A LOOK AT THE DEVELOPMENT OF NEUTRON LOGGING

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INTRODUCTION

In the 1940's neutron logging was commercially developed as an alternate method of determining porosity. The ability to respond to formations behind casing foretold a great future. Unfortunately, however, the same principles which allow a neutron log to predict porosity as a function of the hydrogen index of a formation also produce many undesirable effects. The principles of operation of the compensated neutron log represent the culmination of technology intended to overcome these undesirable effects and to provide a usable tool in the search for petroleum products.

BASIC PRINCIPLES

Neutron logs are primarily hydrogen index logs. Two very important effects in neutron logging are those of hydrogen as the greatest moderating factor and chlorine as the greatest absorber. Hydrogen and chlorine are not the only elements which influence the response of the neutron log, but are the most significant.

Neutrons are generated by several methods, but a common method is the (α,n) reaction (Fig. 1) in which an atom of beryllium absorbs an alpha particle, then subsequently releases an energetic neutron. Some energy in the form of a gamma ray is emitted. The neutrons released generally have a range of energy levels about one or more central values. The free neutrons released by an americium-beryllium reaction are about 4.5 mev. The path of travel (Fig. 2) of an individual neutron will cause it to collide with the nuclei of other atomic particles and at each collision, the neutron will lose some of its energy.

$${}_4Be^9 + {}_2He^4 \rightarrow {}_6C^{12} + {}_0n^1$$

FIGURE 1

At some time, most neutrons will have been absorbed or will have lost enough energy to be in thermal equilibrium with their environment. The collisions which cause this loss of energy are the moderating effect, and the atomic particles collided with are called the moderator. The more nearly the atomic weight of the moderator matches the atomic weight of the neutron, the better is the moderating power of the environment. Hydrogen in the form of formation and borehole fluids provides an excellent neutron moderating environment. Ultimately the neutron will be absorbed (most probably) or it will

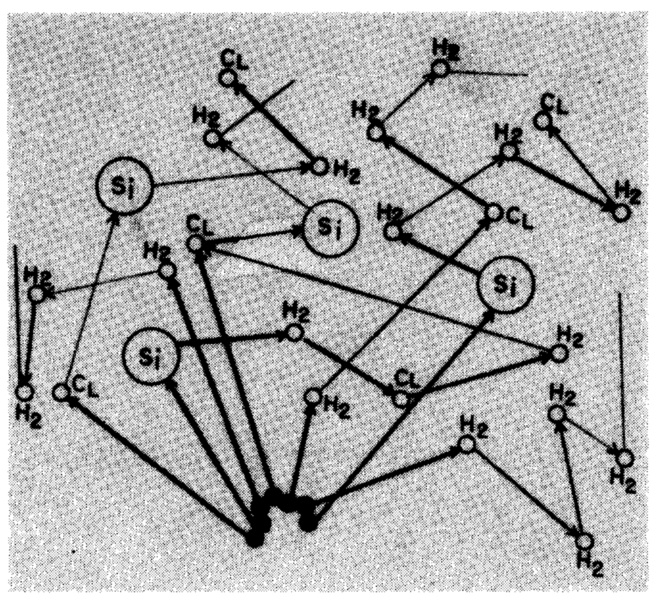

FIGURE 2

decay. The absorption reaction is important in neutron logging to the extent that chlorine has a very large absorption cross section, and is present in the environment. The presence of chlorine reduces the number of neutrons available to be measured.

During the time neutrons are undergoing moderation and while they exist in a thermal state before decaying or being absorbed, the process of diffusion is also taking place. This process reduces the neutron density with ever increasing distance from the source. If there were no decay or absorption, the neutron population would have what is called a 4-pi distribution. (Fig. 3). The cumulative effect of diffusion, absorption, and decay is that very few of the generated neutrons are available to be counted by neutron detectors at typical source-to-detector spacings. Perhaps something on the order of one neutron is counted for every 5,000 - 20,000 generated.

The moderating power of a substance is sometimes called its "slowing-down" power. This is measured by a term called the slowing down length. Typical slowing-down lengths are 5 to 7 cm. for borehole fluids and 2 or more times that for formation solids.[31] This slowing-down length is fairly directly related to porosity. (Fig. 4).

Most solids in a producing environment have slowing-down lengths not greatly different from one another; but the slowing-down lengths of solids do

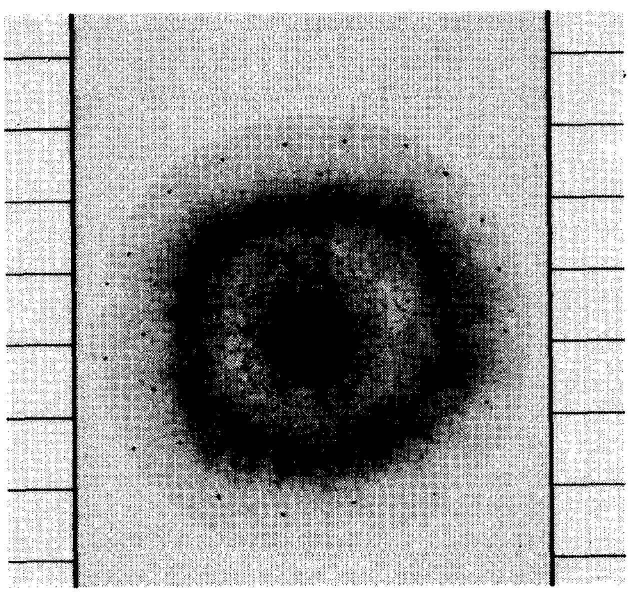

FIGURE 3

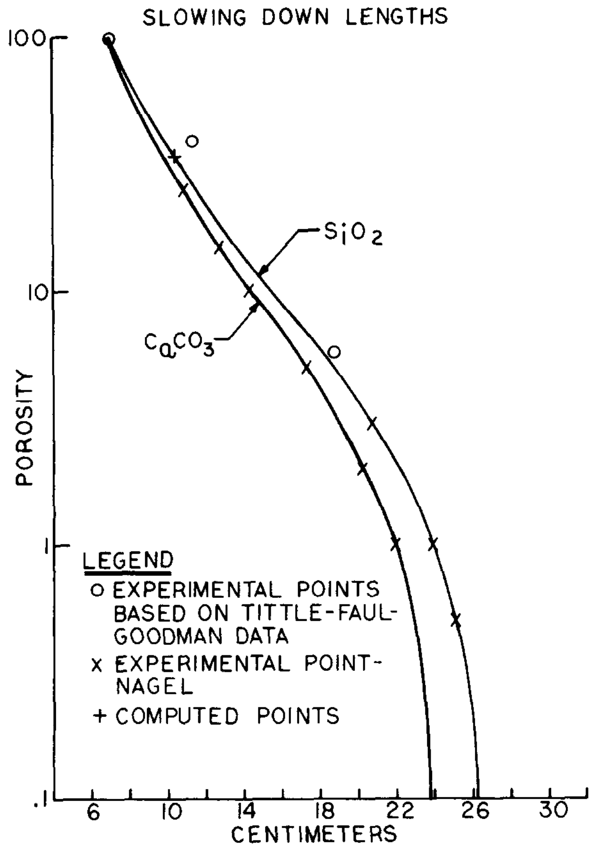

FIGURE 4

differ significantly from the slowing-down length of hydrogen, as indicated above. This relationship causes the relative amount of hydrogen present to be the greatest influencing factor of a neutron log. The amount of hydrogen present is governed partially by the available storage volume. Formation storage is called porosity. Borehole storage is called a limitation of logging ability.

Because hydrogen has the greatest influence on a log, any deviations in the amount of hydrogen present influence the log response. Variations in the formation hydrogen content are the desired measurement parameter, but variations in the borehole hydrogen content are most influential. When the hydrogen present is in the form of a gas, reduction of the fluid density involved causes a greatly reduced amount of total hydrogen present. Figure 5 depicts the influence of temperature on neutron count rate for two different source-to-dectector spacings in water.

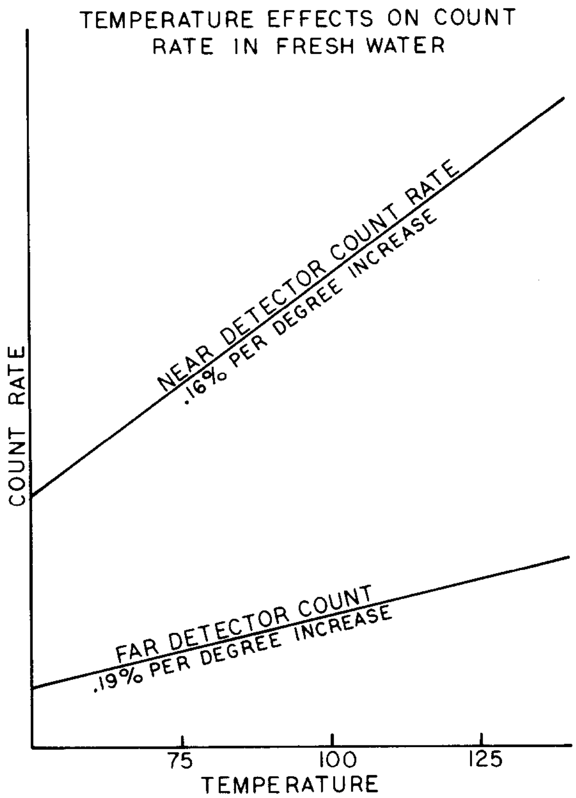

FIGURE 5

These changes are the result of a change in hydrogen content as a function of fluid density and a slight change in thermal energy.

The presence of chlorine in either the borehole or the formation reduces the amount of hydrogen present by displacement, and additionally influences the log response by the introduction of a strong thermal neutron absorber. The chlorine influence may be the result of saline formation fluids, of salt-water-base muds, of an acid spotted in the borehole for stimulation purposes, or of salt in cement.

As long as the response to borehole factors is constant, the neutron log is a response to formation variables and can be used as a porosity log. Even when there are changes in the borehole-response factors at occasional depth, certain portions of a log can be selected and interpreted relative to a particular zone of constant borehole conditions. When the borehole parameters are both unknown, variable, or both unknown and variable, interpretation becomes unreliable (Fig. 6). Irregular borehole size or changing borehole fluids are major factors to be considered in the interpretation of *any* neutron log.

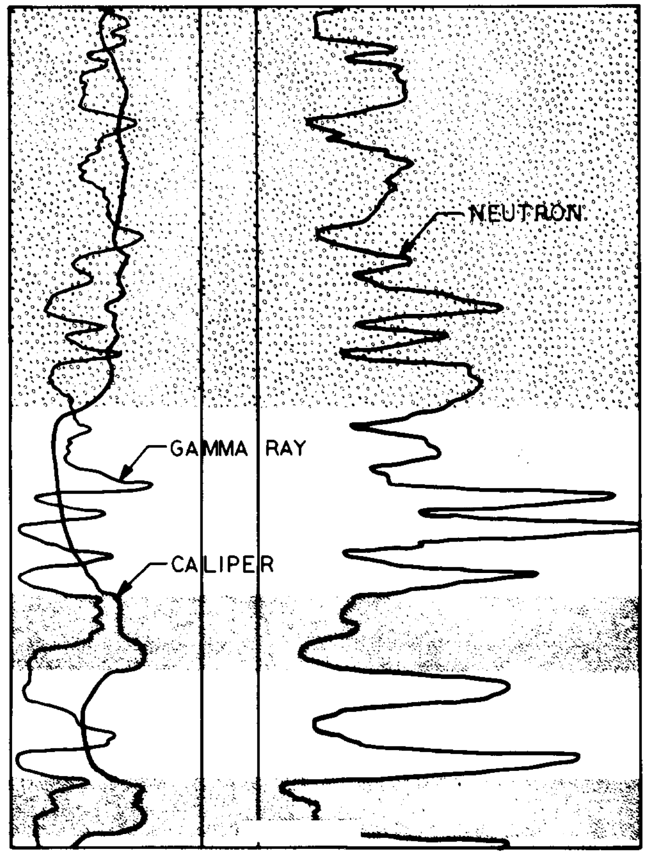

FIGURE 6

Other factors which affect the response of the neutron log are variations of the geometry of the logging tool. Source-to-detector spacings, source strength and type, and lateral positioning of a logging tool will affect the sphere of measurement to some extent. Different tool configurations and various combinations of techniques have been used to improve neutron log quality by controlling these factors. Source-to-detector spacing (Fig. 7) influences the number of neutrons which live long enough to reach the detector and controls the proportion of neutrons detected that have been principally subjected to the influences of the formation. Within the geometry of the borehole, increased spacing reduces, but does not eliminate, the influence of the borehole. Source strength and type control the number and energy of neutrons generated and therefore influence the number which reach the detector. The lateral position of the source, the detector, or both in the borehole will greatly affect both the number of neutrons detected and sensitivity to formation porosity, (Fig. 10). Positive decentralization for small-diameter logging tools in

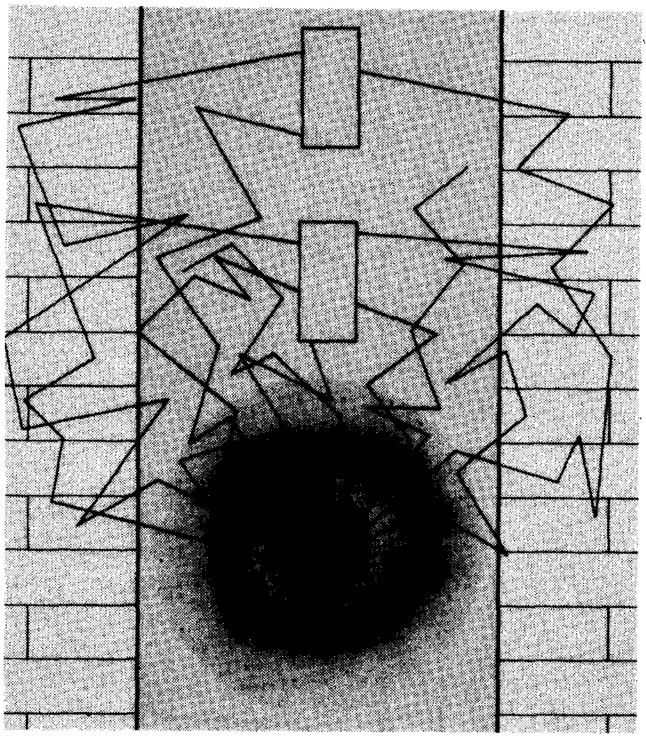

FIGURE 7A

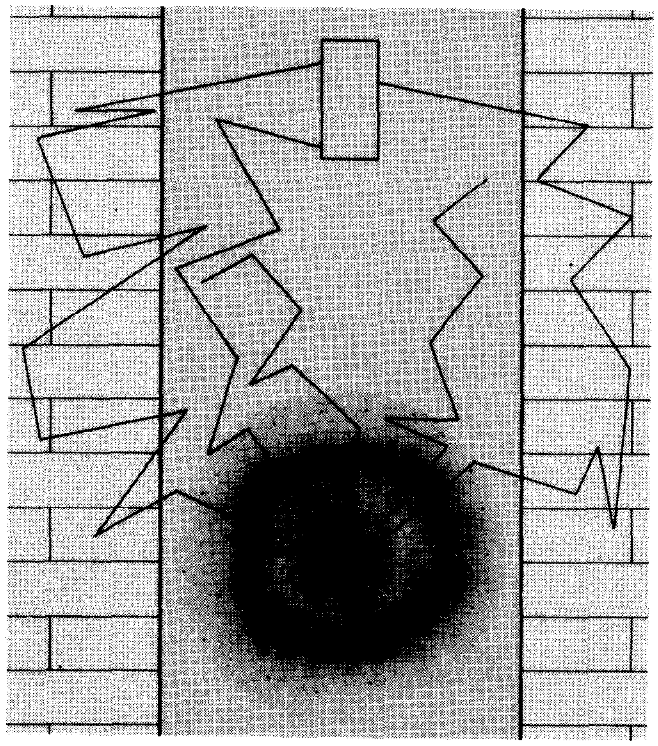

FIGURE 7C

large boreholes should be utilized (Fig. 8). The effect of these geometry factors appears in all neutron logs, but is mostly constant within a given log, and so is

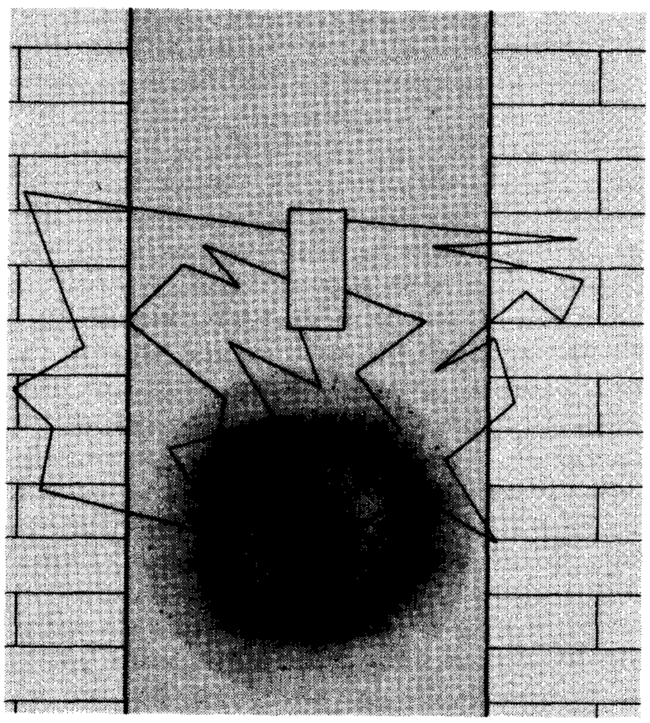

FIGURE 7B

commonly ignored. The number of neutrons detected per unit time must also be considered when evaluating tool geometry factors.

The statistics of a log refer in parts to the effect produced by the fact that neutrons are not created, nor do they react with other particles, at a uniform, repititious rate. They occur randomly, and react randomly; thus the quantity of neutrons measured per unit of time is an average. Deviations from this average are roughly proportional to the square root of the magnitude of the measurement.

BASIC RESPONSES

Based on this discussion of factors influencing the response of a hydrogen index log for porosity, a few generalized conclusions can be drawn.

The tool responds to its total environment, which may be dominated by the borehole.

Increased source-to-detector spacing reduces the dominance of the borehole but must be accompanied by increased source strength to offset statistical effects.

In a high hydrogen environment, the neutron interactions most representative of porosity will take place within a few inches of the source; therefore proximity of the source and detectors to

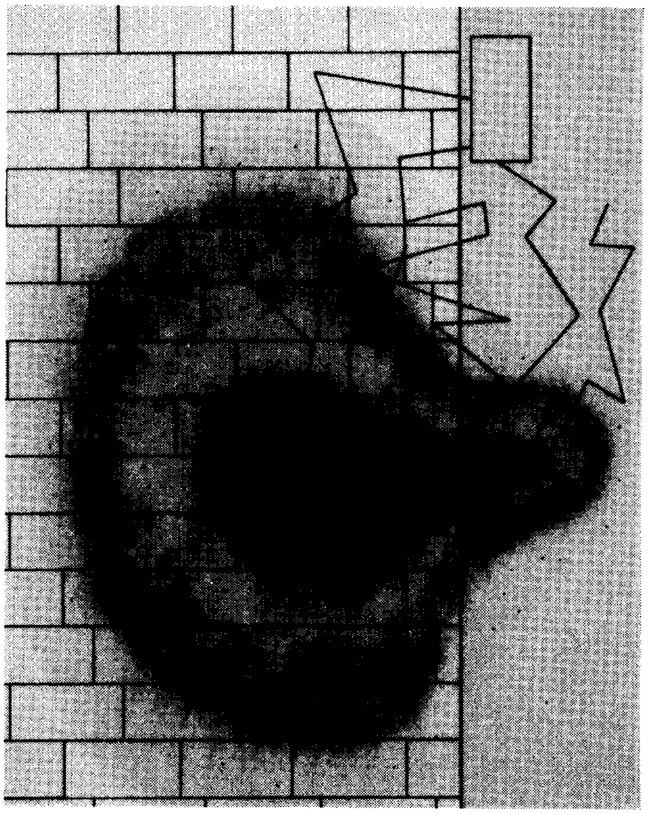

FIGURE 8

the formation is important.

The presence of strong thermal neutron absorbers produces an effect analogous to increased porosity, and reduces the accuracy of measurement because of statistics.

Variations in the borehole part of the environment may produce log responses equal to or greater than changes in formation porosity.

Temperature has an effect on the density of environmental fluids and thus affects neutron response.

Up to this point, a very good case has been presented for not placing confidence in a neutron log. The negative view is not the only applicable one. The neutron log often provides the best and, in some cases, the only direct method of porosity measurement. Other porosity measurement techniques also have limitations, and the neutron method may be more applicable.

The only truly limiting factor in neutron logging for porosity is our understanding. Inexactness in the science of neutron-behavior studies as applied to the real-world logging environment has limited the ability to predict and separate the different factors making up log responses. Neutron reactions are not directly observable; however their behavior in various media have been studied and documented. Mathematical models which predict or explain neutron behavior in the laboratory have been fairly successful. These same theories have provided qualitative results when applied to field conditions, but have left much to be desired quantitatively.

THEORETICAL ADVANCES

Tittle and Allen[2] presented in 1966 an analytical development of one-group, three-region (one energy level, three environment types) neutron-diffusion theory as applied to well logging. They and others[3] presented in 1967 an expansion of this theory to two-group, two-region development. In Figure 7, ϕ (r) represents the thermal neutron flux at distance r from the source, Q represents the source strength, D_2 the thermal diffusion coefficient, L_1 the epithermal slowing down length, and L_2 the thermal diffusion length. This two-group two-region theory states that taking the ratio of two thermal neutron-count rates at suitably different source-to-detector spacings essentially negates the thermal parameter effects. As previously described, the thermal parameters are those which are mostly influenced by borehole conditions. Subsequent development has shown that two groups of energy levels appear to provide adequate explanation of measured parameters, but two regions of environment are not enough to define real-world conditions. Figure 8 illustrates a two-region environment and clearly demonstrates that a logging tool disrupts that envrionment.

$$"\phi_2(r) \approx \frac{QL_2^2}{4\pi D_2(L_1^2 - L_2^2)} \cdot \frac{e^{-r/L_1}}{r}$$

CLEARLY, ESSENTIALLY ALL DEPENDENCE OF A THERMAL NEUTRON MEASUREMENT UPON THERMAL NEUTRON PARAMETERS CAN BE ELIMINATED SIMPLY BY MAKING MEASUREMENTS AT TWO SUFFICIENTLY DISTANT POINTS r_1 AND r_2 AND TAKING THEIR RATIO; THUS

$$\frac{\phi_2(r_1)}{\phi_2(r_2)} \approx \left(\frac{r_2}{r_1}\right) e^{-\frac{(r_1 - r_2)}{L_1}}$$

THIS RATIO IS NOT ONLY INDEPENDENT OF D_2 AND L_2, BUT Q AS WELL."

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FIGURE 9

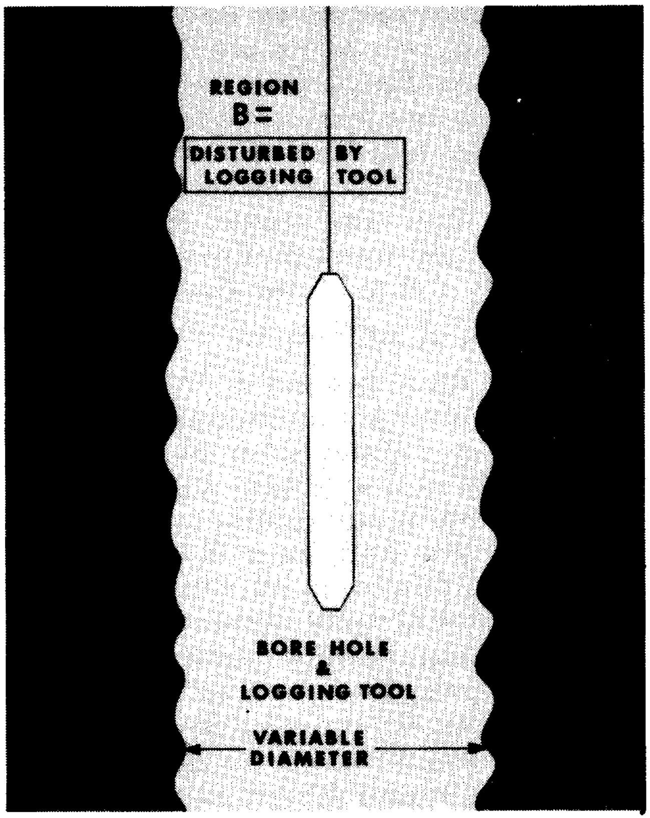

FIGURE 10

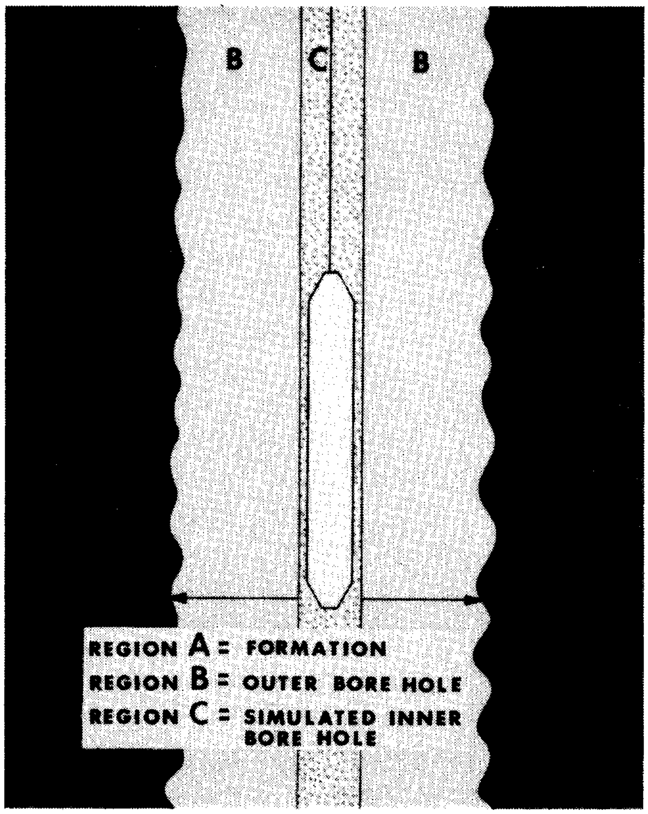

FIGURE 11

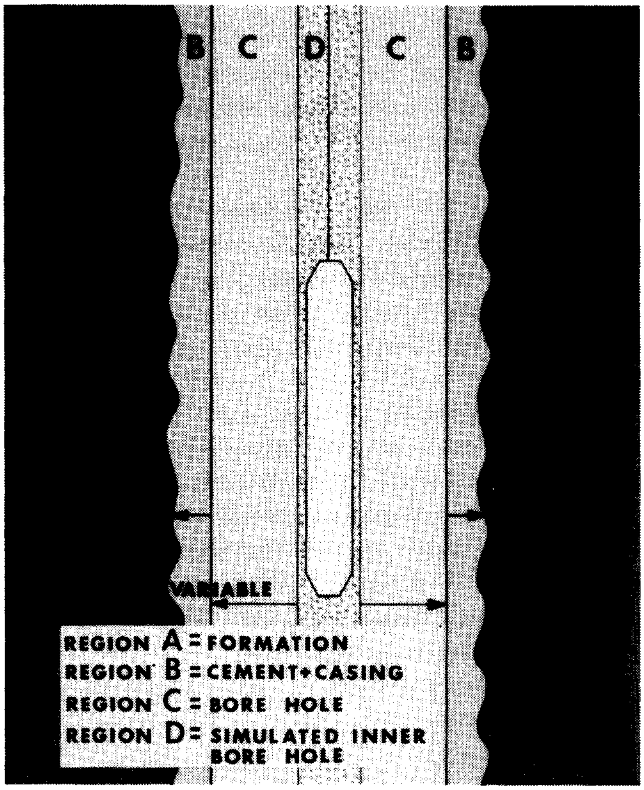

FIGURE 12

TECHNOLOGICAL ADVANCES

The advent of computer technology has removed the tedium and time requirements of many complicated mathematical-problem solutions. This has been translated to improved mathematical models for the expression of nuclear conditions or nuclear reactions. This in turn has allowed experimental verification of theoretical analyses and shown their applicability. This is aptly demonstrated by the compensated neutron theory which has been extended and programmed through two-group three-region theory. Figure 9 illustrates the attempt to refine accuracy of prediction by having a constant, simulated inner borehole with a homogeneous outer borehole. This three-region program has demonstrated much better agreement with experimental data and field logs. Current development extends to four regions to better explain the effects of a logging tool in the measured environment, (Fig. 10). This four-region development is an in-process condition and not a completed study. A presentation of this work to the industry is expected upon its completion.

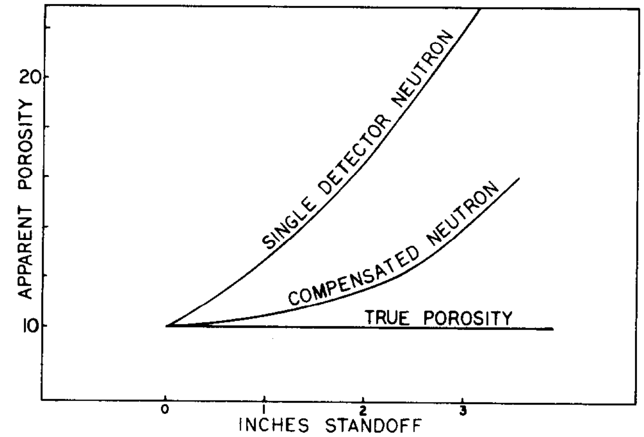

FIGURE 13A

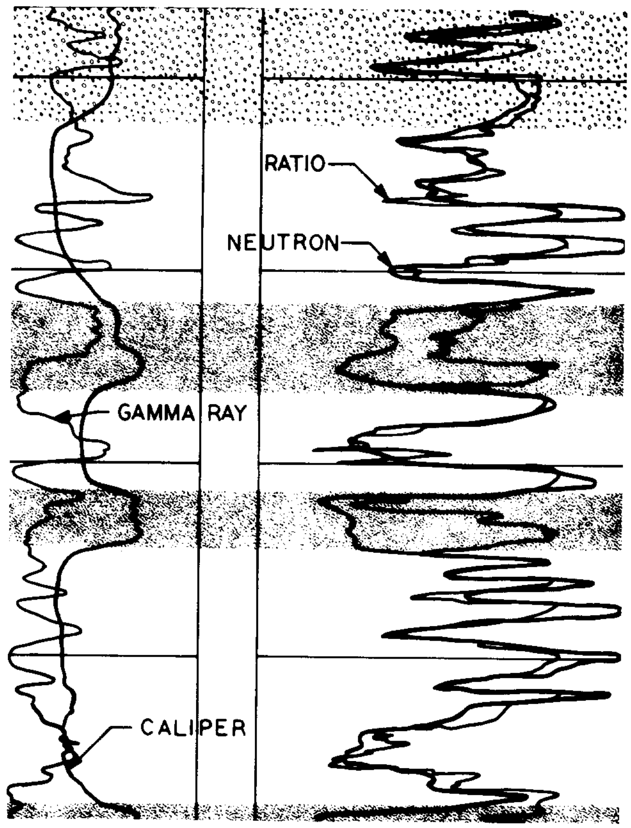

FIGURE 13B

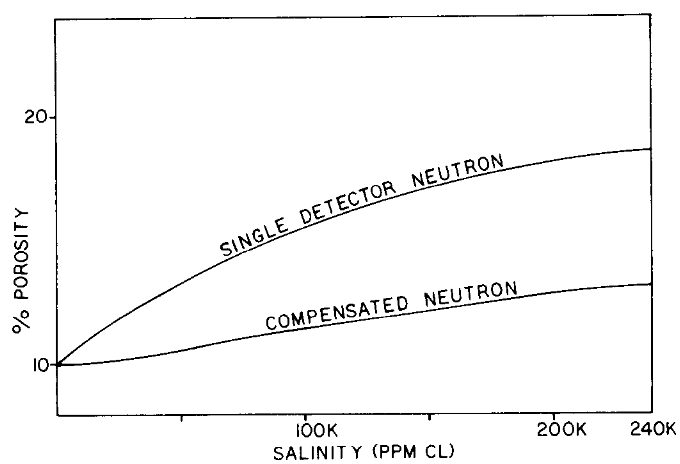

FIGURE 14

CONCLUSIONS

This study has demonstrated that the compensated neutron log does not eliminate the effects of borehole parameters on the log response. What it has shown is improved ability to predict the amount of this influence and to compensate for this by calibration techniques. Comparisons of thermal neutron ratio response to thermal neutron count rate response by Figs. 11 through 16 clearly demonstrate the superiority of the ratio technique of porosity determination.

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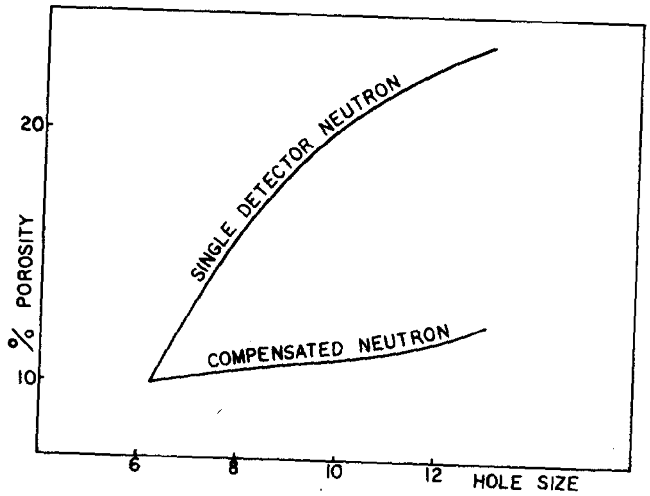

FIGURE 15

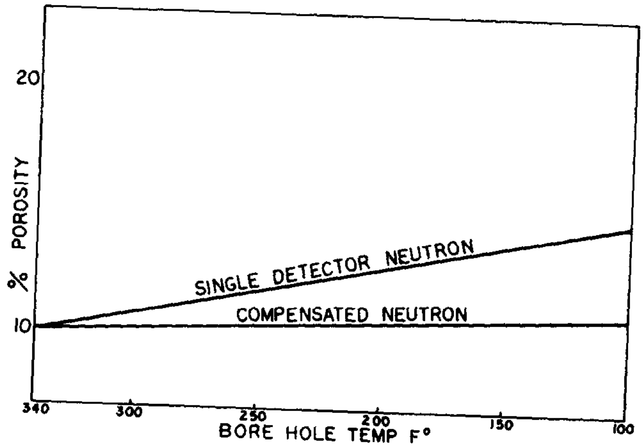

FIGURE 16