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of the United States Geological Survey

Chapter A1

METHODS OF MEASURING WATER LEVELS IN DEEP WELLS

By M. S. Garber and F. C. Koopman

Prepared on behalf of the
U.S. Atomic Energy Commission

A discussion of the techniques developed at
Nevada Test Site and other locations

Book 8

INSTRUMENTATION

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called "Books" and further subdivided into sections and chapters. Section A of Book 8 is on instruments for measurement of water level.

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. "Methods of measuring water levels in deep wells" is the first chapter to be published under Section A of Book 8.

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METHODS OF MEASURING WATER LEVELS IN DEEP WELLS

By M. S. Garber and F. C. Koopman

Abstract

Accurate measurement of water levels deeper than 1,000 feet in wells requires specialized equipment. Corrections for stretch and thermal expansion of measuring tapes must be considered, and other measuring devices must be calibrated periodically. Borehole deviation corrections also must be made.

Devices for recording fluctuation of fluid level usually require mechanical modification for use at these depths. A multichannel recording device utilizing pressure transducers has been constructed. This device was originally designed to record aquifer response to nearby underground nuclear explosions but can also be used for recording data from multiwell pumping tests.

Bottom-hole recording devices designed for oil-field use have been utilized in a limited manner. These devices were generally found to lack the precision required in ground-water investigations at the Nevada Test Site but may be applicable in other areas. A newly developed bottom-hole recording pressure gauge of improved accuracy has been used with satisfactory results.

Introduction

As the demand for water increases, particularly in the arid Southwest, deeper wells will be required so that previously untapped aquifers can be utilized. To evaluate the hydraulic characteristics of these deep aquifers and to accurately record the correspondingly deep water levels in the aquifers, new techniques and new equipment will be needed. Much of the now standard equipment of the ground-water hydrologist either will be completely obsolete or will require modification.

Since 1958 the U.S. Geological Survey, in cooperation with the U.S. Atomic Energy Commission, has been studying the hydrology of the Nevada Test Site. The problem as originally defined was to determine the hydrologic regimen as a basis for ground-water safety evaluations. Exploratory holes have been drilled to depths greater than 10,000 feet in media whose hydrologic properties differ greatly. The procedures described in this report are primarily based on the hydrologic testing program at the Nevada Test Site.

The Survey ground-water program has now expanded in two principal areas of investigation: evaluation of hydrologic conditions in new testing areas and media, with special attention to problems of chamber construction relative to ground water, and detailed studies of hydraulic aquifer response to underground nuclear detonations.

One aspect of the overall problem, that of obtaining accurate and meaningful measurements of borehole fluid levels at great depth, has been explored by the Geological Survey staff at the Nevada Test Site and in the New Mexico district. This report discusses some of the techniques and instrumentation developed.

Purpose and scope

Water levels in aquifers at the Nevada Test Site range in depth from a few hundred to over 2,000 feet, but most are deeper than 1,000 feet. The hydraulic gradients in some of these aquifers are as low as 0.5 foot per mile. The determination of such low gradients requires an accuracy of water-level measurement not ordinarily attainable at these depths; therefore, special equipment and techniques must be used. Great precision is also required in measuring small diurnal changes in water level and small changes in water level during pumping tests. Measurement of water-level changes to the nearest 0.1 foot at depths greater than 1,000 feet is required in many water-resources investigations. This 0.1 foot tolerance at 1,000 feet below land surface represents 0.01 percent of the total measured depth.

In areas such as the Nevada Test Site where depth to water is great and hydraulic gradient is low, corrections for hole crookedness must be made for accurate point-to-point comparisons. Data from numerous borehole directional surveys at the test site indicate a difference of 0.5–7 feet between true and measured depth to water level. Discussion of this factor is beyond the scope of this report, and methods of measuring borehole deviation have been adequately discussed in the drilling-technology literature.

This report discusses available methods of water-level measurement, advantages and disadvantages of each method, and the development of new water-level measuring and recording equipment. Because of the unusual field problems encountered, the Geological Survey's electric-cable device is discussed in detail. A similar discussion appears in this report for the air-line method of measuring water levels.

Previous work

Various water-level measuring techniques have been in use for many years. Several of the methods discussed in this report are not new but are merely modifications of standard procedures.

The steel-tape method was described by Wenzel (1936, p. 31; 1942, p. 115) and more recently by Kazmann (1965, p. 145). Methods of correcting steel-tape measurements for stretch and temperature also are not new and can be found in surveying handbooks. Because no reference of such corrections being applied to deep-water-level measurements could be found, the procedure is described in some detail in this report.

The use of an electrical measuring line for water-depth measurements is a well-established technique. Several devices utilizing this principle are available commercially. Additionally, the water level is routinely detected by most of the sondes utilized in borehole geophysical logging. Brief general descriptions of the technique are given in Kazmann (1965, p. 146) and Anderson (1964, p. 150).

The air-line method is routinely used in industry, and descriptions of this method are also given in Kazmann (1965) and Anderson (1964).

Several electromechanical water-sensing devices and pressure-sensing transducers were described by Shuter and Johnson (1961). A multiwell transducer system was utilized in studies at the National Reactor Testing Station in Idaho (Keys, 1961, p. 117). Mechanical recording devices are discussed in Stevens (no date).

Methods of Water-Level Measurement Studied

The graduated steel tape, air line, and electric sounding cable are the three principal measuring devices used at the Nevada Test Site. Also, a variety of remote recording devices have been used with varying degrees of success. The methods employing each of these measuring devices are examined in the discussion that follows.

Steel tape

Surveyor's tape has been used for many years by the Geological Survey as the principal water-level measuring device. It is available in lengths up to 1,000 feet. Because most of the water levels at the Nevada Test Site are deeper than 1,000 feet, a specially made 2,000-foot tape was obtained for the project (fig. 1). Coefficients of stretch and temperature expansion for this tape were provided by the manufacturer.

The tape reel is motor driven and has means for both mechanical and electrical braking. The wellhead mechanism is equipped with a spring balance that enables the operator to maintain tape tension within desired limits and, thus, to prevent damage or loss

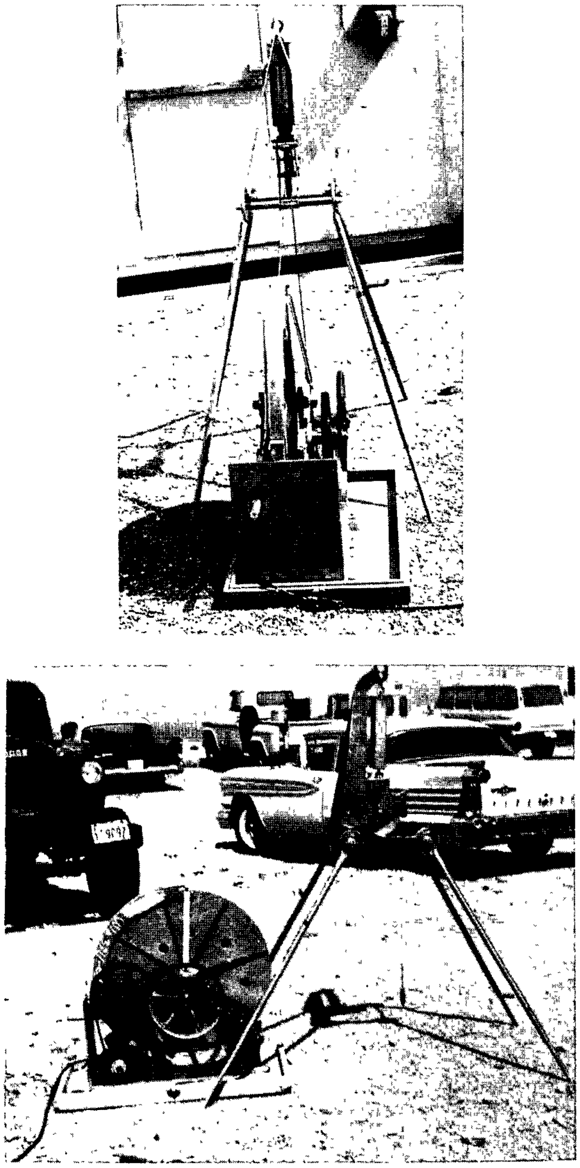


Figure 1.—2,000-foot steel measuring tape.

of the tape. The total weight of the tape is 16 pounds, and maximum tension is never allowed to exceed 35 pounds. The tape is always spooled directly from the reel into the well and back onto the reel and never allowed to accumulate on the ground. In this way, kinking and wear are minimized.

The water level in a well is measured by suspending a known length of tape below a datum mark so that the lower few feet of tape are below water level. The lower portion of tape is usually coated with blue chalk or some other substance that exhibits a marked color change when wetted. In deep holes, wetted chalk tends to dry out as the tape is removed from the hole, and the result is an erroneous reading or none at all. To prevent this condition, the chalked tape can be protected by a perforated tygon tube, or a paste that exhibits a permanent color change on contact with water can be used in place of chalk. The water-level measurement is obtained by subtracting the length of the wetted portion from the total length suspended below the datum mark.

The errors in this method were not evaluated by comparison with errors in other methods because no more accurate field method was available at the Nevada Test Site. Certain instrument-error corrections may be employed, however, such as those for effects of thermal expansion and of stretch produced by the suspended weight of the tape and the plumbing weight. Though these errors are small and may be neglected in many well measurements, they become significant at high temperatures and for measured depths in excess of 1,000 feet.

If the tape is free of kinks, has not been permanently stretched (calibration not disturbed), and is hanging as freely as possible in the well, the principal instrument errors result from thermal expansion and stretch. Small random errors may be caused by slight differences in the tape's position in the well, twists in the tape each time the tape is suspended into the well, capillarity at the fluid contact mark, and slight differences in the operator's technique. Several successive measurements will rarely differ by more than 0.1 foot even at depths of over 1,700 feet. This gives repeatability of more than 1 part in 17,000, or about 0.006 percent.

The largest error results from thermal expansion of the tape. The temperature coefficient of linear expansion is 63×10^{-7} foot per foot per degree Fahrenheit where expansion is zero at 70°F. As shown in table 1, the effect of thermal expansion on a 2,000-foot tape is significant.

Table 1.—Effect of thermal expansion on a 2,000-foot steel tape

Temperature (°F)	Change in length (ft)
50	−0.26
60	− .13
70	0
80	+ .13
90	+ .26
100	+ .39
110	+ .52
120	+ .65
130	+ .78
140	+ .91

The coefficient of stretch supplied by the manufacturer is 1.75×10^{-5} foot per foot per pound of applied tension. Stretch results from the tension applied to the tape by its own suspended weight and from the plumbing weight. The formula for the stretch correction follows (R. W. Stallman, written commun., 1963):

$$C_s = \frac{L^2WS}{2} + PLS$$

where

C_s = stretch correction, in feet,
L = length of suspended tape, in feet (corrected for thermal effects),
W = weight of tape per foot = 0.008 lb,
S = coefficient of stretch = 1.75×10^{-5} ft per ft per lb, and
P = weight of plumb bob in pounds (usually 0.25–0.50 lb).

The following example shows the manner in which these corrections may be applied and also provides some indication of the order of magnitude of these corrections. A nomograph for calculating thermal expansion of the steel tape is presented in figure 2.

Example

Measured depth = 1,751.23 ft (average of 3 readings)
Temperature = 85°F at surface; 104°F downhole; and 94.5°F average
Temperature coefficient = 63×10^{-7} ft per ft per °F
Depth corrected for thermal expansion = measured depth − [measured depth × (average temperature − 70°F) × temperature coefficient]
= $1{,}751.23 - [1{,}751.23\ (94.5 - 70)\ (63 \times 10^{-7})]$
= 1,751.23 − 0.2704
= 1,750.96 ft

C_s = stretch correction
L = 1,750.96 ft
W = 0.008 lb
S = 1.75×10^{-5} ft per ft per lb
P = 0.50 lb

$$C_s = \frac{L^2WS}{2} + PLS$$

$$= \frac{(1{,}750.96)^2 \times 0.008 \times 1.75 \times 10^{-5}}{2} + (0.50 \times 1{,}750.96 \times 1.75 \times 10^{-5})$$

= 0.215 ft + 0.015 ft

Stretch correction = 0.23 ft
Corrected depth = depth corrected for thermal expansion − stretch correction
= 1,750.96 ft − 0.23 ft
= 1,750.73 ft (this is 0.50 ft less than the uncorrected value.)

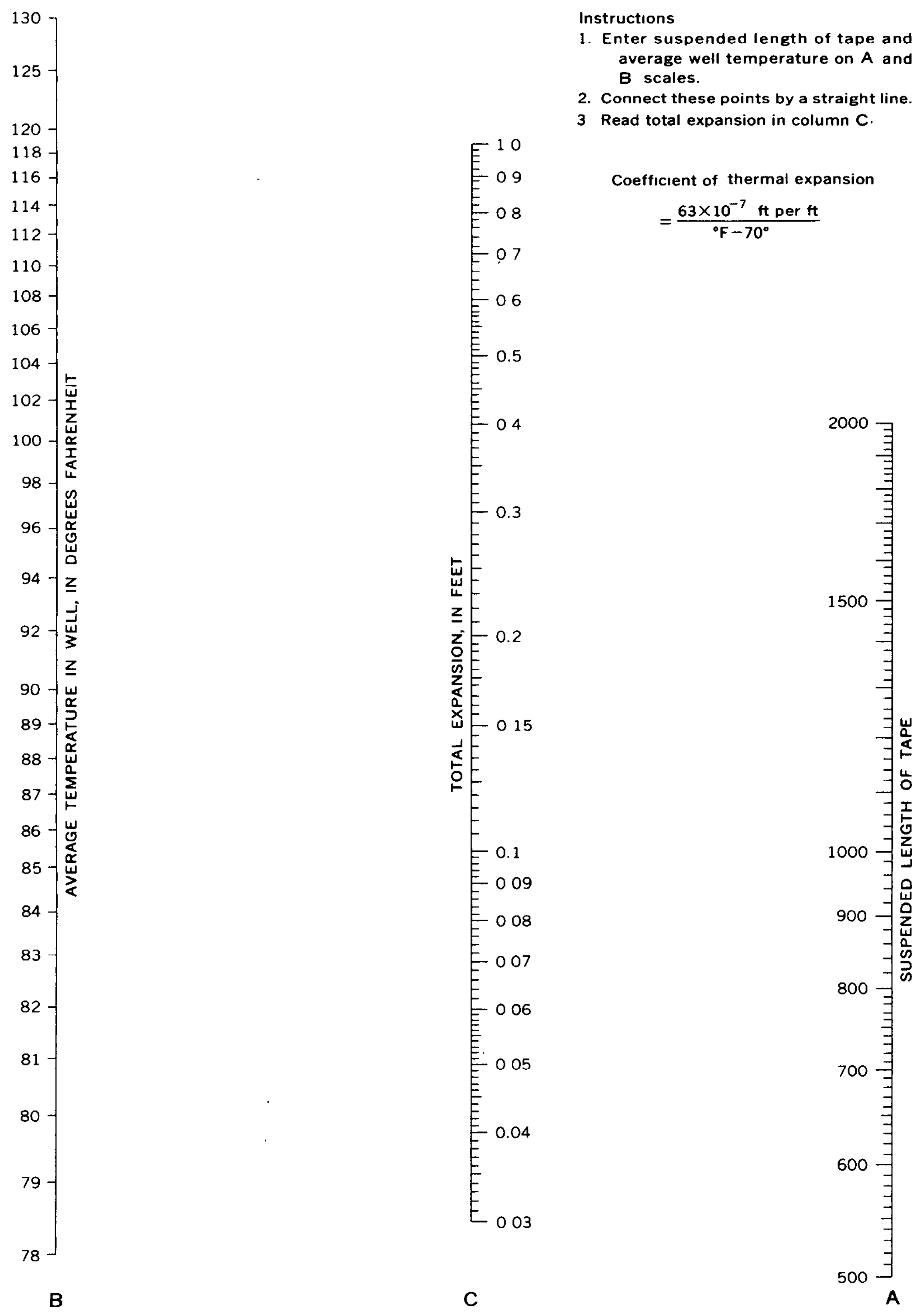


Figure 2.—Nomograph for determining thermal expansion of steel surveying tape.

Because of its accuracy and because no more accurate field method could be found, the steel tape is used as a standard of comparison for calibrating other measuring devices at the test site. In its use as a secondary standard, the steel tape is not routinely corrected for temperature and weight because the calibration is normally performed in a test well specifically set aside for calibration purposes; the temperature in this well varies little below 100 feet, and the same weight is used on the tape during each calibration run. The tape is seldom used as a routine measuring tool in the field because it is a delicate device requiring considerable time and care in its use. The tape reel and wellhead device shown in figure 1 were designed by A. C. Doyle (U.S. Geol. Survey, Mercury, Nev.).

Electric cable

The equipment used in this method was originally constructed in the Geological Survey equipment-development laboratory at Columbus, Ohio. The device is versatile and performs several functions: water-level measuring, well sounding, fluid sampling, and vertical fluid-velocity measuring. The cable, winch, and depth indicator (fig. 3) are combined in a single unit. The motor assembly slides in place at the rear of the unit and is secured by a single bolt on the underside. The depth indicator, depth-measuring wheel, and water-level indicator are mounted on the end of the boom at the front of the device. For storage, this boom may be removed and the top plate containing the winch may be removed and inverted so that the cable reel is inside the unit. Wing nuts are used throughout.

A single-conductor armored cable having a diameter of 0.087 inch is used. The armored shield serves as a ground conductor. The measuring wheel has an effective circumference of 1.500 feet and is connected to the depth indicator by gears. When measuring passage of cable over a wheel, where the cable is in contact with the wheel for more than a few degrees of arc, the effective radius must be measured from the center of the

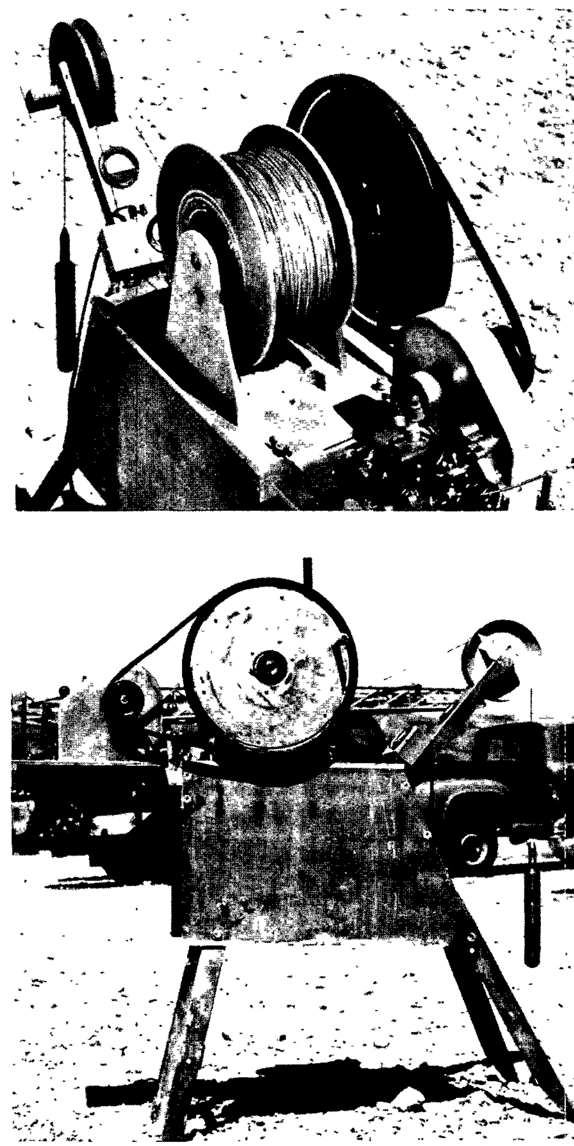


Figure 3.—Electric cable well-measuring device.

cable to the center of the wheel. If the cable is straight and is in tangential contact with the wheel, then only the wheel radius need be considered in calculating the measuring-wheel circumference. The smallest graduation on the counter is 0.2 foot, and interpolation can be made to less than 0.1 foot. Minute changes in water level can be detected by measuring between scribed marks on the circumference of the measuring wheel. In this manner, water-level changes as small as 0.01 foot can be observed. Water level can be detected electrically by one of five methods: self-potential, fluid conductivity, capacitance, inductance, or a float-actuated magnetic reed switch.

The self-potential water-level probe consists of a threaded magnesium element screwed into an insulated sleeve in a brass shell (fig. 4*A*). The magnesium element is connected to the central wire of the cable, and the brass shell acts as the ground. When the probe enters water, a potential is developed between the dissimilar metals; the borehole fluid acts as an electrolyte. This potential causes a deflection on the water-level indicating meter. Probes of two sizes, 0.75 inch and 1.50 inch in diameter, are in common use; the smaller is either plastic or brass, and the larger is brass. Both have provisions for applying various plumbing weights. The large probes have 4-pound and 10-pound weights.

The fluid-conductivity probe (fig. 4*B*) is only slightly different from the self-potential probe. The magnesium element is replaced by a brass screw, and a small potential is applied at the surface. The conductivity of the fluid permits a current to flow in the circuit.

The capacitance probe consists of a transistorized oscillator sealed with a 0.75-inch-diameter metal barrel with a teflon-coated electrode centered within the lower portion of the probe. A small electric current from the surface meter and the battery circuit causes the oscillator to resonate when the electrode is submerged. The effect of submergence is noted on the meter by a change in the power requirements of the oscillator.

The inductance probe (fig. 4*D*) consists of a coil of fine wire positioned against a thin stainless metal diaphragm within a sealed compartment of a 0.75-inch diameter metal barrel. Upon contact of the diaphragm with fluid, the inductance of the coil is changed, and this effect is registered by a meter or lights at the surface. More than two conductors are needed to operate the inductance probe.

The float-actuated probe was developed at the Nevada Test Site when the need arose for an electric water-level probe having no electrical contact with the borehole fluids. Its major application is in test holes drilled by the air-rotary method, where detergent foam accumulating on top of the water makes measurements with standard electric probes erratic, if at all possible. The probe consists of a float-actuated magnetic reed switch (fig. 4*E*) enclosed in a protective shell. The density of the surrounding float is adjusted so that the float will not be buoyed up by the foam but will float in water. Similar to the conductivity probe (fig. 4*B*), this probe also requires a small operating potential.

The uphole indicating device consists simply of a sensitive direct-current voltmeter for the self-potential probe; the conductivity and magnetic reed-switch probes require that either a battery be added to the circuit or an ohmmeter be used. The inductance and capacitance probes (fig. 4*C*, *D*) developed in the New Mexico district require specialized uphole equipment.

The operation of the electric-cable device is easily understood, but a few simple standardized procedures must be followed in order to minimize gross errors. After the device has been set up over the well and the fluid-contact point of the probe has been set at datum, the cable is lifted slightly to reduce tension on the wheel, enabling the operator to zero the counter by turning the wheel. The cable is then released and the settings are checked. The probe is slowly lowered into the well manually. Care must be taken to prevent slippage of the cable over the measuring wheel. Because of surface tension, readings of the water level made when the probe enters water will differ from readings made when the probe leaves water (breaks surface tension). To standardize procedure and to minimize backlash in the counter, as well as to maintain cable tension, the second reading is always used.

To minimize error in water-level measurement in a given well, three independent measurements should be made and averaged. The datum point should be rechecked after each water-level measurement. After the probe

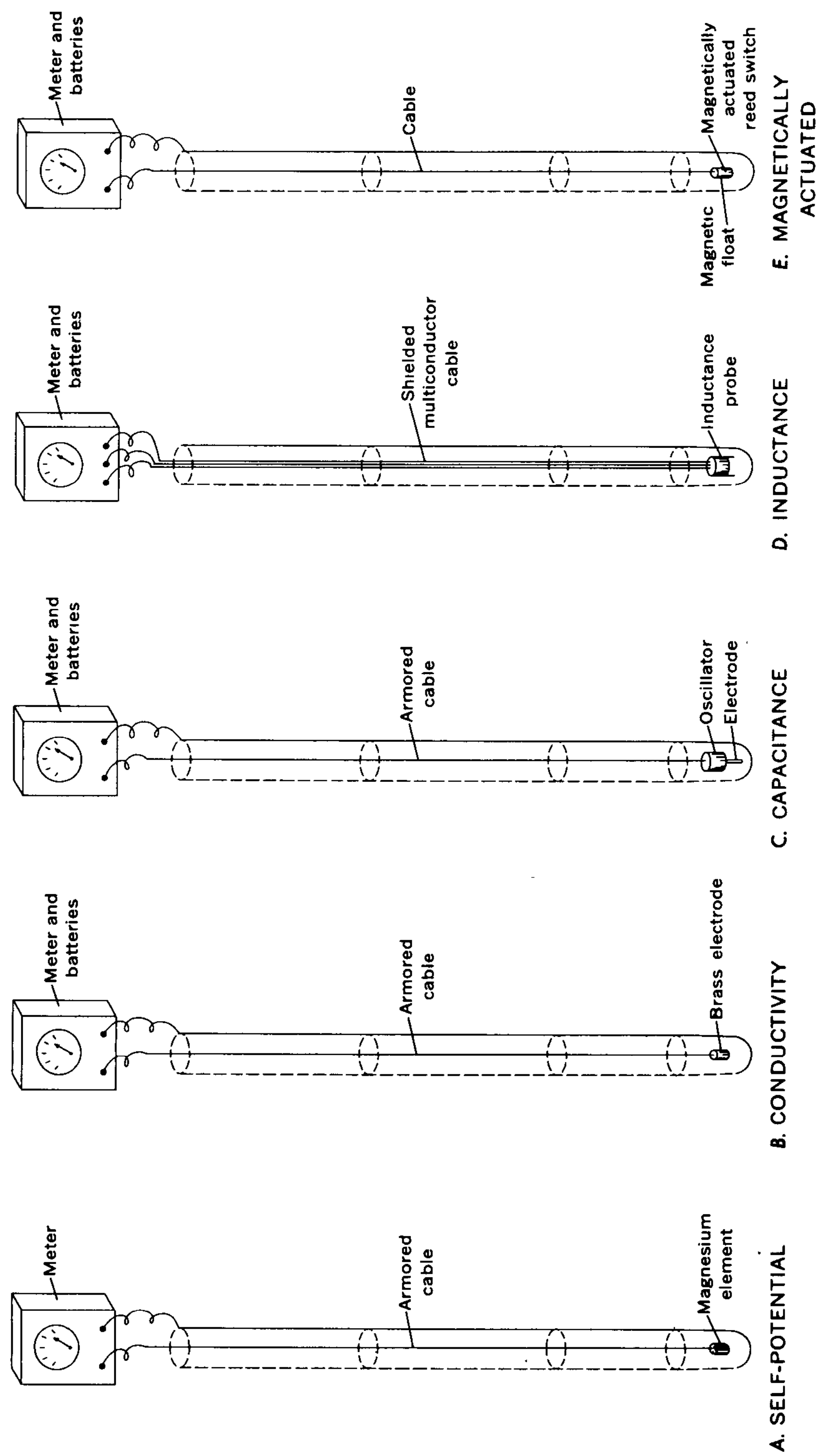


Figure 4.—Water-level sensing probes used with electric-cable device.

has been returned to the surface, the datum point should be rechecked by holding the fluid-contact point of the probe level with the measuring point and reading the depth indicator. This "out reading" probably will not be zero but some small negative value resulting from the elasticity of the cable and from the increased tension caused by drag along the casing as the cable was withdrawn. Because of excess drag and possible slippage resulting from a loosely spooled cable, the first of a group of measurements is sometimes omitted. Largely divergent readings indicate either excessive cable stretch or slippage.

Inaccuracies in measurements made by the electric-cable method result principally from wear of the aluminum-alloy measuring wheel's cable-contact surface and, to a lesser extent, from small reductions in cable diameter (Young, 1963). There are several other possible causes of error; these will be treated in detail in the following discussion.

Gross errors resulting from slippage over the measuring wheel may occur, but, as previously shown, these are easily detected by comparison of readings of several successive measurements. An idler wheel placed over the cable on the measuring wheel would minimize slippage. Instrumental errors result from stretch in the cable, changes in cable diameter, thermal expansion, and wear of the measuring wheel.

Two types of stretch must be considered: the initial stretch or fatigue of a new cable, and stretch resulting from elasticity. The initial stretch is usually dissipated after a short period of use. Elastic stretch is controlled by maintaining tension in the cable at all times during measurement. Because the cable is measured into thé hole under tension and, therefore, in the stretched condition, errors in the measured length resulting from this factor should be small. However, additional stretch resulting from the use of unusually heavy probes has been noted (I. J. Winograd, oral commun., 1963). Any stretch that occurs in the cable after it passes the measuring wheel cannot be measured. Similarly, any increase in cable length occurring in the well as a result of thermal expansion cannot be evaluated. The net result of such changes would be an apparently high water level. Fortunately, these errors are small when compared with the error caused by wear of the measuring wheel, and all errors are combined in the calibration process.

Random errors resulting from slight differences in operational technique are minimized by standardization of procedure. They rarely exceed ±0.5 foot for any one set of measurements.

The procedure followed for calibration consists of comparing averages of three or more steel-tape and cable measurements made in the same well and within a short time. The difference between the two averages is divided by the average of the steel-tape measurements. The result is the correction per foot, which is positive if it is to be added to the cable measurement and negative if it is to be subtracted.

$$\frac{L_t - L_c}{L_t} = \text{correction foot per foot}$$

L_t = average tape measurement
L_c = average cable measurement

Example

$$L_t = 1{,}051.6 \text{ ft}$$
$$L_c = 1{,}055.1 \text{ ft}$$
$$\text{correction} = \frac{1{,}051.6 - 1{,}055.1}{1{,}051.6}$$
$$= 0.0033 \text{ ft per ft}$$
$$\text{applying correction to cable measurement} = 1{,}055.1 \text{ ft} \times -0.0033 \text{ ft} = -3.5 \text{ ft}$$
$$\text{corrected cable} = 1{,}055.1 - 3.5 = 1{,}051.6 \text{ ft}$$

Calibration records of three cables are presented graphically with respect to time in figure 5. The change in error with time is principally the product of progressive wear of the measuring wheel. This is illustrated in figure 5 where, in one instrument, replacement of the measuring wheel reduced the error by a factor of about 2. The measuring wheel shown on the unit in figure 3 has a

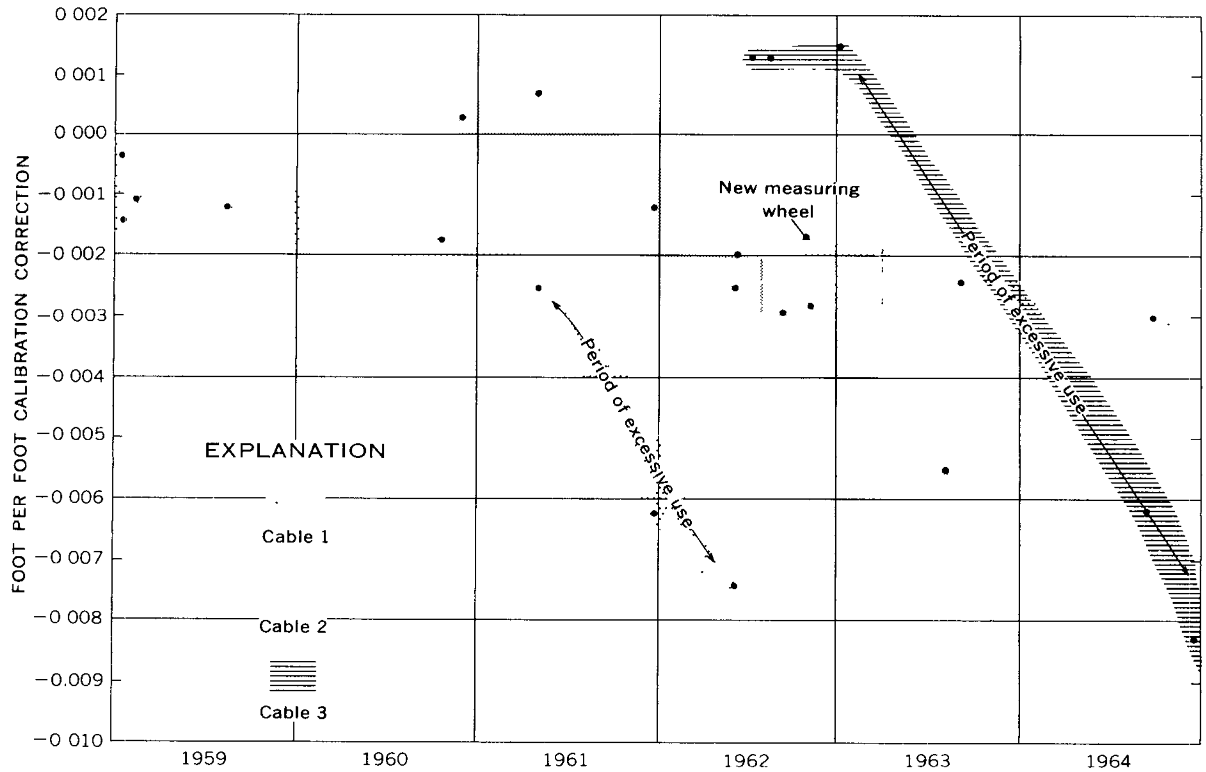


Figure 5.—Calibration curves for three cable devices. Points represent calibration runs.

broad V-notched slot with a rounded base to accommodate the cable and to allow for some lateral motion of the cable as it is spooled onto the storage drum. The cable wrap, over the measuring wheel, is about 120°. To maintain positive contact with the cable, the measuring wheel is made of soft aluminum alloy. Unfortunately, the lateral cable motion resulting from the spooling action of the cable causes wear on the sides of the V-notch, broadening and deepening the base and sometimes producing a double groove in the measuring wheel.

An adjustable measuring wheel is in use in the New Mexico Water Resources Division office. This wheel consists of a tygon plastic core sandwiched between two side panels. By adjusting the tension on the tygon core, slight changes in radius resulting from wear can be eliminated.

Small errors due to a reduction in cable diameter also contribute to the overall error. Slight changes in error with depth were noted. These changes might be due to nonlinearity in cable stretch or to slight changes in cable diameter under increased tension. The change in error with depth has thus far been found to be small and is treated by interpolation. The scatter of points in any one calibration period (fig. 5) results from calibration at different depths.

The previous discussion shows that the error per foot is extremely small and that other errors, such as those introduced by the operator, are applied to the entire measured length. If the cable is not withdrawn from the well, measurements of small short-period relative changes in water level are therefore affected only by the calibration error. Measurements of relative changes in water level can be made to within ± 0.01 foot, and graduations equivalent to 0.01 foot of cable travel have been scribed on the circumference of the measuring wheel for this purpose.

The measuring wheel is precision machined for utmost accuracy, and its measuring surface as well as the cable passing over it must be kept clean at all times or highly erroneous readings will result.

The repeatability of measurement with these devices is less than ± 0.5 foot for one instrument, and corrected measurements made with two different devices will differ by no more than 1.0 foot, or ± 0.05 percent in the 2,000 ft depth range. Individual measurements of water level made with the cable device are reported to the nearest one-tenth of a foot. However, measurements of water-level change, where the device is left inhole for any period, are reported to the nearest one-hundredth of a foot.

Air line

The air-line method is widely used by well drillers and water-system operators as a simple and quick means of obtaining water-level measurements. Although it is not as precise as the previously discussed methods, its speed and simplicity and almost maintenance-free operation make it a very practical method in certain applications. It is especially applicable for use in pumped wells, where water turbulence may preclude the use of more precise devices.

A small diameter copper or iron tube is installed in the annular space between the pump column and the casing. This tube is usually strapped to the pump column, and the two are usually installed simultaneously. The only requirements are that the air-line tube be free of leaks, be open at the bottom, and extend several feet below the lowest pumping water level. The air line should preferably be straight and plumb and the depth of the lower opening must be known if absolute depths to water are sought. The top of the air-line tube is connected to a source of compressed gas. An air-pressure gage of the bourdon type, or a manometer, may be used to measure the pressure in the air line. Gages reading directly in feet of water are available and are easiest to use with this method, but readings of pressure may be multiplied by 2.31 for conversion from pounds per square inch to feet of water.

Because large volumes of air are required for measurement of water levels by this method at the Nevada Test Site, motor-driven air compressors are used. For gage protection, a valve is placed just below the gage (fig. 6*A*) and is opened after the initial surge of air has subsided. Pressure is increased until all the water has been expelled from the air line. The pressure will then stabilize as the imposed pressure gradient in the air line is dissipated, and the gage can be read. The gage reading indicates the length of the expelled water column (the height of water above the air-line opening). To obtain the water level, the length of this column is subtracted from the length of the air line.

When a series of air-line measurements is being made—for example, during a pumping test—it is only necessary to record gage pressures in the field. For pump-test analysis, these data can be plotted directly and can be used in much the same manner as actual readings in feet of water.

If the depth of the air-line opening is not known, or if a change in its position is suspected to have occurred, the following calculation suggested by S. W. Lohman (written commun., 1953) may be used (fig. 6*B*). It can be employed only if the water level can be measured by an auxiliary method (not through the air line). The sum of the depth to water (D_w) and length of expelled water column (L_c) is equal to the total effective length of the air line (L_e). This calculation eliminates errors resulting from inaccuracies in measuring the length of the air line as well as some gage errors.

The accuracy of the air-line method depends upon several factors. If the effective air-line length is known, the remaining errors are caused by inaccuracies in the gage. Errors due to thermal expansion and hysteresis are small. Errors resulting from hysteresis can be eliminated by reading the gage just after it reaches maximum deflection. Starting friction and nonlinearity may be large but can be minimized through proper calibration. Random errors, such as backlash, and errors in interpolation and parallax reduce the precision of the method. The method basically

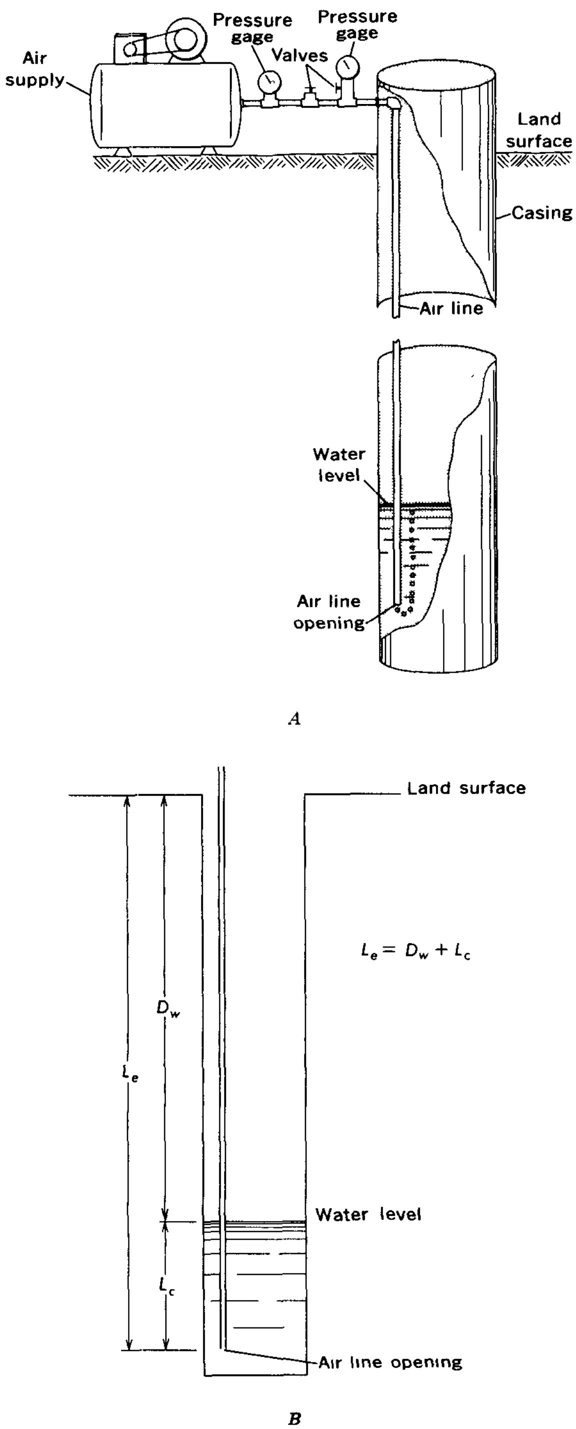


Figure 6.—Air-line method. *A*, measuring water level by the air-line method. *B*, calculation for determining effective length of air line.

lacks precision because true air-line depth cannot always be determined, and because most gages available are graduated to within only 0.25 psi (pounds per square inch) (0.58 ft of water). Even with gages having graduations as small as 0.1 psi, the maximum possible resolution (0.23 ft) would be only half that of the steel tape. Table 2 compares some typical water-level measurements made by air line with measurements made by steel tape or electric cable. A large systematic error is apparent in some of these measurements and is probably due, at least in part, to starting friction.

In the air-line method, as in all pressure-dependent methods, the fluid density must be considered. The equivalent of 2.31 feet per psi is true only for water at 68°F. For water of higher temperature and correspondingly lower density, different values should be used. A graph showing the change in density of distilled water over a wide temperature range is presented in figure 7. Data for this graph were derived from the "Handbook of Chemistry and Physics" (Chemical Rubber Publishing Co., 1960–61).

Dissolved solids in moderate amounts exert little effect upon fluid density. As an example, calculations for varying amounts of dissolved solids having a density of 2.5 (water density taken as unity) show that at 100 ppm (parts per million), density is 1.00006; at 200 ppm, density is 1.00012; and at 1,000 ppm, density is 1.0006. The effect of dissolved solids upon density is at least one order of magnitude less than the effect of temperature upon density.

Use of density data in comparing water levels in wells having large differences in water temperature will provide only a partial correction for water-level discrepancies resulting from differences in water density. The use of density data does not give exact correction because it "corrects" only that portion of the water column between the air-line opening and the water level, but it can be used for making rough comparisons.

Because of the extreme length of the air column, the natural density gradient of the air in the column must be considered. If it were possible to measure air-line pressure at some point above water level, this measurement would be slightly greater than one made

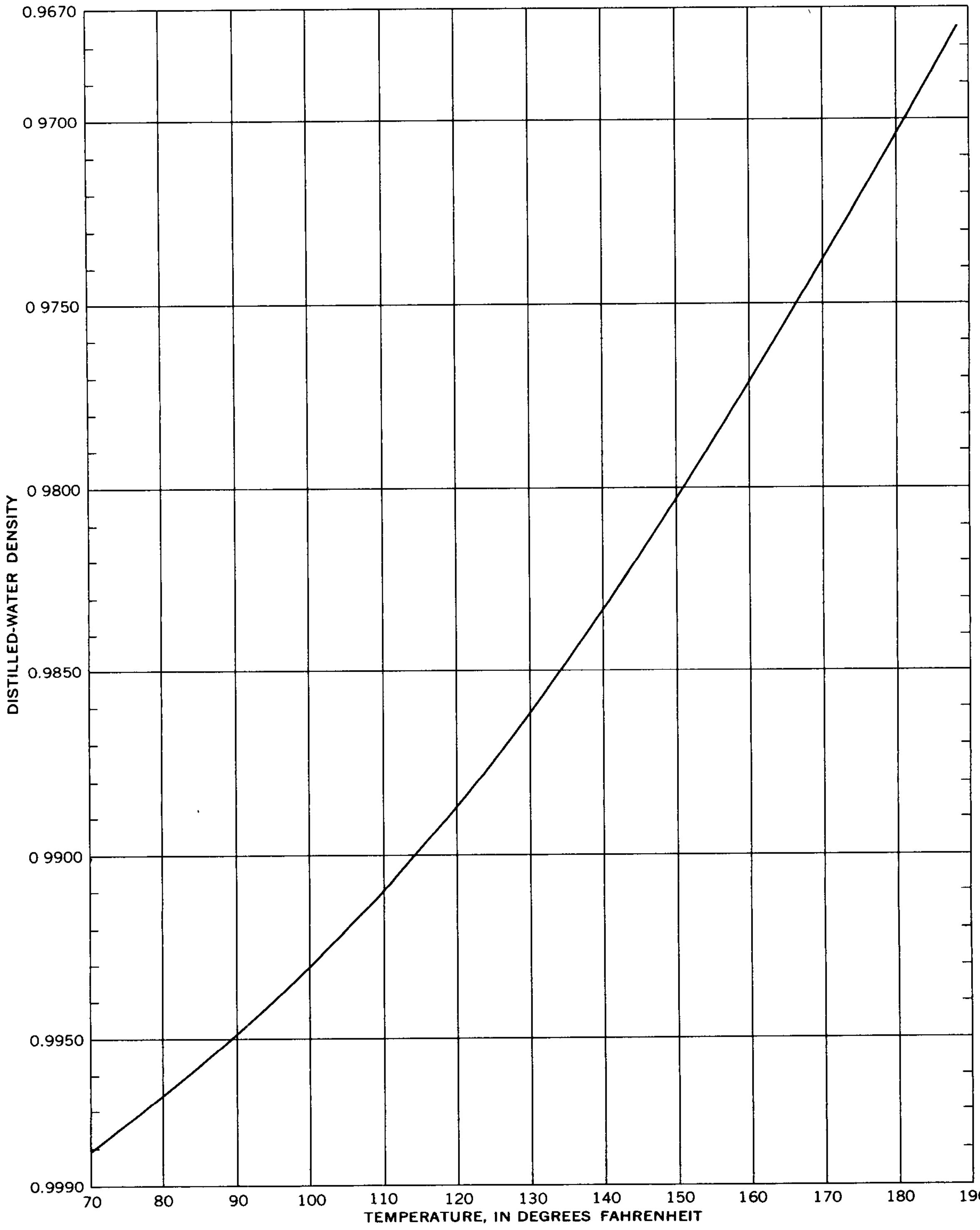


Figure 7.—*Distilled-water density for temperature range 70°–190°F* (data from "Handbook of Chemistry and Physics," Chemical Rubber Publishing Co., 1960–61).

Table 2.—Comparison of water-level measurements made by air line to measurements made by steel tape and electric cable

[After Hood, 1961, p. 49]

Well	Date of measurement	Water level (ft below land surface)		Difference	Remarks
		Air line	Tape or cable		
5A	9–24–59	696.9	695.7	+1.2	Static.
	10– 7–59	696.6	695.9	+0.7	Do.
5B	8–27–59	687.5	682.8	+4.7	Do.
	8–27–59	730.2	725.9	+4.3	Pumping.
	8–28–59	730.2	726.2	+4.0	Do.
	8–29–59	688.6	684.5	+4.1	Recovering.
	8–31–59	688.1	683.4	+4.7	Static.

at land surface; the pressure difference is due to the different densities of the earth's atmosphere at different altitudes. This effect is approximately 0.1 inch of mercury per 100 feet of vertical difference. For a more accurate determination, Babinet's formula for determining heights by the barometer (Smithsonian Institution, 1939, p. LVIII and 160) can be used. This formula is accurate to within about 1 percent. Babinet's formula (transposed to solve for downhole barometric pressure) is:

$$B_o = -B\,\frac{(z+c)}{(z-c)}$$

where

B_o = barometric pressure at water level,

B = barometric pressure at measuring point,

z = depth of water level below measuring point,

c = a constant dependent upon average borehole temperature (use following table reproduced from Smithsonian tables).

Example

Barometric pressure at measuring point = 28.0 in.

Depth to water = 511.2 ft

Average bore temperature = 80°F (c = 58,094)

$$B_o = -B\,\frac{(z+c)}{(z-c)}$$

$$= -28.0\,\frac{(511.2+58{,}094)}{(511.2-58{,}094)}$$

$$= -28.0 \times \frac{58{,}605.2}{57{,}582.7}$$

$$= -28.0 \times 1.018$$

$$B_o = 28.504 \text{ in.}$$

$$B_o - B = 0.504 \text{ in. (1 in. mercury} = 1.13 \text{ ft water)}$$

$$= 0.504 \times 1.13 = 0.57 \text{ ft water}$$

Recording devices

Devices for recording fluctuations of water levels are of two general types: remote (surface) and downhole. These devices may be either mechanical, electronic, or electromechanical. A further distinction is the manner in which the fluctuations are detected. A float or an electromechanically actuated

Direct variation of constant with temperature

Average temperature (°F)	65	70	75	80	85	90	95	100
c	56,344	56,927	57,511	58,094	58,677	59,260	59,844	60,427

water-seeking probe may be used to detect vertical changes of the water surface in the hole, or a mechanical or electrical pressure gage submerged several feet below the water surface may be used to detect changes in fluid pressure resulting from water-level fluctuations. The principal advantage of pressure-sensing devices is that they may be used in packed or otherwise sealed-off zones in a well. Also, their response to rapid changes of fluid pressure is generally better than that of mechanical devices.

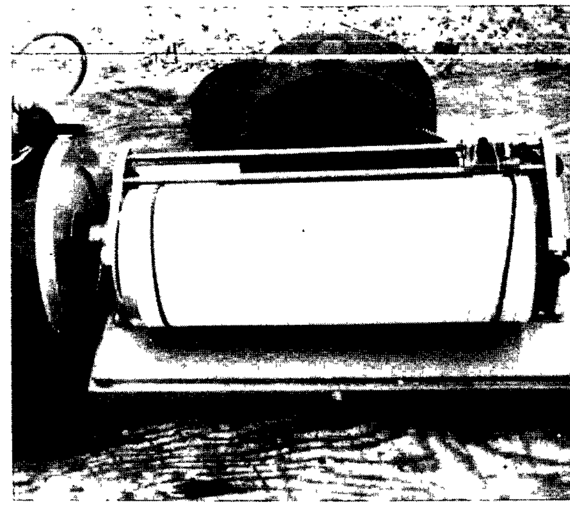
Surface recording devices

The simplest uphole recording device commonly in use consists of a cylindrical recording chart actuated mechanically by a float that follows the water level (fig. 8*A*). A small diameter stranded cable or a flat steel tape is attached to the float, and a counter balance and is suspended over a pulley on the recorder. The pulley is connected to the chart by gears so that the chart rotation is proportional to float movement. A clock drive slowly moves a recording pen across the chart.

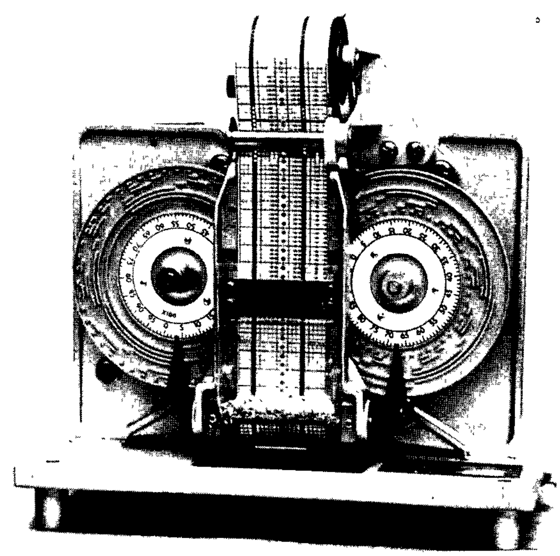
A digital, punched-tape, recorder (fig. 8*B*) is gradually coming into use in several areas. This recorder consists of a code wheel positioned by the float cable and a clock-operated tape advance and punch mechanism. The recorder produces a parallel, binary coded decimal tape having a resolution of 0.01 foot and a maximum directly readable range of 99.99 feet.

When these devices are used, the hole must be straight so that the cable will be free to move; however, a certain amount of loss in sensitivity resulting from cable friction can sometimes be tolerated. The effect of friction can be reduced by using the largest float possible. Test-site holes generally exhibit large deviations, and use of mechanical recorders has been limited to wells having water levels of 1,000 feet or less, or in holes that are nearly plumb.

For observation of water-level fluctuation in deeper wells or in crooked holes, it was necessary to make several modfiications to the existing recorder. Early modification schemes for the mechanical recorder (Shuter and



A



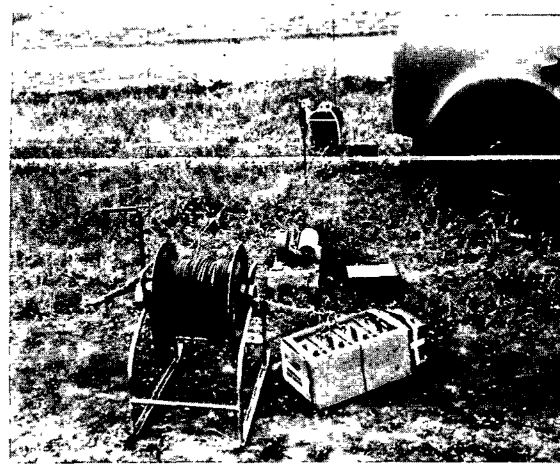
B

Figure 8.—Two types of water-level recorders. *A*, mechanical water-level recorder in operation. *B*, digital water-level recorder.

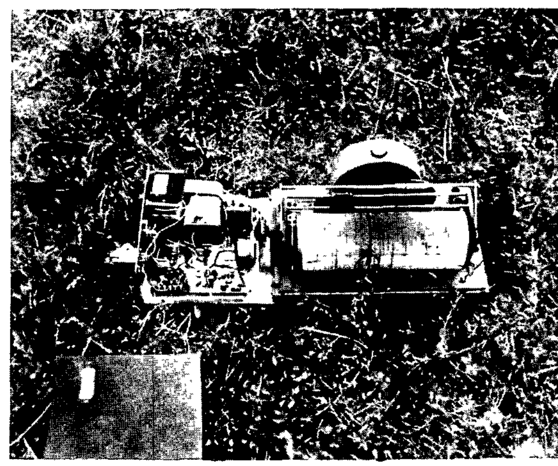
Johnson, 1961) sense fluctuation of water-level mechanically or electrically by use of a cable suspended from the surface to the water level. No counterweight is used, and the cable is stored on a motor-driven reel. As the water level changes, cable is reeled in or out of the hole by the motor-driven reel, which rotates the attached recorder pulley. These modified units were designed principally for operation in small-diameter wells, and they were not fully suited to operation at the Nevada Test Site because the extreme depth to water would require a rather large reeling device. Also, they do not permit remote placement of the recorder. An electromechanically actuated water-seeking probe was developed (Koopman, 1963). In this device the probe package, mechanically similar to the units described above, is anchored to the well casing just above water level, and the probe is free to follow water-level fluctuations. Movement of the water-seeking probe is converted into an electrical signal, which remotely positions the recording-chart drum (fig. 9*B*). The signal wire from the downhole device does not move and may be anchored to the wellhead when the unit is installed. Unlike the mechanical recorder, which must be installed over the well, the modified recorder may be placed at any distance from the wellhead. This feature is especially useful when monitoring the effect of underground nuclear detonations on water levels in wells. Instrument damage from ground shock can be minimized by placing the recorder at a much greater distance from ground zero than the well. Recorders have been installed up to 2,500 feet from the wellhead, and they could be installed even farther from the wellhead if necessary. The modified mechanical recorder is shown in figure 9*A*.

This modification could be applied to the digital recorder (fig. 8*B*). The modified surface unit could also be used with any one of a variety of pressure-sensing transducers.

A transducer is basically a device for converting energy in one form to energy of another more usable form (a radio loudspeaker or a microphone might be considered a transducer). More specifically, in physical measurement the term "transducer" is applied to devices that, through energy conversion, either introduce or receive energy from a system being examined. The transducers used in the measurement system described in this report are pressure-sensing devices which convert pressures to electrical voltages in a uniform proportion. The ratio of conversion is usually expressed in volts or millivolts output for each pound of applied pressure.



A



B

Figure 9.—Modified recorders. *A*, modified mechanical recorder, typical installation. *B*, closeup view of remote-reading conversion of mechanical water-level recorder.

A pressure-sensing transducer generally consists of two elements: an actuating, or sensing, element coupled to a transducing element (Cerni and Foster, 1962, p. 56). The actuating mechanism may be a diaphragm, bourdon tube, bellows, or any other similar device. Transducing elements utilize a variety of physical phenomena such as electrical resistance, inductance, capacitance, photo conductivity or piezoelectricity. Some units are self-excited and generate their own signal; other units require an external power source for operation. Outputs may be in analog form, where output voltage frequency or pulse rate varies smoothly in proportion to input pressure, or in digital form where output follows input pressure variations in discrete coded steps.

The transducers used with the device shown in figure 11 were of the potentiometric and strain-gage type. The potentiometric transducer contains an actuating element that converts applied pressure to linear or rotational movement and operates the slider of a small potentiometer. Actuating elements are usually bourdon tubes or bellows. Transducing elements may be either wire-wound or composition-carbon potentiometers. The sensitivity of these transducers is limited by the sensitivity of the actuating element, the backlash in the linkage, and the resolution of the transducing element. Resistance of a wire-wound potentiometer, for example, advances in a steplike manner as the slider is moved across the windings. Response to short pressure pulses is also limited. Sensitivity of potentiometric pressure transducers is generally limited to about 1 percent of full-scale rating. Error introduced by temperature fluctuations may be significant, but such devices are usually operated in a temperature-compensated bridge circuit.

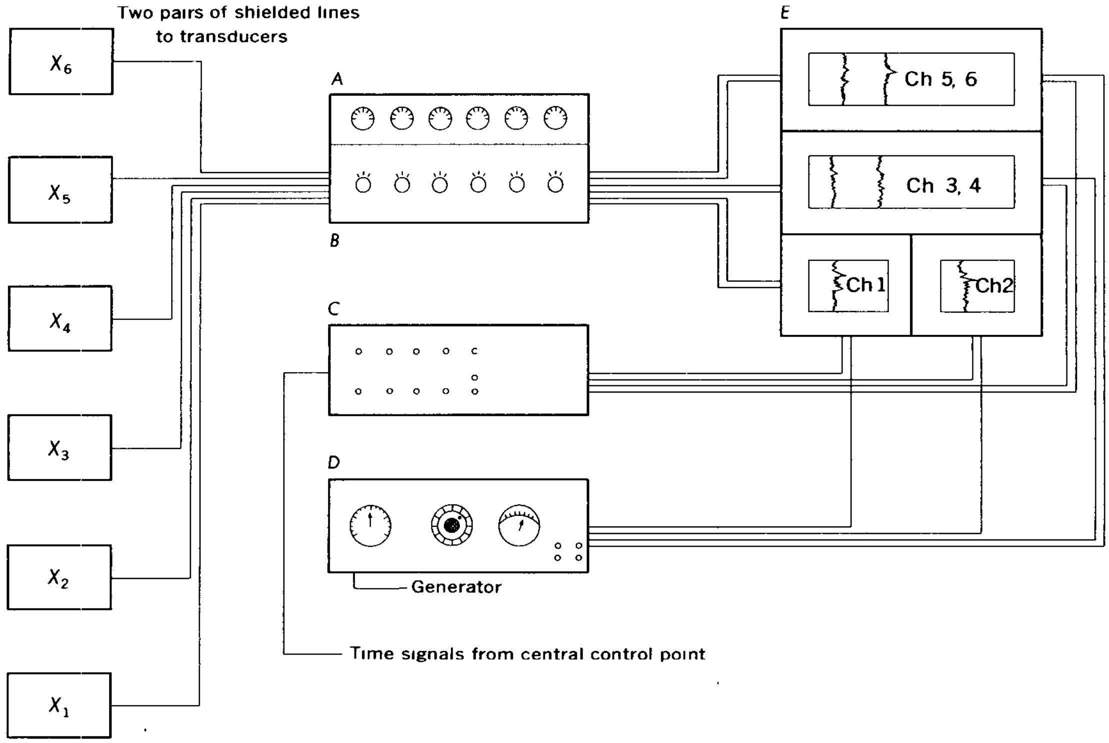
The strain-gage pressure transducer is an extremely sensitive device capable of responding to pressure pulses 1 millisecond or less in duration and equally capable of measuring static or gradually varying pressures. The strain-gage transducing element consists of a grid of very fine wire. As the grid is stretched or strained, gradual changes occur in its resistance. The strain gage may be bonded directly to a pressure diaphragm or may be stretched between a point on the diaphragm and some rigid point within the transducer case. The latter is called an unbonded strain-gage transducer. Like the potentiometric units, strain gages are temperature sensitive, and temperature-compensating circuitry must be used.

The accuracy of strain-gage pressure transducers used in the equipment shown in figure 11 is between 0.15 percent and 0.5 percent of full scale, but the resolution of these units is infinitesimal. The thermal shift in sensitivity of most of the units used at the Nevada Test Site (with internal temperature compensation) is 0.01 percent of full scale per degree Fahrenheit change within the temperature range $-65°-+250°$F. Zero shift has a similar magnitude. The output voltage of a strain-gage unit is only a few millivolts and must be amplified before it can be used in a recording system.

The transducer must be placed several feet below the water level and be anchored to the casing either by a mechanical device or by a pneumatic packer. The principal advantage of the transducer over the mechanical or electromechanical sensing devices is its ability to respond to rapid pressure changes of the type that normally occur in aquifers affected by underground nuclear detonations. A major disadvantage of the modified recording device, when applied to measuring aquifer response to nuclear tests, is its slow response time (the amount of time required to rotate the chart drum to null position). These objectionable features were greatly improved upon in the system utilized to measure aquifer effects from the underground nuclear test in Tatum Dome, Mississippi, in the latter part of October 1964 (figs. 10, 11).

This system utilized two types of pressure transducers: potentiometric and strain gage. Excitation and signal conditioning for six data channels was accomplished in the unit shown in figure 11. The information was then fed to a bank of strip-chart recorders. All the recorders had high-speed pen drives ranging in speed from 0.125 to 1 second for full-scale deflection. A representative record from this system is presented in figure 12.

The exciter-signal conditioner unit was designed to operate with either potentiometric or strain-gage transducers. Although strain-gage transducers yield signals in the low millivolt range, they have almost infinite resolution and generally offer more accurate re-



X_1–X_6, pressure transducers, *A*, exciter control panel; *B*, signal-conditioning panel, *C*, timing control panel, *D*, power monitoring and distribution, *E*, recorders, channels 1–6 as indicated

Figure 10.—System used to measure response of aquifers to nuclear experiment in Mississippi, October 1964.

sponse than do potentiometric units. In addition to their rapid response, the recorders chosen for this system have high input impedances so that their current drain is negligible. This condition makes the system almost immune to temperature-dependent resistance changes in the signal transmission lines. In this system, resolution was limited by the type of recorders used and was about 0.5 percent of recorder full scale. Long-period drift for the entire system appeared to be less than ± 2 percent in any one day. Short-term drift was negligible. A block diagram of the system is shown in figure 10. A system such as this could very easily be used to record all data during a multiwell pumping test.

Bottom-hole recording devices

The bottom-hole pressure recording device has long been utilized in petroleum drill-stem testing. It is small and completely self-contained. The device typically consists of a pressure-sensing element (a bourdon tube) linked to a scribing stylus. The stylus is slowly moved by clock drive along the inner surface of a chart cylinder containing a coated bronze-foil chart. Time is indicated in the axial direction perpendicular to pressure. A typical chart is shown in figure 13. For precise chart interpretation, a special optical micrometer must be used. Bottom-hole pressure recorders are available for pressure ranges from 500 to more than 10,000 psi. Chart speeds permit 12, 24, 48, or 72 hours of recording per chart.

Because all recording is done downhole, results are not known until after the instrument has been removed from the well and the chart has been inspected. If a chart did not scribe or a clock did not operate, much valuable time and information could be lost. Because of this uncertainty, two clocks and two

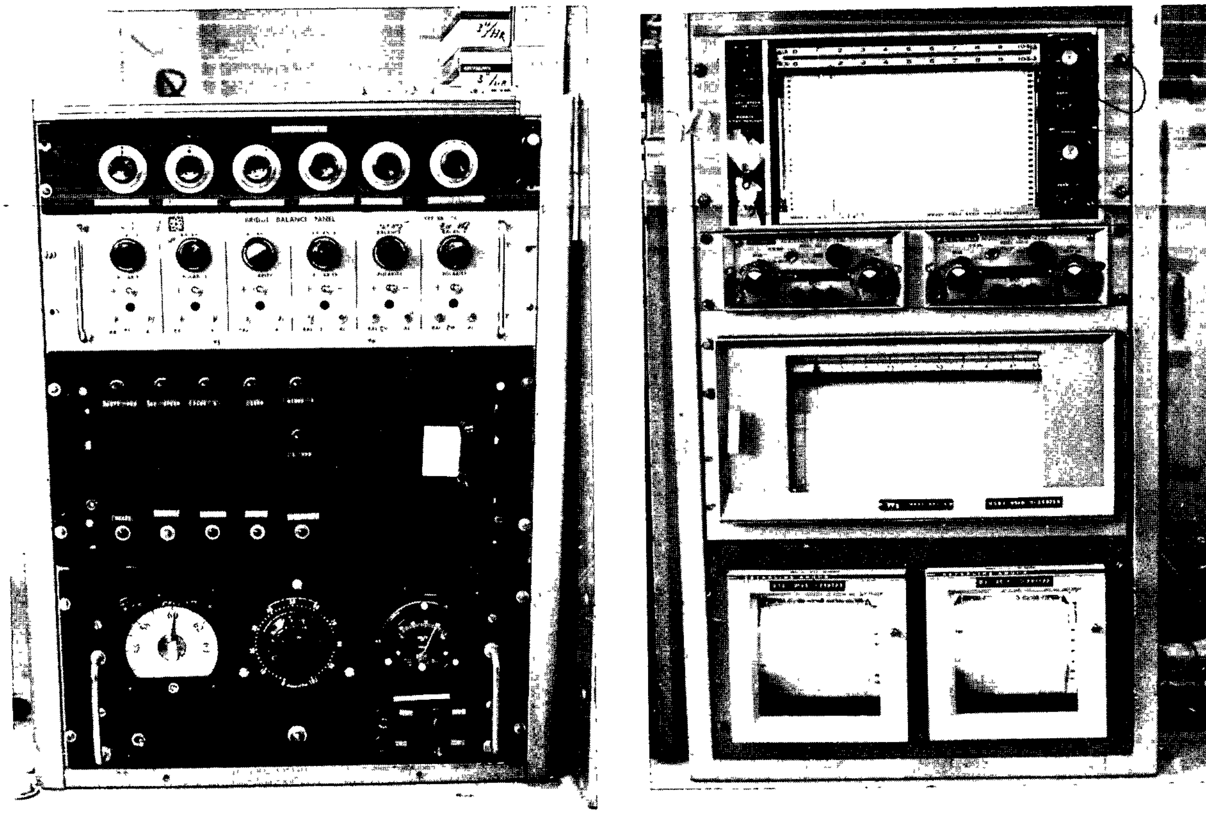


Figure 11.—Equipment for measuring aquifer response.

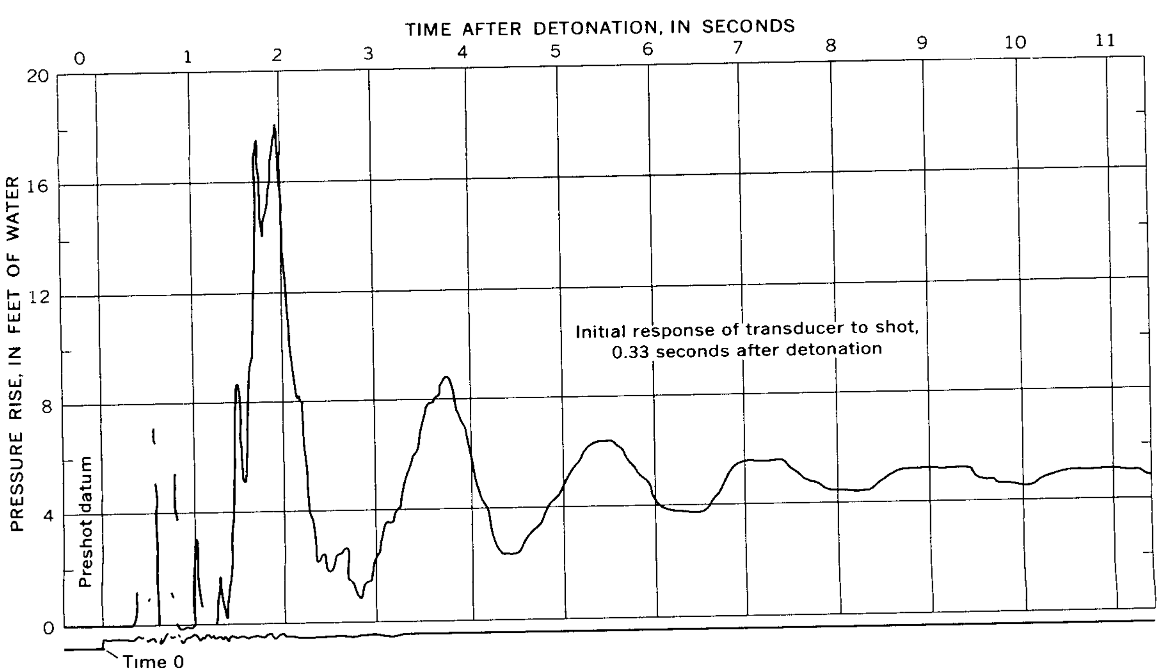


Figure 12.—Record of early pressure response in well HT-5 to Salmon event, Tatum Dome, Lamar County, Miss.

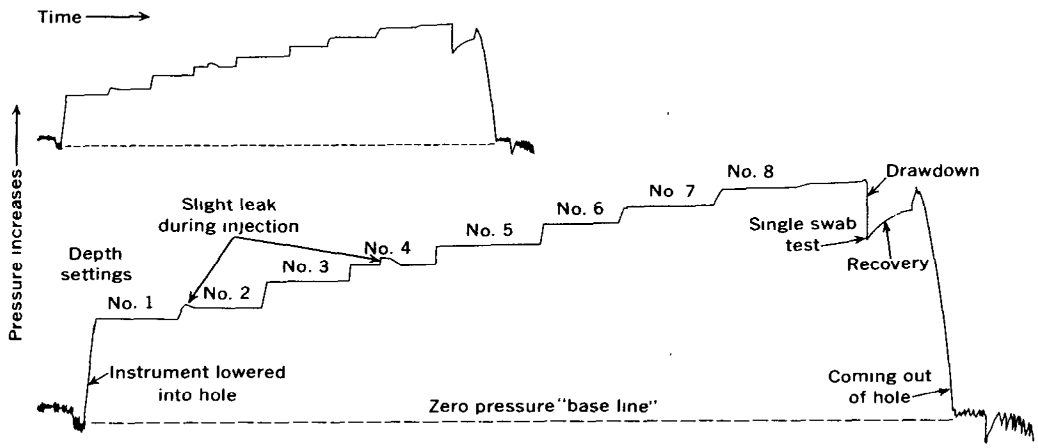


Figure 13.—Record taken from a bottom-hole pressure recorder (3× enlargement of original shown in upper left). Pressure "bomb" was placed above inflatable packer to monitor for by-pass during eight injection tests.

charts should be used in tandem for each pressure instrument. The cost for a second record is nominal.

Recording bottom-hole pressure gages are usually accurate to ±0.25–1.0 percent of full scale (± 1.25–5 psi for a 500 psi gage instrument). Sensitivity may be as good as 0.5 psi for lower range instruments (Einarsen and others, 1958, p. 743). The lack of sensitivity in these devices limits their applicability in hydraulic testing for measurement of very small water-level fluctuations. However, they are included with drill-stem testing tools widely used to determine the hydraulic properties of oil-bearing formations, and these tools are potentially useful for aquifer testing (Bredehoeft, 1965).

Bottom-hole pressure gages are used in the hydraulic testing at the Nevada Test Site. The permeability of zones in some deep wells at the site is tested using inflatable rubber packers. Two spaced packers are used to isolate the section of bore wall in the straddled zone (fig. 14). After the packers are inflated, the tubing is opened to the straddled zone and injection or swabbing tests are made. Pressure-recording devices, installed above the upper and below the lower packer, monitor leakage from adjacent zones. If such leakage occurs, it can easily be seen on the record (fig. 15).

NOTE: Fractured aquifer tested either by swabbing fluid from hole or by injection of water at a constant rate or in a slug

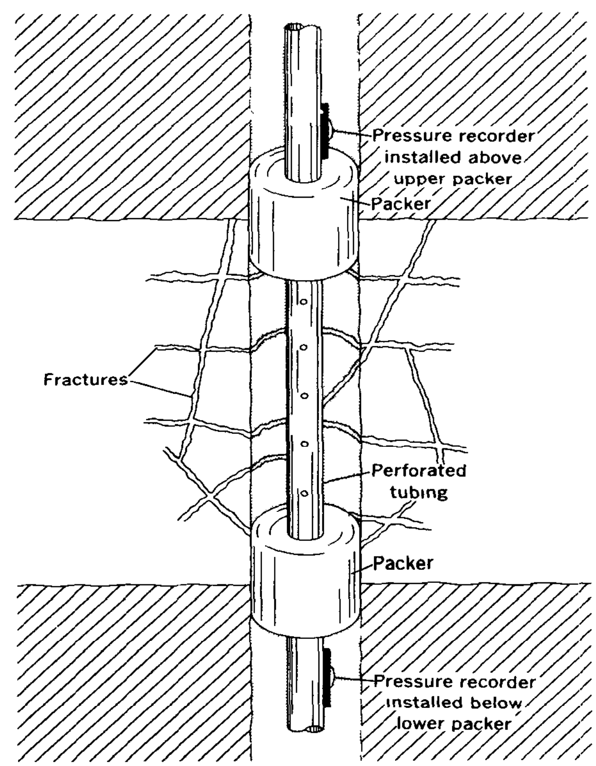


Figure 14.—Typical straddle-packer installation.

Gage accuracy and sensitivity have been greatly advanced in a newly developed device. The Sun precision bottom-hole pressure gage has an accuracy of ± 0.025 percent of full

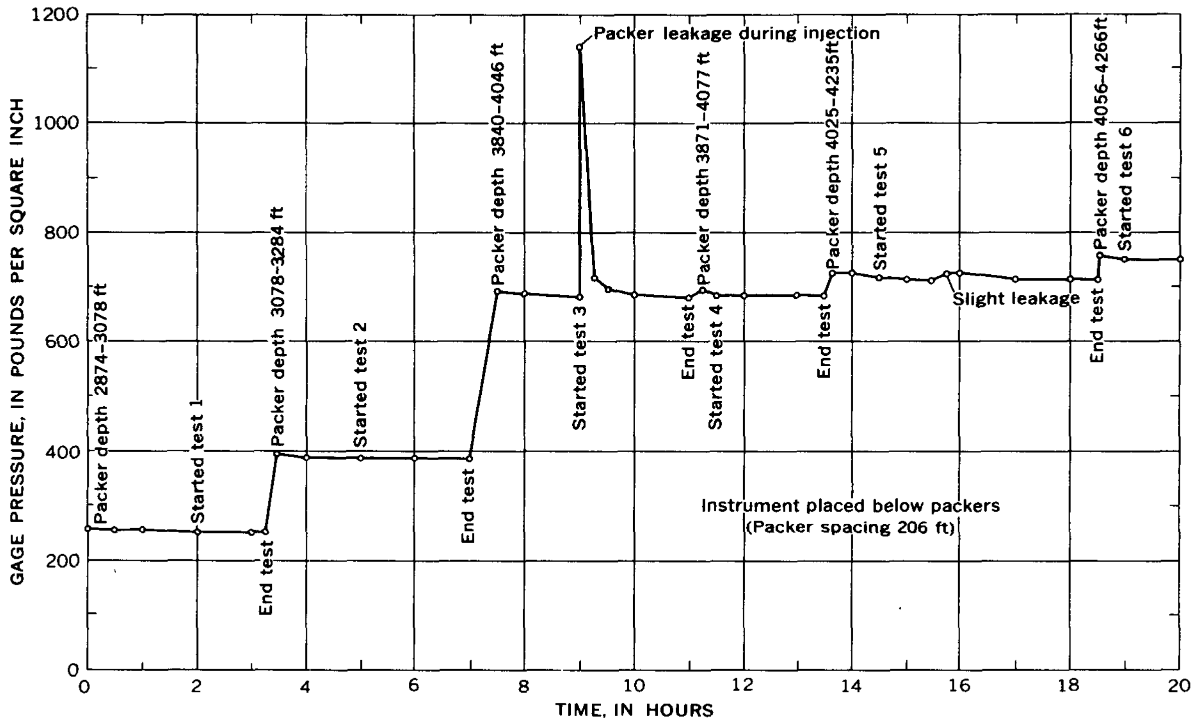


Figure 15.—Bottom-hole pressure record showing pressure buildup and packer leakage during series of hydraulic tests.

scale and a sensitivity of 0.005 percent of full scale (Jones and Bennett, 1963, p. 1,277). This device utilizes an electronic nulling system that provides a 22:1 amplification of stylus rotation to bourdon-tube rotation without applying load to the bourdon element. Recordings are made periodically at preset intervals of 90 seconds, 15 minutes, or 30 minutes, with respective chart lives of 36 hours, 14 days, and 28 days. This gage has been successfully used to observe the hydraulic effect in wells from underground nuclear tests.

Summary

Each of the methods discussed in this report has certain advantages and disadvantages in its use in any water-level measuring program. Additionally, each of these devices has special applications as shown in table 3.

Table 3.—Applications at the Nevada Test Site of methods discussed in this report, and advantages and disadvantages of each method
[X indicates applicability of the methods]

Method	APPLICATION: Water-level measurements 500 ft or less	Water-level measurements in 1,500-ft range	Observation of natural water-level fluctuation	Pumping test[1] where fluid-level changes are large	Hydraulic tests with small fluid-level changes (<0.2 ft)	Observation of underground nuclear detonations	Advantages	Disadvantages
Steel tape	x	x	Non-recording devices.	possible	possible	Non-recording devices.	Most precise method	Slow, must remove from well to read; delicate.
Electric cable	x	x	Non-recording devices.	x	x	Non-recording devices.	Rugged, simple, adequate field precision.[2]	Large instrumental error; requires periodic calibration.
Air line	x	x	Non-recording devices.	x	Lacks precision.	Non-recording devices.	Fast, simple, not affected by foam. Precision depends largely on air gage used.	Needs air compressor, air line must be airtight, limited by gage inaccuracies.
Mechanical recorder	These devices only record fluctuations in fluid level.		x	x	x	May be used if well is located at safe distance.	Precise, permanent record.	Limited to relatively straight holes less than 1,000-ft deep.
Transducer systems	These devices only record fluctuations in fluid level.		x	x	Possible, lacks precision at present.	x	High-speed response, permanent record.	Needs frequent attention.
Bottom-hole recording pressure gage.	These devices only record fluctuations in fluid level.		Lacks precision.	x	Lacks precision.	x	Easy to install, needs no attention while in operation, permanent record.	Record not visible during use.
Modified bottom-hole recording pressure gage.	These devices only record fluctuations in fluid level.		Possible application.	x	do	x	Same as above. Also can operate unattended for periods up to 28 days; greater precision than standard unit.	Do.

[1] Or other hydraulic test including packer test.
[2] High resolution (0.01 ft.) when kept in hole for measuring small water level fluctuations.

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