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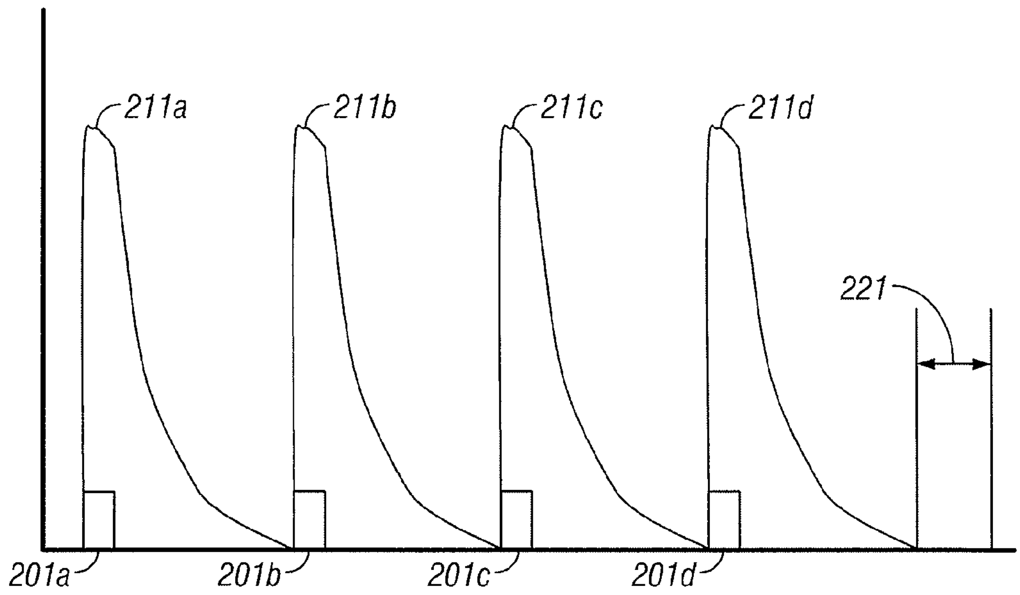
[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR DETERMINING SILICON CONTENT OF THE EARTH FORMATIONS IN CASED WELL BORES

FIG. 3



(57) Abstract: Measurements made with a pulsed neutron source and three or more gamma ray detectors are used to estimate the silicon and oxygen content of earth formations.

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METHOD AND APPARATUS FOR DETERMINING SILICON CONTENT OF THE EARTH FORMATIONS IN CASED WELL BORES

BACKGROUND OF THE INVENTION

[0001] This invention relates generally to oil and gas well logging tools. More particularly, this invention relates tools for measuring the Silicon content of rock formations through the use of gamma rays generated by a pulsed neutron source.

[0002] In petroleum and hydrocarbon production, it is desirable to know the porosity and density of the subterranean formation which contains the hydrocarbon reserves. Knowledge of porosity and density is useful in calculating the oil saturation and thus the volume of oil in-place within the reservoir. Knowledge of porosity is particularly useful in older oil wells where porosity information is either insufficient or nonexistent to determine the remaining in-place oil and to determine whether sufficient oil exists to justify applying enhanced recovery methods. Porosity information is also helpful in identifying up-hole gas zones and differentiating between low porosity liquid and gas.

[0003] If the density of the formation is known, then porosity can be determined using known equations. A variety of tools exist which allow the density of the reservoir to be determined. Most of these tools are effective in determining the density (and hence porosity) of the reservoir when the wellbore in which the tool is run is an uncased reservoir and the tool is able to contact the subterranean medium itself. However, once a well has been cased, there exists a layer of steel and concrete between the interior of the wellbore where the tool is located and the formation itself. The well casing makes it difficult for signals to pass between the tool and the reservoir and visa versa. In addition, the cement can confuse the measurement of formation properties.

[0004] United States Patent Application Ser. No. 11/115,792 of *Gilchrist* discloses a method and apparatus for estimating formation density of a subterranean formation using a pulsed neutron source and three gamma ray detectors. The method disclosed therein may be used in cased boreholes. The present invention is directed towards using an apparatus similar to that disclosed in *Gilchrist* for determining an elemental composition of formations. This problem of determining elemental composition has been addressed, for example, in US 4722220 to *Herron,* US 4317993 to *Hertzog*, US application Ser. No. 10/916921 (now US Patent 7,205,535) of *Madigan* et al. The method discussed here is much simpler and can be used with existing tools for density determination.

SUMMARY OF THE INVENTION

[0005] One embodiment described herein is a method of estimating a quantity of at least two elements in an earth formation. The method includes irradiating the earth formation with a source of neutrons within a borehole, moving logging tool with a velocity within the borehole and using at least three detectors on the logging tool to detect gamma rays produced in the earth formation as a result of the irradiating, using the velocity of the logging tool for processing counts made by be the detectors to estimate the quantity of the at least two elements, and recording the estimated quantity of the two elements on a suitable medium. The two elements may be silicon and oxygen. Half-lives of the gamma rays may be between 2 seconds and 500 seconds. The irradiating may include pulsing the neutron source. Estimating the velocity of the logging tool may be done using measurements made by the three detectors over an energy window characteristic of oxygen excitation. The method may further include calibrating the three detectors by making measurements in a formation having high background radiation with the neutron source deactivated. The method may further include using the estimated quantity of the two elements for determining a mineralogy of the earth formation, a water saturation of the earth formation, a void space in a gravel pack, and/or a porosity of the earth formation.

[0006] Another embodiment is an apparatus for estimating a quantity of at least two elements in an earth formation. The apparatus includes a source of neutrons configured to irradiate the earth formation from within the borehole, a logging tool configured to move with a velocity within the borehole, the logging tool having at least three detectors configured to detected gamma rays produced in the earth formation as a result of the irradiating. The apparatus also includes a processor configured to processed counts made by the three detectors using the velocity of the logging tool to estimate the quantity of the two elements, and record the estimated quantity of the two elements on a suitable medium. The two elements may be silicon and oxygen. The gamma rays produced by the irradiation may have a half-life between 2 seconds and 500 seconds. The processor may be configured to estimate the quantity of the two elements by solving a set of simultaneous equations involving counts made by the three detectors. The neutron source may be a pulsed neutron source. The processor may be further configured to estimate the velocity of the logging tool using measurements made by the three detectors over an energy window characteristic of oxygen excitation. The processor may be further configured to calibrate the three detectors using measurements in a formation having high background gamma radiation with the neutron source deactivated. The processor may be further configured to use the estimated quantity of the at least two elements for determining a mineralogy of the earth formation, a water saturation of the earth formation, a void space in a gravel pack, and/or a porosity of the formation. The apparatus may further include a conveyance device configured to convey the logging tool into the borehole.

[0007] Another disclosed embodiment is a computer-readable medium for use with an apparatus for estimating a quantity of at least two elements in an earth formation. The apparatus includes a source of neutrons configured to irradiate the earth formation from within a borehole and a logging tool configured to move with a velocity within the borehole, the logging tool having at least three detectors configured to detect gamma rays produced as a result of the irradiating. The medium includes instructions which enable a processor to process counts made by the at least three detectors using the velocity of the logging tool to estimate the quantity of the at least two elements, and record the estimated quantity of the at least two elements on a suitable medium. The medium may include a ROM, an EPROM, an EEPROM, a flash memory, and/or an optical disk.

BRIEF DESCRIPTION OF THE FIGURES

[0008] The present invention is best understood with reference to the accompanying figures in which like numerals refer to like elements and in which:

FIG. 1 is an overall schematic diagram of the nuclear well logging system of the present invention;

FIG. 2 illustrates the generation of gamma rays by inelastic scattering and capture of thermal and epithermal neutrons; and

FIG.3 schematic he illustrates the pulsing and data acquisition according to one embodiment.

DETAILED DESCRIPTION OF THE INVENTION

[0009] The system shown in **FIG. 1** is suitable for use with the present invention. Well **10** penetrates the earth's surface and may or may have casing **51**. Disposed within well **10** is subsurface well logging instrument **12**. The system diagramed in **FIG. 1** is a microprocessor-based nuclear well logging system using multi-channel scale analysis for determining the timing distributions of the detected gamma rays. Well logging instrument **12** includes an extra-long spaced (XLS) detector **17**, a long-spaced (LS) detector **14**, a short-spaced (SS) detector **16** and pulsed neutron source **18.** In one embodiment of the invention, XLS, LS and SS detectors **17, 14** and **16** are comprised of suitable material such as bismuth-germanate (BGO) crystals or sodium iodide (NaI) coupled to photomultiplier tubes. To protect the detector systems from the high temperatures encountered in boreholes, the detector system may be mounted in a Dewar-type flask. This particular source and flask arrangement is an example only, and should not be considered a limitation. Also, in one embodiment of the invention, source **18** comprises a pulsed neutron source using a D-T reaction wherein deuterium ions are accelerated into a tritium target, thereby generating neutrons having an energy of approximately 14 MeV. This particular type of source is for exemplary purposes only and not to be construed as a limitation. The filament current and accelerator voltage are supplied to source **18** through power supply **15**. Cable **20** suspends instrument **12** in well **10** and contains the required conductors for electrically connecting instrument **12** with the surface apparatus.

[0010] The outputs from XLX, LS and SS detectors **17, 144** and **16** are coupled to detector board **22**, which amplifies these outputs and compares them to an adjustable discriminator level for passage to channel generator **26**. Channel generator **26** is a component of multi-channel scale (MCS) section **24** which further includes spectrum accumulator **28** and central processor unit (CPU) **30**. MCS section **24** accumulates spectral data in spectrum accumulator **28** by using a channel number generated by channel generator **26** and associated with a pulse as an address for a memory location. After all of the channels have had their data accumulated, CPU **30** reads the spectrum, or collection of data from all of the channels, and sends the data to modem **32** which is coupled to cable **20** for transmission of the data over a communication link to the surface apparatus. Channel generator **26** also generates synchronization signals which control the pulse frequency of source **18**, and further functions of CPU 30 in communicating control commands which define certain operational parameters of instrument **12** including the discriminator levels of detector board **22**, and the filament current and accelerator voltage supplied to source 18 by power supply **15**.

[0011] The surface apparatus includes master controller **34** coupled to cable **20** for recovery of data from instrument **12** and for transmitting command signals to instrument **12**. There is also associated with the surface apparatus depth controller **36** which provides signals to master controller 34 indicating the movement of instrument **12** within well **10**. The system operator accesses the master controller **34** to allow the system operator to provide selected input for the logging operation to be performed by the system. Display unit **40** and mass storage unit **44** are also coupled to master controller **34**. The primary purpose of display unit **40** is to provide visual indications of the generated logging data as well as systems operations data. Storage unit **44** is provided for storing logging data generated by the system as well as for retrieval of stored data and system operation programs. A satellite link may be provided to send data and or receive instructions from a remote location.

[0012] In a well logging operation such as is illustrated by **FIG. 1**, master controller **34** initially transmits system operation programs and command signals to be implemented by CPU **30**, such programs and signals being related to the particular well logging operation. Instrument **12** is then caused to traverse well **10** in a conventional manner, with source **18** being pulsed in response to synchronization signals from channel generator **26**. Typically, source **18** is pulsed at a rate of 1000 bursts/second (1 KHz). This, in turn, causes a burst of high energy neutrons on the order of 14 MeV to be introduced into the surrounding formation to be investigated. As discussed below with reference to **FIG. 2**, this population of high energy neutrons introduced into the formation will cause the generation of gamma rays within the formation which at various times will impinge on XLS, LS and SS detectors **17, 14** and **16**. As each gamma ray thus impinges upon the crystal-photomultiplier tube arrangement of the detectors, a voltage pulse having an amplitude related to the energy of the particular gamma ray is delivered to detector board **22**. It will be recalled that detector board **22** amplifies each pulse and compares them to an adjustable discriminator level, typically set at a value corresponding to approximately 100 KeV. If a pulse has an amplitude corresponding to an energy of at least approximately 100 KeV, the voltage pulse is transformed into a digital signal and passed to channel generator **26** of MCS section **24**.

]0013] In addition, as would be known to those versed in the art, many of the functions of the components described with reference to **FIG. 1** may be carried out by a processor. It should also be noted that the system described in **FIG. 1** involves conveyance of the logging device into the well by a wireline. However, it is envisaged that the logging device could be part of a measurement while drilling (MWD) bottomhole assembly conveyed into the borehole by a drilling tubular such as a drillstring or coiled tubing. In addition, it should be noted that **FIG. 1** illustrates a tool in an open hole. The method and apparatus are equally well suited for use in cased holes.

[0014] FIG. 2 shows an illustration of the logging tool suitable for use with the present invention. The apparatus illustrated is that of the Reservoir Performance Monitor (RPM) of Baker Atlas Incorporated. A measurement device **100** comprises a neutron source **101** and three axially spaced apart detectors described below. The number of detectors shown in the embodiment of **FIG. 2** is only an example of the number of detectors employed in an embodiment of the present invention. It is not a limitation on the scope of the present invention. The measurement device of the present invention may comprise two or more detectors. The neutron source **101** may be pulsed at different frequencies and modes for different types of measurements. The short-spaced (SS) detector **105** is closest to the source **101**. The long-spaced (LS) detector is denoted by **106**, and the furthest detector **107** is referred to as the extra-large spaced (XLS) detector. Fast neutrons (approximately 14MeV) are emitted from the source **101** and enter the borehole and formation, where they undergo several types of interactions. During the first few microseconds (μs), before they lose much energy, some neutrons are involved in inelastic scattering with nuclei in the borehole and formation and produce gamma rays. These inelastic gamma rays **120**, have energies that are characteristic of the atomic nuclei that produced them. The atomic nuclei found in this environment include, for example, carbon, oxygen, silicon, calcium, and some others.

[0015] Two or more gamma-ray detectors are employed, in one or more modes of operation. Such modes include, but are not limited to, a pulsed neutron capture mode, a pulsed neutron spectrometry mode, a pulsed neutron holdup imager mode, and a neutron activation mode. In a pulsed neutron capture mode, for example, the tool pulses at 1 kHz, and records a complete time spectrum for each detector. An energy spectrum is also recorded for maintaining energy discrimination levels. Time spectra from short-spaced and long-spaced detectors can be processed individually to provide traditional thermal neutron capture cross section information, or the two spectra can be used together to automatically correct for borehole and diffusion effects and produce results substantially approximating intrinsic formation values.

[0016] In a pulsed neutron spectrometry mode, the instrument pulses at 10 kHz, for example, and records full inelastic and capture gamma ray energy spectra from each detector. These data are processed to determine critical elemental ratios including carbon/oxygen and calcium/silicon from the inelastic spectra and silicon/calcium from the capture spectra. A pulsed neutron holdup imager mode yields both energy spectra and time decay spectra from each detector simultaneously. Measurements can be used to determine holdups of gas, oil, and water. When combined with other production logs, the measurements made herein can provide a comprehensive production profile picture, even in deviated or horizontal wells. A neutron activation mode provides water-flow measurements using one of several data acquisition methods. Stationary measurements are made in either of two modes, and measurements at different logging speeds can be used to segregate different flow rates in either an annulus or in an adjacent tubing string. Various spectra of count rates from these can be used either individually or in combination as needed for each measurement mode.

[0017] With the neutron generator turned off, the measurement apparatus can also be used to detect the distribution of materials, tagged with radioactive tracers, that are injected into the well during well treatments. In this manner, the effectiveness of operations such as hydraulic fracturing or gravel pack placement can be evaluated.

[0018] In an embodiment of the present invention, a pulsed neutron generator with improved reliability and higher output is coupled with high-speed downhole microprocessor-controlled drivers and detector electronics. The system supports multiple frequency operation and different detection gate timings to make the different measurements. The modes of operation can be selected from the surface with no need to pull the tool out of the well.

[0019] After just a few μs, most of the neutrons are slowed by either inelastic or elastic scattering until they reach thermal energies, about 0.025 eV. This process is illustrated schematically in **FIG. 2** as the sequence of solid arrows **110**. At thermal energies, neutrons continue to undergo elastic collisions, but they no longer lose energy on average. A few μs after the neutron generator shuts off, this process is complete. Over the next several hundred μs, thermal neutrons are captured by nuclei of various elements – again producing gammas rays, known as capture gamma rays **130**. A capture gamma ray energy spectrum yields information about the relative abundances of these elements.

[0020] The present disclosure deals with measurements made by the logging tool **12** when it is in motion. Of particular interest is analysis of an interval such as **65** in the formation **55.** By analyzing measurements made with the three detectors while the tool is in motion, it is possible to estimate the quantities of elements such as oxygen, silicon and iron in the interval **65.** This is discussed next.

[0021] An exemplary sequence of pulsing is schematically illustrated in **FIG. 3**. Shown therein is a sequence of pulses **201a, 201b, 201c, 201d** of the pulsed neutron source **18.** The gamma ray measurements corresponding to the pulses are denoted by **211a, 211b, 211c, 211d.** We first focus on measurements made during an interval such as **221** which, typically, starts about 2 ms after the initiation of pulse **201d.**

[0022] We denote by BKS, BKL and BKX the measurements made by the short, long and extra long detectors **16, 14** and **17** respectively during an interval such as **221**. This interval may start about 2 ms after of the pulse **201d**. In particular, the pulsing of the neutron source activates oxygen, silicon and iron present in the near-wellbore environment. The characteristic half-lives for gamma ray emission from oxygen and silicon are 7.13 seconds and 134 seconds respectively, while the half-life for iron is of the order of seven hours. When measurements are made in a cased borehole, the signal from iron will be ubiquitous. The detector count-rates are, for the case where the source-detector spacings are 1, 2 and 3 feet respectively, then given by the following simplified equations

$$\begin{aligned} BKS &= (background + Iron) + \frac{Si(t0)}{2^n} + \frac{O(t0)}{2^m} \\ BKL &= (background + Iron) + \frac{Si(t0)}{2^{2n}} + \frac{O(t0)}{2^{2m}}, and \\ BKX &= (background + Iron) + \frac{Si(t0)}{2^{3n}} + \frac{O(t0)}{2^{3m}} \end{aligned} \quad (1).$$

In **eqn. 1**, it is assumed that during the observation time, there is very little decrease in radiation from the activated iron so that it may be included with the background gamma radiation. Si(t0) and O(t0) are the initial contributions to the total count-rate from the activated silicon and oxygen respectively. The parameters *m* and *n* are derived from the half-lives of oxygen and silicon respectively and the velocity of tool motion. Those versed in the art would recognize that relative values of the exponents in **eqn. 1** for the different detectors are related to the relative source-detector distances. For example, if the source-detector spacings are 1, 2 and 4 feet, the exponents would be m, 2m and 4m (and n, 2n and 4n) and are an exponential function of the time it takes a particular detector to pass a specific point in the of earth formation. The half life $t_{1/2}$ defines an exponential decay constant $\lambda = \frac{t_{1/2}}{\log(2)}$.

[0023] Thus, as the tool is moved past, the counts made by the three detectors are indicative of the amounts of oxygen, silicon and iron in an interval such as **65** in the earth formation **55 (see FIG. 1). Eqn. 1** is set of three simultaneous equations which can be solved to estimate the value of the silicon count at time zero (which is proportional to the quantity of silicon present in the volume sensed by the tool). This value is sensitive to the source output and the tool velocity. The source output from the RPM tool is very stable and should not be a problem. However, the tool velocity needs to be known accurately.

[0024] In one embodiment, surface measurements of tool velocity are used. In another embodiment, tool velocity is determined from a combination of accelerometer measurements and surface measurements. Such a method is discussed, for example, in US 7142985 to *Edwards* et al., having the same assignee as the present disclosure and the contents of which are incorporated herein by reference. In other embodiments of the disclosure, actual tool velocity is determined directly from the gamma-ray measurements. These are discussed next.

[0025] In one embodiment, measurements are made at the three detectors over energy windows specific to the oxygen excitation and gamma ray decay. The lower and upper bounds of the energy window are selected such that the majority of the gamma rays generated by activated oxygen are detected and discriminated from other background events. An exemplary window would be from 3 MeV to 8 MeV. Under these conditions, we have three measurements and three unknowns. The unknowns are the background gamma ray count, the initial count rate from oxygen, and the tool velocity. These three equations can be solved to give the tool velocity. This tool velocity is then used for solving the set of **eqns. (1)** above. In yet another embodiment, the method described in United States patent application 10/879620 (now US Patent 7,186,971) of *Riley* et al., having the same assignee as the present disclosure and the contents of which are incorporated herein by reference. The method described by *Riley* is directed towards determination of a rate of flow of fluids in the vicinity of the borehole using measurements from the three detectors which use windowed energy levels corresponding to oxygen. Among the methods disclosed in *Riley* is a correlation of signals OA1, OA2 and OA3 at the three detectors. In the present instance, a similar method is used to determine the velocity of tool motion past an interval such as **65**.

[0026] Part of the calibration of the tool is based upon logging in a formation having high background gamma radiation, such as a shale, with the neutron source deactivated. When the tool is conveyed past such an interval, all three detectors should have the same readings independent of the tool speed when a particular detector is adjacent to the shale. Alternatively, surface calibration may be carried out using a method similar to that for calibration of the natural gamma ray tool.

[0027] At a logging speed of 5 ft/m, the time taken for the detectors to pass over the formation that has been irradiated is 12 seconds for the short spaced, 24 seconds for the long spaced and 36 seconds for the extra long spaced detector. Under these conditions, the equations become:

$$\begin{aligned}
BKS &= (background + Iron) + \frac{Si(t0)}{1.06404} + \frac{O(t0)}{3.21102} \\
BKL &= (background + Iron) + \frac{Si(t0)}{1.13218} + \frac{O(t0)}{10.7672}, and \qquad (2). \\
BKX &= (background + Iron) + \frac{Si(t0)}{1.20469} + \frac{O(t0)}{33.10755}
\end{aligned}$$

If a value of one hour is used for the iron half-life, the difference in the contribution of iron to the count rates of the three detectors is less than one part in two thousand.

[0028] It is further contemplated that a logging tool with four detectors would provide an overdetermined set of equations (1) and may provide improved accuracy in the presence of measurement noise. It is envisaged that the method described above may be suitable for identifying any two elements for which the half-life is between about two seconds and 500 seconds at practical logging speeds.

[0029] The estimated silicon and oxygen in the formation may typically be recorded on a suitable medium and used for further operations. There are a variety of possible uses of the method described above. Since sandstones consist primarily of SiO_2 while carbonate rocks (limestones and dolomites) should normally contain no silicon, the Si/O ratio may be used to distinguish between sandstones and carbonate rocks in the earth formation. This knowledge is helpful in designing perforations in the casing and fracturing operations that may be carried out in the earth formation. The formation density measurement combined with the Si and O measurements described above are used for diagnostics for evaluating void space in gravel packs and taking appropriate remedial action. In combination with an independent estimate of porosity, the estimate of oxygen can be used to derive a water saturation of the formation based upon the fact that a hydrocarbon-filled pore space would contain no oxygen.

[0030] The processing of the measurements made in wireline applications may be done by the surface processor **33,** by a downhole processor, or at a remote location. The data acquisition may be controlled at least in part by the downhole electronics.

Implicit in the control and processing of the data is the use of a computer program on a suitable machine readable medium that enables the processors to perform the control and processing. The machine readable medium may include ROMs, EPROMs, EEPROMs, Flash Memories and Optical disks.

[0031] While the foregoing disclosure is directed to the specific embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all such variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

CLAIMS

What is claimed is:

1. A method of estimating a quantity of at least two elements in an earth formation, the method comprising:
   (a) irradiating the earth formation with a source of neutrons within a borehole;
   (b) moving a logging tool with a velocity within the borehole and using at least three detectors on the logging tool to detect gamma rays produced in the earth formation as a result of the irradiating;
   (c) processing counts made by the at least three detectors to estimate the quantity of the at least two elements, the processing using the velocity of the logging tool; and
   (d) recording the estimated quantity of the at least two elements on a suitable medium.

2. The method of claim 1 wherein the at least two elements comprise silicon (Si) and oxygen (O).

3. The method of claim 1 wherein half-lives of the gamma rays produced by the irradiation is between about two seconds and 500 seconds.

4. The method of claim 1 wherein estimating the quantity of the at least two elements further comprises solving a set of simultaneous equations involving the counts made by the at least three detectors.

5. The method of claim 1 wherein the irradiating further comprises pulsing the neutron source.

6. The method of claim 5 wherein the detecting further comprises making measurements at a starting time at least 2 ms after a start time of a pulse.

7. The method of claim 1 further comprising estimating the velocity of the logging tool using measurements made by the at least three detectors over an energy window characteristic of oxygen excitation.

8. The method of claim 1 further comprising calibrating the at least three detectors by making measurements in a formation having high background gamma radiation with the neutron source deactivated.

9. The method of claim 1 further comprising using the estimated quantity of the at least two elements for determining at least one of: (i) a mineralogy of the earth formation, (ii) a water saturation of the formation, (iii) a void space in a gravel pack, and (iv) a porosity of the formation.

10. The method of claim 1 wherein the borehole comprises a cased borehole.

11. An apparatus for estimating a quantity of at least two elements in an earth formation, the apparatus comprising:

(a) a source of neutrons configured to irradiate the earth formation from within a borehole;

(b) a logging tool configured to move with a velocity within the borehole and having at least three detectors configured to detect gamma rays produced in the earth formation as a result of the irradiating; and

(c) a processor configured to:

(A) process counts made by the at least three detectors using the velocity of the logging tool to estimate the quantity of the at least two elements, and

(B) record the estimated quantity of the at least two elements on a suitable medium.

2. The apparatus of claim 11 wherein the at least two elements comprise silicon (Si) and oxygen (O).

13. The apparatus of claim 11 wherein half-lives of the gamma rays produced by the irradiation is between about two seconds and 500 seconds.

14. The apparatus of claim 11 wherein the processor is configured to estimate the quantity of the at least two elements by further solving a set of simultaneous equations involving the counts made by the at least three detectors.

15. The apparatus of claim 11 wherein the neutron source further comprises a pulsed neutron source.

16. The apparatus of claim 15 the detectors are further configured to make measurements at a starting time at least 2 ms after a start time of a pulse.

17. The apparatus of claim 11 wherein the processor is further configured to estimate the velocity of the logging tool using measurements made by the at least three detectors over an energy window characteristic of oxygen excitation.

18. The apparatus of claim 11 wherein the processor is further configured to calibrate the at least three detectors using measurements in a formation having high background gamma radiation with the neutron source deactivated.

19. The apparatus of claim 11 wherein the processor is further configured to use the estimated quantity of the at least two elements for determining at least one of: (i) a mineralogy of the earth formation, (ii) a water saturation of the formation, (iii) a void space in a gravel pack, and (iv) a porosity of the formation.

20. The apparatus of claim 11 further comprising a conveyance device configured to convey the logging tool into the borehole.

21. The apparatus of claim 11 wherein the borehole comprises a cased borehole.

22. A computer-readable medium for use with an apparatus for estimating a quantity of at least two elements in an earth formation, the apparatus comprising:

(a) a source of neutrons configured to irradiate the earth formation from within a borehole; and

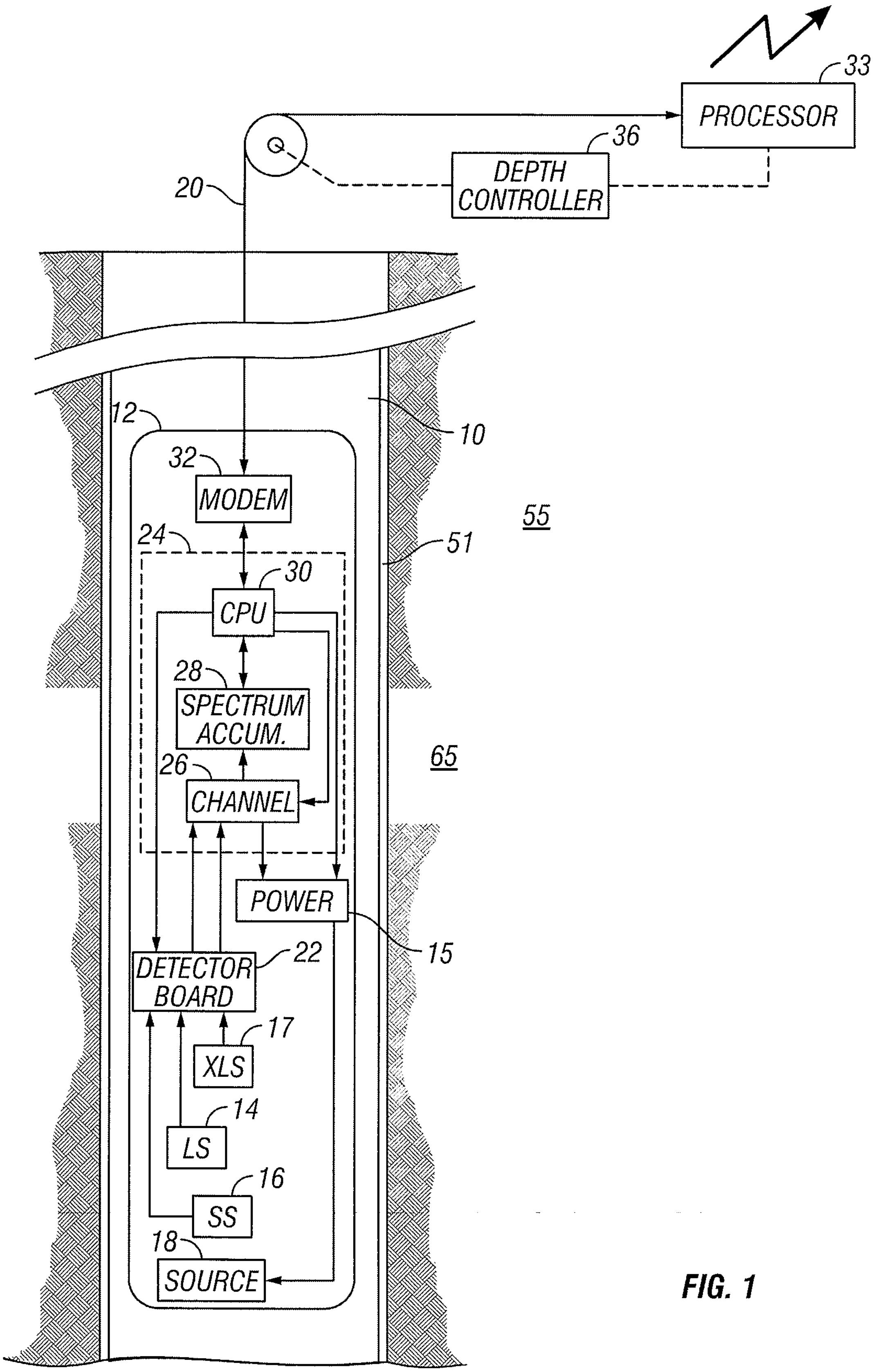
(b) a logging tool configured to move with a velocity within the borehole and having at least three detectors configured to detect gamma rays produced in the earth formation as a result of the irradiating;

the medium comprising instructions which enable a processor to:

(c) process counts made by the at least three detectors using the velocity of the logging tool to estimate the quantity of the at least two elements; and

(d) record the estimated quantity of the at least two elements on a suitable medium.

23. The medium of claim 22 further comprising at least one of: (i) a ROM, (ii) an EPROM, (iii) an EEPROM, (iv) a flash memory, and (v) an optical disk.



33
PROCESSOR
36
DEPTH CONTROLLER
20
12
10
32
MODEM
55
24
51
30
CPU
28
SPECTRUM ACCUM.
65
26
CHANNEL
POWER
15
22
DETECTOR BOARD
17
XLS
14
LS
16
SS
18
SOURCE

FIG. 1

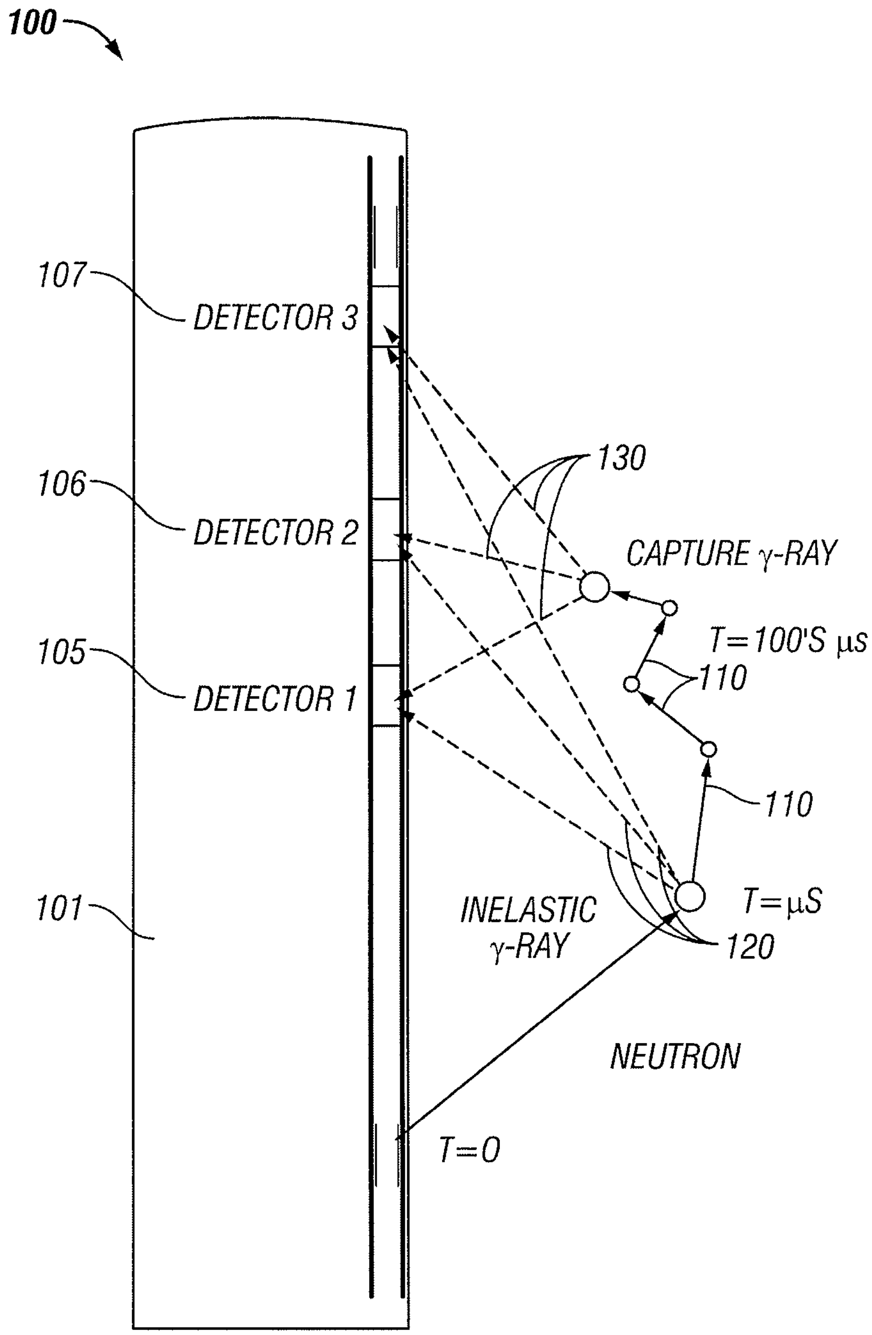

100
107
DETECTOR 3
106
DETECTOR 2
105
DETECTOR 1
101
130
CAPTURE γ-RAY
T=100'S μs
110
110
INELASTIC
γ-RAY
T=μS
120
NEUTRON
T=0

FIG. 2

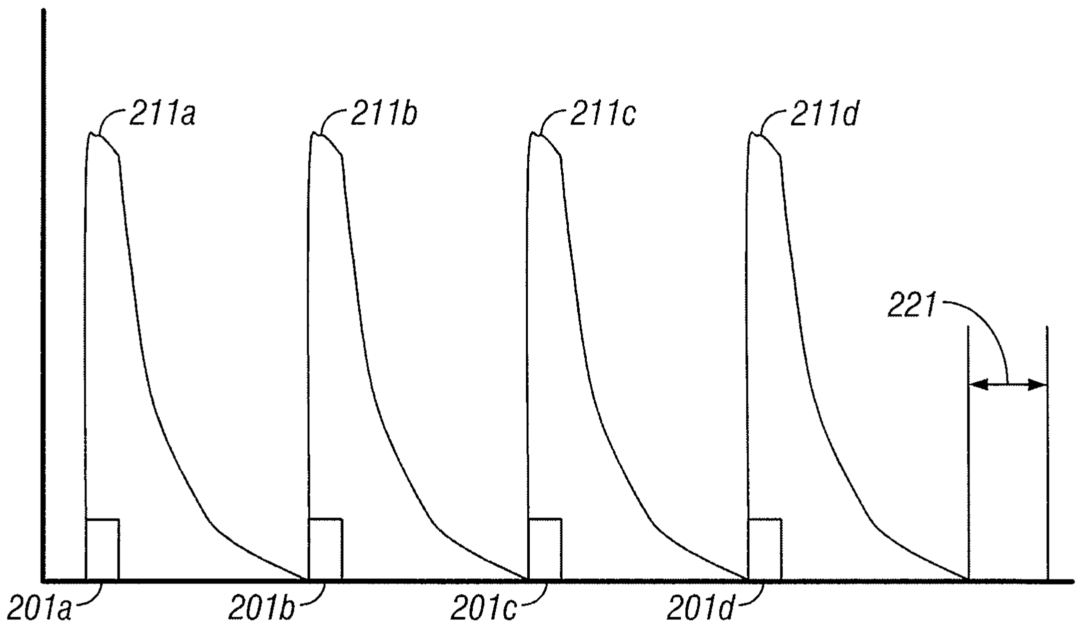


FIG. 3