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 PERMEABILITY LOGGING WITH RADIOACTIVE ISOTOPES HAVING
 HIGH AND LOW ENERGY GAMMA RAYS
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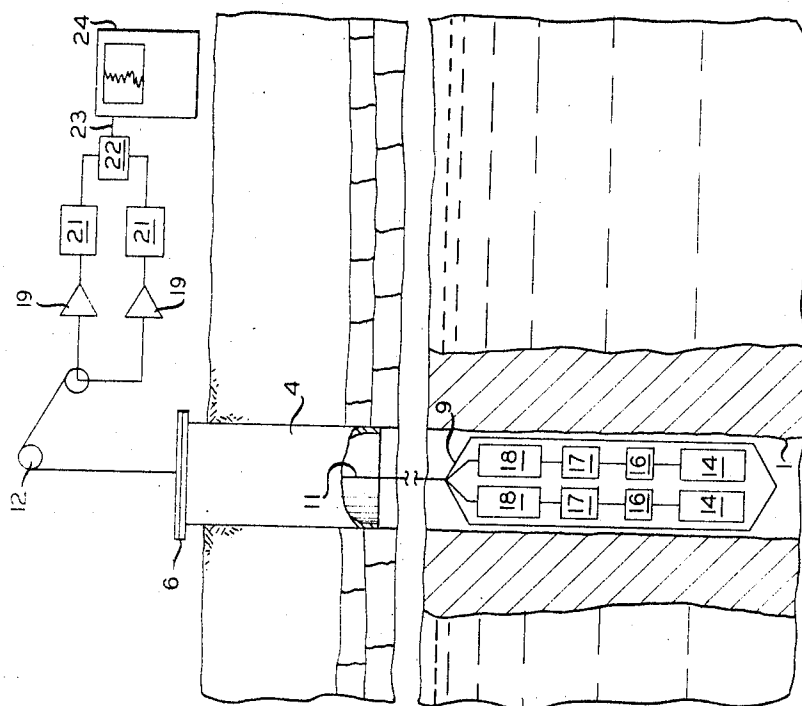


FIG. 2

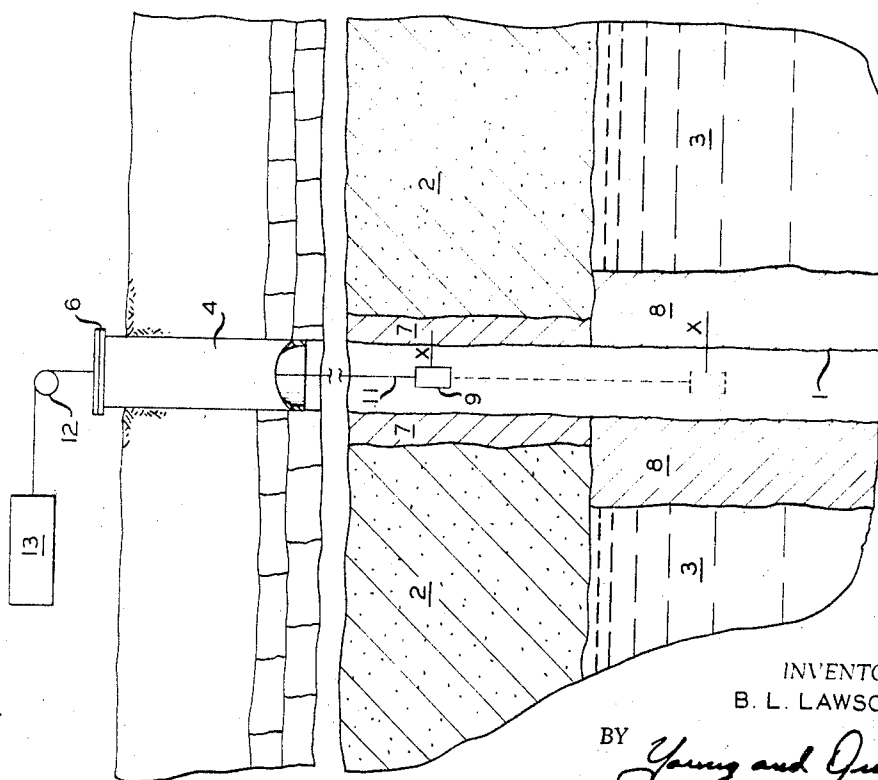


FIG. 1

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2

PERMEABILITY LOGGING WITH RADIOACTIVE ISOTOPES HAVING HIGH AND LOW ENERGY GAMMA RAYS

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8 Claims

ABSTRACT OF THE DISCLOSURE

Permeability of a formation is determined by incorporating a radioactive material, capable of emitting high and low energy gamma rays, into a drilling fluid and measuring the intensities of the high and low energy gamma rays which emanate from the material. The higher attenuation of the low energy gamma rays as compared to the attenuation of the high energy gamma rays, as the distance of penetration into the formation increases, will indicate the permeability of the formation.

This invention relates to the determination of the permeability of a substance. In another aspect, this invention relates to a method of and apparatus for determining the permeability of the formations traversed by a well bore.

In the drilling of bore holes in the earth, it is the customary practice to employ a drill bit secured to the lower end of a string of hollow drill pipe. The bore hole is formed by rotating and lowering the drill pipe in a manner which allows the drill bit to dislodge pieces of earth. Drilling fluid, commonly referred to as "drilling mud," is circulated down through the string of drill pipe, out through the drill bit, and upwardly to the surface between the string of drill pipe and the walls of the bore hole. As the drilling fluid is being circulated, it serves to transmit the dislodged pieces of earth from the bottom of the hole to the surface. The drilling fluid also serves to lubricate and cool the drill bit while it is being rotated. Drilling fluids frequently employed comprise a water suspension of gel-forming materials which impart desirable characteristics to the fluid.

As drilling continues and the bore hole increases in depth, the pressure of the fluids present in the subterranean formations also increases. In order to prevent these fluids from flowing into the bore hole, it is necessary to provide a greater pressure on the walls of the bore hole than the pressure of the fluids in the formations. This can be accomplished by increasing the specific gravity of the drilling fluid such that the pressure obtained by the hydrostatic column of drilling fluid on the formations is greater than the pressure of the fluids present in the formations. The specific gravity of the drilling fluid can be increased by adding suitable materials such as barytes.

Since the pressure of the drilling fluid on the formation is greater than the pressure of the fluids within the formations, the drilling fluid will flow outward into the formations away from the bore hole. The actual amount of drilling fluid which penetrates a formation and the depth of such penetration depends on the permeability of that formation. The permeability of a formation can be defined as its ability to conduct or transmit a fluid due to a pressure differential across it. Thus, when the drill bit encounters a highly permeable formation, the drilling fluid will flow a substantial distance outward into the formation. Conversely, when the drill bit encounters a formation with very little permeability, there will be almost no drilling fluid penetrating the formation. In either event, the depth of penetration of the drilling fluid from

the well bore into a formation is proportional to the permeability of that formation.

It is desirable to determine the permeable formations traversed by a drill bit because these formations can contain oil and gas which can subsequently be produced through the bore hole.

According to this invention, the depth of penetration of the drilling fluid into a formation and hence the permeability of that formation can be determined by incorporating a radioactive material into the drilling fluid, measuring the intensities of the high and low energy gamma rays emanating from the radioactive material after it has flowed outward into the formation along with the drilling fluid, and determining the ratio of the measured intensities. It was discovered that the low energy gamma rays emanating from the radioactive material become more attenuated than the high energy gamma rays as the depth of penetration increases. Thus, if the ratio is expressed as intensity of low energy gamma rays to intensity of high energy gamma rays, the ratio will decrease as depth of penetration and permeability increases because the low energy gamma rays will become attenuated more than the high energy gamma rays.

This invention has several advantages over the prior art methods wherein a radioactive material is forced outward into the formations adjacent a well bore and the increase in radioactivity is used as an indication of permeability. According to this technique of the prior art, it is apparent that a wash-out or void space adjacent the well bore will become concentrated with radioactive material and thereby indicate a zone of high permeability. When a wash-out or void is encountered during the practice of this invention, it will not be identified as a permeable zone because the permeability is expressed as a ratio; and since there has been no penetration to attenuate either the low or high energy gamma rays, except that due to the fluid itself, the ratio will remain substantially constant.

In one embodiment of this invention, the radioactive material used is of a type capable of emitting both high and low energy gamma rays.

In another embodiment of this invention, two separate radioactive materials are employed. In this embodiment, one of the radioactive materials emits high energy gamma rays and the other radioactive material emits low energy gamma rays.

Accordingly, it is an object of this invention to provide an improved method and apparatus for determining the permeability of the formations traversed by a well bore.

Another object of this invention is to provide an improved method and apparatus for determining the permeability of the formations traversed by a well bore irrespective of wash-outs of the formations adjacent the well bore.

Various other objects, advantages, and features of this invention will become apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

FIGURE 1 is a vertical section of a bore hole showing the depth of drilling fluid penetration into the surrounding formations; and

FIGURE 2 is a detailed view of a radiation detector lowered into a bore hole for the purpose of measuring the intensities of the gamma rays emanating from the radioactive material.

Referring now to the drawings, wherein like reference numerals are used to denote like elements, the invention will be more fully described. In FIGURE 1, a bore hole 1 is shown as having been drilled through formations 2 and 3. A casing 4 in the upper portion of the hole is provided with a suitable flange or casing head 6. The drilling

fluid which has been used during the drilling operation is provided with a radioactive material capable of emitting both high and low energy gamma rays. Alternatively, the drilling fluid can be provided with two radioactive materials one of which will emit high energy gamma rays and the other low energy gamma rays. A portion of the drilling fluid including the radioactive material is shown as having penetrated the formations 2 and 3 into the zones 7 and 8, respectively. A bore hole instrument 9 is suspended in the bore hole 1 by means of a cable 11 which passes over a pulley 12. Suitable winch means 13 is used to raise and lower the instrument 9 in and out of the bore hole.

FIGURE 2 of the drawing shows the bore hole instrument 9 and the surface equipment in detail. The bore hole instrument 9 comprises a pair of gamma radiation detectors 14 which function to measure the intensity of the gamma rays emanating from the radioactive material. The detectors 14 can be any suitable type of conventional detector. One type of detector is a scintillation counter comprising a sodium iodide, thallium activated, crystal and a photomultiplier tube. The signals from each of the detectors 14 are separately preamplified at 16, amplified at 17, and passed to discriminators 18. The discriminators function to establish signals in response to the intensity of the gamma rays. One discriminator will establish a signal in response to the intensity of the high energy gamma rays and the other discriminator will establish a signal in response to the intensity of the low energy gamma rays. These signals are separately passed through suitable lines attached to cable 11 to amplifiers 19 which serve to amplify the signals from the individual discriminators. The amplified signals are separately passed to a pair of integrating circuits 21 which function to establish a voltage in response to the intensity of the signals from the amplifiers 19. The voltages from each of the integrating circuits 21 are compared by applying them to a ratio circuit 22 which establishes a signal in response to the ratio of the voltages produced by the integrating circuits. This signal is passed via line 23 to a recorder 24 which records the magnitude of the ratio signal produced by the ratio circuit.

It will be appreciated that for the sake of clarity, the details concerning the construction of the amplifiers, the integrating circuits, and the ratio circuit have been omitted since their individual features form no part of the invention.

In the practice of this invention, the drilling fluid is provided with a radioactive material capable of emitting gamma rays in the energy range of from zero to 0.8 mev. and from 1.0 to 5 mev. It is generally preferred to consider the gamma rays in the energy range of from zero to 0.8 mev. as the low energy gamma rays and those in the energy range of from 1.0 to 5 mev. as the high energy gamma rays. Although the concentration of radioactive material in the drilling fluid is arbitrary, for economic reasons it is generally preferred to use from about 10 to 500 microcuries of radioactive material per barrel of drilling fluid.

The following table identifies some of the radioactive isotopes which can be used in accordance with one embodiment of this invention. It should be noted that this table represents only a few of those isotopes which emit gamma rays within the high and low energy ranges. Those isotopes which are identified are done so for the purpose of illustration only and are not considered to be limiting of the invention.

TABLE I.—RADIOACTIVE ISOTOPES WHICH EMIT HIGH AND LOW ENERGY GAMMA RAYS

Isotope	Half-Life	High Energy	Low Energy
Cadmium, 115 m.....	43 days.....	1.3 mev.....	0.49 mev.
Iron, 59.....	44.3 days.....	1.3 mev.....	0.19 mev.
Antimony, 124.....	60 days.....	2.1 mev.....	0.6 mev.

Table II below identifies several radioactive isotopes which can be used in accordance with another embodi-

ment of the invention. The isotopes identified in Table II are likewise for the purpose of illustration, and are not considered to be limiting of the invention.

In this embodiment of the invention, a desirable amount of low energy isotope and high energy isotope are added to the drilling fluid. Again, the concentration of radioactive material in the drilling fluid is arbitrary. For economic reasons, it is preferred to add from about 10 to 500 microcuries of both the high and low energy isotopes to each barrel of drilling fluid.

TABLE II.—RADIOACTIVE ISOTOPES WHICH EMIT HIGH ENERGY GAMMA RAYS

Isotope	Half-Life	Energy
Antimony, 124.....	60.9 days.....	2.11 mev.
Europium, 152.....	12.7 years.....	1.40 mev.
Europium, 154.....	16.0 years.....	1.40 mev.
Cobalt, 60.....	5.3 years.....	1.33 mev.
Iron, 59.....	44.3 days.....	1.29 mev.
Scandium, 46.....	84.2 days.....	1.12 mev.
Zinc, 65.....	246.4 days.....	1.12 mev.

RADIOACTIVE ISOTOPES WHICH EMIT LOW ENERGY GAMMA RAYS

Isotope	Half-Life	Energy
Cesium, 134.....	2.1 years.....	0.79 mev.
Cesium, 137.....	30 years.....	0.66 mev.
Zirconium, 95.....	65 days.....	0.75 mev.

The intensity of the gamma rays determined by the detectors can be expressed by the equation

$$I = I_0 e^{-\mu x} \quad (1)$$

wherein:

I_0 is proportional to the number of curies of radioactive isotope per barrel of drilling fluid,
 μ is the absorption coefficient and is expressed negatively because there is a loss in intensity in passing through a formation,
 x is proportional to the depth of penetration of the radioactive isotope into a formation, and
 e is the base of the natural logarithms.

By defining I_h as the intensity of high energy gamma rays and I_l as the intensity of the low energy gamma rays, the corresponding intensities of each can be expressed by the equations

$$I_h = I_{oh} e^{-\mu_h x} \quad (2)$$

and

$$I_l = I_{ol} e^{-\mu_l x} \quad (3)$$

wherein:

I_{oh} is proportional to the number of curies of high energy radioactive isotope per barrel of drilling fluid,
 I_{ol} is proportional to the number of curies of low energy radioactive isotope per barrel of drilling fluid,
 μ_h is the absorption coefficient of the formation to the high energy gamma rays,
 μ_l is the absorption coefficient of the formation to the low energy gamma rays,
 x is proportional to the depth of penetration of the radioactive isotope into the formation, and
 e is the base of the natural logarithms.

These intensities can be compared by expressing them as a ratio. The ratio R of the intensity of the low energy gamma rays I_l to the high energy gamma rays I_h can be expressed by the equation

$$R = \frac{I_l}{I_h} = \frac{I_{ol} e^{-\mu_l x}}{I_{oh} e^{-\mu_h x}} = \frac{I_{ol}}{I_{oh}} e^{-(\mu_l - \mu_h)x} \quad (4)$$

It is apparent from this equation that the ratio R and hence the permeability varies only in response to a change in the factor x because the factors I_{ol} , I_{oh} , μ_h remain constant for a particular formation and for a given number of curies of radioactive isotope per barrel of drilling fluid. Since the factor x is representative of the depth of pene-

tration of the drilling fluid, it is likewise representative of the permeability.

Referring again to FIGURE 1 of the drawing, it will be seen that the depth of penetration of the drilling fluid in formation 3 is greater than the depth of penetration in formation 2. It will also be seen that the distance x is greater in formation 3 than in formation 2. Since the factor x appears as a negative exponential in the ratio equation, it is apparent that the ratio of the intensities will be lower for formation 3 than for formation 2.

While the invention has been described in connection with the use of two gamma radiation detectors, it is within the scope of this invention to employ a single detector. When a single detector is used, it is gated to separately measure the intensities of the high and low energy gamma rays with the two signals subsequently being applied to a ratio meter.

It is also within the scope of this invention to incorporate radioactive materials with the drilling fluid which will emit gamma rays at three or more energy levels. In this application of the invention, it is possible to make intercomparisons between the several measured intensities and to make intercomparisons between the several ratios obtained.

It is further within the scope of this invention to express the permeability as the ratio of the intensity of the high energy gamma rays to the intensity of the low energy gamma rays. By expressing the ratio in this manner, it is apparent that the ratio will increase in value for an increase in permeability because the denominator, I_1 , will decrease at a higher rate than the numerator, I_2 , in response to an increase in the value of x .

Although the invention has been described in considerable detail for the purpose of explaining the invention, it is apparent that such detail is for this purpose only, and that many variations and modifications of the invention can be entertained without departing from the scope and spirit thereof.

I claim:

1. A method of determining the permeability of a formation traversed by a well bore comprising passing a radioactive material into said formation, wherein said radioactive material emits gamma radiation of at least two energy levels, measuring the intensities of the high energy gamma rays and the low energy gamma rays emanating from said radioactive material, and comparing said measured intensities.

2. A method of determining the permeability of a formation traversed by a well bore comprising passing a radioactive material capable of emitting high energy gamma rays and low energy gamma rays into said formation, measuring the intensities of the high energy gamma rays and the low energy gamma rays emanating from said radioactive material, and comparing said measured intensities.

3. A method of determining the permeability of a formation traversed by a well bore comprising passing a first radioactive material capable of emitting high energy gamma rays and a second radioactive material capable of emitting low energy gamma rays into said formation, measuring the intensity of the high energy gamma rays emanating from said first radioactive material, measuring the intensity of the low energy gamma rays emanating from said second radioactive material, and comparing said measured intensities.

4. A method of determining the permeability of a formation traversed by a well bore comprising passing a radioactive material into said formation, measuring the

intensity of the gamma rays up to an energy of about 0.8 mev. emanating from said radioactive material, measuring the intensity of the gamma rays within the energy range of from about 1.0 to 5 mev. emanating from said radioactive material, and comparing said measured intensities.

5. A method of determining the permeability of a formation traversed by a well bore comprising passing a mixture of radioactive materials including a first radioactive material capable of emitting gamma rays up to an energy of about 0.8 mev. and a second radioactive material capable of emitting gamma rays within an energy range of from about 1.0 to 5 mev. into said formation, measuring the intensity of the gamma rays emanating from said first radioactive material, measuring the intensity of the gamma rays emanating from said second radioactive material, and comparing said measured intensities.

6. A method of determining the permeability of a formation traversed by a well bore comprising adding a radioactive material to the drilling fluid used in the drilling of said well bore, measuring the intensity of the gamma rays emanating from said radioactive material after said radioactive material has become deposited in said formation during the drilling of said well bore, establishing a first signal responsive to the intensity of the gamma rays having an energy up to about 0.8 mev., establishing a second signal responsive to the intensity of the gamma rays having an energy range of from about 1.0 to 5 mev., establishing a first voltage responsive to said first signal, establishing a second voltage responsive to said second signal, and determining the ratio of said first voltage to said second voltage.

7. A method of determining the permeability of a formation traversed by a well bore comprising adding a mixture of radioactive materials including a first radioactive material capable of emitting gamma rays up to an energy of about 0.8 mev. and a second radioactive material capable of emitting gamma rays within an energy range of from about 1.0 to 5 mev. to the drilling fluid used in the drilling of said well bore, measuring the intensity of the gamma rays emanating from said radioactive materials after said radioactive material has become deposited in said formation during the drilling of said well bore, establishing a first signal responsive to said measured intensity of the gamma rays emanating from said first radioactive material, establishing a second signal responsive to said measured intensity of the gamma rays emanating from said second radioactive material, establishing a first voltage responsive to said first signal, establishing a second voltage responsive to said second signal, and determining the ratio of said first voltage to said second voltage.

8. A method of determining the permeability of a formation according to claim 7 wherein said first radioactive material is added in an amount of from about 10 to 500 microcuries per barrel of drilling fluid, and said second radioactive material is added in an amount of from about 10 to 500 microcuries per barrel of drilling fluid.

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