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# Techniques of Water-Resources Investigations of the United States Geological Survey

## Chapter E2

# BOREHOLE GEOPHYSICS APPLIED TO GROUND-WATER INVESTIGATIONS

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Book 2

COLLECTION OF ENVIRONMENTAL DATA

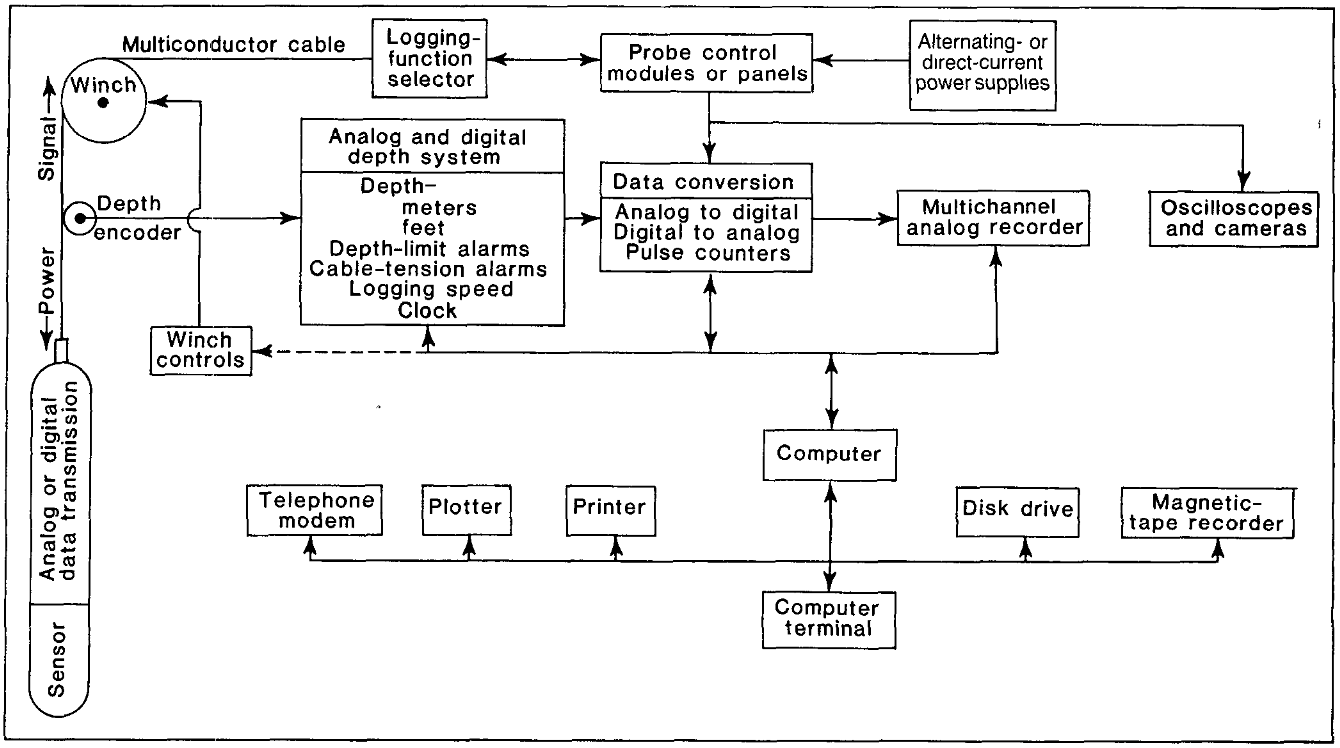

Figure 21.—A modern analog and digital logging system.

although it does not provide quantitative measurement of resistivity. A spontaneous-potential log may provide useful data on bed contacts, but the log tends to be featureless in many water wells. A high-resolution caliper log may provide unambiguous location of contacts in some kinds of lithology.

# Logging Equipment

A thorough understanding of the theory and principles of operation of logging equipment is essential for both equipment operators and log analysts. Equipment operators need to know enough about how each logging system works to be able to recognize and correct problems at the well site and to select the proper equipment configuration for each new logging environment. Log analysts need to be able to recognize, by looking at the logs, logging-system malfunctions and improperly recorded logs. The maximum benefit usually is derived from a logging operation in which operators and analysts work together in the logging truck to select the most effective adjustments for each log and to obtain more detailed logs on sections of interest.

A logging system can be subdivided into subsystems or components to simplify the description. A schematic block diagram of a modern analog and digital logging system is shown in figure 21. The logger components shown in this diagram can be mixed or matched in the fashion of modern computer systems. In this manual, logging-system components are described in the following categories: probes, cable and winch (including depth system), control modules, and recording. Specific information on each type of logging probe and ancillary equipment is included in the section on that type of log. Other related information is discussed in the sections on planning the logging operation, quality control, and calibration and standardization.

## Probes

Logging probes, also called sondes or tools, enclose the sensors, sources, electronics for transmitting and receiving signals, and power supplies. The probes are connected to the cable by a cable head screwed onto the top of the probe. Most probes are made of stainless steel or other noncorroding materials. Electric-logging probes commonly have lead electrodes; acoustic probes incorporate rubber and plastic materials for acoustic isolation and transmission. Probes vary in diameter from less than 1 in to more than 4 in. The standard size used in most oil-well operations is 3⅝ in; most probes used in ground-water studies are smaller. Lengths vary from about 2 to 30 ft or more; weight may be as much as several hundred pounds. Some electric- and acoustic-logging devices are flexible; others are rigid. They are designed to withstand pressures of many thousands of pounds per square inch, based on the maximum depth they are expected to reach, plus a safety factor for heavy drilling mud.

Most probes used in ground-water hydrology today (1985) transmit an analog signal to the land surface for processing. The signal usually is a varying voltage or pulses that vary in frequency. The new generation of probes converts variations in response to a digital signal for transmission up the cable. With this approach, some of the data processing can be done in the probe. For example, count rates can be divided by a constant to decrease losses in the cable. Data from several sensors also can be transmitted in a single probe. Digital probes offer the added advantage of easy switching and control from the land surface by means of a computer keyboard.

Most older probes, including many used in ground-water hydrology, are axially symmetric and are not side collimated. That is, they send and receive signals 360° from the probe axis; they are not intentionally decentralized. Many modern nuclear probes, often called borehole-compensated probes, are decentralized and side collimated, and they use several detectors. They are decentralized with caliper arms or bow springs, and are side collimated with appropriate shielding material around the source of energy and the detector. Using the ratio of count rates from two detectors provides some amount of compensation for borehole effects. Compensated acoustic-velocity probes are centralized with bow springs or rubber fingers; they may use two transmitters and four receivers to transmit an average signal. Operation of centralized probes in greatly deviated boreholes can be very difficult. If centralizers are rigid enough to center the probe adequately, sometimes the probe will not go down the hole.

As wells get deeper and geothermal exploration increases, temperature becomes a limiting factor for many probes and must be considered when selecting probes for such an operation. Few standard logging probes will operate properly at temperatures greater than 100 °C, and many demonstrate thermal drift before that temperature is reached. Thermal drift caused by changes in the temperature of the electronics in a logging probe is common and may produce a misleading log. A temperature log of a well in which temperature drift is suspected may be useful in confirming drift in other logs, but only a test in a controlled-temperature environment will provide direct evidence that the problem exists and data to allow the logs to be corrected. The U.S. Geological Survey has designed and tested probes that have operated at temperatures as high as 260 °C, but such probes are large and expensive (Keys, 1982).

Water leaks are rare in logging probes, but they do occur. Most probes are sealed with double O-rings at the joints; faulty O-rings usually are responsible for leaks. O-rings need to be kept clean and lightly greased and must be inspected frequently for nicks. If a probe does fill with fresh water, it usually is possible to remove the electronics, which are mounted on long boards, and dry them out at the well site, so that logging operations can be resumed. Probes may operate for years with no malfunctions; most failures can be attributed to a broken or intermittent solder joint. Commonly, a broken joint can be located and repaired at the well site. If a probe cannot be repaired, it usually is possible to send it to the manufacturer or a repair facility and to receive a similar probe by return air freight, so that the logging job can be completed. The replacement probe must be calibrated if the logs are to be used quantitatively.

Probes should be stored and transported with care. Large probes usually are stored horizontally in a probe rack where they can be locked down to prevent movement; small probes may be stored in a vertical rack. Logging probes stored in a strong, well-padded box will be less likely to sustain damage.

## Cable and winch

Most logging cable is double-wrapped with steel wire to protect the insulated conductors inside and to serve as a strength member. This armor serves as one of the electrical conductors in single-conductor cable. Many portable water-well loggers still use single-conductor cable because it is lighter and less expensive than multiconductor cable. However, in recent years there has been a trend toward using four-conductor cable for water-well logging, because it permits quantitative resistivity and acoustic logs to be recorded. Other advantages of multiconductor cable are that it allows a large number of logs to be recorded at one time and has greater strength for use with heavy probes and in deep wells. Cable having seven conductors is standard for oil-well logging and is used in deep water wells and geothermal wells. A Teflon type of insulation should be used on high-temperature cables; special steel is needed for the armor if corrosive fluids may be encountered.

Logging cable is expensive and must be treated with care if it is to be useful for a long time. Kinks should be avoided at all times. The cable should be wiped or washed before it is stored on the drum after logging in corrosive fluids, and light oiling may be helpful to prevent rusting. Cable wipers and line coolers can be used to clean the cable automatically as it comes out of the well. A line cooler is essential for hot cable because hot cable may crush the drum as it shrinks if it is not precooled. The cable should be spooled on the drum with a level wind; any backlashes on the drum can be carefully removed manually. Shorts or open conductors occur more frequently in mistreated cable and may necessitate cutting the cable and reinstalling the cable head.

The cable head usually is the most troublesome component of a logging system. Electrical leakage in a cable head is common; when this occurs, the cable head usually must be reinstalled, a time-consuming procedure. A volt-ohm meter is carried on every logging truck to check for cable and cable-head leakage and shorts. To decrease the occurrence of leaks, the O-rings in the cable head should be examined and greased frequently, and the cable head filled with grease as specified by the manufacturer. When a cable head is being reinstalled, the correct number of strands in the armor must be cut so the breaking strength is decreased to less than that of the cable. The purpose of eliminating some strands is to ensure that the cable will part or pull out at the head if the probe becomes lodged in the well. Retrieving or fishing for a lost probe is easier if there is no cable above it; cable also is expensive and difficult to grind up with a drill bit if it is left in a well. Drawings and dimensions of the cable head and all probes should be kept on the logging truck as aids in fishing for lost probes. With this information, a fishing tool can be made that may enable the probe and cable head to be removed from the well. Some commercial firms will rent or sell fishing tools and supervise the retrieval operation. Proper tightening of the joint between the cable head and the logging probe and continuous awareness of well conditions are important in decreasing the chance of losing a probe.

Most winches are powered by alternating-current electric motors or are driven mechanically or hydraulically from a power takeoff on the truck. They need sufficient power to break the cable if necessary. If the winch is powered by an alternating-current generator, the generator should be oversized for the load, so that voltage decrease does not affect the electronics. Some suitcase-type loggers have a hand-crank winch, but this is practical only to depths of 500 ft, and only if the probes are light in weight. An adjustable, powered, level wind is needed to prolong cable life. Slip rings provide the electrical connection between the cable and the electronics at the land surface. Although they tend to be trouble free, they should be inspected and cleaned periodically, particularly if noise caused by winch rotation is observed on logs.

Logging cable is passed over a measuring sheave between the winch and the well. Electrical signals from an optical encoder, or selsyn, or a speedometer type of cable are used to transmit the rotation of the measuring sheave to the recording systems. The measuring sheave is precisely machined to provide accurate cable measurement and must be kept free of dry drilling mud and ice. The accuracy of cable-measuring systems should be checked periodically. When the measuring point on a probe reaches the reference point at the wellhead, the magnitude of any error should be recorded on the log. Depth errors tend to be greater with lightweight probes and rapid logging speeds, probably because of slipping on the measuring sheave. Depth errors can come from many sources; most result from operator error rather than equipment malfunction, and frequent checks are needed to detect them.

Two types of warning systems are used in some logging trucks to decrease the chance of loss of or damage to equipment. A weight indicator is essential for logging deep wells to warn the operator if the probe has become lodged in the hole while moving in either direction. The weight indicator may be connected to an adjustable audio alarm so the operator does not have to watch the indicator constantly. A depth alarm, which can be preset to sound before the bottom and top of the well have been reached, can be helpful to a busy operator who has many duties during logging.

The cable leads from the measuring sheave over one or more sheaves at the wellhead before going down the borehole. These sheaves should be sufficiently large in diameter to avoid damage to the cable, and the groove in the sheave must be machined to fit the diameter of the cable. For water-well logging, a sheave that will attach to different-sized casing in several different ways can be carried on the logging truck. Surface casing may vary from 2 to 20 in or more in diameter; wells may be located in pump houses, where access is difficult.

If the logging equipment is to be used regularly to log a large number of test holes and water wells, an adjustable boom with a sheave mounted on the end can save considerable time in setting up to log. A boom similar to that shown in figure 22 also can make it much easier to handle long and heavy probes. Small folding booms have been designed that will mount on the roof of a carryall or station wagon. When large probes are being used and neither a boom nor a drill rig is available for mounting the sheave, a tripod can be constructed out of heavy pipe. A large logging truck like that shown in figure 22 is necessary only if a large suite of heavy probes is carried or if deep wells are logged.

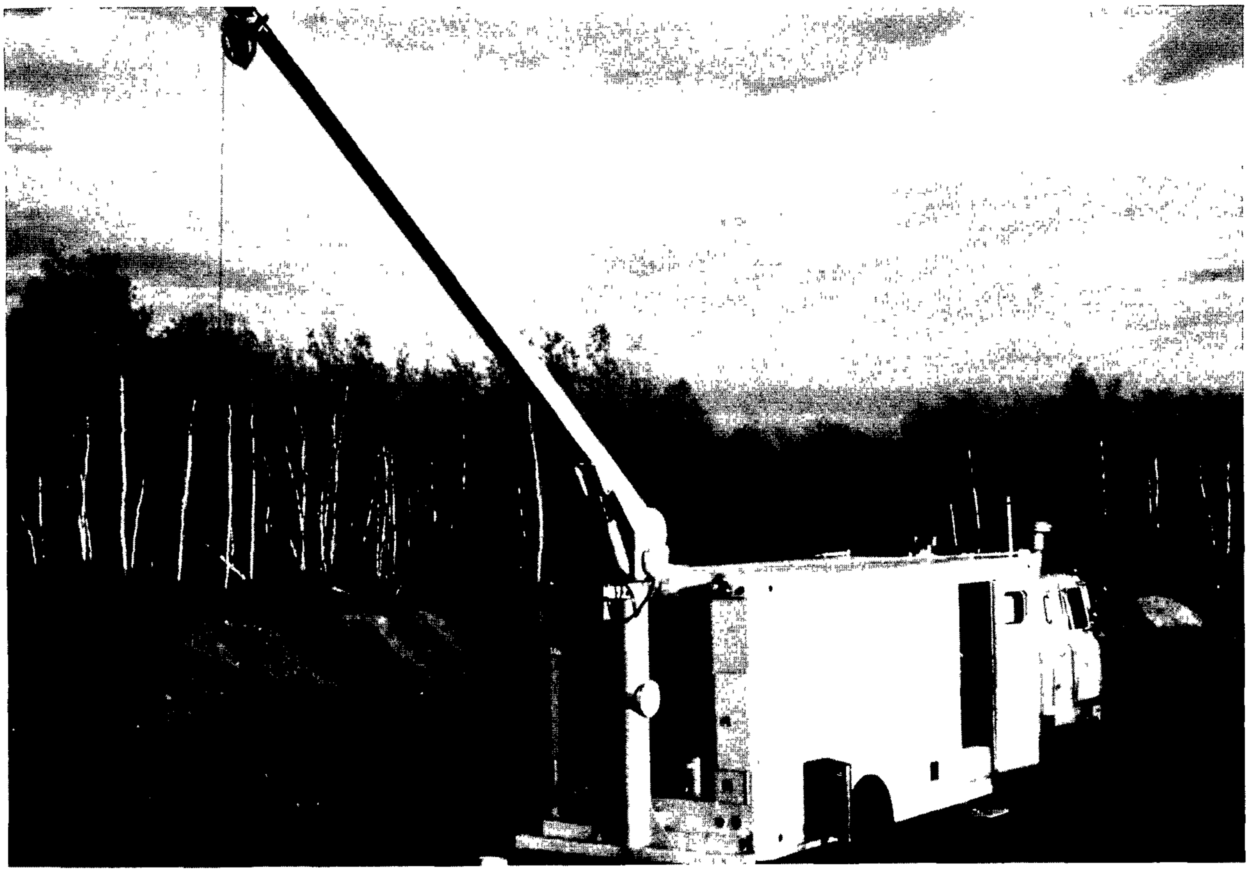

Figure 22.—Large logging truck used for deep-well logging.

## Control modules

Control modules or panels are used to make most of the adjustments necessary to obtain each type of log. Plug-in modular design is desirable, because the modules can be replaced readily in the event of failure. If a widely used design is selected, modules can be bought from several different manufacturers, and modules can be added as funds permit. Modules also take up less space than panels and usually can be connected to a common power supply. A photograph of the inside of a U.S. Geological Survey research logging truck is shown in figure 23. Both control modules and panels are mounted in standard relay racks. Although this logging truck contains more than the usual number of modules and panels, many of the modules are of standard design, widely used in water-well logging.

Most logging equipment includes a function-selector switch that allows the operator to choose the proper combination of modules, panels, and power supplies to record each kind of log. On some loggers, switching is accomplished by plugging wires into the appropriate module or panel. A pilot light on each module or panel shows that the power is on. The module may contain controls for adjusting the voltage and current of the power to the probe; meters may be included to indicate these values. Additionally, the module or panel will have switches to select recording scales and positioning of the pen on the recorder. Further selection of scales and positioning usually is possible with controls located on the recorder. Additional controls or switches that may be on a module or panel, depending on the logging function, include time-constant adjustment or smoothing, recorder-channel selection, and internal calibration.

Some modern logging trucks use a computer instead of modules or panels to control logging functions (fig. 24). The operator determines the way each log is to be run, and instructions, based on displayed questions, are entered from a terminal keyboard. These instructions can be transmitted to probes, power supplies, modules or panels, and recorders.

## Recorders

A variety of recorders is available for geophysical-logging equipment because almost any recorder man-

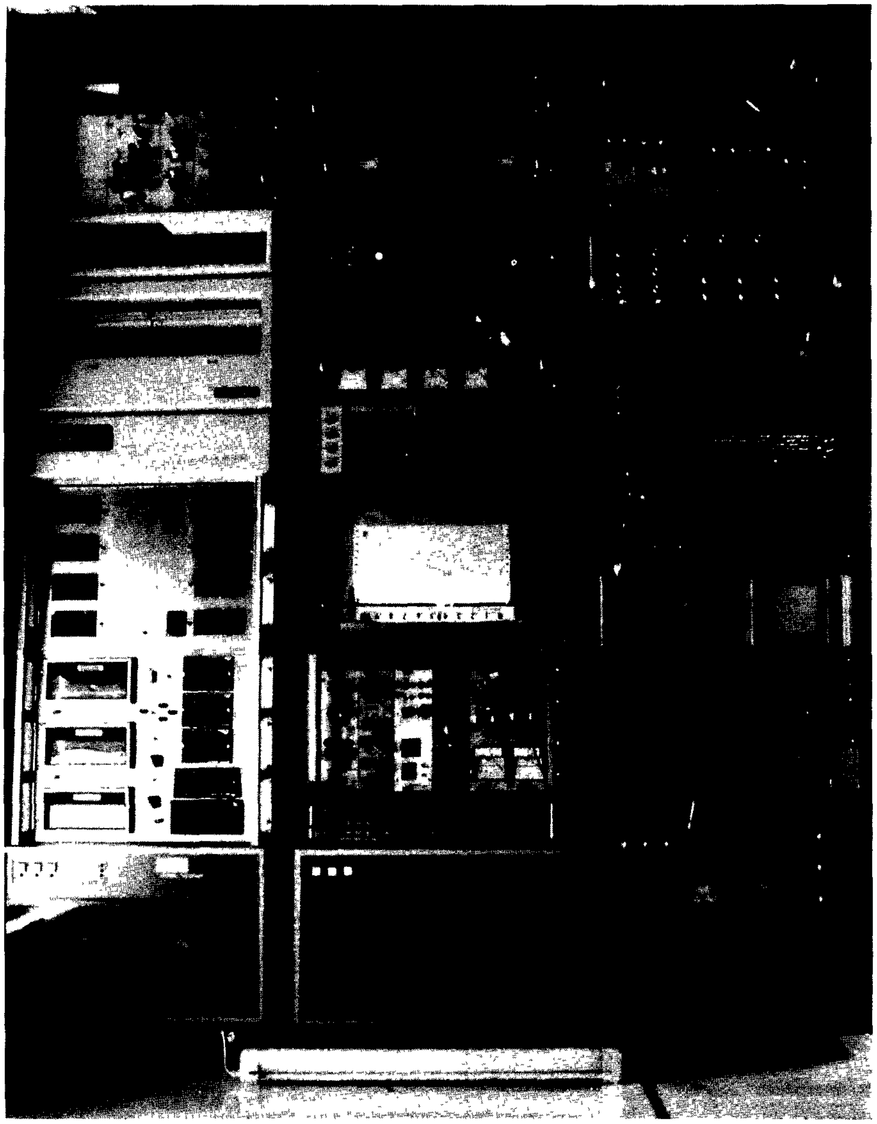

Figure 23.—Electronic control panels and modules, and analog and digital recording systems, in a modern logging truck.

ufactured today can be adapted to this use. Most of the recorders currently (1985) used in ground-water applications are of the pen-and-ink type, with one to four pens. Ozalid-type recorders, using light-sensitive paper, are widely used in oil-well logging by commercial service companies; laser recorders are coming into use. Ozalid recorders are suitable for logging very deep wells and recording a large number of curves simultaneously; the disadvantage is that the log cannot be studied as it is being recorded, but only after it is finished. Also, it is difficult for the untrained eye to distinguish all the overlapping curves on such a log, even when dots and dashes are displayed.

Pen-and-ink recorders are relatively inexpensive and are widely available in many styles. Pens are available in many colors, so that traces can be readily distinguished. The common pen types are ink-reservoir or capillary, felt-tip, and ballpoint. All these pen systems have shortcomings, but felt-tip and ballpoint pens can be replaced easily, which makes them more suitable for a logger that is not used on a regular basis. Ink-reservoir pens that are used and cleaned frequently provide good service, but they may leak ink during rapid pen travel. An important consideration in selecting the type of pen is legibility of copies made on a duplicating machine. Different colors may be indistinguishable on copies, and some colors may not reproduce well.

The number of pens or recording channels is a function of the number of logs that can be recorded

Figure 24.—Winch controls and computer in a modern logging truck.

simultaneously and the cost of additional channels. Recorders should have at least two channels, so that spontaneous-potential and single-point-resistance logs can be recorded simultaneously. Four channels permit two normal-resistivity logs, a spontaneous-potential log, and a gamma log to be recorded at the same time, if the probe is properly designed. Two or more channels also permit recording of a log on several scales to provide the needed response range and sensitivity. Extra channels also provide spares that can be easily selected if a channel malfunctions. Most analog recorders permit independent adjustments for each channel; these usually are gain or attenuation and position or basing. Gain allows the operator to control the amplitude of pen deflection for a given probe signal. Positioning permits the manual location of the pen on the chart without changing gain. Recorders generally are among the more trouble-prone surface components of a logging system.

Chart paper is marked with vertical and horizontal divisions consistent with the logs to be made. In the United States, a 1-in scale in both directions, subdivided into tenths, is most common. In other parts of the world, paper with scales in metric units is used. For oil-well logging, an American Petroleum Institute (API) horizontal scale is used for many logs; a logarithmic scale is used for some. Most of the paper used in these commercial service trucks has two recorder tracks, 2.5 and 5 in wide, and the logs are confined to those tracks. Recorders from 2 to 10 in wide are used for ground-water applications, but 10 in is practical for most purposes, except the portable suitcase type of loggers. For greatest versatility, all pens should be capable of recording on the full width of the paper.

When a log is started, depth should be adjusted so that even footage to the nearest 10 ft plots on a major division on the paper. Most loggers used for ground-water purposes do not have a system for automatically indicating the depth on the chart paper. Depths frequently need to be manually written on the chart paper, and checks should be made to ensure that the readings from the depth indicator agree with the divisions on the chart paper. The horizontal-scale values also should be written on the log at the time it is set up, and the pen positions, set by internal calibrators, should be marked across the entire span of log response. Selection of the appropriate log scales is essential to obtaining the maximum information from logs; scale selection is described in the section on quality control. Recording paper that is too narrow will not permit adequate resolution of a large range of data. Backup curves are provided on most commercial logs as a solution to this problem, but they tend to make log reading difficult.

Because log headings are not put on the log until after it is completed, all pertinent information should be written on the log as it is being recorded, including information about the well, probe, module adjustments, logging speed, and calibration. Log headings can be used as a reminder to ensure that all pertinent information is noted.

Many modern loggers incorporate digital recording equipment, so that data from the probe are recorded simultaneously in digital and analog format. Although digital recording is becoming standard, it will never completely replace analog recording because of the need to study a log as it is being made. Without analog capability, malfunctions or incorrectly selected logging parameters may not be recognized until it is too late for correction. In addition to use in computer interpretation, digitizing of logs onsite has several other benefits. Because the digital record contains all the unprocessed data before it is sent to the analog recorder, no information is lost if the analog trace goes off scale. This allows the horizontal scale on the analog record to be selected at optimum sensitivity to display small-amplitude features. Valid logs can be plotted later from the digital data, even though the analog surface equipment may have malfunctioned. In some logging trucks, replotting with corrections immediately after the log is made also is possible. If a modem is available, a digitized log can be transmitted over the telephone, or the tape or disk can be mailed, for rapid data processing.

Several different types of digital recorders are used. The most common at the present time (1985) is magnetic tape, either standard computer-compatible tape or cassettes. The larger reel-to-reel tape has the capacity to store more data from deep wells or many logs. Floppy disks also can be used; they have the advantage of smaller size, they allow random access, and they also can be used to store computer programs for onsite processing of data. Either a digital display or a printer usually is available to display the digital data being recorded. Most logs are digitized at 0.5-ft intervals; 0.1-ft intervals may be desirable if high resolution is needed in shallow wells, but sampling with more than a few data points in one sample volume is redundant and does not improve resolution. Digital recording does not slow the logging speed of most logs. However, for nuclear logs, recording one to three samples of the count rate at each depth usually is desirable. The need to space these samples sufficiently close together for thin-bed resolution may require logging speeds of about 25 ft/min or slower.

Probes that transmit pulses, such as nuclear probes and some temperature probes, require only a digital ratemeter at the land surface to send data to a digital recorder. Probes that transmit an analog signal, such as the analog voltage from resistivity electrodes, require an analog-to-digital converter. Newer probes that transmit digital information up the cable require no data conversion at the land surface. Digital-to-analog converters are required to replot digitized logs. Replotting can be done on the analog recorder in the logging truck or on a computer-compatible X-Y plotter.

# Planning a Logging Program

The first decision to be made in planning a logging program is the equipment and operators to be used. The selection may be based in part on the needed logs, because some of the more expensive and newer equipment may not be available from all sources. Within the U.S. Geological Survey three basic options are available: (1) buy or rent the equipment and do the logging with staff personnel, (2) pay for logging by an internal service unit on a job basis, or (3) contract for logging by a commercial service company.

## Buying a logger

Although ordering a logger from a catalog may seem simple, many options must be considered that are beyond the scope of this manual. Several basic decisions need to be made regarding the logger. How much cable is needed? The answer is, At least 500 ft more than the deepest hole anticipated. How many conductors should the cable have? At least four if quantitative logging is needed. What kind of recording should be used? At least two-pen analog, or four-pen analog if multiconductor cable is to be used, and digital recording if computer-log-analysis techniques are to be used.

Owning logging equipment is justified only if it will be used on a regular basis. The main advantages of owning equipment are availability whenever needed, complete control over logging procedures, and, possibly, smaller costs per foot of borehole logged.

## In-house service logging

At present (1985), logging is available on a fee-per-job basis within the U.S. Geological Survey; major private companies may have a similar arrangement. The main advantages of paying by the job are that someone else takes care of equipment maintenance and operator training, and costs may be less if logging is infrequent. This approach will mean better use of equipment but only fair availability and control of log quality. The last factor depends to a large degree on the training and experience of the operators. Onsite quality control by the group paying for the logs is just as necessary for Government-owned equipment as for commercially owned equipment. The procedures described in the section on quality control should be followed.

## Contract logging

Commercial logging services are available throughout the United States and in many foreign countries, from companies that range from multinational corporations to one-person operations. The larger companies are based almost entirely on oil-well operations; smaller companies rely mostly on water wells, mineral test holes, or coal-exploration holes. Oil-well-logging equipment is larger and, therefore, more expensive, so the costs per foot of log are much greater. Oil-well-logging probes may be too large for some ground-water test holes, and a large drill rig is needed on the hole to suspend the upper logging sheave. The major service companies have trucks available only in oil-exploration or producing areas, and mileage costs are substantial. In spite of these drawbacks, oil-well type of equipment increasingly is being used in ground-water studies and development, because deeper production and disposal wells justify the cost and may require this type of equipment.

A number of smaller local companies specialize in water-well or mineral logging; some drillers own their own logging equipment. Usually, the smaller equipment owned by these companies does not permit all the logging techniques available from larger companies; digital recording may not be available. Depth charges, standby time, and mileage costs will be less for these small companies, but they may not have the calibration facilities that most larger companies have. Even if calibration is available, the written agreements or disclaimers from most commercial service companies contain a statement to the effect that the accuracy of the data is not guaranteed.

The total cost of commercial logging may be difficult for the inexperienced person to calculate from price lists, because of the various unit costs involved. Depth and operation charges usually are listed per foot, and a minimum depth is specified. Mileage is usually charged for distances of more than 150 mi per round trip. The well must be ready for logging when the equipment arrives because standby charges are relatively expensive. The customer is required to sign an agreement before any logging is done, stating that he or she assumes full responsibility for the cost of any probes that are lost, the cost of all retrieval or fishing operations for lost probes, and the cost of any damage to the well. If a radioactive source is lost, fishing is required by law, and the well must be filled with cement if the source is not recovered. Probe-protection charges may be paid per probe, or per trip in and out of the borehole, but this form of insurance cannot be legally purchased by Government agencies because they are considered to be self-insured. Some Government drilling contracts include the cost of commercial logging, and the driller may pay for probe protection.

## Selecting a suite of logs

The most effective logging programs are designed on the basis of the information that is needed, the rock types to be penetrated, and the construction of the test holes or wells to be logged. Commonly, all logs available are made, even though an examination of controlling factors, based on an understanding of the principles of the various logging techniques, would allow preselection of only those logs most likely to produce useful data. This is because bringing a logging truck back to a well to record an essential log that was not recorded on the first trip is expensive. For example, an acoustic-velocity log probably will not provide useful data in unconsolidated or slightly consolidated sediments, but might yield information on the strength of some unconsolidated formations, and this information might be useful in some situations. The caliper log is essential to the interpretation of most logs and always is made in an open hole, so that caliper logs are almost always run even when caliper logs would not provide a direct measurement of formation properties. If not enough logs of different types are made, the results from synergistic log analysis are likely to be inferior.

Some types of logs, resistivity, flowmeter, and caliper logs among others, are available in several varieties. For example, a bow-spring caliper is inappropriate when high-resolution hole-diameter information is needed, and a three-arm averaging caliper will provide no useful information in a borehole that has substantial deviation. An understanding of the differences between the various probes is essential for selection of the right one for the job. The detailed information needed for this selection is presented in the sections on the various logging techniques. The basic information needed to simplify selection among the more commonly used logs is provided in table 2. A cross reference to more detailed descriptions of the types of logs listed in the first column also is provided (in the second column).

Table 2.—Criteria for selection of logs

| Type of log | Varieties and related techniques | Properties measured | Potential applications | Required hole conditions | Other limitations |
|---|---|---|---|---|---|
| Spontaneous potential. | | Electric potential caused by salinity differences in borehole and interstitial fluids. | Lithology, shale content, water quality. | Uncased hole filled with conductive fluid. | Salinity difference needed between borehole fluid and interstitial fluids correct only for NaCl fluids. |
| Single-point resistance. | Conventional, differential. | Resistance of rock, saturating fluid, and borehole fluid. | High-resolution lithology, fracture location by differential probe. | Uncased hole filled with conductive fluid. | Not quantitative; hole-diameter effects significant. |
| Multi-electrode. | Normal, focused, or guard. | Resistivity, in ohm-meters, of rock and saturating fluids. | Quantitative data on salinity of interstitial water; lithology. | Uncased hole filled with conductive fluid. | Normals provide incorrect values and thicknesses in thin beds. |
| Gamma. | Gamma spectral. | Gamma radiation from natural or artificial radioisotopes. | Lithology—may be related to clay and silt content and permeability; spectral identifies radioisotopes. | Any hole conditions, except very large, or several strings of casing and cement. | |
| Gamma-gamma. | Compensated (dual detector). | Electron density. | Bulk density, porosity, moisture content, lithology. | Optimum results in uncased; qualitative through casing or drill stem. | Severe hole-diameter effects. |
| Neutron. | Epithermal, thermal, compensated activation, pulsed. | Hydrogen content. | Saturated porosity, moisture content, activation analysis, lithology. | Optimum results in uncased; can be calibrated for casing. | Hole-diameter and chemical effects. |
| Acoustic velocity. | Compensated wave form, cement bond. | Compressional wave velocity. | Porosity, lithology, fracture location, and character, cement bond. | Fluid-filled, uncased, except cement bond. | Does not see secondary porosity; cement bond and wave form require expert analysis. |
| Acoustic televiewer. | Acoustic caliper. | Acoustic reflectivity of borehole wall. | Location, orientation, and character of fractures and solution openings, strike and dip of bedding, casing inspection. | Fluid-filled, 3- to 16-inch diameter. | Heavy mud or mud cake attenuate signal; very slow log. |
| Caliper. | Oriented, 4-arm high-resolution bow spring. | Hole or casing diameter. | Hole-diameter corrections to other logs, lithology, fractures, hole volume for cementing. | Any conditions. | Deviated holes limit some, significant resolution difference between tools. |
| Temperature. | Differential. | Temperature of fluid near sensor. | Geothermal gradient, in-hole flow, location of injected water, correction of other logs, curing cement. | Fluid-filled. | Accuracy and resolution of tools varies. |
| Conductivity. | Resistivity. | Most measure resistivity of fluid in hole. | Quality of borehole fluid, in-hole flow, location of contaminant plumes. | Fluid-filled. | Accuracy varies, requires temperature correction. |
| Flow. | Spinner, radioactive tracer, brine tracer, thermal pulse. | | In-hole flow, location, and apparent hydraulic conductivity of permeable interval. | Fluid-filled. | Spinners require higher velocities. Needs to be centralized. |

# Quality Control of Logs

Control of the quality of geophysical logs recorded at the well site is the responsibility of all concerned, from the organization making the logs to the analyst interpreting them; the ultimate responsibility lies with the professional who ordered and accepted the logs. Commercial logging-service companies require that a representative of the customer (for example, the U.S. Geological Survey) be at the site to sign for and accept responsibility for the operation and for the logs. Oil companies commonly assign a project geologist or engineer to this job, and he or she is expected to ensure that the logs meet minimum quality standards. Neither private logging companies nor Government logging organizations accept responsibility for the accuracy of the data recorded. Agreements signed prior to logging by commercial companies usually include a disclaimer regarding the accuracy of the log data; therefore, the customer needs to ensure that the best practices are followed. A quality-assurance program begins before the logging truck arrives at the well site; this program requires continuous input from the inspector or observer at the site. The quality control of oil well logs has been described in detail by Bateman (1985).

## Prelogging contacts

To obtain the most useful data, the logging program should be discussed in detail with a local representative of the Government organization or the private company that will do the logging. Such discussions also may aid in deciding what logs to order. The following information is needed during prelogging discussions and will decrease the possibility of problems:

1. Purpose of logging—What information is needed from logs?
2. Construction of well—Depth, diameters, deviation, caving, or lost circulation zones, casings, cement, screens, junk in the borehole, fluid type, temperature, and pressure range expected.
3. Access for logging—Roads, parking for logging truck, drill rig on borehole (required by most commercial logging companies), wellhead construction (in detail, if a lubricator is needed), and time available for logging.
4. Conditions—Lithologic, fluid, or hole conditions that might affect log response.

Item 4 includes a number of factors that might not be evident; they are described in detail in the section on borehole effects and in the sections on individual types of logs. For example, rocks having unusually large or small values of bulk density may require special scales or probe modifications. If forewarned about large resistivity or inadequate cementation, the logging organization may be able to suggest electric and acoustic probes that would provide more accurate data.

If quantitative logs are required, discussion of questions and logging specifications early in planning will improve the data and identify potential errors; examples of these questions follow:

1. How is each probe calibrated, and how often?
2. What field standards are carried on the logging truck? Is system response checked against these standards before and after each log?
3. What is the range of resistivity, porosity, bulk density, and so forth within which each probe will operate and for which each probe is calibrated?
4. What vertical and horizontal scales are available? If onsite digitizing is requested, what digitizing intervals are available, and what is the recording medium and data format?
5. What will be the logging conditions, such as speed, scales, calibration and standardization, reruns to demonstrate repeatability, and so forth?

## Quality control at the well

A geoscientist who understands the project objectives and the local geohydrology should be in the logging truck during the entire operation. This observer's first task is to specify the order in which the logs are to be made. Usually, fluid logs are run first, if the fluid in the well has had time to reach equilibrium; nuclear logs are always run last, or through the drill stem if necessary, to lessen the possibility of losing a radioactive source. Logging sequence is also based on the need for one log to help select the optimum logging criteria for a later log. For example, single-point-resistance and gamma logs may indicate the thicknesses of potential aquifers and thus aid in selection of the resolution needed, and a caliper log may indicate that certain logs would not be meaningful.

The observer usually makes preliminary interpretations of the logs as they come off the recorder. Based on the immediate analysis of field prints of logs, reruns can be requested, if problems on the logs can be demonstrated. Usually, at least partial reruns will be made at no additional cost, if the contractor is at fault and the probe is still on the cable. After the logging truck has left the site, no-cost reruns are rarely possible. The observer should ask questions if he or she does not understand part of the operation. Notes on problems that occur can be abstracted on log headings. A few symptoms that may indicate equipment malfunction can be recognized during logging; these include periodic oscillations, nonlinear response, temperature drift, noisy sections, and rapid transients. Almost-straight sections (no horizontal pen response) are not always invalid, but generally they indicate problems. If reruns do not repeat within the statistical range expected, the observer may request periodic repeats to determine if well conditions actually are changing. Most reruns are at least 100 ft long and include intervals where log values change markedly. In evaluating new logs, copies of logs previously run in the well, or in nearby wells, are helpful. If old logs are not available, a description of the rock types penetrated by the well will aid in anticipating log response. When the logs appear to be incorrect, changes in speed, time constant, scales, spacing, and so forth may improve the record.

Selection of the horizontal and vertical scales that will provide the most useful data and the required resolution without "noise" is difficult, but is among the most important aspects of log-quality control. To some degree, the ability to digitize logs onsite permits more latitude in the selection of scales, because later the digitized logs can be plotted at more suitable scales; however, the digitizing intervals must have been properly chosen for this to be possible. Advice on scales to use may come from the log analyst, based on objectives and real-time analysis of the logs as they come off the recorder. Vertical scales are chosen on the basis of hole depth, needed bed resolution, and ease of comparing with other data. A vertical scale of 10 ft of borehole per inch of chart paper is common for shallow holes, for which detailed information is required, but 20 ft of borehole per inch of chart paper is probably the most widely used scale over a depth range of several hundred to several thousand feet. The most common vertical scale for logs of oil wells is 50 ft/in; 100 ft/in also is used. The U.S.Geological Survey has used 2 ft/in or less, when fractures were being studied and when other logs were being compared directly with an acoustic-televiewer log. Selection of horizontal scales is even more difficult, because of the range of data that may be present and the need to detect small changes. Except for temperature and fluid-resistivity logs, logs are recorded while the probe is being pulled up the borehole. Logging up allows operators to observe the responses of most probes, except caliper, on the trip down the borehole, to help select the best scale. Many commercial logs are recorded on a scale that is too compressed, in the interest of simplifying the logs by eliminating multiple backup curves. The wider paper used on much water-well equipment permits expanded scales without backup curves. If the data range is too great for the resolution needed, the best technique is to record the signal from the probe on two different recorder channels at different gain settings. Thus, one log will remain on scale, and the other will show the needed detail. This technique is commonly used on temperature logs of geothermal wells, where a great temperature range is expected, but small changes may indicate depths where water is entering the well. In a shallow well, reruns to observe changes or at different scales may be economically justified; in deep wells, however, the cost of standby time and the larger logger may make reruns too expensive.

Logging speed usually is checked with a stopwatch, using the depth indicator, because many logging speedometers are not accurate. Depth readout should be checked periodically against the analog record and at the depth reference point for the well when the probe returns to the land surface. The direction and size of the depth discrepancy is noted on the log heading. Depths are recorded frequently on the log. A common practice on large commercial trucks is to manually add a depth correction when the magnetic cable markers differ substantially from the depth display. This practice should be discouraged, or at least a note should be made of the depth at which corrections are made. A uniformly distributed error can be corrected easily in a computer; random, unknown corrections by the operator cannot be reconstructed. Depth errors that are not consistent throughout a suite of logs usually can be recognized by careful correlation of anomalies between logs. Core data may provide some information on correct log depths; however, core depths commonly are incorrect. Lack of depth correlation between logs made at various times by different organizations is common and usually results from the use of a different depth reference. Most commercial logs are referenced to the kelly bushing on the drill rig, which may be 17 ft or more above ground level.

Depth errors can be caused by both equipment malfunction and operator error. A mechanical backup measuring system will help detect errors caused by a malfunctioning electronic measuring system. An incorrectly machined measuring sheave or a sheave that is coated with ice or mud will affect both types of measuring systems. If either the logging truck or the sheaves at the well are allowed to move, a depth error will be introduced. The sag in the cable from the rear of the logging truck to the well will decrease gradually as the weight of the cable in the well increases, and this will introduce an error. Cable stretch is a significant factor only in deep wells and can be corrected for, but errors caused by the probe sticking, while traveling either up or down, are more difficult to interpret. Hole deviation is common and must be corrected for if vertical depth must be known. The recorder-paper drive can slip, and the paper may not be "scale stable" because of humidity changes. Common operator errors include setting the starting depth on the display incorrectly, writing the starting depth incorrectly, and not allowing for the mechanical slack present in most paper-drive systems.

The observer must remember so many factors to help control the quality of logs that many major oil companies provide a quality-control checklist (Lynch, 1962). Most of these lists are many pages long, because they include specific items for each type of log. The checklist that follows has been shortened by combining many of the log-specific criteria; expanded checklists for individual logging operations can be created from the detailed descriptions of the various logging techniques elsewhere in this manual. A checkmark is adequate to indicate that the particular requirement has been met; a significant deviation from that requirement should be noted in detail. Logging programs for special purposes may require additional checklist items. For example, logging a series of ground-water monitoring wells at a waste-disposal site will require careful cleaning of probes and, possibly, of the cable between wells; care must be taken to avoid contamination of personnel. Log headings that have blanks for a complete set of well and log data also can serve as partial quality-control checklists. An example checklist follows:

LOG QUALITY-CONTROL CHECKLIST

Hole no.__________ Location ______________________________ Date __________
Logging organization ______________________________ Type of log __________
Observer ____________________________________________________________
Log heading completed ______________________________________________
Depth reference and errors noted ____________________________________
Proper logging speed maintained _____________________________________
Pre- and post-logging standardization recorded _________________________
Repeat-log interval __________________________________________________
Scales and changes labeled ___________________________________________
Curves readable with no off-scale deflections __________________________
Sample of drilling mud or water collected ______________________________
Changes in fluid resistivity recorded __________________________________
Logs appear reasonable _______________________________________________
Problems noted on log headings _______________________________________
Did operator make requested changes? __________________________________

## Log headings

Log headings contain information of two types: information on the well, and data pertaining to the logging equipment and operations. Well information usually is provided by the observer, but it is recorded by the logging operator. Data on the equipment and logging operations are best recorded before the logging tool is removed from the cable. The completed heading should be attached to the analog record at the well site. A short reference to the log-heading information entered on the digital recording of each log enables the two records to be related. This reference should include the following information, at a minimum: borehole number, date, log type, and run number. If necessary, the log heading can be typed in the office and permanently attached to the original of the log, so it will appear on all copies. The format of a log heading is not important; the information is essential.

The well-information section of the heading should contain all of the following, if known:

- Well name and number (lease, operator, and field name if in an oil field)
- Location—township, range, section, distance from nearest town, and so forth, and owner (API number if in an oil field)
- Name of driller, date drilled, drilling technique, and depth drilled
- Elevation of land surface
- Height of casing above land surface
- Depth reference
- Complete description of all casing, type, size, and depth intervals
- Location of cement, perforations, and screens
- Borehole diameter (or bit size) and depth intervals
- Fluid type, level, resistivity of mud and mud filtrate at measured temperature, and bottom-hole temperature

The log-information section of a heading should contain different information for each type of log, although the same heading can be used for similar logs. The following information is needed on the heading for each log:

- Type of log, run number ____ of ____ , date _____
- Number or description of logging truck

- Names of logging operator(s) and observers
- Probe number and description—diameter, type, detector(s), spacing, centralized or decentralized, source type and size, and so forth
- Logging speed
- Logging scales—vertical (depth) and horizontal, including all changes and depths at which changes were made
- Recorder scales—millivolts (span) and positioning
- Module or panel settings—scale, span, position, time constant, and discrimination
- Power supply—voltage and current
- Calibration and standardization data—pre- and postlog digital values recorded on heading and annotated at selected points on the analog strip-chart record
- Other logs of the well run on the same date
- Problems or unusual responses during logging (mark at appropriate depth on log)

Incomplete log headings prevent quantitative analysis of logs and make qualitative analysis much more difficult. The increasing emphasis on ground-water-quality problems means that logs will be used more for monitoring in the future and that preexisting logs may provide baseline data, if they are properly labeled. Lack of information on well construction may make even the simplest log analysis impossible. Log headings may be printed up in quantity, with blanks for each item large enough for all needed data. For small records of geophysical data, such as pictures of oscilloscope traces or acoustic-televiewer photographs, stick-on labels have proven effective in encouraging the recording of essential data.

# Calibration and Standardization of Logs

If logs are to be used for any type of quantitative analysis or to measure changes in a ground-water system over time, they must be properly calibrated and standardized. The importance of standardization can be illustrated by the gamma log, which is most commonly used to identify lithology and stratigraphic correlation. Studies in various sedimentary basins throughout the world have demonstrated locally that the gamma log can also identify particle-size distribution and permeability. Such relations cannot be demonstrated unless the logs used have a standardized response. A gradual change in gamma response across a depositional basin may signal a change in the percentage of clay and silt, or it may be a result of equipment drift. A change in gamma response over several years may signal migration of uranium daughter products in ground water, or equipment drift. Calibration and standardization also may help establish comparability between logs made with different equipment.

For purposes of this manual, calibration is considered to be the process of establishing environmental values for log response in a semi-infinite model that almost simulates natural conditions. Environmental values are related to the physical properties of the rock, such as porosity and acoustic velocity. The signal from a probe may be recorded in units, such as pulses per second, that can be converted to environmental values with calibration data. Calibration usually is done before going to the well site to log. Standardization is the process of checking the responses of the logging probes at the well site, usually before and after logging. Standardization involves the use of some type of a portable field standard that most likely is not infinite and may not simulate environmental conditions. Because the terms “calibration” and “standardization” are not used in the same way in the oil-well-logging industry, the user must understand the procedure to know with certainty what has been accomplished. The basic principles of these techniques are described in the following sections, but the specific procedures are described in the sections for each type of log.

## Calibration

Calibration of probe response should be done in a medium that closely simulates the chemical and physical composition of the earth materials that are to be measured. For example, a neutron probe that is to be used to measure the porosity of sandstone would not be calibrated in limestone unless the correction factor is known. Calibration pits or models are nearly infinite with respect to probe response. In a model that is infinite with respect to probe response, the response of the probe does not change substantially if either the diameter or the thickness (height) of the model is increased when the probe is located in the center of the model.

Calibration pits or models are maintained by the larger commercial service companies; these are not readily available for use by other groups, although it is possible to arrange to use some of the private pits. Four sets of calibration pits or models currently (1985) available for public use are listed in table 3. The American Petroleum Institute maintains a limestone pit for calibrating neutron probes and a simulated shale pit for calibrating gamma probes at the University of Houston, Houston, Tex.; these have been accepted internationally as the standards for oil-well

Table 3.—Calibration pits available for public use

[in, inch; ft, feet; gm/cc, grams per cubic centimeter]

| Name and location | Who to contact | Probes that can be calibrated | Physical properties | Drill-hole sizes | Dimensions of pits | Remarks |
|---|---|---|---|---|---|---|
| American Petroleum Institute Calibration Facility; University of Houston, Houston, Tex.: two pits. | University of Houston, Cullen College of Engineering. | Two pits:<br>1. porosity-neutron gamma-gamma; | 1. Six stacked blocks of limestone and marble; stacks average 1.9, 19, and 26 percent porosity. | 7⅞ in diameter, uncased. | 1. 6 ft diameter, 18 ft high; | Call to reserve; daily fee. |
| | | 2. simulated shale-gamma. | 2. Concrete twice as radioactive as the average midcontinent shale, with concrete of low radioactivity above and below. | 5½ in diameter, inside casing. | 2. 4 ft diameter, 24 ft high. | |
| Department of Energy, Grand Junction, Colo.: 20 models or pits. | Department of Energy, Grand Junction Operations office, or the prime contractor at the Department of Energy office. | Gamma calibration in percent $U_{238}$; and gamma spectra in percent K; and parts per million U and Th. Also gamma-gamma and magnetic susceptibility. | Uranium ore mixed with concrete; barren zones above and below. Content of radioactive elements, water, and bulk density known for most pits. Magnetic susceptibility. | Most 4+ in, uncased; 2- to 8-in hole-size calibration. Some cased, 2, 4, 6, and 8 in inner diameter. | 4 to 7 ft diameter, 4.5 to 16 ft high. | Call to confirm available; no charge. |
| Bureau of Mines density pits; Denver Federal Center, Lakewood, Colo.: three pits. | U.S. Geological Survey, Water-Resources Division, Borehole Geophysics Research Project, Building 25, Denver Federal Center, or Geologic Division, Geophysics Branch. | Gamma-gamma, acoustic, resistivity, and magnetic susceptibility. | Concrete of known density: 1.73, 2.33, and 3.00 gm/cc. | 2, 3, 5, and 8 in. | 4.3 and 12.5 ft diameter, 8.2 and 9.2 ft high. | Usually available weekdays; call to confirm; no charge. |
| Department of Energy: Fractured igneous rock calibration models; Denver Federal Center, Lakewood, Colo.: three models or pits. | U.S. Geological Survey, Water-Resources Division, Borehole Geophysics Research Project, Building 25, Denver Federal Center, or Geologic Division, Geophysics Branch. | Fracture detection probes, neutron, gamma-gamma, short-spaced resistivity, and acoustic velocity. | Coarse-grained and medium-grained granite and altered diabase with artificial fractures intersecting and 6 in to 1 ft from the borehole. Known porosity, bulk density, acoustic velocity, and resistivity. | 7⅞-in core hole. | 8 ft diameter (octagonal), 20 ft high. | Usually available weekdays; call to confirm; no charge. |

logging. The pits are available for a nominal daily fee, but they are used enough that reservations are advisable. Pits for calibrating gamma-gamma probes are available for no charge at the Denver Federal Center, Lakewood, Colo. At the same location, three pits constructed of blocks quarried from three different igneous rocks are available for calibrating several types of probes. The igneous rock pits are probably the first ever made for these rock types. They contain artificial fractures of several different orientations that intersect the borehole and fractures that do not intersect the borehole. These fractures are discussed in more detail in the section on acoustic televiewers. The U.S. Department of Energy maintains a set of gamma probe calibration pits in Grand Junction, Colo. This complete set of pits provides several different borehole sizes in blocks having the same concentration of radioisotopes, a desirable feature because borehole-diameter effects always must be considered when applying calibration data to logs.

Boreholes that have been carefully cored, and the cores analyzed quantitatively, also may be used to calibrate logging probes. To decrease depth errors, core recovery in calibration holes should be about 100 percent for the intervals cored; log response can be used to select samples for laboratory analysis. A computer technique for matching core and log depths has been described by Jeffries (1966). The importance of using log response as the basis for selecting cores for analyses is shown in figure 25. The neutron log and cores are from Madison Limestone test well 1, Wyoming. The log is shown only for the cored intervals. Although the overall trend in porosity matches fairly well, average porosity from the core is less than average porosity from the log. A plot of the core analyses versus values from the neutron log at corresponding depths is given in figure 26. Based on the core analyses, it is apparent that porosity cannot be read directly from this commercial neutron log, which was calibrated for limestone. The scale on the log was labeled "porosity index," so no claim was being made for correct porosity values. The cross plot in figure 11 indicates that considerable dolomite is present in this well, which is probably the reason for the large values on the neutron log. A cross plot like the one in figure 11 can be used to correct porosity values for matrix effects, and it does provide values that are more similar to the core measurements.

Because of the possibility of depth errors in both core and logs, and of bed-thickness errors, samples should be selected from thicker units, where log response is consistent. The number of samples to be analyzed is a function of the variability of the property being measured; a completely homogeneous, isotropic material needs only one sample; an infinitely variable material needs an infinite number of samples. The statistics of sampling are beyond the scope of this manual. The core should be analyzed for more than the required properties, such as porosity or bulk density. Mineralogy and chemical composition are important because the responses of many logs depend on rock chemistry. The chemistry of interstitial fluids also may be important; changes in pore fluid during the period the borehole is being used for calibration may cause errors, as will core resaturated with water of different quality for laboratory tests. Laboratory analyses should measure the same physical property that controls log response, if possible. For example, effective porosity does not control the response of neutron and gamma-gamma logs unless it is the same as total porosity.

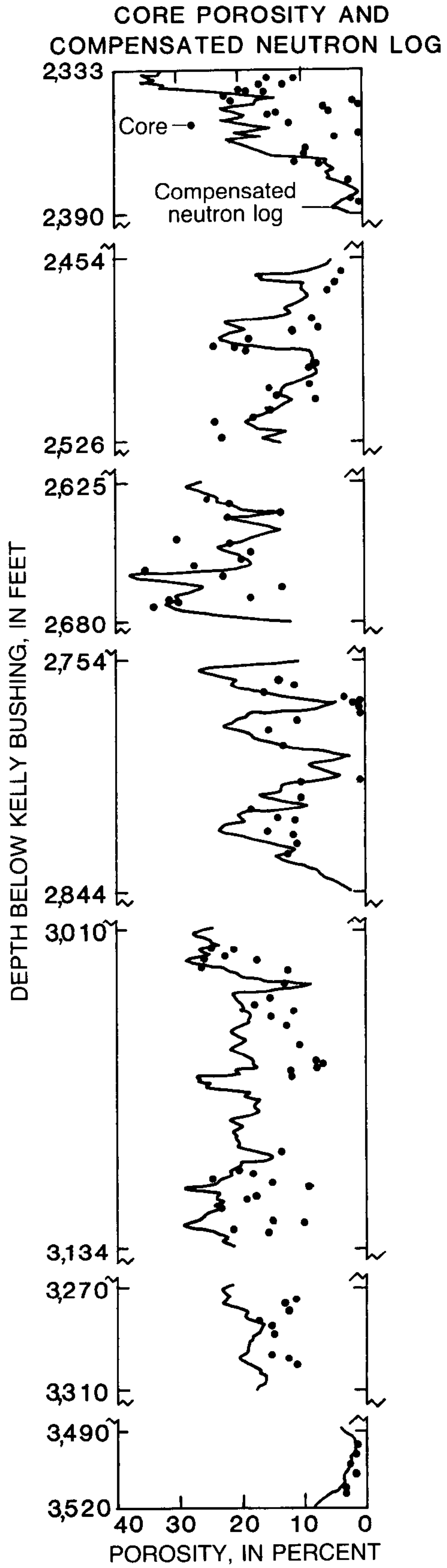

Figure 25.—Porosity from core analyses and compensated neutron log for cored intervals, Madison Limestone test well 1, Wyoming.

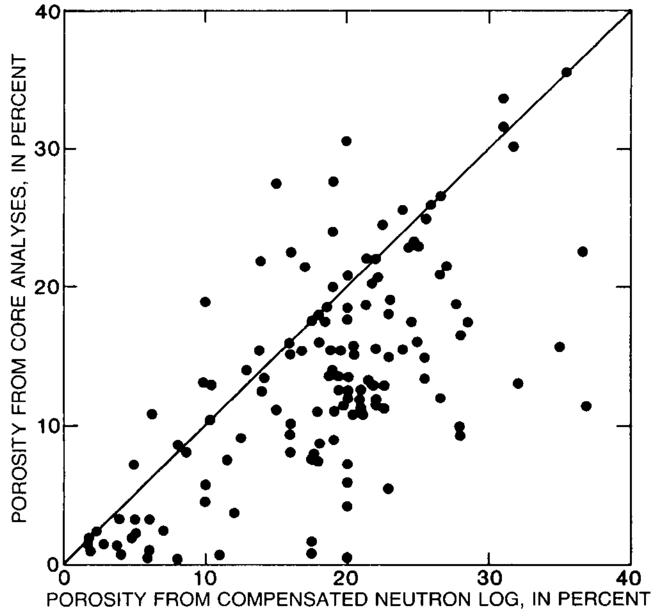

Figure 26.—Porosity from core analyses versus porosity from a compensated neutron log, Madison Limestone test well 1, Wyoming.

Care must be taken to ensure that the components of a calibration facility—the fluid, rock matrix, and borehole—do not change over time. An example of change is wear of the borehole caused by centralizing or decentralizing bow springs or caliper arms. A well frequently used for testing the acoustic televiewer at Mobil Oil's Dallas Research Center has three obvious grooves worn by the centralizing bow springs of televiewer probes.

At least three, and preferably more, values are needed to establish a calibration curve using pits; many more values are needed if core is used. Log values for calibration should be based on both continuous logging runs and stationary measurements. Measurements are best made at depths where the physical property being measured is consistent, if the depth interval is greater than the vertical dimension of the volume of investigation of the probe. Particularly for the nuclear probes, the logs should be run very slowly, and the stationary measurements should be long term to decrease statistical error. If spacings or other probe parameters are to be changed, then calibration is needed at each of these adjustments. The field standards to be used on the logging truck should be checked before and after calibration to determine the relation between log values given by these standards and calibration values, and to ensure probe stability during the testing period. Corrections to nuclear logs may have to be made for the decay of radioactive sources based on half-life.

## Standardization

Field standards should be checked before and after each log is recorded, and the values should be written on the log if the data are to be used quantitatively. Frequent standardization of probes provides the basis for correcting for system drift over time. Radioactive decay of sources used in probes or in calibration is the only form of drift that can be calculated; standardization is needed to check the calculations. Obviously, equipment for checking field standards must be portable and easily used, but it also must be stable and affected little by the different conditions at each well site. An example of a nonstable standard is a once-used commercial neutron "calibrator" that changed as the plastic insert gradually absorbed water. Most field standards are not infinite with respect to the probes on which they are used, so they are affected by the environment. The best that can be done to reduce these extraneous effects is to raise the standard and probe off the ground and move away from the logging truck. Neutron probes, for example, are affected by moisture changes at the ground surface near the probe; a pair of folding sawhorses is useful for reducing ground effects. Values for field standards usually are point values, and these digital values should be recorded on the log heading. Several long-time readings, at least 100 s, are needed for nuclear probes. While the readings are being recorded, the analog recorder should be operated on time drive so variations in probe output are recorded as a function of time. If drift is observed on the analog record, the final measurement should be made after the readings have stabilized. The long-time value is then divided to produce the same count-rate units as the log.

Two or more field standards should be used to provide at least two values; more values may be included if size and time involved are not limiting factors. These values should be in the same range as the borehole data being recorded. For example, a 100-percent porosity value is fairly easily obtained for a neutron probe in a large volume of water, but this small count-rate point does not establish probe response at less than 1 percent porosity where the count rate will be more than an order of magnitude greater. Some standardization can be done in a borehole; zero resistivity can be measured in a water-filled steel casing of sufficient length to include all electrodes. Casing of known diameter also provides an excellent check of caliper and flowmeter calibration. Logs for which there are no standardization data cannot be used with confidence because all logging probes are susceptible to malfunction and drift and the effects of any malfunction or drift may not be identified readily on a rapidly varying log.

## Test 1.—PRINCIPLES, EQUIPMENT, AND LOG-ANALYSIS TECHNIQUES

1. Geophysical well logging reduces project costs because it
   - a. Eliminates the need for coring.
   - b. Provides more information from each borehole.
   - c. Enables lateral and vertical extrapolation of test results.
   - d. Aids in the selection of depth intervals for hydraulic testing.
2. The intrinsic accuracy of geophysical logs is usually limited by
   - a. Inadequate electronic circuits.
   - b. Borehole effects.
   - c. Operator error.
   - d. The fluid in the borehole.
3. Some geophysical logs can indicate permeability because
   - a. Porosity and permeability are always related.
   - b. Clay content can be related to permeability.
   - c. Water flow measured in a well is an index of permeability.
   - d. Computer analysis of several logs provides accurate values of permeability.
4. Which of the following geophysical logs measure(s) porosity directly?
   - a. Neutron.
   - b. Acoustic velocity.
   - c. Gamma-gamma.
   - d. Resistivity.
5. The formation-resistivity factor ($F$) is equal to
   - a. Porosity ($\phi$).
   - b. $1/\phi^2$.
   - c. Water resistivity ($Rw$).
   - d. Saturated-rock resistivity divided by water resistivity ($Ro/Rw$) .
6. Synergistic analysis of geophysical logs is beneficial because it
   - a. Helps in identifying errors in individual logs.
   - b. Can improve the accuracy of data on porosity from logs.
   - c. Can provide more diagnostic identification of lithology.
   - d. Might decrease the number of logs needed.
7. Computer analysis of geophysical logs
   - a. Eliminates the need to understand the logs.
   - b. Decreases project costs.
   - c. Can correct some operator errors.
   - d. Is the best means to collate data from a large suite of logs.
8. The volume of investigation of a logging probe
   - a. Usually is related to the source-detector spacing.
   - b. Limits the resolution of thin beds.
   - c. Includes all material 5 ft from the borehole.
   - d. Varies with rock type.
9. Quality control of geophysical logs is the responsibility of the
   - a. Equipment operator.
   - b. Company providing the equipment.
   - c. U.S. Geological Survey observer at the site.
   - d. Project chief who planned the operation.
10. Standardization (field calibration) of geophysical logs should be done
    - a. Only when a problem is identified.
    - b. Daily.
    - c. Before and after every log.
    - d. Whenever the operator has time.
11. The difference between a portable or suitcase logger and a large oil-well-logging truck is
    - a. Related mostly to depth capability and the availability of a suite of probes rather than to log response.
    - b. Basically the number of cable conductors and recording capability.
    - c. The size (diameter) of the borehole that can be logged.
    - d. The cost.
12. Digital recording of geophysical logs at the well site is desirable because it
    - a. Is more accurate than digitizing the analog record.
    - b. Is less expensive than digitizing later (assuming digital recording equipment is available).
    - c. May permit correction of analog errors.
    - d. Can be done faster than analog recording.

# Electric Logging

The term "electric logging" sometimes is used to encompass all types of geophysical logs. In this report, electric logging refers only to logs that measure potential differences due to the flow of electric current in and adjacent to a well. Logical subdivisions of electric logging are spontaneous-potential and resistivity logging, although the latter can include a variety of techniques for measuring rock resistivity. Many types of resistivity logs that have been used in the petroleum industry but very little in ground-water hydrology are discussed briefly here.