallons per minute per foot of drawdown. The computation of specific capacity is as follows:

$$\text{Relative specific capacity} = \frac{Q}{(h - h_i)}$$

where: Q = gallons of water accepted by interval isolated with straddle packers during 1-minute time interval. At the mesa the time interval 3-4 minutes after the tool is opened is commonly used.

h = static water level of the hole--or interval tested--in feet below land surface.

h_i = average water level in the tubing in feet below land surface in 1-minute interval used for determining Q. At the mesa the water level at 3.5 minutes is used.

The figures for relative specific capacity determined by the preceding method are reasonably accurate for relatively impermeable zones; they are too low in highly permeable zones.

The most consistently low water-yielding rock types at the mesa are zeolitized ash-fall and ash-flow tuffs. Relative specific capacity values for 198-ft intervals tested in the zeolitized tuff range from <0.001 to 0.10 gpm per foot of drawdown and average <0.02. A larger spread in values of relative specific capacity occurs in intervals where welded tuff and rhyolite are predominant. Relative specific capacity values for welded tuff range from <0.001 to 0.78 gpm per foot of drawdown and average <0.20; relative specific capacity values for rhyolite and vitrophyre range from <0.001 to 0.50 gpm per foot of drawdown and average <0.20.

W. E. Hale (written communication, 1964) has prepared a method and graph for estimating the yield of water to openings of a particular size in saturated rock. The method is based upon relative-specific-capacity values in a drill hole. Water-yield tests of sections at the mesa usually are made in about 200-ft intervals, and the results are reported as yield in gallons per minute per foot of drawdown for the interval. This unit must be converted to a permeability unit in order to compute the anticipated yield from various openings in the saturated rock. For a 200-ft interval, the conversion factor is 10. That is, a relative specific capacity of 0.1 gpm per foot of drawdown in a 200-ft section indicates a rock with a permeability of roughly 1 gpd per sq ft (gallons per day per square foot). The anticipated influx of water into a chamber is dependent upon the dimensions of the room, the depth below water table, and the permeability of the rock. Because of construction difficulties and safety hazards presented by water influx, the most desirable rock type within which chambers may be constructed is zeolitized tuff. Within this rock type intervals with relative-specific-capacity values of 0.001 to 0.02 gpm per ft are considered most favorable. For all computations, the rock type to be excavated is assumed to have transmissibility equal in value to that of the same section penetrated by and tested in the drill hole.

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