CALIBRATION AND STANDARDIZATION OF GEOPHYSICAL WELL-LOGGING EQUIPMENT FOR HYDROLOGIC APPLICATIONS

By Richard E. Hodges

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Multiply SI units	By	To obtain inch-pound units
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter per minute (m/min)	3.2808	feet per minute
meter (m)	3.28	feet

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ABSTRACT

Hydrologists and technicians working with logging equipment at the site of a borehole need a summary of calibration and standardization procedures for small-diameter probes used for obtaining geophysical logs for hydrologic applications. Reliable data can be obtained from geophysical logs by using sound calibration procedures. Such factors as probe hysteresis, dead time, non-linearity, drift, and borehole effects need to be considered and taken into account. This report provides a basis for developing a calibration program for geophysical well-logging equipment used in ground-water hydrology. Probes discussed are: caliper, temperature, nuclear (natural gamma, gamma-gamma density, and neutron porosity), and electric.

INTRODUCTION

Calibration is an essential step in the quantitative evaluation of geophysical well logs, yet it is one of the most overlooked aspects in well-log analysis. Calibration equipment varies from simple calibrators or standards, such as caliper calibration bars with holes drilled at known distances for controlled diameter measurements, to specially constructed boreholes or pits penetrating materials of uniform properties for density- and porosity-probe calibration. The purpose of this report is to summarize calibration and standardization techniques for hydrologic applications, and to provide an introduction to the procedures needed to establish a calibration program. Step-by-step calibration procedures for each type of probe commonly used by the U.S. Geological Survey are described in this report.

Calibration is the process of assigning values to geophysical measurements. Because most measurements made in well logging are indirect measurements, measured values need to be related to rock or aquifer properties of interest. For example, many caliper probes record changes in a variable resistor, where resistance values are related to the average displacement of the caliper arms. The slidewire of the resistor is connected to the arms of the caliper probe, causing the resistance to change as a function of borehole diameter. As a result, the resistance output of the probe needs to be related to borehole diameter. In the case of a neutron-porosity probe, the output is a varying pulse rate. The number of pulses per second produced by the probe is related to the hydrogen content of the materials surrounding the borehole; that content is an indication of the porosity in a saturated formation. Therefore, the neutron-porosity probe measures the pulse per second caused by neutrons interacting with a lithium-iodide

(LiI) or a helium-3 (He3) detector; that measurement then is related to porosity by a suitable calibration procedure.

Although this report emphasizes the practical problems related to numerical values on geophysical well logs, the reader needs to be aware that both mathematics and statistics have been used for development of most calibration procedures. Equipment has been designed to insure that there is a significant statistical correlation between actual measurements and the property of interest. Even so, there may be additional important variations related to other rock properties and borehole properties not normally considered.

CALIBRATION OF CALIPER PROBES

The four basic caliper probes are:

1. Three-arm caliper. This caliper has three arms connected to one central piston that changes a variable resistor, and produces a signal proportional to the average deflection of the three arms. This probe is probably the most common type of caliper probe used by the U.S. Geological Survey.
2. Single-arm caliper (rugosity probe). This caliper has a single arm, and is usually used simultaneously with another probe, such as the gamma-gamma-density probe. The primary purpose of the arm is to decentralize the logging probe. Such decentralized probes are sensitive to borehole-wall roughness. This information about variations in borehole diameter (rugosity) is needed in log-interpretation calculations.
3. Pad-type caliper. This caliper is not used often by the U.S. Geological Survey because it is insensitive to small borehole-diameter changes. This caliper usually is used in conjunction with a large, multifuction probe of the type used in oil-field applications. This caliper serves a dual function in that the pad contains other instrumentation for measuring density and porosity that need to be measured by a decentralized probe. The primary purpose of the caliper arm (pad) is probe decentralization, but the large size of the pad makes the caliper insensitive to rugosity.
4. Four-arm caliper (X-Y). This caliper has two independent pairs of arms; it produces two traces at right angles to each other. The primary purpose of this probe is for determining borehole volume and detecting any ellipticity in the borehole.

The calibration of all four of these caliper probes is almost the same; they are calibrated at the logging site before and, in some instances after obtaining the log. Calibration equipment consists of a bar with either notches or holes cut or drilled in it at measured radii (fig. 1), or a set of rings of known diameter. If a bar is used, it needs to be designed for the probe. For multiarm probes, the notches or holes are measured from the center line of the probe (example: for a 10-cm-diameter borehole, the outer edge of the notch will be 5 cm from the center line of the probe). For a single-arm probe, the bar will be notched so the end of the arm and the opposite side of the probe correspond with the borehole diameter. Calibration involves inserting the probe into the calibration device, so that all arms are making contact with the ring or the

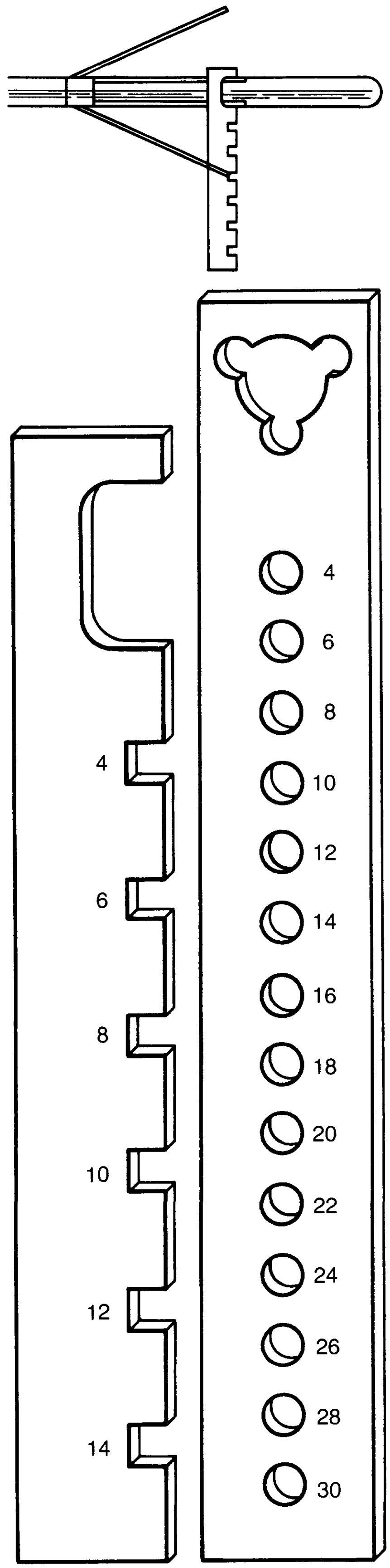


Figure 1.--Calibration bars for caliper probes.

body of the probe, and the appropriate arm is making contact with the bar (fig. 1); at least three different diameters need to be used to include the range expected to be encountered. All measurements need to be recorded on the log. Because the caliper probe is a mechanical device, it is helpful if you make your calibration in two directions (moving from smallest to largest diameter and then reversing the procedure). This will enable you to determine how much hysteresis there is in your probe and indicate the potential error there can be at any given point on the log. Usually the same devices are used for calibration and onsite standardization. The accuracy of calibration can be checked by logging up into casing of known inside diameter.

CALIBRATION OF TEMPERATURE PROBES

Temperature-probe calibration requires a stable temperature bath to submerge the entire probe body, or at least several centimeters of the probe, above the sensor. The temperature regulator is set at the desired temperature, but a calibrated laboratory thermometer positioned near the probe sensor is used to verify the temperature. Record each temperature and the corresponding probe output, after allowing time for the bath to reach equilibrium. Tabulate your readings and compile a graph of probe output versus temperature for quick reference at the logging site.

Two temperature points--freezing (obtained using a bucket of ice water) and boiling--are easy to obtain at the logging site. These two temperatures provide a good standard to check the operation and accuracy of the probe. Some probes with glass-bead thermistors will be damaged by boiling temperatures, so care needs to be taken. Some probes also have a resistor to switch in, in place of the sensor. This switch replaces the sensor with a precision resistor that causes a known count rate or probe output to be generated, which is useful for checking probe operation and stability.

CALIBRATION OF NUCLEAR PROBES

Natural gamma, gamma-gamma density, gamma spectral, and neutron porosity are commonly used probes. Nuclear logs can be obtained with or without casing in the borehole. The problem with logging through casing is not knowing what the borehole conditons are behind the casing. Because all these logs are effected by borehole rugosity, grout and various other conditions that are difficult to determine, the value of the data may be in questionable.

All nuclear logs are obtained with a probe that transmits pulses or digital data. These probes produce a series of pulses with count rates varying as a function of the intensity of the radiation field. All nuclear logging systems have similar equipment, including a probe a ratemeter or pulse counter (if digital), and a recorder. All equipment needs to be calibrated by a qualified person with precision equipment to avoid measurement errors. However, with the use of onsite standards, pulse generators, and small test sources, you can make some checks and measurements to determine if your equipment is working properly after it is calibrated.

The first step in calibrating a nuclear logging system is to calibrate the ratemeters and recorder by sending them to the manufacturer or to a local service representative for your equipment who will calibrate them using techniques and equipment traceable to National Bureau Standards (NBS). After this equipment has been calibrated, a pulse generator, a digital pulse counter, a portable onsite standard for the probe, and a matched pair of radioactive sources can be used to make some important measurements.

DEAD TIME

Two factors that need to be determined for all nuclear probes--, system stability and dead time--, can be determined simultaneously. Dead time is the time that is required for the system to receive a pulse, process it, and get ready to receive the next pulse. Dead time is usually between 10 and 30 microseconds. Because dead time is so short, it accounts for a small portion of total measuring time at low count rates. However, dead time can cause a large error at higher count rates (fig. 2). The two-source method (Scott, 1980) is an easy method for determining dead time (fig. 3). To use this method, two radioactive sources that are almost identical in strength are needed. With both sources in their shields, make a series of measurements, using the digital pulse counter to determine background radiation. A series of 10-second or 100-second measurement periods, used to obtain an average pulse-per-second rate, are more accurate than one long measurement period of 1,000 seconds. This provides a check of the thermal or time stability of your system by determining if the count rate is drifting higher or lower with each measurement period. After the background radiation is determined, place one of the sources (S_1) near the probe; make a series of measurements and determine the average pulse-per-second rate. Leaving S_1 in place, set the second source (S_2) near the probe, but far enough from S_1 so as to not interfere with S_1. Make another series of measurements and determine the average pulse-per-second rate. This will be the value for S_{12}. Next, remove source S_1 and obtain the value for S_2 alone, as before.

Dead time can be calculated using the equation:

$$t=2(n_1+n_2-n_{12})/(n_1+n_2)n_{12} \qquad (1)$$

where t is dead time,
n_1 is S_1 count rate minus background radiation,
n_2 is S_2 count rate minus background radiation, and
n_{12} is S_{12} count rate minus background radiation.

After dead time has been determined, it can be used to correct the measured count rate to actual count rate by using the equation:

$$N=n/1-nt \qquad (2)$$

where N is the corrected or actual count rate, and
n is the measured count rate.

After the ratemeters and recorder have been calibrated and dead time has been determined for each probe system, calibration can be done.

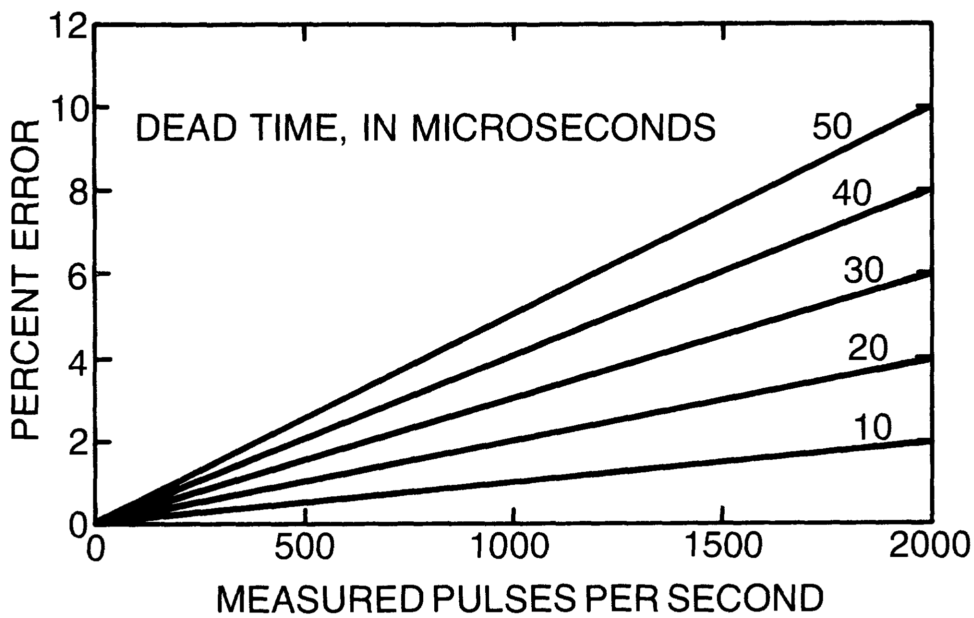


Figure 2.--Percentage of error that can be produced with different dead times.

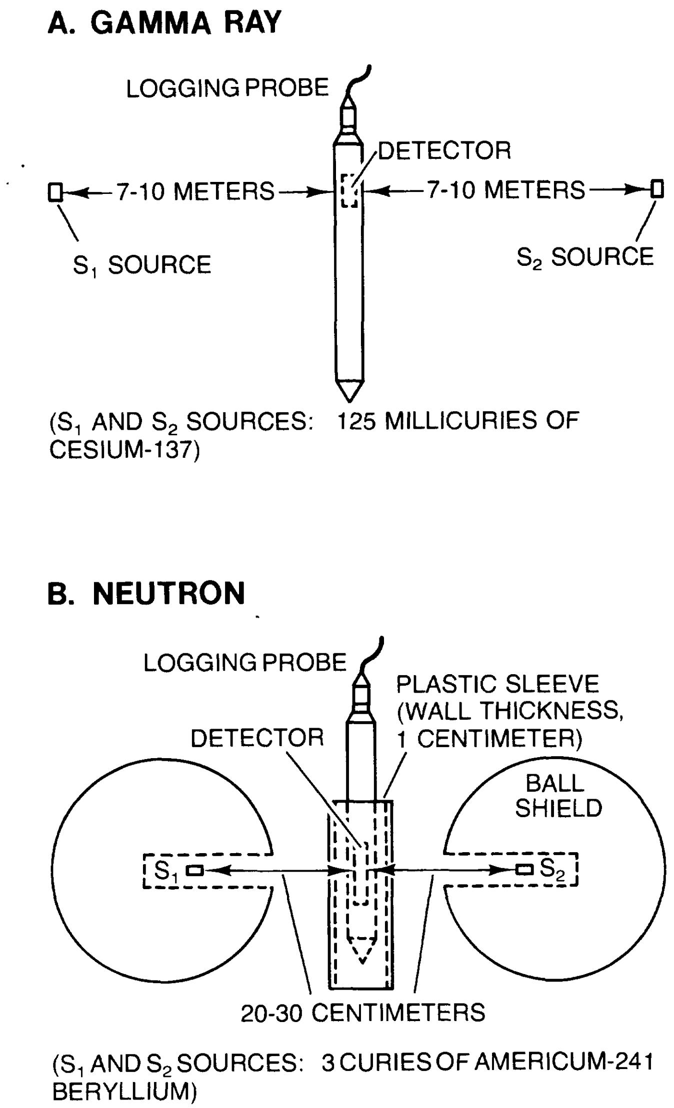


Figure 3.--Plan-view sketches of probe and radioactive source position needed to make dead-time measurements; (A) natural-gamma probe; (b) neutron-porosity probe (modified from Scott, 1980).

USE OF CALIBRATION PITS

Calibration pits are the primary source of calibration data for nuclear probes. Two calibration pits are available at the University of Houston, Tex., one for natural-gamma probes and one for neutron-porosity probes. These pits are considered the standard in the petroleum industry. Almost all commercial gamma and neutron logs are calibrated in units derived from these pits. Another set of calibration pits are located at the U.S. Department of Energy's facility in Grand Junction, Colo. These pits were developed primarily for the uranium logging industry, but also are used for calibrating gamma-spectral probes or KUT (potassium, uranium, and thorium) logs, as they are commonly referred to.

The purpose of a calibration pit is to provide an environment under which measurements can be made with known conditions. Dimensions of the calibration pit need to be such that the diameter exceeds the diameter of investigation of the logging probe and the thickness of the material is large enough so as not to be effected by an overlying or underlying layer (bed thickness effect). The material measured in the pit needs to be as uniform in its characteristics as possible for each zone. Because most calibration methods are based on a linear correlation between probe response and desired formation properties (each calibration line specified by slope and intercept), zones need to be available with at least two but preferably more different values. All characteristics such as borehole diameter, fluid quality, probe position, and temperature need to be constant for each calibration. After these conditions are provided for a given probe, additional calibrations can be made to determine corrections for borehole-diameter changes, probe standoff, and mudcake thickness.

ONSITE STANDARDS

Onsite standards are devices that enable simulation of a reading of the rock characteristic to be measured in area where calibration pits are not available. These devices need to have long-term stability and produce repeatable measurements. The manufacturer of your equipment can supply you with an onsite standard for your probe or you can design your own. Some examples of onsite standards that are available for different probes are described here. An onsite standard for natural-gamma probes may consist of a rectangular frame with two low-level radioactive sources, typically cesium-137, mounted on each top corner of the frame. The logging probe then is clamped to the frame with the detector centered between the two sources, and a measurement is made (fig. 4). An onsite standard for neutron-porosity probes can be a cylinder or a box-shaped sleeve made from a material with a substantial hydrogen content (fig. 5). The sleeve is positioned on the probe at various points to simulate different values of porosity. Currently (1988), there is no accurate, portable onsite standard for gamma-gamma-density probes. Geophysical loggers use density calibration blocks of magnesium, aluminum, and acrylic; at best, they can be considered semiportable. These are a primary calibration for the probe.

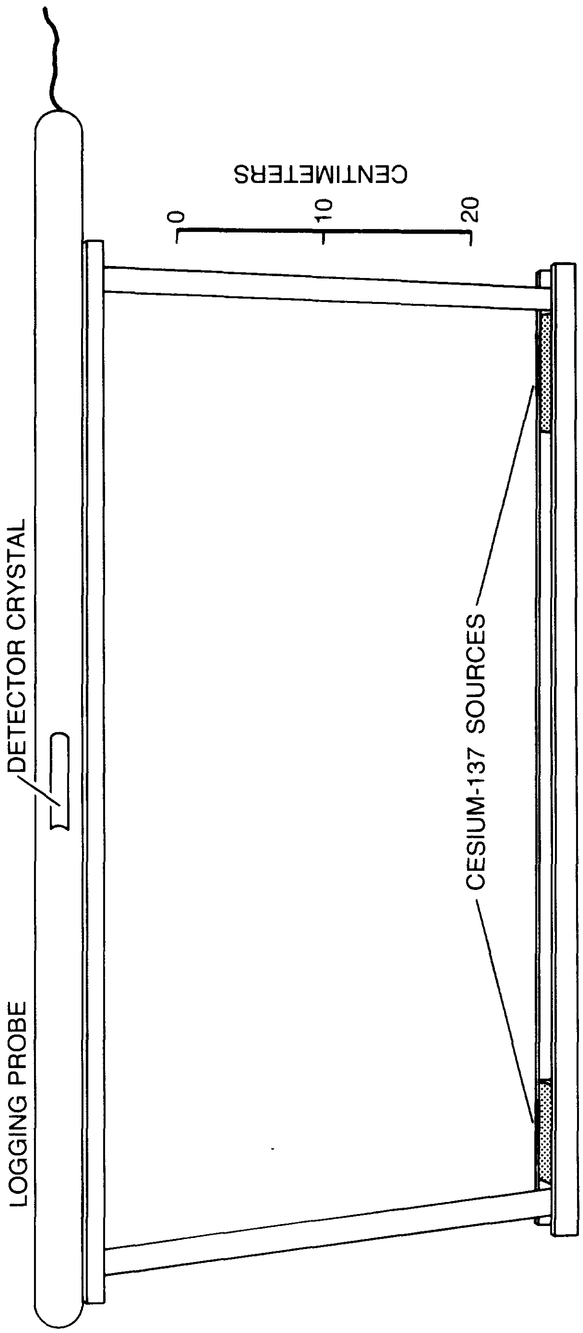


Figure 4.--Onsite standard for natural-gamma probes.

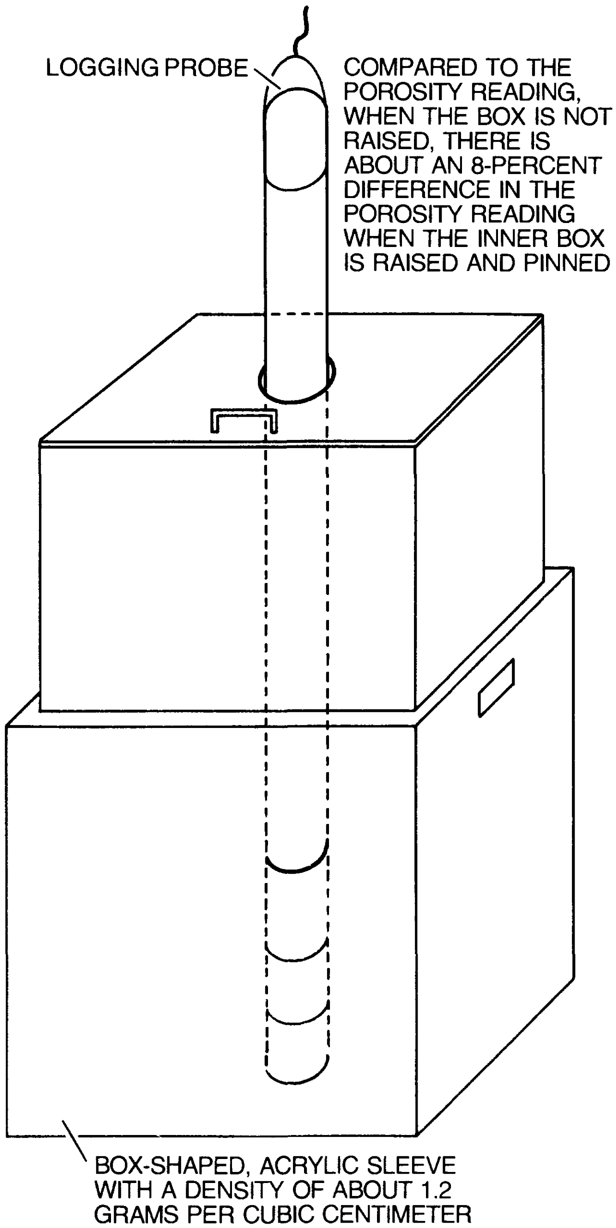


Figure 5.--Onsite standard for neutron-porosity probes.

NATURAL-GAMMA PROBES

The most widely used calibration for natural-gamma logs is the American Petroleum Institute's (API) gamma-ray unit. An API gamma-ray unit is defined as 1/200th of the difference in radiation between the central and either the upper or the lower radiation zones in the API gamma-ray calibration pit (fig. 6) at the University of Houston. Radioactivity of the material in the original API pit was designed to simulate twice the average radioactivity of mid-continent shale from North America.

The procedure for calibration:

1. Clamp the onsite standard to the probe, make a series of measurements at intervals of 100 seconds or longer, and determine the average of the measurements.
2. Remove the onsite standard from the probe, lower the probe to the bottom of the pit, raise the probe so that the detector is at the center of the lower radiation zone, make a series of measurements for 100 seconds, or longer and determine the average, raise the probe so that the detector is at the center of the central radiation zone, make measurements for 100 seconds as before, raise the probe so that the detector is at the center of the upper radiation zone, and make another series of measurements.
3. Lower the probe to the bottom of the pit and raise the probe continuously at a slow speed (about 1.5 m/m) to the top of the pit; make continuous measurements during the raising of the probe.
4. Remove the probe from the pit, clamp the onsite standard to the probe, make a series of measurements at intervals of 100 seconds or longer, determine a average of the measurements, and compare this average with the average determined in step 1 to verify that no drift has occurred in the probe or in the electronics.
5. Calculate 1 API gamma-ray unit to determine the number of pulses per second that equals 1 API gamma-ray unit; this calibrates the probe in API gamma-ray units.
6. Divide the average of the measurements made using the onsite field standard by the number of pulses per second equal to 1 API gamma-ray unit; this calibrates the onsite standard in API gamma-ray units and provides data for checking calibration and proper probe operation in the future.

This procedure needs to be followed for each probe even if the same size crystal is used. However, onsite standards may be used to determine the approximate relation between the response of different probes.

GAMMA-GAMMA-DENSITY PROBES

Two basic types of gamma-gamma-density probes exist: single detector and dual detector probes. Both probes use a radioactive source, usually cesium-137, however, the dual detector is decentralized (pressed against the borehole wall by means of a caliper arm or by a decentralizing bow spring or both) and collimated (shielded to prevent detection of gammas rays arriving from the borehole side of the probe), allowing for some borehole compensation.

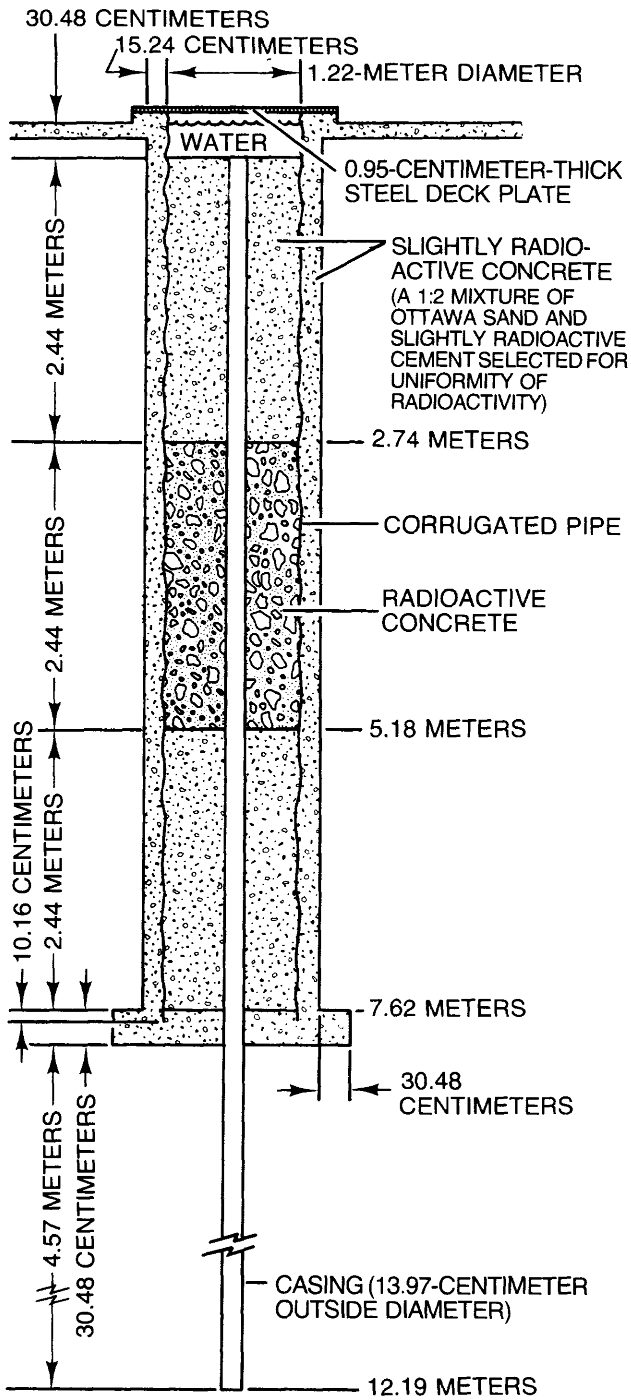


Figure 6.--Gamma-ray calibration pit at University of Houston, Tex. (modified from American Petroleum Institute, 1974).

Borehole factors that need to be considered when analyzing gamma-gamma-density logs are: borehole rugosity, borehole diameter, mudcake thickness, and whether the hole is dry or fluid filled. Unfortunately, calibration facilities for small-diameter gamma-gamma-density probes are limited. At times calibration blocks from a commercial logging company may be used, but they will probably have holes or grooves in them for larger diameter probes (10-cm-diameter or larger). Small-diameter calibration pits are available at the Federal Center in Denver, Colo. The facility, which is operated by The U.S. Geological Survey, includes three concrete calibration pits with bulk densities of 1.7, 2.3, and 3.0 g/cm^3. All three pits have 76.2-mm-diameter boreholes; the pit with a density of 2.3 g/cm^3 also has 127.0-, 203.2- and 304.8-mm-diameter boreholes (fig. 7). These boreholes, combined with values from magnesium, aluminum, and acrylic calibration blocks (bulk densities of 1.76, 2.62, and 1.28 g/cm^3, respectively), can result in accurate calibrations in a 76.2-mm-diameter borehole, and also indicate some borehole-diameter effects.

As with the natural-gamma probe, the first step in calibration is to verify calibration of the recording equipment, and to determine dead time and stability of the probe. At least two calibration blocks need to be purchased with the probe--a magnesium block (bulk density of 1.76 g/cm^3), and an aluminum block (bulk density of 2.62 g/cm^3). Place the probe in the groove machined in the block, making certain that the detectors and source are within the ends of the block, and that the probe is set snug in the groove, with no gaps between the probe and the calibration block, to obtain valid readings. The probe should always need to be in the same position lengthwise with respect to the block. The blocks need to be placed in an area away from other sources of radiation and about 0.5 m off the ground. This will allow for consistency between readings and minimize error. Make a series of 100-second or longer measurements and determine the average as you complete the measurements for each block. For a dual-detector probe, plot the density of the material, in grams per cubic centimeter, versus the count rate of each detector. For the short-spaced detector, use linear scales for both types of data (fig. 8). For the long-spaced detector, use a linear scale for density and a logrithmic scale for count rate (fig. 9). Each detector is now calibrated in density units assuming a smooth borehole, no mudcake, and the probe is snug against the wall of the well.

After calibrating each detector in density units, start assessing the effects of borehole conditions. This is best done with a dual-detector probe by plotting the apparent density measured by the short-spaced detector versus the apparent density measured by the long-spaced detector, to develop a spine-and-rib plot (fig. 10). To obtain these data requires at least two pits with a sufficient borehole diameter to accept either the probe and liners for mudcake simulation or the probe and collars for standoff simulation. Again, make a series of readings for each simulated condition and plot them. From these data, the log analyst can develop algorithms for computer analysis as a final step. This calibration procedure is described in detail by Scott (1977).

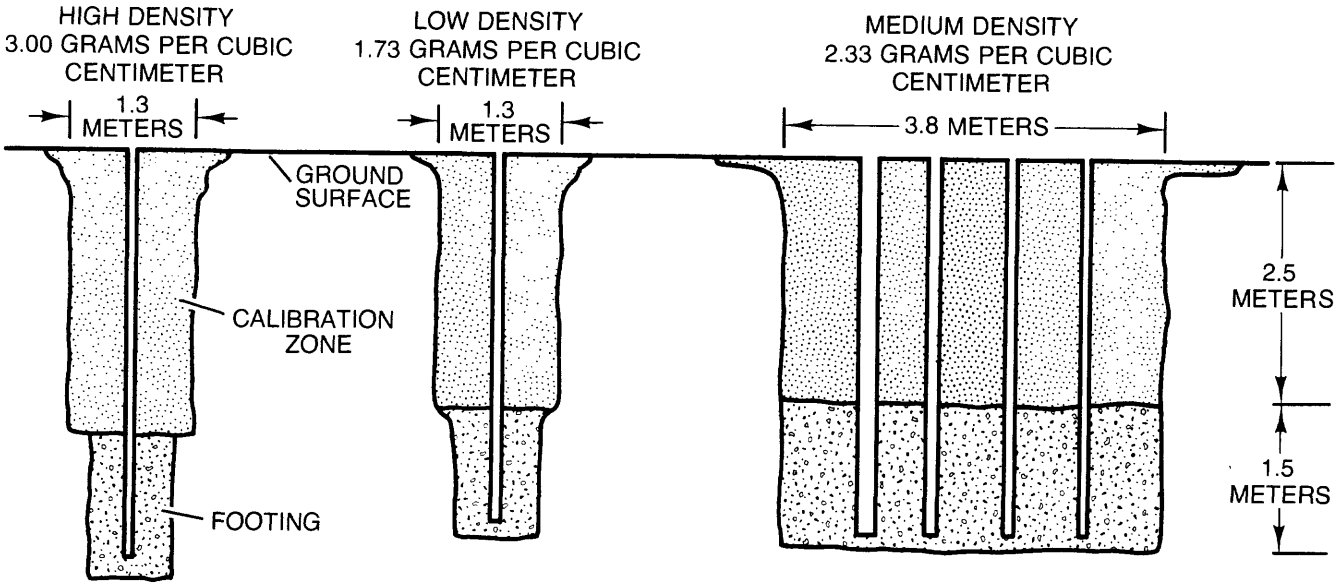


Figure 7.--Density calibration test pits at the Federal Center in Denver, Colo. (modified from Scott, 1977). Borehole diameters in the high-density and low-density pits are 76.2 millimeters, and those in the medium-density pit are 76.2, 127.0, 203.2 and 304.8 millimeters.

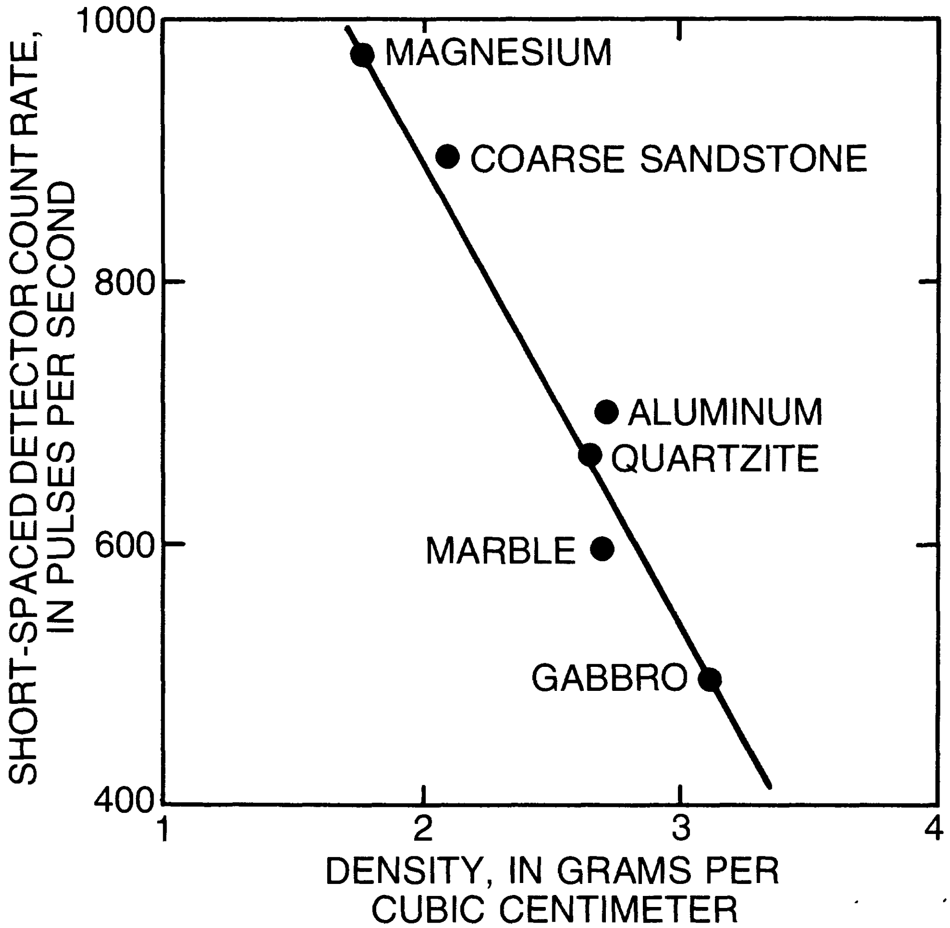


Figure 8.--Density versus count rate for a short-space detector in a 30-centimeter-diameter, water-filled borehole.

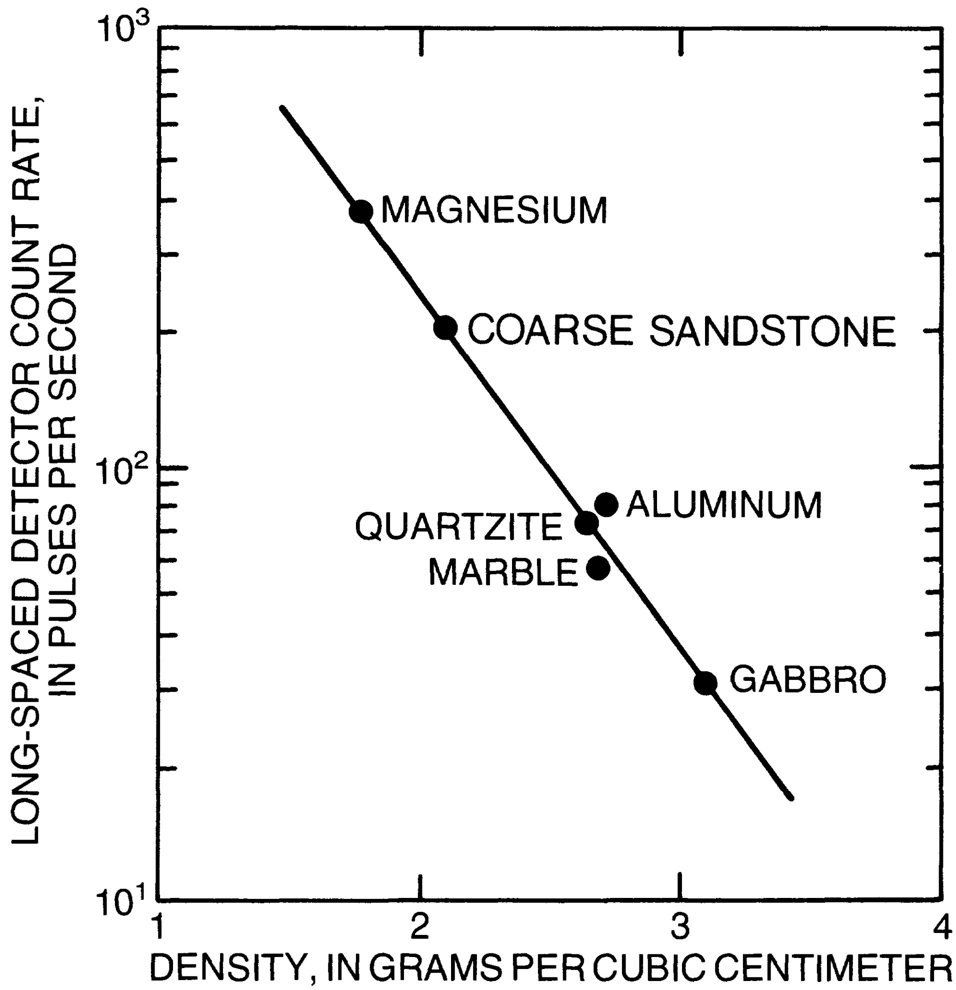


Figure 9.--Density versus count rate for a long-spaced detector in a 20-centimeter-diameter water-filled borehole.

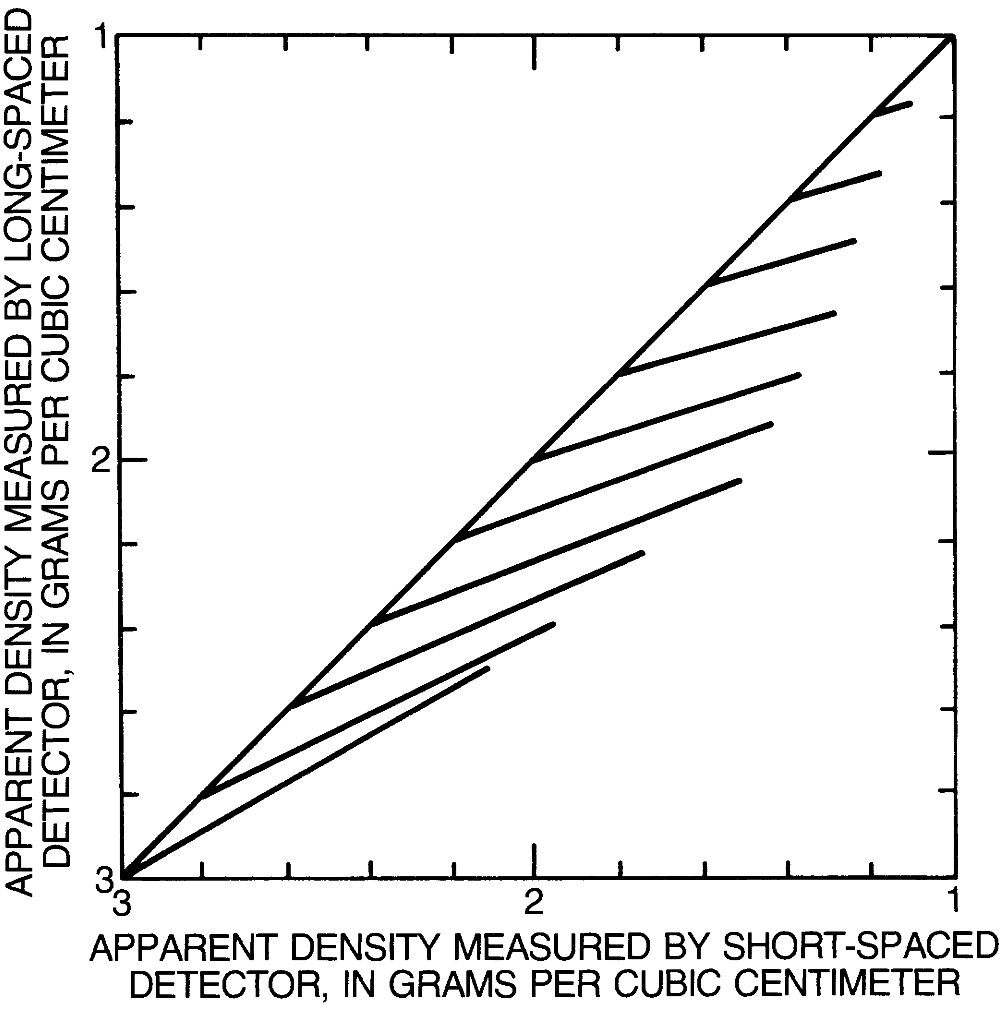


Figure 10.--Spine-and-rib plot of apparent density measured by short- and long-spaced detectors for simulated mudcake thicknesses ranging from 32 to 125 millimeters and simulated mudcake (barite enriched) density of 1.5, 2.0, and 2.0 grams per cubic centimeter (modified from Scott, 1977).

NEUTRON-POROSITY PROBES

Neutron-porosity probes, like the natural-gamma and gamma-gamma-density probes, emit pulses. The first step is to calibrate your recording equipment and make a dead-time correction as described previously. Neutron-porosity logs are calibrated in limestone porosity units. These are measured in the API limestone porosity pit and are the industry standard. Three porosity zones and a 100-percent water reference point are available (fig. 11).

The procedure for a calibration is:

1. Make series of measurements of 100 seconds or longer onsite standard, and determine the average in pulses per second. Repeat this for each available position of the standard.
2. Remove the onsite standard from the probe, lower the probe to the bottom of the three porosity zones, positioning the probes detector at the middle of the zone. Make a series of measurements for 100 seconds or longer and determine the average pulses per second. Repeat this for each of the other two porosity zones and for the water reference point (API recommended depths are 2.74, 4.57, and 6.40 meters).
3. Lower the probe to the bottom of the calibration pit and raise the probe continuously at a slow speed (about 1.5 m/m to the top of the pit; make continuous analog and or digital measurements during the raising of the probe.
4. Remove the probe from the pit and repeat the measurements made in step 1 above. This will verify that no drift has occurred in the probe or in the electronics.
5. Plot the log of porosity versus the linear count rate in pulses per second, similar to the plots in figures 12 and 13.

The probe is now calibrated in apparent limestone porosity. This is important to remember because, for any rock type or matrix other than limestone, a correction factor needs to be applied. There are charts available from various commercial logging companies that contain approximate correction factors, but most of these curves were developed for their probes and may not apply to yours. Also note that calibration of the neutron-porosity log is based on the correlation between count rates and the logarithm of porosity rather than a direct correlation with porosity. Another concern as with most probes is the borehole effect. The effects of lithology and borehole diameter on porosity reading are shown in figures 12 and 13.

ELECTRIC PROBES

Electric probes for hydrologic applications primarily consist of point-resistance and normal-resistivity probes. The point-resistance probe, commonly referred to as the single-point probe, is a qualitative probe used primarily for lithologic correlation purposes. The only possible calibration is ohms per scale unit of recorder deflection. To obtain this calibration, place a fixed resistor across the electrodes of the probe. By changing the value of the resistor, you can calibrate the recorder response in ohms. The use of a resistance decade box for the resistor provides an easy method of quickly calibrating the probe at the logging site. Note that these calibrated

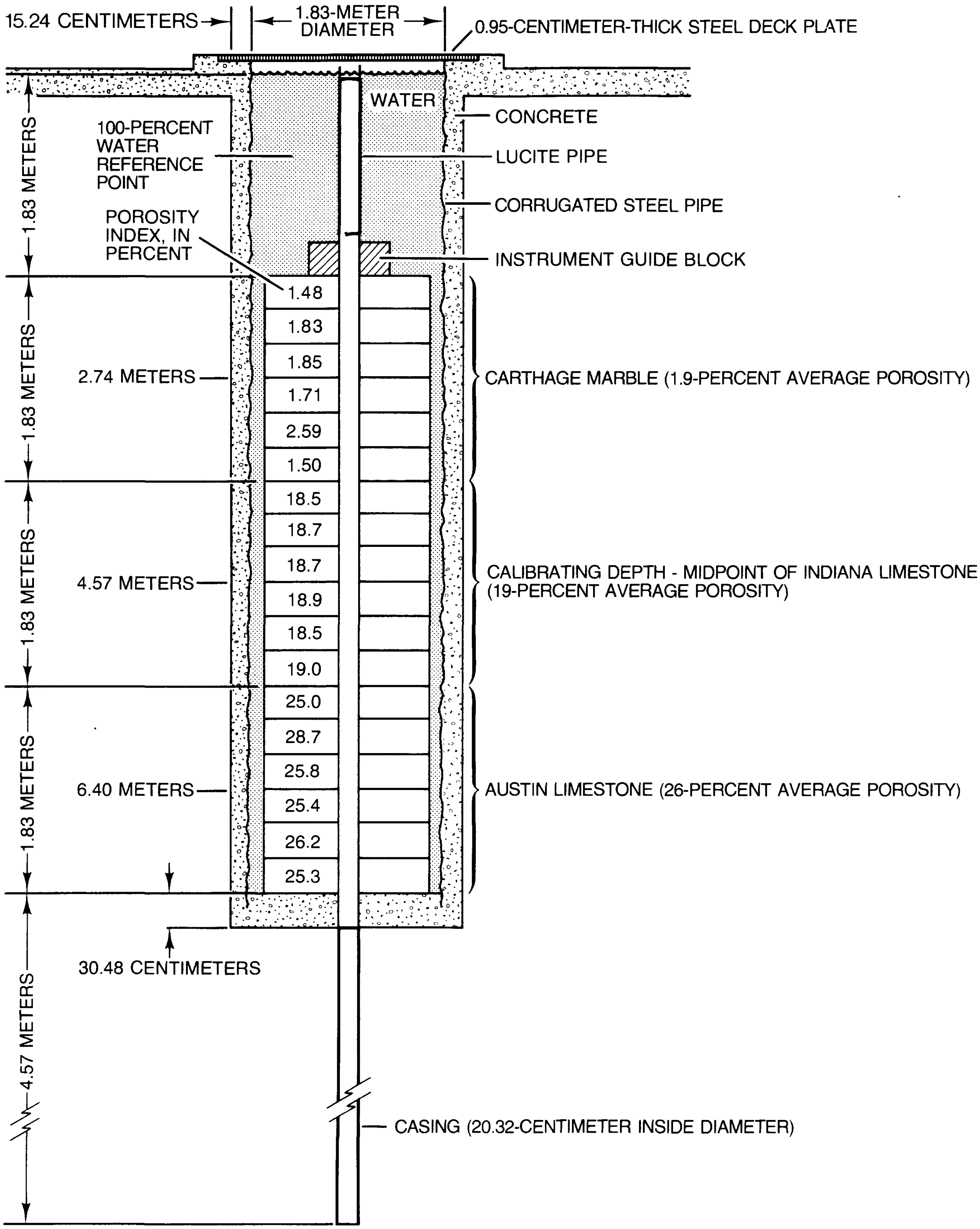


Figure 11.--Neutron calibration pit at University of Houston, Tex.

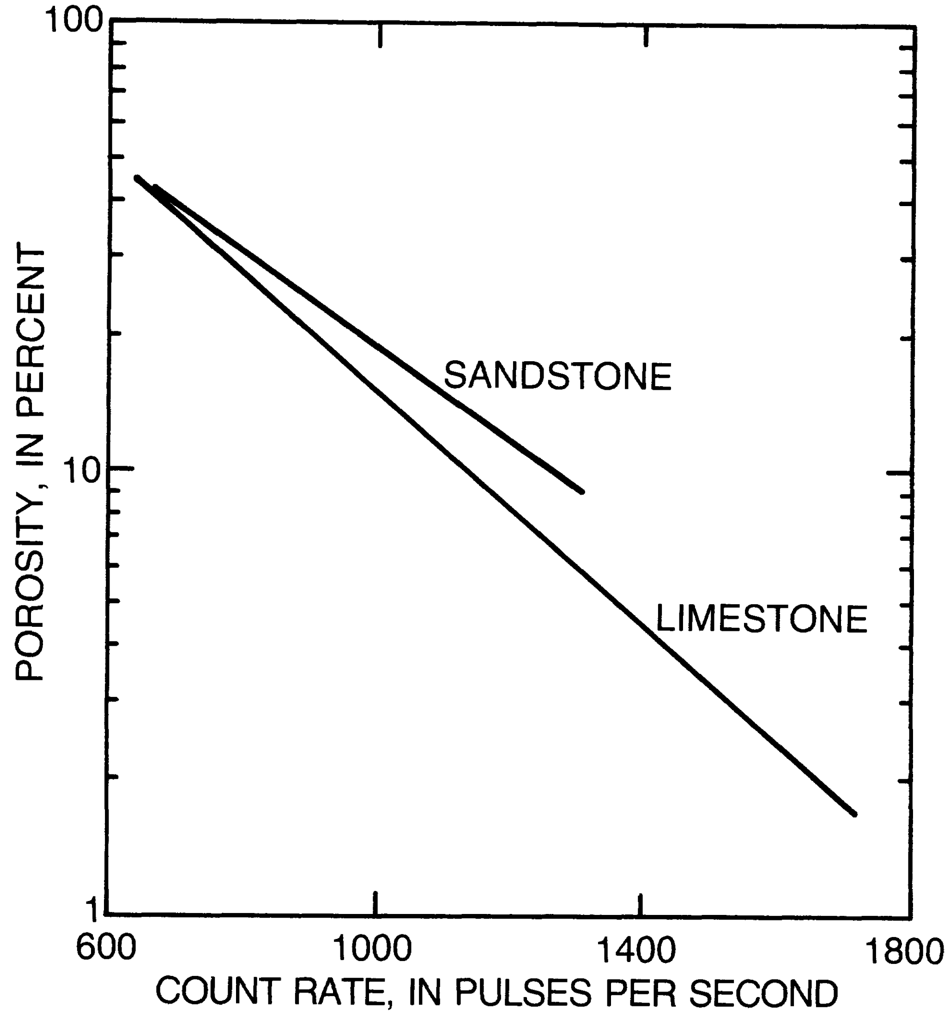


Figure 12.--Effect of lithology on porosity measurements of a neutron-porosity probe in a 20-centimeter-diameter, water-filled borehole.

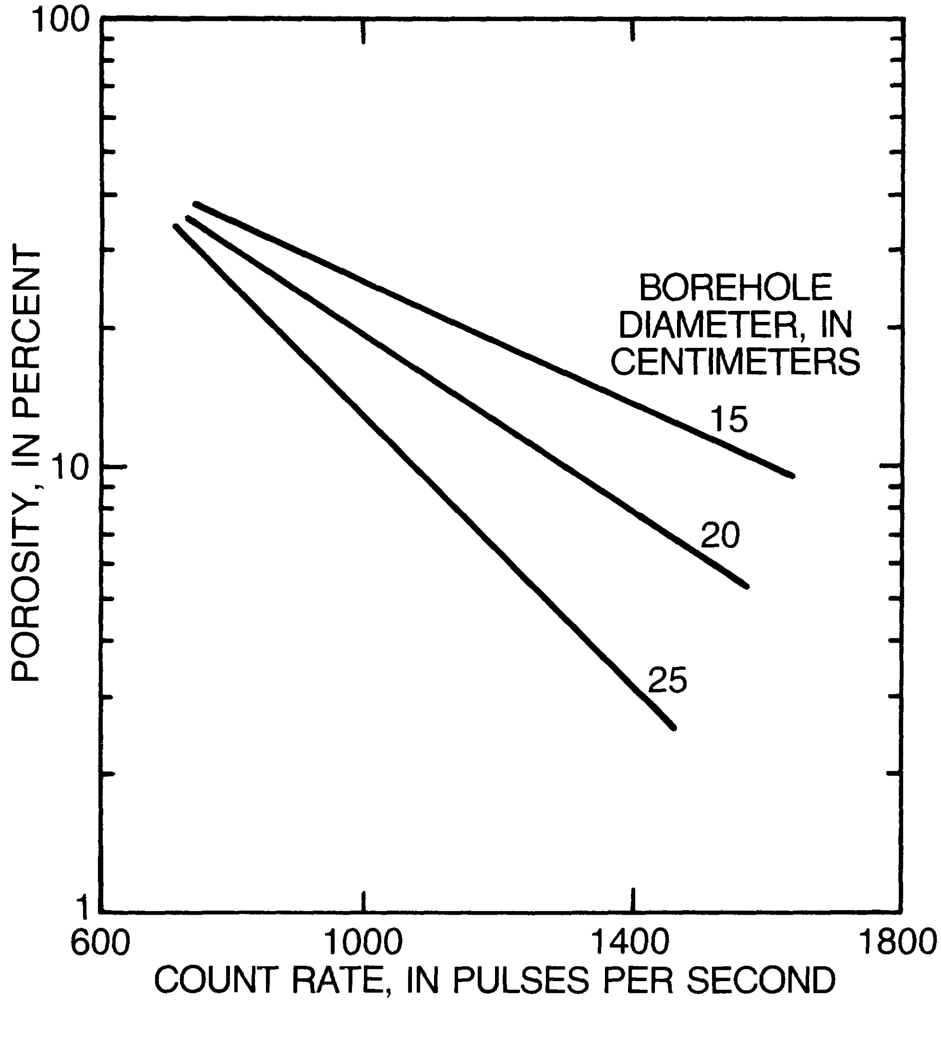


Figure 13.--Effect of borehole-diameter change on porosity measurements of a neutron-porosity probe in water-filled borehole in sandstone.

values represent the total resistance between either downhole and uphole electrodes or between two downhole electrodes in a differential single-point probe; these values cannot be related quantitatively to the resistivity of a specific sample volume.

The normal-resistivity probe is a quantitative probe that gives a reading in ohm-meters. Calibration can be accomplished by building a clamp-on calibrator (fig. 14). By changing the contact from the 40.6-cm electrode to the 162.6-cm electrode and substituting the values for R_f (equivalent formation resistance), you can calibrate a normal resistivity system in ohm-meters. Caution needs to be taken when using this method of calibration as there is the potential for serious electrical shock from the electrodes. If values, other than the ones listed, in the table in Figure 14 are desired use the formula:

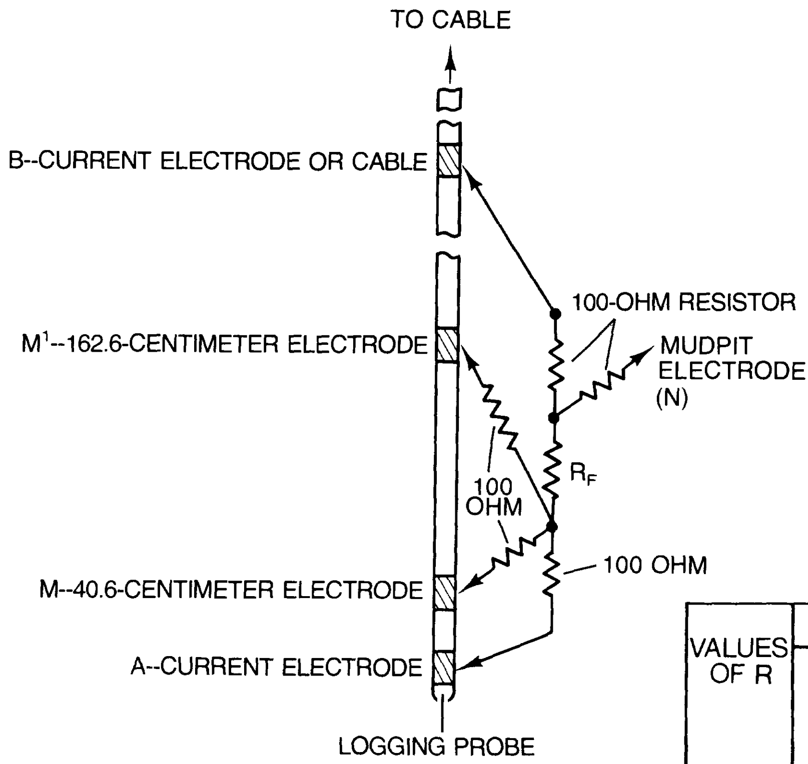
$$R_f = R/4\pi\ AM \qquad (3)$$

where R_f is equivalent resistance of the formation;
R is resistivity, in ohm-meters; and
AM is electrode spacing, in meters.

This relation is based on a theoretical formula for a measured potential difference between two electrodes in an infinite medium of constant electrical resistivity, R. All manufacturers of normal-resistivity systems include internal calibration resistors in the surface module that can be used; instead of a clamp-on calibrator however they only provide a limited range for calibration. An external calibrator needs to be used either if the resistivity value is beyond fixed values of the internal resistors or if more sensitivity is needed.

CORE ANALYSIS

Core analysis also can be used to calibrate logs, and in some instances, this method of calibration can be accurate. There are some factors that need to be considered for this method to be used accurately. The first and probably the foremost concern is to identify depth intervals with good core recovery and uniform log response. The zone of interest needs to be thick enough so that the signal recorded from the logging probe represents only that zone. There also needs to be sufficent core recovery from the zone so that the sample to be analyzed can come from the center of the zone, thus minimizing possible depth errors in either the log or the drilling-depth record. If a zone is chosen where log values vary markedly, an error in footage of just a few inches can cause a major error in fitting core values to log values. Another area of concern is borehole condition. If the zone has a washout or any other condition that will cause the probe to stand off from the wall of the borehole, you will have an error in the log that would be difficult to relate to the core analysis. In addition, a core analysis represents a small volume of rock whereas the logging probe is measuring a much larger volume. Therefore, what you measure in the core may not be representative logging probe. This is especially true for depth intervals with nonuniform secondary porosity. After the intervals for core analysis are selected, a calibration curve can be developed.



VALUES OF R	VALUES OF R_F ELECTRODE-SPACING, IN CENTIMETERS	
	162.6	40.6
10	1.96	0.49
10^2	19.6	4.9
10^3	196	49.0
10^4	1960	490

Figure 14.--Clamp-on calibrator for normal-resistivity probe (modified from Keys and MacCary, 1971).

Another approach using core analysis to calibrate a log is to use a cross-plot technique. Core value versus log response in pulses per second, is plotted for each depth resulting in an oval-shaped distribution of points. The scatter is not measurement error, but rather is expected differences in measurements attributed to differences in sample volume and depth errors. By fitting a line to the scattered points, you can obtain average values for any point on the log for which core data are not available. One advantage with this method is that it incorporates an average of numerous points; this minimizes potential errors from any one measurement. As with other calibration methods, different curves needs to be developed for different lithologies. MacCary (1980) suggests several examples of curves that can be used in a familiar area by using average values for the formation to calibrate log response.

Curves can be developed that are adequate or possibly more accurate than curves developed in calibration blocks for a particular borehole by using core analysis and calibrating to the particular conditions in that borehole, such as mudcake thickness and borehole diameter.

CONCLUSIONS

While it is true that any measurement in a borehole starts with the downhole probe, it also is true that recording equipment that is not calibrated and operating properly can not reliably receive the downhole signals and record them. The use of onsite standards establishes repeatability to ensure that a probe is operating properly. However, onsite standards are not substitutes for calibrations in appropriate calibration facilities. Any major repair or replacement of parts or detectors in a probe is justification for re-calibration. Some electronic components and detectors can drift or deteriorate, so that periodic re-calibration is needed. Understanding calibration procedures, and confidence that probe calibration procedures have been done correctly are important to the quantitative analysis of geophysical well logs for hydrologic applications.

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