

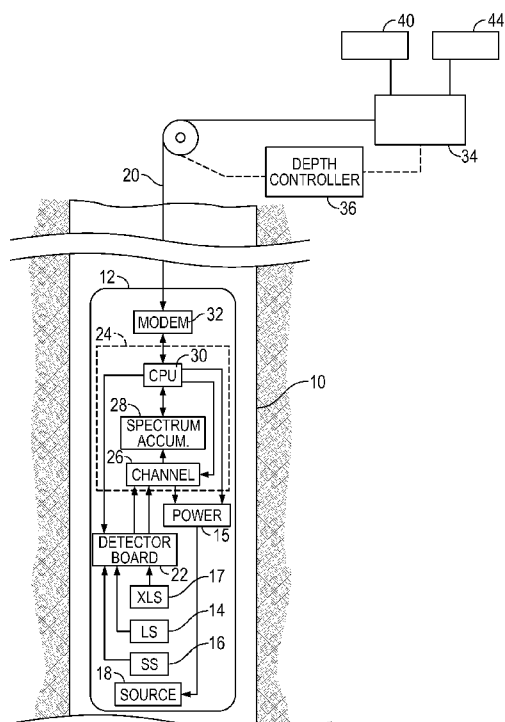


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[Continued on next page]

(54) Title: MEASUREMENT OF FORMATION POROSITY USING A SINGLE GAMMA RAY DETECTOR

(57) Abstract: A pulsed neutron source is used in a porosity logging tool with a single gamma ray detector coated with a neutron absorbing material. By using a ratio of the spectral peak associated with hydrogen to a spectral peak associated with the neutron absorbing material, the formation porosity is estimated.





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**TITLE: MEASUREMENT OF FORMATION POROSITY USING A SINGLE
GAMMA RAY DETECTOR**

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BACKGROUND OF THE DISCLOSURE

[0001] This disclosure relates generally to oil and gas well logging tools. More particularly, this disclosure relates to tools for measuring rock formation porosity through the use of gamma ray signals created when neutrons emitted by a pulsed neutron source interact with the materials surrounding the tool and with the material of the tool itself. This disclosure relates to a neutron porosity tool that uses a single gamma ray detector covered with neutron absorbing material like B¹⁰ isotope for the porosity measurements.

[0002] In petroleum and hydrocarbon production, it may be desirable to know the porosity of the subterranean formation that contains the hydrocarbon reserves. Knowledge of porosity may be used in calculating the oil saturation and thus the volume of oil in-place within the reservoir. Knowledge of accurate porosity values is particularly useful in older oil wells where porosity information derived from open hole porosity logs is either insufficient or nonexistent. This porosity information is useful in determining remaining oil in-place and in determining whether the remaining oil in-place justifies applying enhanced recovery methods. Porosity information is also helpful in identifying up-hole gas zones and differentiating between low porosity liquid and gas.

[0003] A variety of tools exists which allow the porosity of the reservoir to be determined. Most of these tools are effective in determining the porosity of the reservoir around the wellbore in which the tool is run. There are devices that work with cased holes as well as uncased holes. A common feature of these prior art tools is the necessity of having at least two neutron detectors. The present disclosure is directed towards a tool in which a single gamma ray detector is used for estimating formation porosity.

SUMMARY OF THE DISCLOSURE

[0004] One embodiment of the disclosure is a method of evaluating an earth formation. The method includes: obtaining an indication of a porosity of the earth formation using gamma rays measured by a single gamma ray detector, where the earth formation has been irradiated by a neutron source and the gamma ray detector is coated with a neutron absorbing material.

[0005] Another embodiment of the disclosure is an apparatus configured to evaluate a subterranean formation from within a wellbore. The apparatus includes: a pulsed neutron source configured to be conveyed in the wellbore and irradiate the earth formation; a single gamma ray detector coated with a neutron absorbing material and configured to measure gamma rays resulting from the irradiation; and a processor configured to use the measured gamma rays for obtaining an indication of a porosity of the earth formation.

[0006] Another embodiment of the disclosure is a non-transitory computer-readable medium product having instructions thereon that when read by a processor cause the processor to execute a method, the method comprising obtaining an indication of a porosity of an earth formation using gamma rays measured by a single gamma ray detector, where the earth formation has been irradiated by a neutron source and the single gamma ray detector is coated with a neutron absorbing material.

BRIEF DESCRIPTION OF THE FIGURES

[0007] The present disclosure 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 disclosure;

FIG. 2 illustrates a prior art methods for determination of formation porosity using two neutron detectors;

FIG. 3 illustrates an embodiment of the present disclosure in which a single gamma ray detector with a coating of B^{10} is used;

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FIG. 4 shows an exemplary capture gamma ray spectrum measured by a SS detector having a B^{10} coating and an LS detector having a B^{10} coating;

Fig. 5 shows a plot of the ratio R_{BtoH} of the "B" peak intensity to the H peak intensity for limestones of different porosity;

Fig. 6 shows a plot of the ratio R_{BtoH} of the "B" peak intensity to the H peak intensity for sandstones of different porosity; and

Fig. 7 shows a plot of the ratio R_{BtoH} of "B" peak intensity to the H peak intensity for a tight limestone as a function of borehole diameter.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0008] The system shown in **Fig. 1** is a system for logging based on the use of pulsed neutron generator according to the present disclosure. Well **10** penetrates the earth's surface and may or may not be cased depending upon the particular well being investigated. 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. In the prior art, 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**. The principles of the logging will be discussed first with respect to this prior art embodiment. In one embodiment of the present disclosure, as discussed below, only a single detector is used. In the prior art, 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 disclosure, 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 energies 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

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apparatus. In the present disclosure, the arrangement of the single detector is discussed further below.

[0009] The outputs from XLS, LS and SS detectors **17**, **14**, and **16** may be coupled to detector board **22**, which may amplify these outputs and compares them to an adjustable discriminator level for passage to channel generator **26**. Channel generator **26** may be 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**.

[0010] The surface apparatus may include master controller **34** coupled to cable **20** for recovery of data from instrument **12** and for transmitting command signals to instrument **12**. Master controller **34** may include a processor. In some embodiments, the processor may be separate from the master controller **34**. The surface apparatus may include depth controller **36** which may be configured to provide signals to master controller **34** indicating the movement of instrument **12** within well **10**. The system operator may access 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.

[0011] 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. 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 **17**, **14**, and **16**, a voltage pulse having an amplitude related to the energy of the particular gamma ray may be 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**. The high energy neutrons emitted by the source create gamma ray signals through inelastic scattering. Neutrons emitted by the source also interact with nuclei of the surrounding formation through elastic scattering and, as a result, lose energy. When the neutron energy becomes of the order of kT after multiple elastic interactions, such thermalized neutrons may be captured by nuclei of the surrounding material and capture gamma rays can be emitted. The gamma ray spectrum measured by the tool described above between 2 neutron bursts is mainly comprised of gamma rays emitted in capture reactions and is called capture gamma ray spectrum.

[0012] 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

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conveyance of the logging device **12** into the well **10** by a wireline. However, it is envisaged that the logging device **12** could be part of a measurement while drilling (MWD) bottom hole assembly conveyed into the borehole by a drilling tubular such as a drill string 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.

[0013] Turning now to **Fig. 2**, the principles of a prior art device for the porosity measurement are discussed. The device includes a source of fast neutrons **18**, which can be either a chemical source of neutrons or pulsed neutron generator. The device has a short spaced (SS) neutron detector **16** at a distance Z_1 from the source **18** and a long-spaced (LS) neutron detector **14** at a distance Z_2 from the source **18**. These detectors **14**, **16** perform the measurements of mainly thermal neutron component of neutron flux passing through areas **216** (for SS detector) and **214** (for LS detector) and this component is proportional to the count rate measured by each detector. The ratio of count rates measured by SS and LS detectors is used to determine formation porosity. This ratio R can be described by formula:

$$R = \frac{CR_{SS}}{CR_{LS}} \sim \frac{FTN_{SS}}{FTN_{LS}} \sim \frac{n(Z_1)}{n(Z_2)} = f(\rho) \quad (1),$$

where

R – count rate ratio;

CR_{XX} – count rate;

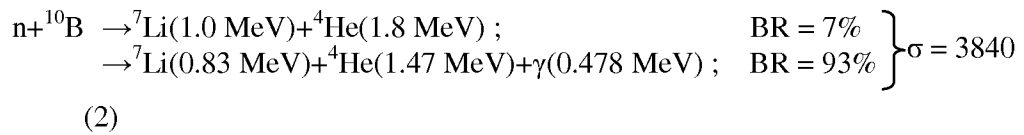
FTN_{XX} – flux of neutrons passing through the detector;

$n(Z_x)$ - concentration of thermal neutrons in point Z_x ; and

$f(\rho)$ – function of formation porosity.

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[0014] Turning now to **Fig. 3**, an illustration of the device according to one embodiment of the present disclosure is shown. The tool **12** includes a source of fast neutrons **18** such as a pulsed neutron generator. The gamma ray detector **314** is at a distance Z_0 from the source **18**. Detector **314** is covered with the B^{10} layer **316** thick enough to absorb more than 99% of thermal neutrons passing through the detector. The Neutron – B^{10} reaction is described by (2);



where the total value of the reaction cross-section σ is for the thermal neutrons with energy $E_n = 0.025 \text{ eV}$.

[0015] The reaction (2) causes the emission of gamma rays with $E_\gamma = 0.478 \text{ MeV}$. As a result, capture gamma ray spectrum measured by the detector **314** of such a tool contains the “boron” peak at $\sim 0.5 \text{ MeV}$ which is the superposition of two peaks – the boron peak itself due to gamma rays produced by reaction (2) with energy $E_\gamma = 0.478 \text{ MeV}$ and the peak which is due to gamma rays with $E_\gamma = 0.511 \text{ MeV}$ generated by positrons born inside of the detector (see **Fig. 4**). This capture spectrum also contains hydrogen peak at 2.222 MeV (see **Fig. 4**), which is due to the capture interaction of hydrogen nuclei and thermal neutrons which causes the emission of gamma rays with energy $E_\gamma = 2.222 \text{ MeV}$.

[0016] The intensity of boron peak itself, the component of the observed “B” peak which is due to 0.478 MeV gamma rays, is proportional to thermal neutron flux passing through the surface of gamma ray detector covered with B^{10} isotope:

$$I_B = S(E_\gamma = 0.478 \text{ MeV}) \otimes \text{FTN} \sim n(Z_0) \quad (3)$$

where S is gamma ray detector response function. The intensity of observed peak in the spectrum (“B” peak) can be described by:

$$I_{\text{“B”}} = I_B + I_{0.511} \quad (4)$$

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where $I_{0.511}$ is the intensity of the component which is due to 0.511 MeV gamma rays.

The intensity of this component can be described by:

$$I_{0.511} = S(E_\gamma = 0.511 \text{ MeV}) \otimes \sigma_{pp}(E'_\gamma) \otimes \int \gamma(\vec{r}, E''_\gamma) \left(\delta(E'_\gamma - E''_\gamma) \exp(-\sigma_\gamma(\vec{r})\vec{r}) + CT(E''_\gamma, E'_\gamma, \vec{r}) \right) \frac{d^3\vec{r}}{4\pi r^2} \quad (5)$$

where

$\gamma(\vec{r}, E''_\gamma)$ is the distribution of gamma rays in the tool-borehole-formation (TBF) system formed by the interaction of thermal neutrons of the thermal neutron cloud formed in TBF system by the pulse of fast neutrons emitted by pulsed neutron generator with the material of TBF system;

$\sigma_{pp}(E'_\gamma)$ is the probability for gamma ray which reaches the detector with energy E'_γ to create electron – positron pair;

$CT(E''_\gamma, E'_\gamma, \vec{r}) = \int d\vec{r}' \exp(-\sigma_\gamma(\vec{r}')r') \exp(-\sigma_{Comp}(E''_\gamma \rightarrow E'_\gamma, \vec{r}')(\vec{r} - \vec{r}'))$ is gamma array flux created by Compton scattering in the system;

$\sigma_\gamma(\vec{r}')$ is the gamma ray adsorption coefficient of the system; and

σ_{Comp} is gamma ray Compton scattering coefficient of the system.

For (5) the center of the coordination system coincides with the center of the gamma ray detector.

[0017] The intensity of hydrogen peak is described by :

$$I_H = S(E_\gamma = 2.2 \text{ MeV}) \otimes \int \gamma(\vec{r}, E_\gamma = 2.2 \text{ MeV}) \exp(-\sigma_\gamma(\vec{r})\vec{r}) \frac{d^3\vec{r}}{4\pi r^2} \quad (6)$$

Here $\gamma(\vec{r}, E_\gamma = 2.2 \text{ MeV})$ is the flux of gamma rays with $E_\gamma = 2.2 \text{ MeV}$ born in the point $\vec{r}$ due to capture interaction of thermal neutrons with hydrogen nuclei in this point. This parameter is proportional to the concentration of thermal neutrons $n(\vec{r})$ at the same point:

$$\gamma(\vec{r}, E_\gamma = 2.2 \text{ MeV}) = \sigma_{capture} n_H(\vec{r}) n(\vec{r}) \quad (7)$$

where $n_H(\vec{r})$ is the distribution of hydrogen nuclei in TBF system.

To a zero-order approximation, assuming that gamma ray scattering properties of TBF system changes with $\vec{r}$ much slower than $n(\vec{r})$ does, the relative ratio of the intensities of “boron” and hydrogen peaks in the capture gamma ray spectrum measured by tool shown in **Fig. 3** can be described as:

$$R_{BtoH} = \frac{I_{“B”}}{I_H} = \frac{An(Z_0) + C}{B \int n(\vec{r}) \frac{d^3\vec{r}}{4\pi r^2}} \quad (8)$$

where A, B, and C are some constants. Because the distribution of thermal neutrons in TBF system is defined by the formation porosity, the following expression is valid:

$$R_{BtoH} = g(\rho) \quad (9)$$

where $g(\rho)$ – function dependent on formation porosity which could have as parameters such parameters of the TBF system as lithology of formation, borehole diameter, and others. Hence by measuring the capture gamma ray spectrum using tool illustrated in **Fig. 3**, the formation porosity can be found from the “B” to H peak intensity ratio R_{BtoH} .

[0018] Turning now to **Fig. 4**, capture gamma ray spectra are shown of measurements in a water tank made by a modified device presented in **Fig. 1** where gamma ray detectors had a B¹⁰ coating. The abscissa is the channel number. The curve **401** corresponds to the spectrum measured by LS detector while the curve **403** corresponds to the spectrum measured by the SS detector. **405** indicates the location of the “B” peak at about 0.5 MeV while **409** indicates the H peak at about 2.222 MeV.

[0019] To demonstrate the validity of the method described above, measurements were made in blocks of limestone and sandstone using the tool shown in **Fig. 1** with modified detectors used to make the water tank measurements shown in **Fig. 4**. Shown in **Fig. 5** are the ratios R_{BtoH} of the “B” peak intensity to the H peak intensity for limestones of different porosities. The two endpoints (0% and 100%) correspond to a tight limestone and water tank measurements. The intermediate points are for Austin chalk of 27% porosity and an Indiana limestone with 19% porosity. Over the range of porosities to be expected in practice, the curve **501** for the SS measurements

and the curve **503** for the LS measurements exhibit a reasonably linear behavior that decreases with the porosity increase.

[0020] Similar results have been obtained from measurements in sandstones. Shown in **Fig. 6** are the ratios of the "B" peak intensity to the H peak intensity R_{BtoH} for sandstones of different porosities. The two endpoints (0% and 100%) correspond to a tight sandstone and water tank measurements. The intermediate points are for a sandstone of 33 % porosity and a sandstone with 18 % porosity. Over the range of porosities to be expected in practice, the curve **601** for the SS measurements and the curve **603** for the LS measurements exhibit the presence of a dependence on the porosity that is more complicated than a simple linear dependence.

[0021] Intensities of "B" and H peaks were calculated by integrating the spectral intensity in the channel intervals (41;56) (B peak) and (194;222) (H peak) for SS detector and (39;54) (B peak) and (190;215) (H peak) for LS detector and subtracting the background intensity. Background was approximated by the straight line connecting the spectral points at the edges of the corresponding peak intervals. For the data presented in **Figs. 5-6**, the borehole diameter was 7-7/8 inches.

[0022] The experimental results shown in **Figs. 5-6** suggest that the ratio R_{BtoH} of the "B" peak intensity to the H peak intensity can be used to estimate formation porosity using appropriate calibration curves for the formations of different lithologies.

[0023] Turning now to **Fig. 7**, the ratios R_{BtoH} of "B" peak intensity to the H peak intensity are plotted for a limestone of zero porosity for different borehole diameters where curve **701** is for the SS measurements and curve **703** is for the LS measurements. The abscissa is the reciprocal of the hole diameter in inches. This means that the diameter of the borehole should be included as a parameter into the calibration. Such calibration for a range of borehole sizes, lithology and porosity is a routine matter for wireline applications. For MWD operations, the borehole diameter can be measured during drilling operations such as using the method and apparatus disclosed in US patent 7548817 to *Hassan*. As disclosed in *Hassan*, caliper measurements made during rotation of a bottomhole assembly are processed to

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estimate the location of the bottomhole assembly, and size and shape of the borehole. A piecewise elliptical fitting procedure may be used. These estimates may be used to correct measurements made by a standoff-sensitive formation evaluation sensor such as a neutron porosity tool. The calibration that may be used maybe a table lookup or maybe derived from results of a regression.

[0024] The processing of the measurements made in wireline applications may be done by a surface processor **34**, 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.

[0025] While the foregoing disclosure is directed to the specific embodiments of the disclosure, 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 evaluating an earth formation, the method comprising:
obtaining an indication of a porosity of the earth formation using gamma rays measured by a single gamma ray detector, where the earth formation has been irradiated by a neutron source and the single gamma ray detector is coated with a neutron absorbing material.
2. The method of claim 1 further comprising using, for the neutron absorbing material, B¹⁰.
3. The method of claim 1 wherein using the measured gamma rays further comprises:
 - (i) estimating a spectrum of the measured gamma rays; and
 - (ii) using a first peak associated with the neutron absorbing material and a second peak associated with hydrogen nuclei.
4. The method of claim 1 further comprising using results of a plurality of calibration measurements.
5. The method of claim 4 further comprising making the plurality of calibration measurements over a plurality of lithologies, a plurality of porosities, and a plurality of well bore diameters.
6. An apparatus configured to evaluate a subterranean formation from within a wellbore, comprising:
 - (a) a pulsed neutron source configured to be conveyed in the wellbore and irradiate the earth formation;
 - (b) a single gamma ray detector coated with a neutron absorbing material and configured to measure gamma rays resulting from the irradiation; and

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- (c) a processor configured to:
 - use the measured gamma rays for obtaining an indication of a porosity of the earth formation.
- 7. The apparatus of claim 6 wherein the neutron absorbing material further comprises B¹⁰.
- 8. The apparatus of claim 6 wherein the processor is further configured to use the measured gamma rays by:
 - (i) estimating a spectrum of the measured gamma rays; and
 - (ii) using a first peak associated with the neutron absorbing material and a second peak associated with hydrogen nuclei.
- 9. The apparatus of claim 6 wherein the processor is further configured to use results of a plurality of calibration measurements.
- 10. The apparatus of claim 9 wherein the plurality of calibration measurements are obtained over a plurality of lithologies, a plurality of porosities, and a plurality of well bore diameters.
- 11. A non-transitory computer-readable medium product having thereon instructions that when read by a processor cause the processor to execute a method, the method comprising:
 - obtaining an indication of a porosity of an earth formation using gamma rays measured by a single gamma ray detector, where the earth formation has been irradiated by a neutron source and the single gamma ray detector is coated with a neutron absorbing material.

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12. The non-transitory computer-readable medium product of claim 11 comprising at least one of:

(i) a ROM, (ii) an EPROM, (iii) an EEPROM, (iv) a Flash Memory, and (v) an optical disk.

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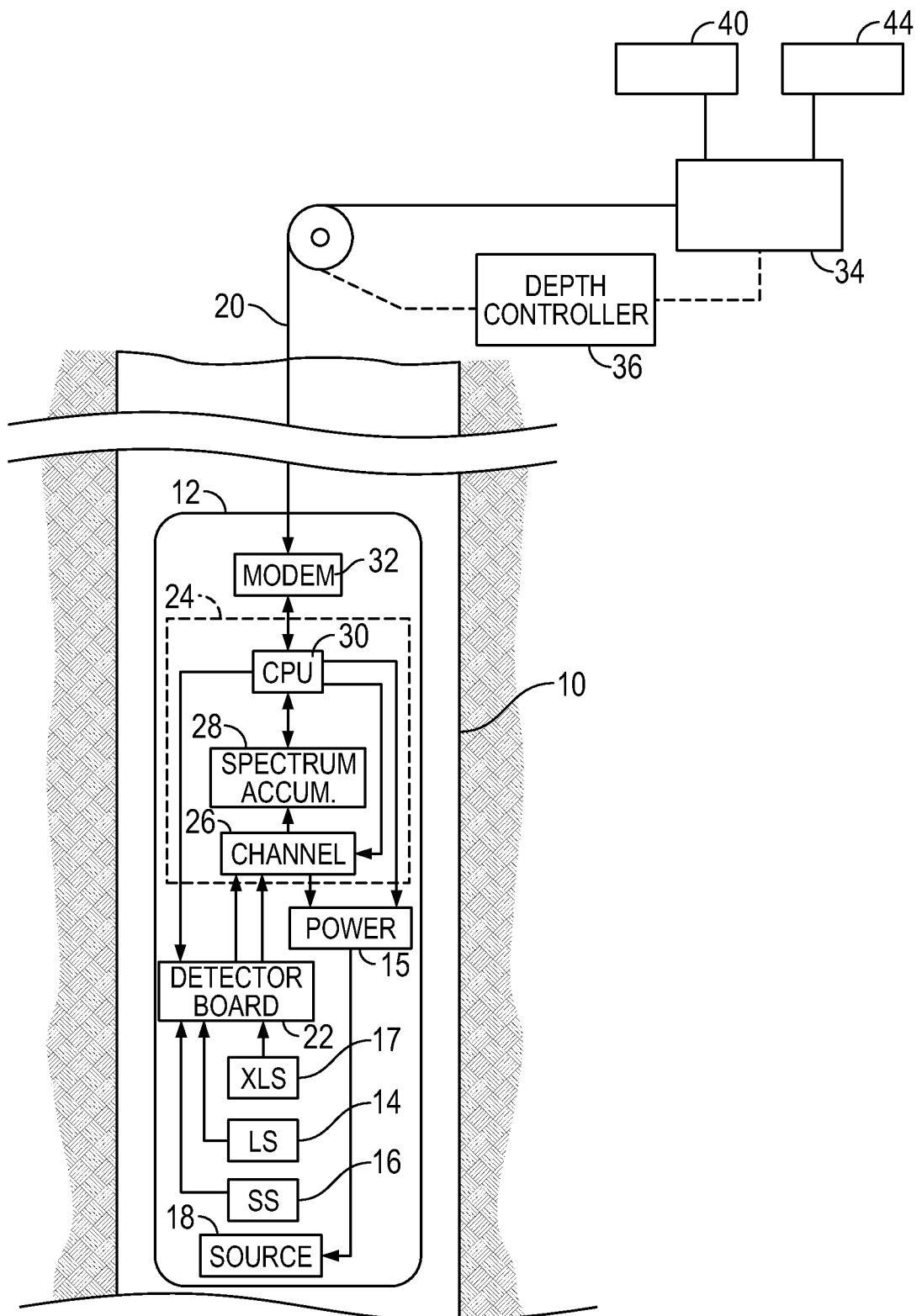


FIG. 1
(Prior Art)

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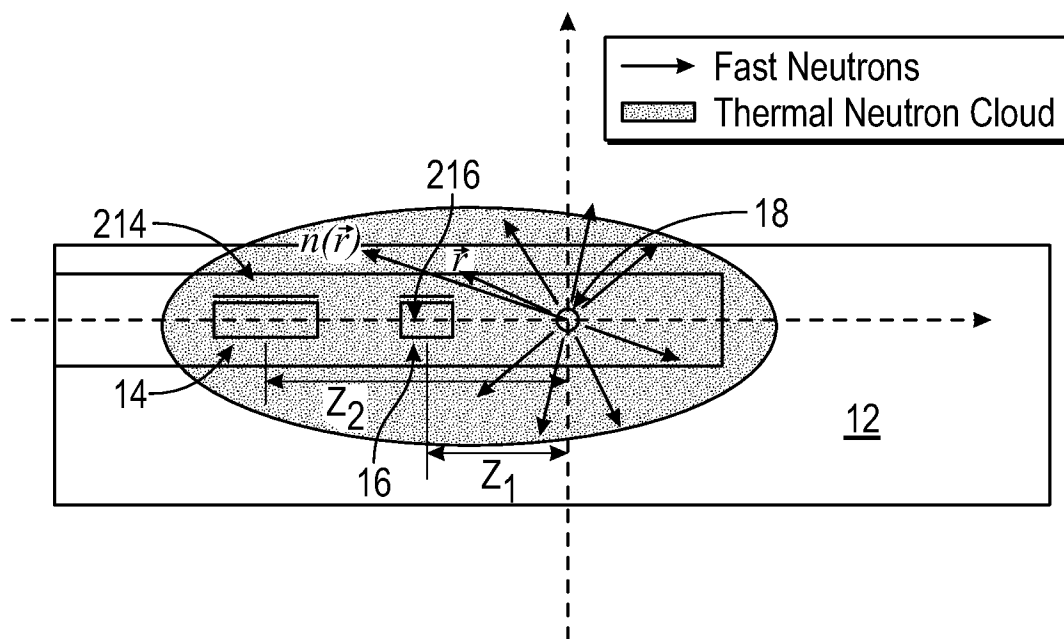


FIG. 2

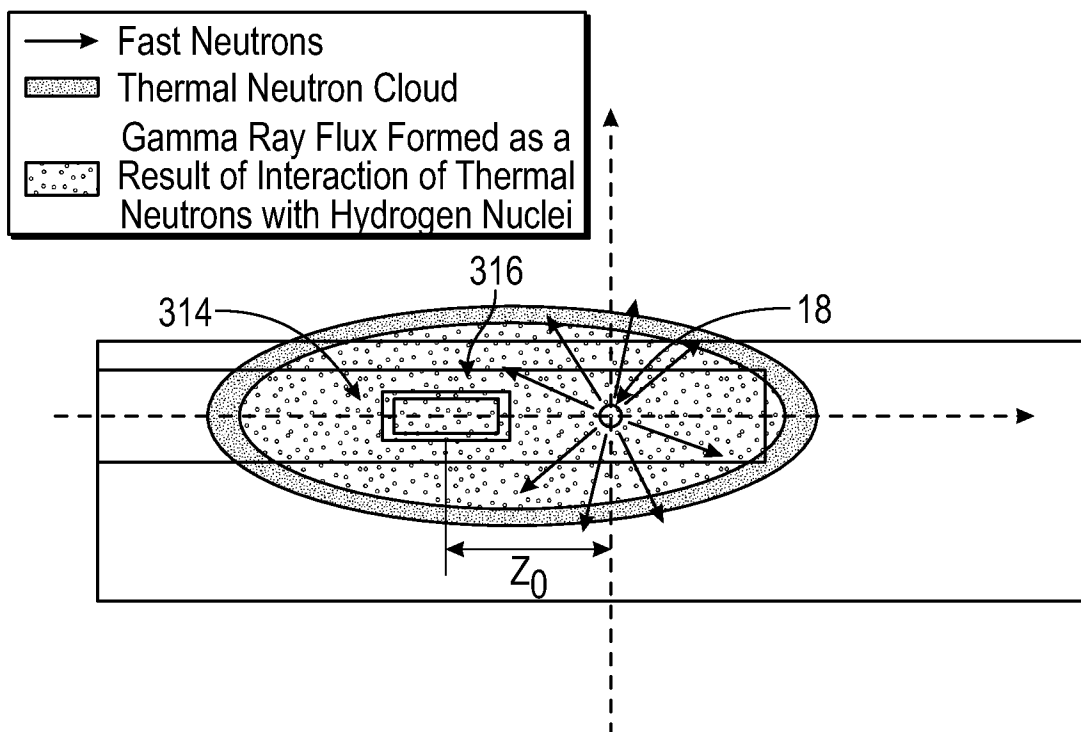


FIG. 3

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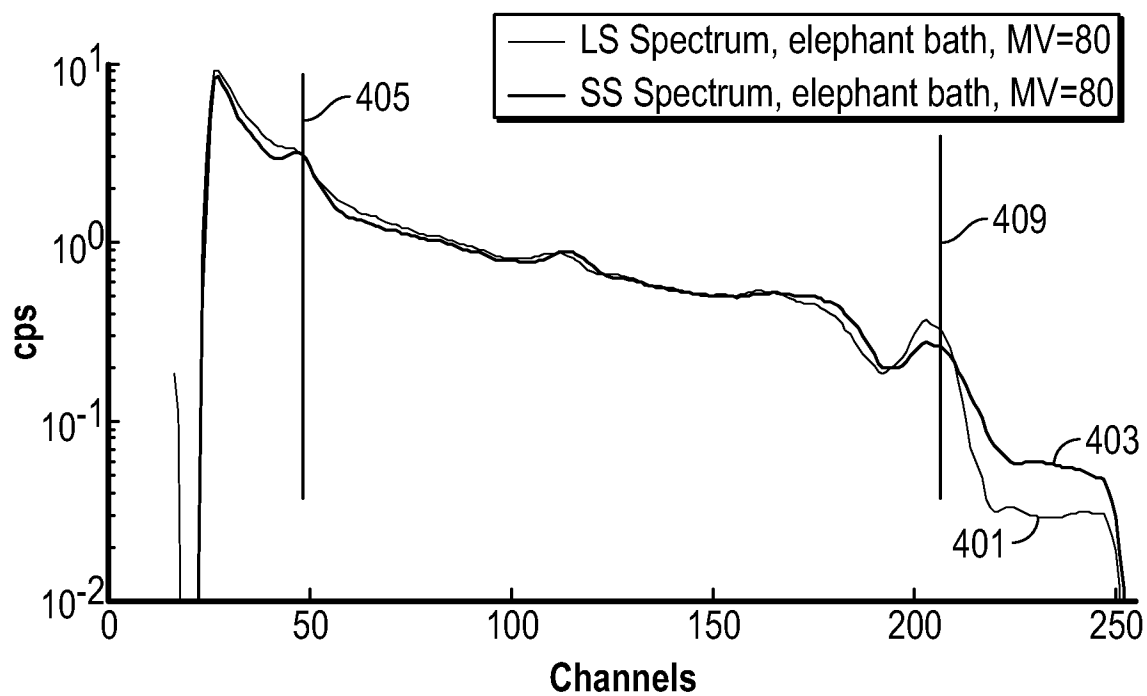


FIG. 4

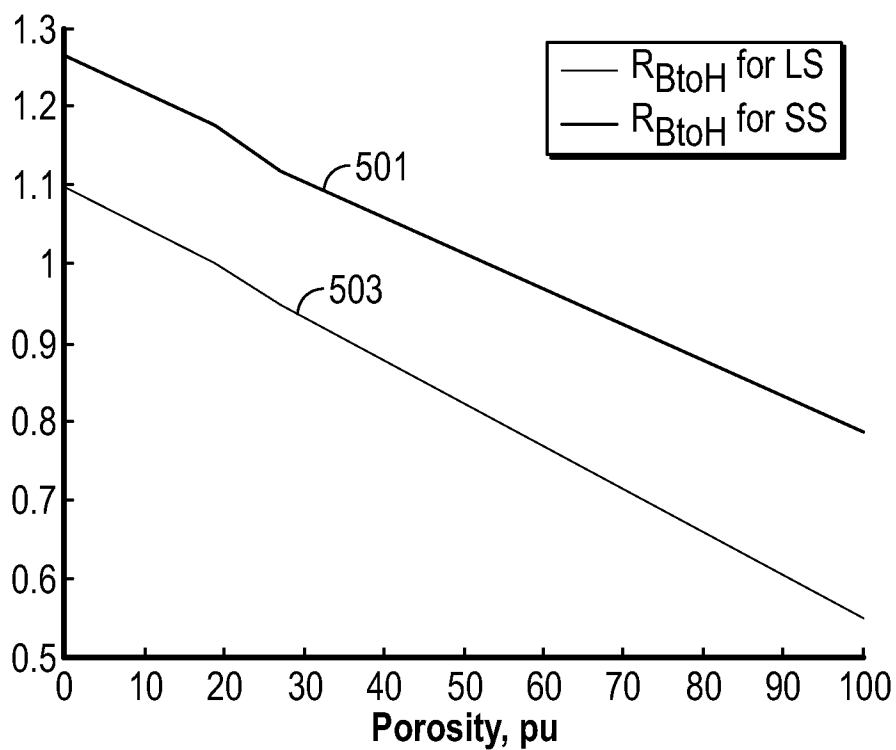


FIG. 5

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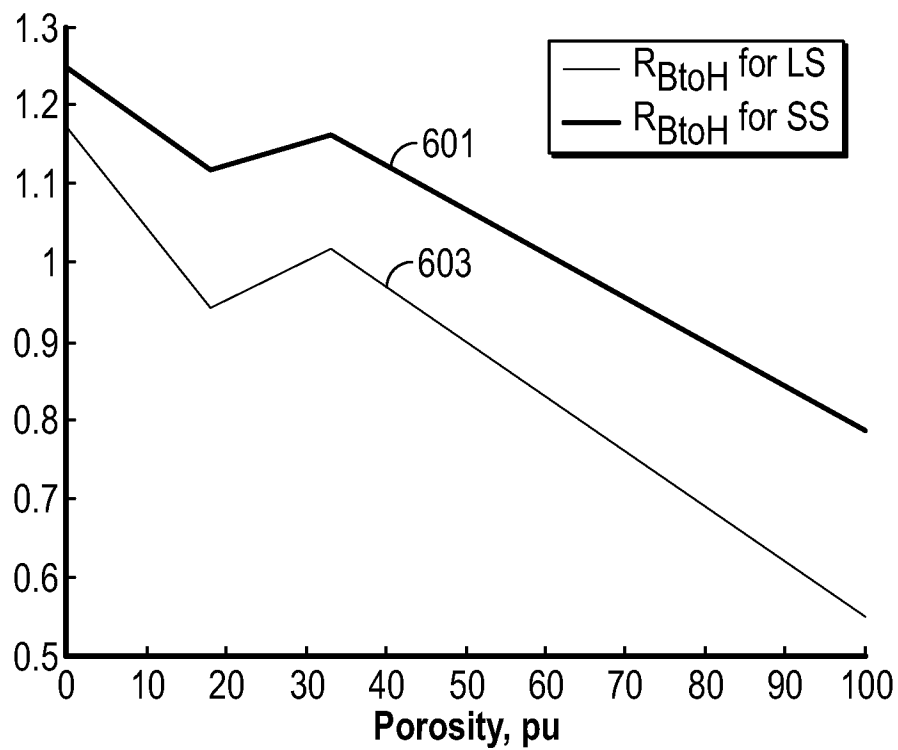


FIG. 6

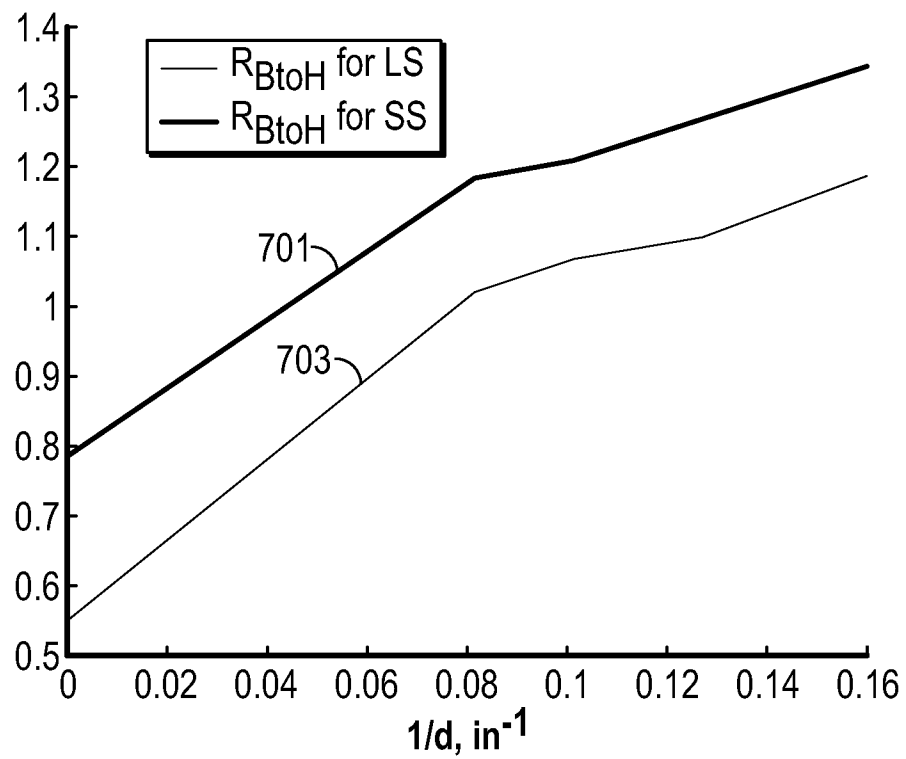


FIG. 7