Some Practical Aspects of Radioactivity Well Logging

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ABSTRACT

Automatic recording of the radioactivity of the earth’s formations provides a log of relative intensities that, if properly interpreted, can be applied to oil-field engineering. Production, engineering, and geological departments regard the radioactivity log as a forward step in the securing of more conclusive information for successful well completions. Explanations of the technique, together with some of the problems to which radioactivity logging have been applied, are presented in this paper.

INTRODUCTION

Those responsible for the completion of new oil and gas wells, or with planning workover operations on old wells, have followed closely the development of radioactivity well logging because they are interested in reducing the number of unknowns that usually are present in such work. Many operators have made use of the log, or are acquainted with at least one of the applications, but it is unlikely that any one operator is familiar with all of the many applications that are possible.

The purpose of this paper is to present a representative example of each of the many applications, wherever the information has been released by an operator, and to illustrate by hypothetical examples other applications, releases for which have not been given. In this way, it is hoped that a better understanding of the scope of this new engineering tool may be obtained.

Although the literature contains many references that describe in detail the theory, development, and application of radioactivity well logging, a brief discussion of the technique may be helpful to those who are investigating the subject for the first time.

All rocks contain radioactive material in varying concentrations. In general, shales contain relatively more radioactive material than sandstones or limestones. These radioactive materials disintegrate with time into other materials of lower atomic weight, and in that process of disintegration the rocks are emitting many rays, the most penetrating of which is the gamma ray. The intensity of emission of the gamma ray is proportional to the quantities of radioactive materials present. A higher rate of emission would be observed, therefore, opposite a shale than opposite a sandstone or limestone.

Since measurable intensities of gamma rays are capable of penetrating as many as five concentric strings of casing, and as the gamma-ray intensity is relative to the formations, the measurements of variations in gamma-ray intensities offer a means of identifying cased-off formations in their proper stratigraphic sequence.

THE GAMMA-RAY CURVE

The measurement of gamma-ray intensities is accomplished by means of an ionization chamber that consists of a heavy cylinder, about 3 ft. long, that contains two insulated electrodes and is filled with an inert gas under high pressure. Under normal conditions no current will flow through the gas when an electrical potential is set up between the electrodes, but when
the chamber is exposed to gamma-ray radiation the gas becomes partly ionized and permits the flow of a very small current between the electrodes. The amount of this current varies directly as the ionization, which, in turn, is proportional to the intensity of the gamma rays acting upon the gas.

An amplifier in the instrument case with the ionization chamber amplifies these small variations in current, and transmits them, through the logging cable of the hoist truck, to the instrument truck. The instrument truck contains additional amplifiers, sensitivity controls, and an automatic pen-type recorder that translate down-the-hole signals into variations in amplitude of a curve that is developed on a strip chart moving in synchronization with the instrument. The curve that records the variation in intensity of the gamma-ray emissions of earth material with depth is called a gamma-ray curve.

Because both sandstones and limestones are recorded as minimum values on the gamma-ray curve, it is almost impossible to distinguish between the two by inspection of the curve alone. To enable positive identification of sandstone and limestone, the neutron curve was developed to complement the gamma-ray curve.

**The Neutron Curve**

The neutron curve is obtained through the use of an instrument identical to that previously described, but with the addition of a neutron source appropriately shielded from the ionization chamber. Neutrons from this source bombard the earth material immediately surrounding the well bore, and the effect of this bombardment is measured by the ionization chamber. The character of the recorded measurement is such that if the formation contains hydrogen, which is commonly associated with well fluids, the intensity of the recorded curve is considerably less than if the formation were dense and devoid of fluid.

Thus, when a minimum value on the gamma-ray curve is interpreted as either sandstone or limestone, a minimum value on the neutron curve would indicate sandstone, and a maximum value would indicate a dense limestone. This responsiveness of the neutron curve to the presence of fluid also makes it possible to identify zones of porosity in limestone or chalk sections. It should be explained that, although the neutron curve is responsive to well fluids, it cannot distinguish between them, and therefore cannot be used to determine the type of fluid in a subsurface rock.

**Bottom-Water Shutoff**

Fig. 1 illustrates a typical "bottom-water" plug-back operation in the Conroe field, Montgomery County, Texas. The original completion was based on coring information, and the casing was set above the producing stratum, with a liner set through the pay zone. Water production had increased to 30 per cent when plugging back operations began.

A gamma-ray log was run to select a more favorable zone, and the results are shown in Fig. 1. The casing seat is indicated clearly on the log by a shift to the left. The top of the liner also is shown by contrast, in the dampening effect of two strings, versus one string, of pipe, indicated by a shift to the right at the point where only one string of pipe was set.

The liner was perforated opposite the shale at a depth of 5058 to 5064 ft., and a satisfactory squeeze job was obtained, following which the well was perforated for production from 5043 to 5048 feet.

On a production test the well flowed at a daily rate of 100.06 bbl. of pipe-line oil on 3/4-in. choke, with a tubing pressure of 500 lb., and a gas-oil ratio of 538 cu. ft. per barrel.

**Plugging Back to Upper Pay**

Before the introduction of electric logging, a log of a well usually consisted of a
composite record constructed from cores, cuttings, and the driller's interpretation of the formations. The accuracy of such a log was affected by lost cores, careless sampling and measurements, and frequently by weather conditions. Fig. 2 illustrates such a log. This well recently became depleted to a point where abandonment or recompletion had to be considered. From an analysis of the condition of the well it appeared advisable to run a gamma-ray log because subsequent wells had cored, and logged, a gas sand that was not reported on the log of this well. Because gas was needed for local operations, the gamma-ray log was run upward from 6150 to 5000 ft. with a permanent zero point at the lower Christmas-tree flange. The core record, corrected to the same measurements of the lower Christmas-tree flange, showed good correlation agreement. The gamma-ray curve logged a sandstone stratum at a depth of 6050 ft., a point at which no cores were reported.

It should be noted, also, that although the zone from 6035 to 6068 was cored, the reported recovery of only the bottom 2 ft. was actually below the stratum found by the gamma-ray log. The sandstones and shale of the section are so unconsolidated that the cores probably were washed out before reaching the surface.

The well was completed in 1935, and since that time it has been produced from

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**Fig. 1.—Typical application of gamma-ray log in bottom-water shutoff, Conroe Field, Texas.**
the gun perforations shown on the graph to the right of the core record. With the gamma-ray log information at hand, the operator squeezed off the old perforations' nonproductive zones. A gamma-ray log with 100 sacks of cement under a pressure of 2500 lb. per sq. in., and set a packer at 6000 ft.—11 ft. above the uppermost perforations. Fifty-eight sacks of cement was left inside the 7-in. casing, and 14 sacks was washed out through the 2½-in. tubing. The top of the cement plug was at 6073 ft., and with this as a new bottom, the 7-in. casing was gun-perforated with 27 holes from 6050 to 6065 ft. After a test to determine the potential, the well was completed as a gas well, with sufficient volume to satisfy the local needs.

**SALT-WATER DISPOSAL**

Fig. 3 illustrates a driller's log and a gamma-ray log of a well drilled and completed by cable tools in February 1920 in the Electra field, Wilbarger County, Texas. The initial daily production was 30 bbl. from a depth of 1905 to 1930 ft., which is the main pay sand of the field.

Because of salt-water encroachment, the operators discontinued the well on production and converted it to an injection well for the disposal of salt water in the upper nonproductive zones. A gamma-ray log was run for the purpose of verifying the stratigraphy of the driller's log, and to determine the exact depth and thicknesses of any cased-off sandstone or limestone formations that could be used for the disposal of salt water.

After the log had been run, the well was plugged back in February 1944, to 1802 ft., where the 7-in. casing was set originally. The well then was gun-perforated with 75 holes in the zone designated A, between 1340 to 1365 ft., and with 39 holes in the zone designated B, between 1483 to 1498 ft. In May 1945 a total of 150 bbl. of salt water per day was being pumped into these two beds at a pressure of 400 lb. per sq. inch.

While the purpose of the gamma-ray log was to verify the stratigraphy, a comparison of the two logs revealed that zones A and B were not indicated on the original driller's log. The absence also of the other sandstone or limestone formations as disclosed by the gamma-ray log is apparent.

![Diagram of Gamma-Ray Log Applied in Plug-Back to Upper Pay](image-url)
Fig. 3.—Gamma-ray log applied in location of salt-water disposal sands.
FIG. 4.—TYPICAL APPLICATION OF GAMMA-RAY LOG IN LOCATION OF POTENTIAL FRESH-WATER SANDS, DRISCOLL FIELD, TEXAS.
from the upper section of the log. The disagreement regarding the tops and thicknesses of the zones will be noted in the 10\% in. surface pipe, which was known to be at some depth below 700 ft. The freshwater-bearing sandstone was found be-

sections of the two logs that are in partial agreement as to the lithology of the zones.

**FRESH-WATER SUPPLY**

Many depleted wells, or dry holes, could be utilized for fresh-water supply instead of abandoning and terminating their period of usefulness.

Fig. 4 illustrates how a dry hole in the Clara Driscoll field, Nueces County, Texas, was used to supply fresh water for a ranch on which the former supply had failed, and incidentally, to supply water for a number of near-by drilling operations.

The gamma-ray log was run to locate a sandstone stratum behind the cemented between 702 and 739 ft., and the casing was gun-perforated from 705 to 735 ft., with 84 holes of 1\%2 in. diameter.

Water rose to within 10 ft. of the surface, and the well was equipped with a windmill and electric pumps on separate strings of tubing. Production of as much as 1500 bbl. of fresh water per day has been reported, with no appreciable reduction in hydrostatic head.

As a result of this work, another rancher, who was in desperate need of water, ordered a gamma-ray log of an abandoned well that was downdip from the well shown in Fig. 4. The same sandstone stratum occurred at a depth of 750 ft., and after the
top 25 ft. of the bed had been perforated the well produced at a comparable rate.

**LOWERED GAS-OIL RATIO**

The Webb sand in the Flour Bluff field was cored continuously, and the cores indicated a gas-bearing stratum. Production data showed that the reservoir had an expanding gas cap. The depletion to non-commercial quantities of oil from the Phillips sand had caused some operators to plug back their wells to the Webb sand, and to test the extreme bottom of the sand. By selectively gun-perforating a precise interval, commercial quantities of crude oil were produced from an indicated gas-bearing stratum. The change of an expanding gas cap to contracting gas cap was caused by water encroachment, which in its movement has cleansed the sand by pushing the oil upward. Only the edge wells on the steeply dipping flanks, however, produce oil.

The operators in this field were faced with the problem of precise recompletion after plug back, and in order to eliminate any doubt, gamma-ray logs were obtained to locate, accurately, the relative positions of the sand and the bottoms of wells after plugging back. Following the survey, the casing was gun-perforated for squeeze-cementing from 6598 to 6600 ft., to separate the gas and oil, and later the bottom 2 ft. was perforated with 24 holes from 6604 to 6606 ft. The results were most encouraging. The well produced at the rate of 108 bbl. of pipe-line oil on ½-in. choke, with a gas-oil ratio of 1450 cu. ft. per barrel. The gamma-ray log is playing a vital role in this field, where low ratios are of prime importance.

**LOCATING ZONES OF POROSITY**

As mentioned earlier, zones of porosity can be identified by combining the gamma-ray and neutron logs. It will be recalled
that a dense limestone normally will be recorded as a minimum relative value on the gamma-ray log whereas on the neutron log it will be reflected as a maximum relative value, because of the absence of formation fluids. Any zone of porosity in a limestone normally will be indicated by a shift to the left of the neutron curve, because of the effect of the hydrogen associated with formation fluids occupying the pore spaces.

**FOR OIL PRODUCTION**

Fig. 6 illustrates the manner in which the foregoing response patterns were used to complete a well in the Wimberly pool, Jones County, Texas, in which the hole was drilled through the Hope limestone, and the casing was set on top of the Gun-sight limestone. No electrical log was run, and no cores were taken.

Gamma-ray and neutron logs were obtained after the casing was set, and the
SOME PRACTICAL ASPECTS OF RADIOACTIVITY WELL LOGGING

hole was deepened to the bottom pay at a total depth of 2509 ft. The sharp break on the neutron curve shows the casing seat to be 2458 ft., which compares with 2460 ft.

FOR GAS PRODUCTION

Another illustration of the application of the two curves in the location of porous zones within limestone sections, and the production of gas known to exist in the sections, is given in Fig. 7. This combination log of a well in the Rodessa field, Louisiana, indicates the porous streaks in the Gloyd lime. The combination radioactivity survey indicates the utility of the tool in fault-line producing fields, where the porosity in the main pay zones is spotted.

The Rodessa field has little information that is correlative from well to well, and the economy in workover operations is paramount. Rather than gun-perforate from correlative core records, the owner of this well preferred to run the survey for a record, and gun-perforate selectively. As the former pay zone was in open hole, it was desirable to log its porosity, and also accurately locate the casing seat, which can be accomplished easily with the neutron log. The 7-in. casing was found at a
depth of 6049 ft., where a sharp shift to the left was observed on the neutron curve. Clear definition of all the formations is depicted by the gamma-ray curve and of the porous zones by the neutron curve, which are indicated on the chart by the crosshatched blocks. To eliminate bottom-hole water adequately, a wire-line bridging plug was set at a depth of 5975 ft., and three sacks of cement was dumped on top.

The Gloyd limestone was selectively gun-perforated according to the neutron indications from 5893 to 5908 ft., and from 5923 to 5932 ft. The production test showed an immediate flow of 310,000 cu. ft. of gas per day, which gradually increased to 350,000 cu. ft. per day.

After acidizing through the gun perforations with 1500 gal. of acid at a maximum pressure of 930 lb. per sq. in., the well increased in flow to 1,000,000 cu. ft. per day, and finally was completed with a test of 1,250,000 cu. ft. per day. When that production declines to a point where further workover is necessary, the additional zones of porosity indicated on the log may be tested, to extend further the life of the well before abandonment.

**Permeability Studies**

Work of an experimental nature is being done with regard to the application of radioactivity logging to obtain what properly may be termed a "relative permeability profile" in limestone producing horizons.

The specific need for such information was suggested by engineering studies in various limestone producing fields for the selective completion of wells to inject gas or water into the producing horizons for secondary-recovery operation.

The procedure consists, essentially, of running a gamma-ray log to provide a lithologic log of the well, and the neutron curve to locate possible fluid-bearing zones. This is followed by pumping a radioactive tracer, mixed with salt water or oil under pressure, into the producing horizon. By successive runs of the gamma-ray curve the distribution of the radioactive fluid into the permeable zones is indicated on the log.

Because the work to date has not been released for publication, a hypothetical illustration is shown in Fig. 8. It will be noted on the log that the intrusion of the radioactive fluids into the most permeable zone is indicated by successive gamma-ray surveys, which complement the neutron log for proper interpretation of porosity and relative permeability.

A convenient radioactive tracer may be obtained by a laboratory process from a bromide of the element radium. This substance may be converted to a salt or soap solution, which is completely miscible with the liquid in a well.

Conceivably, in any one area where radioactive tracers are used, the natural radioactive strength of the subsurface formations may be altered and thus destroy the basic data upon which radioactivity surveys are made. Consideration should be given to the use of radioactive tracers having a relatively short life period, so that the effect of the tracer will disappear in a definite time. Many suitable substances possessing desirable properties are unavailable at present.

It is reasonably assumed that the main purpose of a tracer is not only to study the permeability of one well, which in itself would be significant, but rather to study a series of wells on strike, to determine whether permeability is continuous vertically and horizontally.

The practical application of radioactivity logging in such situations will be determined best from the results of further experimental investigation over a wider range of conditions. It is hoped that it will be a means of supplying pertinent subsurface well data in fields where insufficient information relative to the producing horizons is available not only for intelligent
Fig. 9.—Gamma-ray Illustration
OF ORIGINAL OIL-STRING CEMENTING.
planning of secondary-recovery projects but also for primary-production operations.

**Determination of Cement Placement**

**Original Casing**

Frequently, during the development of a field, or in the completion of a particular well, it is important to determine accurately the actual cement fill-up behind the oil string to compare with the conventional methods now employed.

The vertical travel of the cement, as well as an indication of mass distribution, can be obtained by the use of powdered carnottite mixed with the cement. Carnottite is highly radioactive because of its uranium and potassium constituents, and consequently is an ideal tracer. By proportioning the mixture so that the intensity of the gamma-ray response is considerably greater than that usually obtained from the formation alone, it is easy to distinguish the presence of the cement by comparison with natural formation radioactive intensity.

A mixture containing \( \frac{1}{4} \) to \( \frac{3}{4} \) lb. of carnottite per sack of cement appears to be a satisfactory proportion over a wide range of conditions. The packaged carnotite is introduced at the mixing hopper, and because of its nearly colloidal texture and specific gravity, it remains in fairly stable mixture with the cement slurry without settling out.

![Fig. 9](image.png)

Fig. 9 illustrates a typical investigation of this nature conducted in the New Hope field, Franklin County, Texas. The various steps in the study are shown in sequence from left to right. An electrical log to obtain data on the formations and contained fluids was run. An open-hole caliper survey then was made to determine the variations in the hole diameter. This survey indicated an average diameter of hole of 11 in., which was drilled with an 8\( \frac{3}{4} \)-in. bit; the enlargement was caused by considerable sloughing of shales and unconsolidated sands.

From the data obtained from the caliper survey it was determined that 1200 sacks of cement would be required to protect all possible productive horizons for testing. The 5\( \frac{3}{4} \)-in., 17-lb. casing was landed at a depth of 7929 ft., and was cemented with 1160 sacks of cement, mixed with \( \frac{3}{4} \) lb. of carnotite per sack. Thirteen sacks was left in the casing, 1147 sacks being displaced behind the pipe.

After normal setting time had elapsed, the cement was drilled out to the bottom of the casing and a gamma-ray survey was made. The sharp reduction in intensity at 5262 ft. indicates the upper limit of the carnotite-laden cement.

Although it is possible to record the natural formation radioactivity as the pipe is suspended prior to cement, the risk of sticking the casing is too great. In many fields, the danger of losing instruments by cave-ins is too great to make a base log in open hole, but an alternative is to log an offset well. Such a method was used in this instance, and is shown on the extreme right of Fig. 9.

The illustration shows that the cement protects all the important zones except those immediately below the surface pipe, which can be squeezed later if deemed necessary. In addition, the gamma-ray log correlates extremely well with the caliper and electric logs in revealing that the bulk of the cement was opposite shales, which normally wash out to a greater degree than the sands.

**Squeeze Cementing**

Because the conditions attending the cementing of the oil string permit a fairly close estimate of the travel of the cement, the same is not true of squeeze cementing. For many wells it is of considerable importance to have an accurate knowledge concerning the final location of cement squeezed behind the pipe after the original cementing. Because of the various constrictions and the pressures required, it is
Fig. 10.—Typical squeeze cementing, with carnotite squeeze, Southern Louisiana.
Solid line, first run; broken line, second run.
impossible to predict how much cement can be squeezed, and whether the bulk of the cement will go up or down, or what effect the lateral distribution as a result of compaction and wedging will have on the vertical limits.

Fig. 10 illustrates typical carnotite squeeze cementing on a well in southern Louisiana. The well was prepared for the squeeze by setting a drillable bridging plug on a wire line at a depth of 9462 ft. and gun-perforating from 9438 to 9444 ft., and 9452 to 9458 ft., with six holes in each zone. The base survey shown by the solid-line curve representing the gamma-ray intensities of the natural formation then was run.

The well was squeezed through the two sets of perforations with 165 sacks of cement, mixed with ½ lb. of carnotite per sack of cement at pressures ranging from 2000 to 5000 lb. per sq. in. After a 48-hr. set, the remaining cement and the drillable plug were drilled out, and circulation was begun to free the inside of the casing of any remaining treated cement.

A second gamma-ray survey was run to a point some 26 ft. below the depth of the first one as indicated by the dashed line. By superimposing the second curve on the first gamma-ray curve, the difference in gamma-ray intensities caused by the presence of the radioactive cement behind the pipe is apparent. When emphasized by crosshatching, this difference is clearly discernible.

In this instance the cemented section extends over 157 ft., with the top 132 ft. above the upper perforation, and some 5 ft. below the lower perforation. In other studies of this type it has been noted that the downward travel of the squeezed cement may be as much as one third of the total vertical displacement.

Some conception of the volumetric distribution can be obtained from Fig. 10 by the disclosure that the greater the mass of the treated cement at any point, the greater will be the gamma-ray intensity.

**Plastic Squeeze**

The properties of commercially available plastics, particularly those that pene-
trate interstitial spaces, enable their use to good advantage in replacing cement under certain critical conditions. Various applications of plastics are understood finely ground carnotite, through the old perforations at 4514 and 4516 ft. with a pressure of 1300 lb. that built up to a maximum of 1700 pounds.

Fig. 12.—Gamma-ray exploration for cased-off sands.

After a sufficient interval of time had elapsed to permit the hardening of the plastic, the plug was drilled, and the hole was conditioned for the second gamma-ray survey, the curve for which is shown on Fig. 11 as a dashed line superimposed on the first curve. Again the crosshatched area represents the limits of vertical travel and the relative mass distribution of the tracer-laden squeeze material.

The extreme intensity obtained on the second survey is not the result of massive accumulation of the plastic behind the casing, or extreme penetration into the sand, but of the high concentration of carnotite used. Expressed in terms of pounds per cubic feet of cement, the concentration is roughly equivalent to 1.5 to 1, or approximately six times as much carnotite as was employed in cement studies in generally, but it is not so generally known that carnotite can be retained in suspension by plastics while in the fluid state, thus making it possible to conduct investigations similar to those described for carnotite mixed with cement.

Fig. 11 illustrates the displacement obtained on a plastic squeeze applied experimentally on a well in the East Texas area, in an effort to correct an unsatisfactory gas-oil ratio.

Following the standard procedure, a gamma-ray survey first was run to establish the gamma-ray intensities of the natural formation. This curve is shown by a solid line on the figure. The sand of interest is identified by minimum gamma-ray intensity values between 4495 and 5025 ft.

A wire-line drillable bridging plug was set at 4518 ft., and the well was squeezed with 100 gal. of plastic mixed with 20 lb. of...
which 1/4 lb. of carnotite per sack of cement was used.

**Gamma-ray Illustration for Exploration**

Scores of wells, usually old wells thought to be depleted of all possible oil and gas production, are abandoned annually. Most of these wells were drilled years ago, prior to present-day scientific technology, and no records, other than incomplete driller’s logs, are available.

Many of the wells are abandoned because they have a single pay horizon, but in multiple sands or pay zones it is economically important from the viewpoints of ultimate production, or geophysical correlation, to survey the boreholes. Through geophysical correlation and exploitation, oil wells have been surveyed before abandonment, to obtain information that may be helpful when possible field extensions are considered. Fig. 12 is an example of a survey of a well prior to abandonment in order to test any possible cased-off pay zones.

It is a typical example in the Smackover field, Arkansas, but it is applicable to wells in any area. Many of the producing zones at Smackover are blanket sands, but the Upper Blossom sand is lenticular, and it “shales out” from one location to another. During the development of this field most tests were terminated in the Lower Blossom sand, and shallower zones were disregarded. Subsequent stripper tests and exploratory workovers prompted the survey of depleted wells before abandonment, and excellent production has been reported.

Fig. 12 typifies a gamma-ray exploration for cased-off sands. To eliminate doubt and provide a record, this survey was run to determine the presence of upper beds. A sand was recorded at the Upper Blossom level from 2538 to 2572 ft., with an intermediate sandy-shale break from 2548 to 2558 ft. After plugging back with cement, the casing was gun-perforated with 20 holes in the top of the upper stringer from 2538 to 2541 ft. The well came in flowing 35 bbl. of oil per day, and enough gas to operate three additional wells on the same lease, which reduced the lifting cost of all four wells. Forty-four months later the well was producing 8 bbl. of oil per day, and was providing enough gas to operate the three additional wells.

When this sand is no longer considered a commercial producer of oil, the operator plans to drill out the plug to the Lower Blossom sand, and to attempt to recover more oil from this section by using the gas from the Upper Blossom sand.

**Structural Correlation on Shale**

The natural practice of correlating electrical logs on sandstones or limestones is quite similar to the correlation of several gamma-ray curves, because the gamma-ray curve often is quite similar to the natural potential curve of the electrical log. With gamma-ray logs, however, the correlation on shales is dissimilar. This phenomenal difference is accounted for by the fact that shales vary considerably in their radioactive intensities. The chemical constituents of shales, and their type deposits, make characteristic values apparent on the resultant curve. The correlation on shales in Fig. 13 becomes more significant when it is realized that sands could be correlated as with electrical logs, but precision in the location of the fault plane would not be possible. It is also possible that only one fault plane would be assumed rather than the fault block itself. This precise work was made possible through correlation of shales, which, because of different depositional characteristics, vary in gamma-ray intensity. Bentonites, volcanic ash, and marine shales are characterized particularly by high radioactive values, and they have very distinctive characteristics on a gamma-ray log. In Fig. 13, the two marine shales of each well have been clarified by the heavier lines, and through proper cor-
relation they show the traces of the two apparent fault planes of the block. It is reasonable to assume that with the block field, and they are a great aid in badly faulted fields where the radioactive intensities of shale values are correlatable.

lying between wells C and D, another test drilled between them would find the 840-ft. sand higher in the fault block, and possibly another productive zone. The normal dip is interrupted by shale correlation as it locates a fault through well C, which, however is not present in offsetting well B. The other fault is known to be present between C and D by correlation of the radioactive shales, and is confirmed by the obvious correlation on sands. Structural maps can be made with assurance from gamma-ray logs in any

FIG. 13.—STRUCTURAL CORRELATION ON SHALE.

EMERGENCY LOGGING

Under this heading should be grouped the wells in which physical conditions within are such that competent electrical logs cannot be secured normally, but in which a radioactivity log can be obtained to give much of the needed information.

SALT-WATER MUDS

The difficulty of obtaining electrical curves with sufficient character and definition to be significant in salty muds is well recognized. Under such conditions it is
FIG. 14.—OBTAINING STRATIGRAPHIC
INFORMATION IN SALT-CONTAMINATED MUD.
possible to secure either of the radioactivity curves without regard to the composition of the mud.

Fig. 14 illustrates this condition in a log that covered the doubtful section was run from 8835.5 to 7820 ft. A comparison of the logs over this section shows the definition of the bottom sand on the

wildcat well drilled in Assumption Parish, Louisiana. The characteristics of the mud were normal and six electrical logs were obtained successively as drilling progressed and the salt cap was penetrated. The salt lowered the resistivity of the mud to 0.4 at 93°F., and the final electrical log failed to define a known sand a few feet above the salt.

The casing was landed, and after the cement had been drilled out a gamma-ray log, which is masked out on the electrical log, and the agreement between the two logs on the upper sands, although there is some difference as to their depths.

**Oil-base Drilling Fluid**

Oil-base drilling fluid is used in several California fields to eliminate the infiltration of water where the productive zones are partially depleted and bottom-hole
pressures are low. Since oil is a dielectric substance, it offers greater electrical resistance, and thus makes it difficult to obtain a satisfactory electrical log.

**Fig. 16.—Gamma-ray log after casing is set, Texas Gulf Coast.**

In order to obtain correlation, electric logs have been run by using electrodes that make a sliding contact on the walls of the hole. The nature of this contact with the irregular formation changes in the walls of the hole is unsatisfactory, and tends to produce a curve that is sometimes difficult to interpret.

The gamma-ray log is independent of any contact with the walls of the hole, and reacts normally in oil-base drilling fluids, giving a clear, sharp, definition between sands and shales as shown in Fig. 15. Good correlations are obtained with neighboring electric logs of wells drilled previously with oil-base drilling fluid, and with other gamma-ray logs in the vicinity.

**Threatening Blowout**

Despite the extreme care and precautions normally observed in the drilling of deep exploratory wildcats, there is always the possibility that the unexpected penetration of an unknown high-pressure gas-bearing sand will upset the planned schedules and engineering procedure of electrical logging intervals, and mud controls.

When such a sand is penetrated the use of extremely heavy muds and the speeding up of operations leading to the introduction of casing usually prevents the accumulation of vital information on the bottom section of the hole normally obtained from cores and electrical logs. After casing has been set safely in such a well, a radioactivity log can be run to obtain neglected information, or as a check upon uncertain information relating to the type and depth of formations cased off.

Fig. 16 illustrates the results obtained under these conditions on a wildcat drilled on the Carrizo-Wilcox trend of the lower Gulf Coast. It was necessary to raise the mud weight while drilling below a depth of 10,000 ft., and to maintain it
approximately at 16.8 lb. per gallon. Under these conditions no electrical log was obtained and 5 1/2-in. casing was set through the Wilcox formation. The gamma-ray log shows the top of the Woodbine sand at 3645 ft., and by using the collar finder, a casing seat was located 3 ft. below the top of the Woodbine sand instead of at the base of the Austin chalk. After the well was surveyed and the situation studied, the well was plugged back to 3657 ft., and 15 per cent of the water production was eliminated. Production records in January 1945 showed only 3 per cent water. Future gun-perforating will permit a rejuvenation of the well when the open-hole zone has been depleted of its oil.

The records of other wells on this same lease with questionable casing programs were as follows:

**Fig. 17.—Gamma-ray log indicates presence of partially cased-off sand.**
Discrepancies in well-depth measurements continue to appear, and the problem of obtaining correct measurements has been receiving considerable attention by engineers in recent years. Not only has this problem been evident because of the present trend toward the development of relatively thin strata at greater depths, but in remedial work on old wells in the processes of primary and secondary recovery as well.

Much unnecessary squeeze cementing leads to the attempt to complete wells in zones where inaccurate depth measurements have been reported. Fig. 18 illustrates a typical problem in a Gulf Coast field. According to the gun-perforating record charted on the figure, the casing was gun-perforated from 8839 to 8842 ft., which is in the lower part of the sand, as indicated on the electrical log. The well tested pipeline oil, and was produced for a time until subsequent remedial work was necessary to shut off bottom-hole water. After the original producing zone had been squeezed off, the well was gun-perforated several times between the depths of 8826 to 8842 ft., and on tests following each operation the well produced some oil with excessive quantities of salt water. The last two tests, between 8822 and 8832 and 8826 and 8833 ft., however, showed no production of oil or water.

The gamma-ray log was run to check the accuracy of the electrical log for the purpose of measurements. The producing zone was found somewhat lower than was indicated by the electrical log, accounting for the dry tests that were made in shale strata.

The well was gun-perforated again from 8835 to 8839 ft., and it was completed to produce commercial quantities of oil with some salt water.

**Casing-collar Locator**

Experimental work is being done to develop an electrical collar locator that records the depths of casing collars simultaneously with the gamma-ray log.

The electrical collar detector is an accessory to the subsurface gamma-ray instrument, and is designed to transmit electrically on to the recorder at the surface an indication of the location of each collar. The record for each is made by an independent pen on the same chart with the gamma-ray log. Fig. 19 is an illustration of the casing-collar log together with a typical gamma-ray log.

This device offers a method of obtaining extreme accuracy in well-depth measurements. The formations defined by the gamma-ray log may be correlated definitely with permanent bench marks that are less than half a joint of casing away from a zone of interest. The same casing collars can be relocated by means of a collar-locating device attached to other tools to establish a zone of interest at any future time. Subsequent testing or cement jobs that normally change the apparent total depth of a well will have no effect on the relocation of the collars.

**Conclusions**

The versatility of radioactivity well logging is shown by the numerous examples in this paper. This new tool should be a great aid to the oil industry because it is adaptable to a variety of problems that are met either in new or old wells.

**Acknowledgment**

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FIG. 18.—GAMMA-RAY LOG CLARIFIES MEASURE DISCREPANCY.

FIG. 19.—LOG OF ELECTRICAL COLLAR LOCATOR RECORDED SIMULTANEOUSLY WITH GAMMA-RAY LOG.
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   - Volume 8
     - L. C. Beers: Radioactivity Logging Reclaims Depleted Wells in Long Beach Field, Calif.
     - R. Cantrell: Radioactivity Logs Aid in Making Coast Workovers Worth While.
     - J. L. P. Campbell: Locating Cased-off Production in Old Wells.
   - Volume 9
     - J. L. Neale: Proper Completion Assured by Radioactivity Logs.
     - J. C. Barcklow: Adaptability of Radioactivity Logs to Limestone Zones in Old and New Wells.
     - R. L. Alder: Reecompletions Based on Radioactivity Logs.
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   - Volume 10
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     - C. T. Maxwell: Radioactivity Economics.
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