

[54] NEUTRON ABSORPTION AND OXYGEN LOG FOR MEASURING OIL CONTENT OF FORMATION

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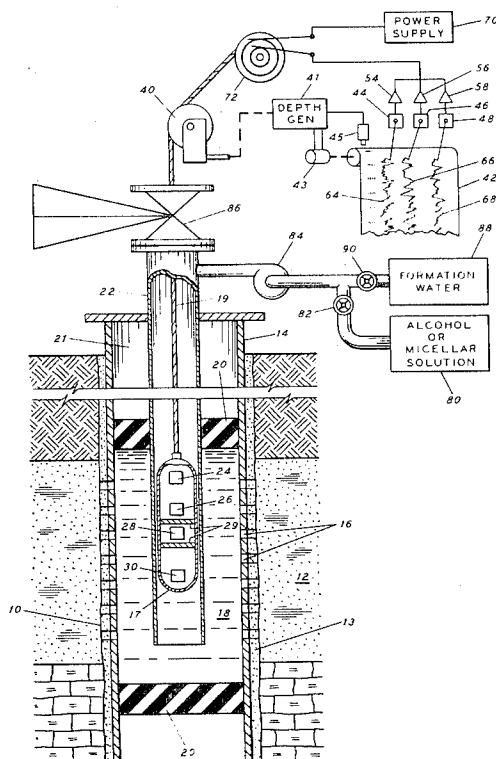
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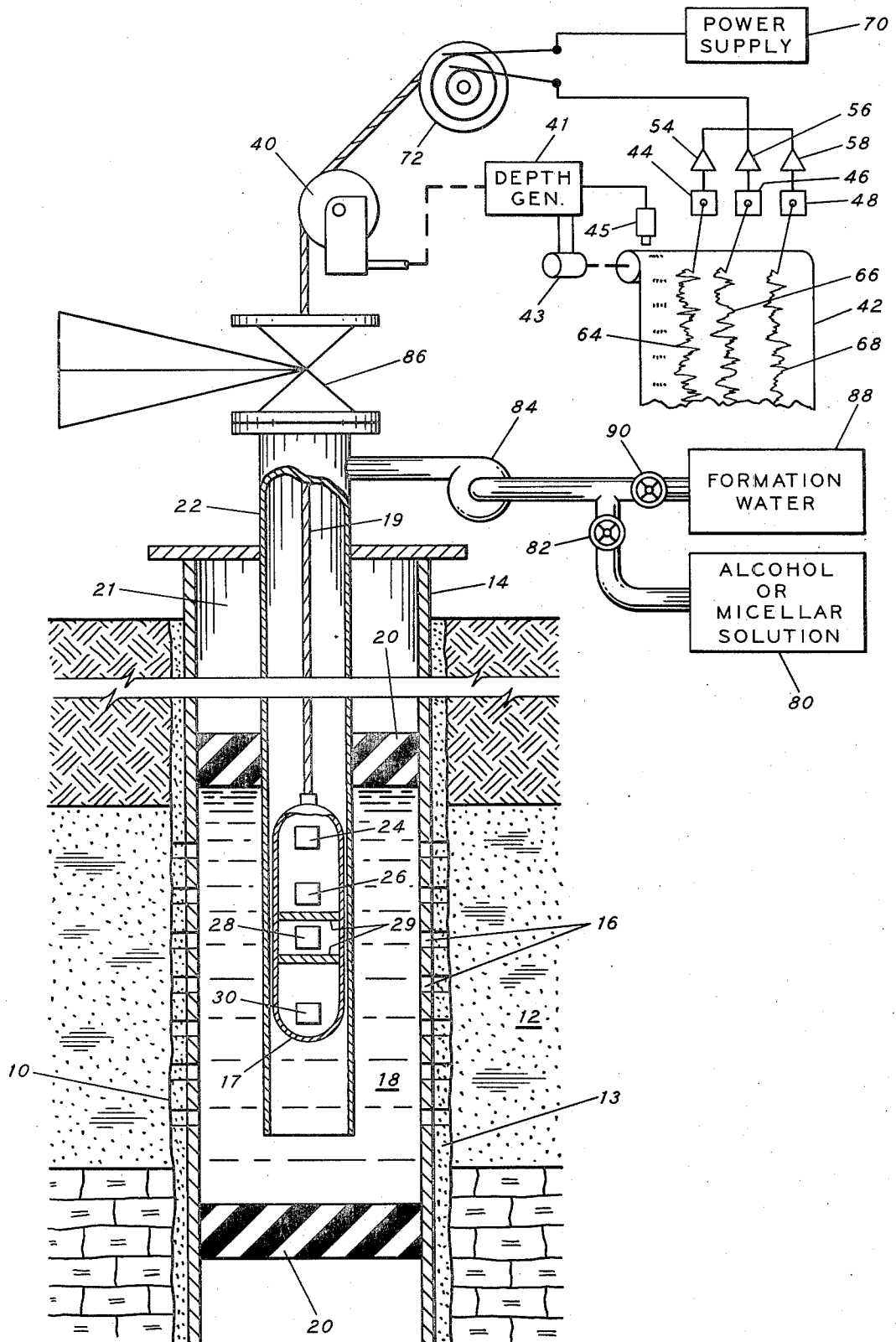
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[57] ABSTRACT

This invention discloses a method for accurately determining changes in the fractional-volume oil and gas content of a reservoir from a cased well bore. The first step of the invention is to record the response of both a thermal-neutron-decay-time log and a neutron activated oxygen log to a reservoir formation traversed by the well bore. A purposeful change is then made in the oil saturation in a given region of the formation surrounding the well bore by injecting fluid under sufficient pressure to displace the connate fluids. This change can constitute the removal of substantially all the oil or the removal of as much oil as can be displaced by a proposed flooding technique. The combination of the thermal-neutron-decay-time log and the oxygen log is then run again to record the response of the same given region. The difference in the oil content around the well bore is then determined from the differences between the two sets of logs in a manner whose details are described hereinafter. The method can be modified to measure changes in fluid content over long periods by running the combination of the thermal-neutron-decay-time log and the oxygen log when knowledge about current saturations is desired. The oil content between the first and second logging runs can have been changed only by production of fluids from the reservoir.

10 Claims, 1 Drawing Figure





NEUTRON ABSORPTION AND OXYGEN LOG FOR MEASURING OIL CONTENT OF FORMATION

FIELD OF INVENTION

This invention relates to radioactive logging methods. More particularly, it relates to the use of neutron-activated radio activity in an earth formation to determine the content of oil in a petroleum reservoir in which the pore space contains oil, water, and gas.

BACKGROUND OF THE INVENTION

The growing importance of secondary and tertiary methods of oil recovery makes it increasingly desirable to be able to determine quantitatively the oil content in a formation that contains the three components, oil, water, and gas, that are characteristically present in partially depleted reservoirs. Because of the strict economic limitations of assisted recovery methods, it is not usually desirable to drill new wells in order that the determination of remaining oil content might be made in uncased holes. Previously proposed methods to measure such oil content from within cased holes depend either on the absence of a gas phase or on the immobility of the remaining oil. Thus, existing methods for measuring oil content are inadequate under conditions that commonly obtain.

The determination of oil content by the method of Owens (William W. Owens, U.S. Pat. No. 3,282,095) is made by running an electric log or a core analysis for water saturation, followed by a neutron-gamma-ray log. Enough hydrogen-containing liquid is then injected into the formation to displace the gas that was originally in the formation, and a second neutron-gamma-ray log is made. From the original water saturation determined with the electric log (or core analysis) and also the original gas saturation determined with the neutron-gamma-ray logs, one can calculate the original oil saturation. It is assumed that sufficient fluid has been injected so that no gas remains at the time of the second neutron-gamma-ray log. Since this method cannot be applied without the independent measurement of water saturation, it can be used only for conditions in which it is economically feasible to drill a new well into a reservoir, because an uncased hole is required to measure water saturation by the electric log method. A new well is required for a fresh core.

A method for logging oil content in cased wells is described by Richardson and Wyman (J. E. Richardson and R. E. Wyman, U.S. Pat. No. 3,562,523) in which the oil content of a reservoir is determined from thermal-neutron-decay-time logging before and after intentional displacement of reservoir water with an artificial brine of known thermal neutron absorptivity. In this method the total capture cross-section for thermal neutrons is measured from the thermal-neutron-decay-time log when the formation around the well bore contains oil at its residual saturation with formation water filling the remaining pore volume. The water in the formation around the well bore is then displaced by a brine having a known capture cross section materially different from that of the original formation water, and the thermal-neutron-decay-time log is run again. The water content of the formation is deduced from the difference between the two logs. It is assumed that no oil was displaced during the process of injecting the brine. The oil saturation is calculated from the measured

water content, using the assumptions that the porosity is known and that the gas content can be neglected. The method of Richardson and Wyman thus provides an accurate measurement of oil content only when the oil in the reservoir cannot be moved by water flooding and when there is no gas present.

A method for determining the residual oil content in cased wells when gas is present has been described by Jorden and Mitchell (James R. Jorden, Jr., and Forrest R. Mitchell, U.S. Pat. No. 3,631,245). Gas content is measured from thermal-neutron-decay time logs run before and after sufficient fluid is injected to displace or dissolve the gas in that region around the well bore to which the logs are sensitive. Oil content is then deduced from changes in the macroscopic cross-section for the absorption of thermal neutrons calculated from the response of thermal-neutron-decay-time logs run before and after the oil in the vicinity of the well is chemically flushed away from the region that affects the log. The Jorden method provides an accurate measurement of oil content if none of the oil has been displaced by the water injected to remove the gas saturation.

It can be seen that previous methods of logging provide accurate measurements of oil content in cased holes when there is gas present but the oil cannot be moved. Previous methods exist to provide accurate measurements in cased holes when the oil is mobile but these methods fail when gas is present. Previous methods exist to measure accurately the oil content when the oil is mobile and gas is present, but such methods can be applied only in an uncased hole.

It is the object of the present invention to provide a method for accurately determining the oil content of a reservoir when the reservoir contains both mobile oil and a significant gas saturation. Since the method can be applied in cased wells, it can be used to measure the oil content in existing wells, to measure in situ the response of a formation to a secondary recovery scheme, or to measure the oil content remaining when production can be expected to cause changes in the saturations of remaining gases and fluids.

SUMMARY OF THE INVENTION

The first step of the invention is the recording of the response of both a thermal-neutron-decay-time log and a neutron activated-oxygen log to a formation traversed by a well bore. A purposeful change is then made in the oil saturation in a given region of the formation surrounding the well bore by injecting fluid under sufficient pressure to displace the connate fluids.

This change can constitute the removal of substantially all the oil or the removal of as much oil as can be displaced by a proposed flooding technique. The combination of the thermal-neutron-decay-time log and the oxygen log is then run again to record the response of the same given region. The difference in the oil content around the well bore is then determined from the differences between the two sets of logs in a manner whose details are described hereinafter. The method can be modified to measure changes in fluid content over long periods by running the combination of the thermal-neutron-decay-time log and the oxygen log when knowledge about current saturations is desired.

BRIEF DESCRIPTION OF THE DRAWING

The drawing is a schematic cross-section of an elevation view of a borehole illustrating the environment of this invention. The drawing represents a logging tool being raised through tubing and indicates the type of logs that are recorded for comparison before and after fluid displacement of the fluids around the cased well bore. As shown, the use of a tool small enough in diameter to be run in tubing is preferred because, as shown, it is then not necessary to remove the tubing and packers in order to log the well. If logging tools that fit inside the tubing are not available or are not sufficiently sensitive, removal and replacement of the tubing and packers is possible with the logging and injection being performed through the casing.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The logging techniques used with this invention measure properties of the formation and the gases and fluids it contains in the immediate vicinity of the well bore. It is therefore necessary to insure that the fluid content in this region reflects as nearly as possible the fluid content throughout the reservoir. Effects associated with rapid production can be minimized by producing the well to be logged slowly or by shutting it in for some time before the logs are recorded.

The oxygen log is based on a detection of the level of radiation emitted by the excited state of O^{16} created by the decay of isotopes of N^{16} after such unstable isotopes have been created from the interaction of high-energy neutrons with O^{16} nuclei.

The thermal-neutron-decay-time log measures the time for the decay of thermal neutrons from which the macroscopic thermal neutron absorption cross section of the matter surrounding the tool can be determined. This measurement is accomplished by detecting the level of the thermal neutron population as a function of the time after an abundance of thermal neutrons are created in the matter surrounding the tool by a pulse of high energy neutrons.

Several forms of thermal-neutron-decay-time, thermal neutron lifetime, or thermal neutron absorption logs are presently available commercially, and techniques have been developed to optimize their use (see, for example, the booklet "Neutron Lifetime Interpretation" by D. W. Hilchie, published by the Dresser Atlas Company). This log is available in combination with a neutron activated oxygen log. The drawing represents schematically the set of instruments commonly available in such a combined tool in a well bore traversing a reservoir formation 12 containing oil, gas (or both) and connate water.

As further shown, well bore 10 is cased with steel casing 14 sealed to formation 12 as by cement 13. Casing 14 is perforated as by perforations 16 for production of oil and gas from reservoir 12 or for injection of fluid into formation 12. In the present arrangement, a production (or injection) tubing 22 is packed off from the remaining part of the annular space 21 between casing 14 and tubing 22 by upper and lower packers 20. These isolate tubing 22 so that only fluids from or to formation 12 can flow through tubing 22. A logging tool housing, or sonde 17, is supported in well bore 10 at the lower end of logging cable 19. Cable 19 is reeled into and out of well bore 10 over sheave 40. A depth mea-

suring unit 41 detects the position of cable 19 and sonde 17 in the well bore and operates drive motor 43 for recording chart 42 so that electrical signals representing counts per second of the neutron activated oxygen log and the neutron decay times (from which the total neutron capture cross section of the formation and any fluids is calculated) can be recorded in accordance with the position of sonde 17 in the well bore 10. The depth is printed on chart 40 by marker 45.

Tool 17, as practiced commercially, is equipped to take measurements as it is pulled upward. A detector 24 measures the level of natural γ radiation prior to activation by neutron source 28. This measurement is recorded as trace 64 on chart 42. A detector 26 measures the γ radiation reflecting the decay of thermal neutrons which are produced in the formation by the pulsed neutron source 28. This is recorded as trace 66 on chart 42. Gamma rays (rather than thermal neutrons) are measured, to indicate indirectly the population of thermal neutrons, for reasons explained in D. O. Seevers' U.S. Pat. No. 3,508,052, issued Apr. 21, 1970. Shields 29, schematically indicated, are present to prevent detection of radiation directly from the source. The detector 26 is gated to sample over a time period of the order of 1 millisecond after a burst of neutrons has been generated by fast neutron generator 28. Generator 28 desirably produces pulses of 14 Mev neutrons by the deuterium-tritium interaction. Substantially all of the usefully measurable change in thermal neutron population will occur within 1 millisecond after each pulse from the generator is cut off.

Detector 30 measures the γ radiation produced by decay of unstable O^{16} which is formed when high energy neutrons of about 14 Mev (produced by bursts of generator 28) strike O^{16} nuclei to form initially unstable N^{16} . This radiation decays with a 7.3 second time constant; and for a given placement of detector 30 there is a corresponding optimum speed of sonde 17. The detection of γ rays from O^{16} is characterized by continuous detection of all such radiations having energies of over about 2 Mev since N^{16} first emits beta rays to form an excited state of O^{16} which in turn instantaneously emits two γ rays of 6.13 Mev and 7.10 Mev in returning to stable O^{16} . The record of radiation detected by detector 30 is trace 68 on chart 42.

The measurements upon which the present method is based could be made with a different geometry and could be made with the thermal-neutron-decay-time and oxygen content measured by separately run logs. However, the combination arrangement as shown in available commercially and is particularly convenient.

As indicated in the drawing the output of the logs are recorded on chart 42 by oscillographs 44, 46 and 48 connected to amplifiers 54, 56 and 58 respectively. In one commercial form of the neutron-life-time log, only the calculated total thermal neutron absorption cross-section is plotted as a trace on record chart 42. In another commercial form of this log the total counts in each of two time channels are recorded. The thermal neutron capture cross-section is calculated from the decay rate of the values of counts in the two time channels at each indicated depth. In the present embodiment, single trace 66 represents directly the neutron capture cross-section. Power source 70 is indicated to supply electrical power through slip ring assembly 72 to cable 19. Assembly 72 also connects the signal out-

put of detectors 24, 26 and 30 to amplifiers 44, 46 and 48.

The total capture cross-section measured by the thermal-neutron-decay-time log can be described by the following equation:

$$\Sigma_1 = \Sigma_M (1 - \phi) + \Sigma_W S_{W1} \phi + \Sigma_G S_{G1} \phi + \Sigma_O S_{O1} \phi, \quad (1)$$

where

Σ_1 = total capture cross-section for the first measurement. (The subscript 1 refers to the condition that obtains at the time of the first measurement.)

Σ_M = capture cross section of the formation rock matrix.

ϕ = porosity of the formation expressed as a fraction.

Σ_W = capture cross section of formation water.

S_{W1} = fraction of the pore volume containing water.

Σ_G = capture cross section of the gas contained in the formation.

S_{G1} = fraction of the pore volume containing gas.

Σ_O = capture cross section of the oil contained in the formation.

S_{O1} = fraction of the pore volume containing oil.

The quantities Σ_W and Σ_O will be known at the outset. The quantity Σ_M will be eliminated by using the difference between successive logs. The quantity Σ_G is in most cases small enough that no error would occur if terms in Σ_G were neglected. They are retained in this discussion because it makes the subsequent derivation easier to follow and because it makes the results valid for the unforeseen case when terms in Σ_G are significant. Equation (1) will be combined with equations described below to determine changes in the oil content ϕS_O .

Neutron activation logging can be applied to measure the oxygen content of the fluids plus the rock matrix in a reservoir (Arthur H. Youmans, U.S. Pat. No. 3,465,151). The log was originally proposed as a means to detect the presence of oil by recognizing oxygen deficiency. However, there is about as much random variation in the oxygen content of a typical rock matrix as there is difference in the total oxygen content when oil instead of water fills the pores. Consequently the log has not been used extensively. The variations in the oxygen content due to variations in rock composition do not negate the use of the oxygen log as proposed here because the quantity used reflects the difference in the oxygen content accompanying changes in the fluid content of a single rock matrix while the rock matrix oxygen content remains fixed. The response of the oxygen log can be represented by the following equation:

$$L_1 = C + K \{ F_M (1 - \phi) + F_W S_{W1} \phi \} \quad (2)$$

where

L_1 = the amplitude of the signal from the oxygen log (again, the subscript 1 denotes the condition at the time of the first measurement).

C = the part of this response due to oxygen that is not in the formation but in the borehole. This quantity will be substantially constant despite all changes in the reservoir.

K = the calibration constant describing the response of the log to the oxygen content of the material in the reservoir.

F_M = the oxygen content of the rock matrix.

F_W = the oxygen content of water.

The quantities C and F_M need not be determined because the response of the log is used only to measure differences that accompany changes in water saturation. The product $K F_W$ must be determined quantitatively. This can be done by measuring the response of the log instrument in a geometry similar to that in the well bore before and after a measured change of the fluid within a rock matrix. This calibration can be done with a rock matrix that is chemically different from the matrix surrounding a well because the calibration procedure is based on the difference in responses. It is important, however, that the hole diameter be nearly the same as that in the well to be measured. This restriction is necessary because the log response to changes in oxygen content will decrease with increasing distance from the tool. Hence the log response should be calibrated with fluids excluded to the distance of the outside diameter of the casing cement in the well. This initial calibration procedure is a part of the procedure of performing the well log and is not thereafter a necessary step in performing the method of this invention.

The next proper step in the method of the present invention is to produce the desired change in the oil saturation in the reservoir around the well bore. When it is desired to measure the original oil content, this step consists of reducing the existing oil saturation substantially to zero in the region measured by the log. This can be done by injecting a displacing agent such as a micellar solution or an alcohol into the region of interest. As indicated in the drawing, such fluid can be pumped from tank 80 thru valve 82 and into tubing 22 by pump 84 when logging tool 17 is withdrawn and wellhead gate valve 86 closed. The displacing agent must itself then be displaced by water with a salinity equal to that of the original formation water. This is because of the large thermal neutron capture cross-section of C1 nuclei. In the present embodiment, cleaned formation water from tank 88 can be injected into tubing 22 thru valve 90 by pump 84 when valve 82 is closed.

The response of the thermal-neutron-decay-time log after the replacement of the original oil leads to a total capture cross section expressed by the following equation:

$$\Sigma_2 = \Sigma_M (1 - \phi) + \Sigma_W S_{W2} \phi + \Sigma_G S_{G2} \phi + \Sigma_O S_{O2} \phi, \quad (3)$$

where the symbols retain the same meanings as in Equation (1), except for the subscript 2, which denotes the condition after the saturations have been changed. The response of the second oxygen log can be represented by the equation:

$$L_2 = C + K \{ F_M (1 - \phi) + F_W S_{W2} \phi \}, \quad (4)$$

where again the subscript 2 indicates the changed condition of the reservoir.

The difference between the total thermal neutron cross sections described by Equations (1) and (3) may be written:

$$\Sigma_2 - \Sigma_1 = \phi (\Sigma_o - \Sigma_w) (S_{o2} - S_{o1}) + \phi (\Sigma_g - \Sigma_w) (S_{g2} - S_{g1}). \quad (5)$$

Similarly, Equations (2) and (4) may be combined:

$$L_2 - L_1 = K F_w \phi (S_{o1} - S_{o2}) + K F_w \phi (S_{g1} - S_{g2}). \quad (6)$$

If the process of changing the oil has produced no change in the gas saturation, either of equations (5) or (6) could be used to determine the original oil saturation. The oil saturation can be determined despite changes in the gas saturation by combining Equations (5) and (6):

$$\phi (S_{o1} - S_{o2}) = (L_2 - L_1 / K F_w) [(\Sigma_w - \Sigma_g) / (\Sigma_o - \Sigma_g)] - (\Sigma_2 - \Sigma_1 / \Sigma_o - \Sigma_g) \quad (7)$$

Equation (7) makes evident the advantages of using this method for quantitative oil content measurements. $K F_w$, Σ_w , Σ_o and Σ_g are known constants. So the oil content is determined from the differences between the two sets of logs.

The application of the method does not depend on any knowledge about the makeup of the rock matrix. Also, it does not depend on any assumptions about the absence of gas or the mobility of the remaining oil.

The change in gas content before and after the process of displacing all the oil can be deduced by combining Equations (5) and (6):

$$\phi (S_{g1} - S_{g2}) = (L_2 - L_1 / K F_w) [(\Sigma_o - \Sigma_w) / (\Sigma_o - \Sigma_g)] + (\Sigma_2 - \Sigma_1 / \Sigma_o - \Sigma_g) \quad (8)$$

The process of displacing the oil involves the injection of a surplus of water into the formation; so in most cases the second gas saturation is substantially zero. In such cases Equation (8) yields the original gas content.

Since the method makes use of the difference in log responses and is correspondingly sensitive to errors, it will be advantageous to perform the logging runs in a way that makes the recorded response as free as possible from random or systematic errors. It will sometimes be advantageous to reduce the effect of random errors by making repeated runs over the zones of interest. It will sometimes be advantageous to reduce systematic errors by making use of the interrelationship of the logs recorded. One principal source of error in the measurement of the cross section for thermal-neutron-decay is the radiation from the oxygen nuclei excited in the measurement process. Since the invention makes use of the radiation from oxygen, the magnitude of this radiation is recorded independently of the thermal-neutron-decay-time log response. A knowledge of the oxygen content can be used to correct the calculated cross section. This correction can be made on some commercial logging tools by simply establishing the quantitative correlation between oxygen content and a signal level to be subtracted from the radiation detected in the measurement of the thermal-neutron-decay-time.

The method of measuring changes in oil content can be applied to measure the effects of proposed field recovery schemes. The change in oil content to be expected from a given flooding technique can be measured by (1) running the combination of the thermal-neutron-decay-time log and the oxygen log when the region around the well bore reflects saturations throughout the reservoir, then (2) using the flooding technique of interest to displace oil away from the well bore, and, if necessary, replacing the flooding material with reservoir water, and finally (3) running the combination of logs again. The change in the oil content due to the flooding technique can then be calculated from Equation (7). This technique can be combined with the determination of the original oil content by running the combination of logs when the region around the well bore reflects first the initial state of the reservoir, again when the region around the well bore reflects the saturations to be expected after a flood, and finally when the region around the well bore has been cleared of oil.

The method can be extended to monitor long-term changes in reservoir saturations. It can be used to deduce which zones are responsible for produced oil. This can be done by running the combination of logs from time to time during the producing lifetime of a field. With such a use, Equations (7) and (8) yield changes in the oil and gas content if the subscript 1 refers to an initial state of the field and the subscript 2 refers to the condition after production has changed saturations. This use of the method can, of course, be combined with an initial measurement of oil and gas content so that actual values of remaining oil content, rather than changes in oil content, can be monitored.

The accurate use of the combination of logs over an extended period of time is possible because changes in instrument sensitivity can be made to have almost no effect on the measurements. Since the thermal-neutron-decay-time log measures the rate of decay of the signal detected rather than the magnitude of the signal, changes in instrument sensitivity have little effect. The oxygen log, on the other hand, depends strongly on instrument calibration. Recalibration to monitor changes in a given well is probably not necessary, however, because the log response from regions in which the well penetrates impermeable formation can be used to eliminate changes in log sensitivity.

ILLUSTRATIVE EXAMPLE

The following is an example of the use of the technique of this invention to measure three quantities of interest: (1) the oil content of a producing zone, (2) the fraction of the original oil content that can be displaced by a particular flooding technique (in this case a water flood), and (3) the oil content remaining in the producing interval of interest after a water flood has been in progress for one year. The numbers in this example represent the responses of two successive logs. It should be noted that such numbers could represent the average of as many logging runs as are necessary to reduce random errors to a desired level. The responses of the logs are represented quantitatively by a single number which corresponds to the average of the logged values over the producing interval of interest. The following table contains the values characteristic of the log and the reservoir fluids:

Outside diameter of casing cement	10 inches
Logging speed	34 ft/min
Distance between neutron source and detector	6 ft
$\Sigma_w = 31.7 \times 10^{-3} \text{ cm}^{-1}$	(30,000 ppm NaCl)
$\Sigma_o = 22.2 \times 10^{-3} \text{ cm}^{-1}$	(dead oil)
Σ_g —negligible	
$KF_w = (1,000-800)/0.35$ count units (see below)	

(The output level of the oxygen log is calibrated by running it in an artificial sand. The outside diameter of the casing in the test is 10 inches. This casing is surrounded by a sand pack with porosity 0.35, and the sand was saturated with water. The response of the oxygen log is 1,000 count units. The same log is run when the sand is dry. The response of the oxygen log is 800 count units. The product $K F_w$ listed in the table above is then computed from Equations (2) and (4).)

After slow production of the well and a one-week period of no production, the value of the capture cross section throughout the interval of interest averages $\Sigma_1 = 24.0 \times 10^{-3} \text{ cm}^{-1}$ and the signal responses from the oxygen log averages $L_1 = 750$ count units.

Packers are set above and below the producing zone and three barrels of water per foot of producing zone are injected into the zone. The salinity of the water injected can be matched to that in the reservoir by using produced water for this injection. The subsequent log responses are $\Sigma_2 = 25.98 \times 10^{-3} \text{ cm}^{-1}$ and $L_2 = 810$ count units.

Then, the zone of interest is flooded with a sufficient quantity of alcohol to clear the remaining oil from the vicinity of the well bore. The alcohol is displaced into the formation by water, and the subsequent log responses are $\Sigma_3 = 27.65 \times 10^{-3} \text{ cm}^{-1}$ and $L_3 = 870$ count units.

The first and third sets of results can be used in Equation (7) to solve for the oil content remaining after the formation around the well bore has been water flooded:

$$\phi S_0 = 0.135 = 1,050 \text{ bbl/acre ft.}$$

The second and third sets of measurements can be used in Equation (7) to solve for the oil content remaining after the formation around the well bore has been water flooded:

$$\phi S_0 = 0.75 \times 580 \text{ bbl/acre ft.}$$

An additional set of logs made one year after the start of a water flooding project are represented by the following response levels:

$$\Sigma_4 = 23.80 \times 10^{-3} \text{ cm}^{-1},$$

and

$$L_4 = 759 \text{ count units.}$$

These values can be combined with those from the third set of measurements in Equation (7) to calculate that the oil in place at the time of the fourth log corresponds to:

$$\phi S_0 = 0.105 \times 815 \text{ bbl/acre ft.}$$

While the foregoing description of my invention indicates that the primary utility is in a cased well bore, the method may also be used in an uncased well bore where the fluid content of the formation around the well bore can be altered as required before the second run of the thermal neutron decay log and the oxygen log.

I claim:

1. A method of measuring differences in fractional-volume oil content and differences in fractional-volume gas content of an earth formation constituting a given depth interval of the region surrounding a well bore, comprising

1. running a neutron-activation oxygen log and a thermal-neutron-decay-time log over said given depth interval,
2. changing the oil content of said earth formation in said region surrounding the well bore,
3. then running a second oxygen log and a second thermal-neutron-decay-time log over said given depth interval, and
4. calculating the desired differences in fractional-volume oil content and fractional-volume gas content of said earth formation within said depth interval from the measured difference in oxygen response between Steps (1) and (3), and the determined difference in neutron capture cross section between Steps (1) and (3).

2. A method of measuring differences in fractional-volume gas content within an earth formation constituting a given depth interval of the region surrounding a well bore, comprising

1. running a neutron-activation oxygen log and a thermal-neutron-decay-time log over said given depth interval,
2. changing the gas content of said earth formation in said region surrounding the well bore.
3. then running a second oxygen log and a second thermal-neutron-decay-time log over said given depth interval, and
4. calculating the desired difference in fractional-volume gas content of said earth formation within said depth interval from the measured difference in oxygen response between Steps (1) and (3), and the determined difference in neutron capture cross section between Steps (1) and (3).

3. A method of measuring differences in fractional-volume oil content of an earth formation constituting a given depth interval of the region surrounding a well bore, comprising

1. running a neutron-activation oxygen log and a thermal-neutron-decay-time log over said given depth interval,
2. changing the oil content of said earth formation in said region surrounding the well bore,
3. then running a second oxygen log and a second thermal-neutron-decay-time log over said given depth interval, and
4. calculating the desired difference in fractional-volume oil content of said earth formation within said depth interval from the measured difference in oxygen response between Steps (1) and (3), and the determined difference in neutron capture cross section between Steps (1) and (3).

4. The method of claim 3 in which the changing of the oil content in the second step includes the removal of substantially all the oil from said formation.

5. The method of claim 3 in which the changing of the oil content in the second step corresponds to a proposed flooding technique for said earth formation wherein a fluid is injected as a pilot test for a field-scale assisted recovery project.

6. The method of claim 3 in which the changing of the oil content in the second step includes production

of the field to reduce the original fluid content of said earth formation over said given depth interval.

7. The method of claim 3 wherein Steps (1) to (4) are performed at least twice, the first time with Step (2) including flooding said region of said earth formation surrounding said well bore with a fluid proposed to be used for assisted recovery of oil from said formation, and the second time with Step (2) including the removal of substantially all the oil from said formation.

8. The method of claim 3 wherein Steps (1) and (4) are performed at least twice, the first time with Step (2) including production of oil from said earth formation over said given depth interval to reduce said oil content, and the second time with Step (2) including removal of substantially all the oil from said formation.

9. A method of measuring differences in fractional-volume oil content within an earth formation constituting a given depth interval of the region surrounding a well bore, comprising

1. running a neutron-activation oxygen log and a thermal-neutron-decay-time log over said given depth interval,
2. changing the oil content of said earth formation in said region surrounding the well bore,
3. then running a second oxygen log and a second thermal-neutron-decay-time log over said given depth interval, and
4. calculating the desired fractional volume oil content of said earth formation by inserting the total capture cross-sections determined in steps (1) and (3), and the amplitudes of the signals from the oxygen log in Steps (1) and (3) into the Equation:

$$\phi (S_{O1} - S_{O2}) = (L_2 - L_1/K F_W) [(\Sigma_W - \Sigma_G)/(\Sigma_O - \Sigma_G)] - (\Sigma_2 - \Sigma_1/\Sigma_O - \Sigma_G)$$

where: the subscripts 1 and 2 refer to the conditions during the first and second measurements respectively,

ϕ = porosity of the formation expressed as a fraction.

S_O = fraction of the pore volume containing oil.
 L = the amplitude of the signal from the oxygen log.

K = the calibration constant describing the response of the log to the oxygen content of the material in the formation.

F_W = the oxygen content of water.

- Σ_W = capture cross section of formation water.
- Σ_G = capture cross section of formation gas.
- Σ_O = capture cross section of the formation oil.
- Σ_1 = total capture cross section from the first measurement.
- Σ_2 = total capture cross section from the second measurement.

10. A method of measuring differences in fractional-volume gas content within an earth formation constituting a given depth interval of the region surrounding a well bore, comprising

1. running a neutron-activation oxygen log and a thermal-neutron-decay-time log over said given depth interval,
2. changing the gas content of said earth formation in said region surrounding the well bore,
3. then running a second oxygen log and a second thermal-neutron-decay time log over said given depth interval, and
4. calculating the desired difference in fractional-volume gas content of said earth formation by inserting the total capture cross sections determined in Steps (1) and (3), and the amplitudes of the signals from the oxygen log in Steps (1) and (3) into the Equation:

$$\phi (S_{G1} - S_{G2}) = (L_2 - L_1/K F_W) [(\Sigma_O - \Sigma_W)/(\Sigma_O - \Sigma_G)] + (\Sigma_2 - \Sigma_1/\Sigma_O - \Sigma_G)$$

where: the subscripts 1 and 2 refer to the conditions during the first and second measurements respectively,

ϕ = porosity of the formation expressed as a fraction.

S_G = fraction of the pore volume containing gas
 L = the amplitude of the signal from the oxygen log.

K = the calibration constant describing the response of the log to the oxygen content of the material in the formation.

- F_W = the oxygen content of water.
- Σ_W = capture cross section of formation water.
- Σ_G = capture cross section of formation gas.
- Σ_O = capture cross section of the formation oil.
- Σ_1 = total capture cross section from the first measurement.
- Σ_2 = total capture cross section from the second measurement.

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