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(54) Title: METHOD OF CALCULATING FORMATION CHARACTERISTICS

(57) Abstract: A method of calculating a formation characteristic includes measuring with at least two detectors spaced apart from each other an intensity of gamma rays, and calculating the formation characteristic by calculating a ratio of the intensity of the gamma rays detected by the two detectors.

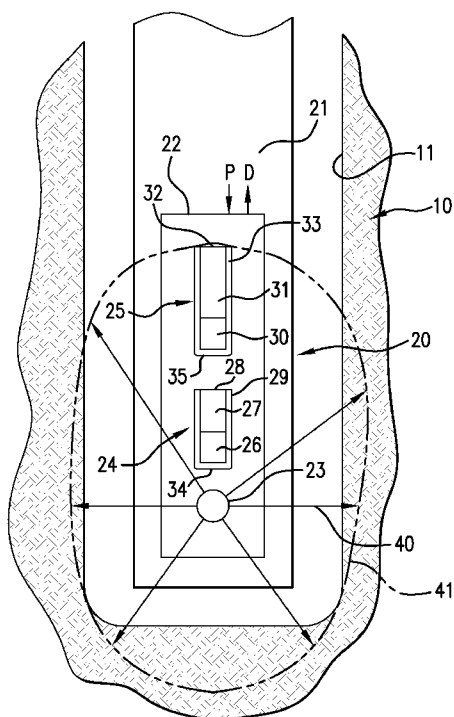


FIG. 1



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TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, **Published:**  
ML, MR, NE, SN, TD, TG).

— *without international search report and to be republished  
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## METHOD OF CALCULATING FORMATION CHARACTERISTICS

## CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Application No. 61/500039 filed June 22, 2011 in the U.S. Patent and Trademark Office, the entire contents of which are hereby incorporated by reference in the present application.

## BACKGROUND

[0002] Various devices are used to calculate characteristics of geological formations in drilling operations. Some devices include radiation emitters to emit radiation into the geological formation and detectors to detect the by-products of the interaction of the emitted radiation with a formation. For example, when the radiation emitter is a neutron emitter, and the emitted neutrons interact with nuclei in the geological formation, gamma rays are released, and detectors are used to measure the spectrum of released gamma rays to determine characteristics of the geological formation.

## SUMMARY

[0003] According to one embodiment, a method of calculating a formation characteristic includes measuring with at least two detectors spaced apart from each other, an intensity of gamma rays, and calculating the formation characteristic by calculating a ratio of the intensity of the gamma rays detected by the two detectors.

[0004] According to another embodiment, a gamma ray measurement system includes a neutron source; a first detector; a second detector; and a computing device configured to receive from the first and second detectors detection signals corresponding to a detected gamma ray intensity of each of the first and second detectors, and configured to calculate a formation characteristic based on a ratio of a gamma ray intensity detected by the first detector to a gamma ray intensity detected by the second detector.

[0005] According to yet another embodiment, a method of measuring a characteristic of an earth formation includes: covering at least two detectors with a layer of a boron isotope B10, cadmium or samarium; inserting the at least two detectors and a neutron source into a borehole; emitting neutrons from the neutron source; detecting gamma rays generated by a reaction of the B10 isotope, cadmium or samarium and neutrons; and calculating the characteristic of the formation by detecting a ratio of intensities of gamma rays detected by the at least two detectors.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Referring now to the drawings wherein like elements are numbered alike in the several Figures:

[0007] FIG. 1 illustrates an embodiment of an assembly configured to perform measurements of formation properties;

[0008] FIG. 2 is an exemplary spectrum of gamma rays detected by a detector of the assembly of FIG. 1;

[0009] FIG. 3 illustrates a dependence of the ratio of the intensity of gamma rays with particular energy detected by a first detector and by a second detector of the assembly of FIG. 1 on formation porosity measured for formations with sandstone and limestone lithologies.

[0010] FIG. 4 illustrates a gamma ray measurement system according to one embodiment;

[0011] FIG. 5 is a flow chart illustrating an embodiment of a method of detecting formation properties; and

[0012] FIG. 6 illustrates an embodiment of a measurement unit configured to perform measurements of formation properties.

## DETAILED DESCRIPTION

[0013] FIG. 1 illustrates an assembly 20 configured to measure characteristics of an earth formation. In one embodiment, the assembly 20 is configured to be inserted into a bore hole 11 in a geological formation 10 (e.g., via a borehole string, a drill string or a wireline) to gather data about the geological formation 10, such as density, porosity, and composition. In the embodiment shown in FIG. 1, the formation detection assembly 20 is disposed in a shaft 21 and includes a measurement unit 22.

[0014] The assembly 20 may be embodied with any suitable carrier. A "carrier" as described herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Exemplary non-limiting carriers include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, downhole subs, bottom-hole assemblies, and drill strings.

[0015] In one embodiment, the measurement unit 22 of the assembly includes at least one neutron source 23 and a plurality of detectors, such as a short space (SS) detector 24 and a long space (LS) detector 25. The neutron source 23 emits fast neutrons 40, which interact with matter in the borehole and/or formation, lose energy, and become thermalized. The thermalized neutrons form a thermal neutron cloud 41, and the characteristics of the thermal neutron cloud 41, such as special distribution of thermal neutron flux, correlates with the properties of the matter that makes up the geological formation 10 such as hydrogen index and formation porosity. The neutron source 23 may be one of a chemical neutron source and a pulsed neutron generator.

[0016] The thermal neutron flux passing the detectors is converted into detectable particles, e.g., gamma rays, which can be detected by the SS detector 24 and the LS detector 25 by the material 29 and 33 that converts thermal neutrons into gamma rays 29 and 33. The material 29 and 33 converting neutrons into gamma rays 34 and 35 can be boron isotope B10. In one embodiment, each of the SS detector 24 and the LS detector 25 are made of a piece of scintillation material and optically coupled photodetector. For example, the SS detector 24 and the LS detector 25 include a respective crystal 26 and 30, and a respective light sensor 27 and 31. In the present embodiment, the crystals 26 and 30 are NaI crystals, and the light sensors 27 and 31 are photomultiplier tubes. In alternative embodiments, other scintillation crystals such as  $\text{LaBr}_3\text{:Ce}$ , YAP, GYSO or BGO are used to detect gamma rays emitted in the process of neutron interaction with material converting neutrons into gamma rays.

[0017] In the embodiment shown in FIG. 1, the SS detector 24 is located closer to the neutron source 23 than the LS detector 25. According to one embodiment, the neutron source 23, the SS detector 24, and the LS detector 25 are co-linear. According to another embodiment, the source and/or the detectors are laterally adjacent, as illustrated in FIG. 6. In FIG. 6, a measurement unit 70 includes a first detector 71 and a second detector 72 laterally adjacent to each other. Each of the first detector 71 and the second detector 72 includes a layer of material 73 and 74 that reacts with neutrons to generate a gamma spectrum, such as a B10 isotope. The detectors 71 and 72 detect the gamma spectra, and the detected spectra are used to determine characteristics of a geological formation 10. The measurement unit 70 may also include a neutron source 75, to emit neutrons to generate a thermal neutron cloud, as discussed above with respect to FIG. 1.

[0018] Referring again to FIG. 1, in one embodiment, at least a portion of each of the SS detector 24 and the LS detector 25 is coated with a layer 29 and 33 of material configured

to convert neutrons into gamma rays, such as a B10 isotope. For example, the thermal neutrons contact the B10 layers 29 and 33 and generate gamma rays with a particular energy  $E_\gamma=0.478$  MeV which are detected by the SS and LS detectors 24 and 25. In one embodiment, the B10 isotope coating 29 and 33 covers a first end 34 and 35 of the SS and LS detectors 24 and 25 facing the neutron source 23. The B10 isotope coating 29 and 33 may also cover the sides of the SS and LS detectors 24 and 25, including selected surfaces of the crystals and/or photodetectors. In the present embodiment, a second end 28 and 32 of the SS and LS detectors 24 and 25 facing away from the neutron source 23 is not covered by the B10 isotope coating 29 and 33. Other materials converting neutrons into gamma rays can be used instead of the boron isotope B10, such as cadmium and samarium. In other embodiments the material converting neutrons into gamma rays can be deposited at the gamma ray detector surface in the form of axial or circumferential strips or can have any other shapes.

[0019] Power P can be supplied to the assembly 20 performing measurement of the formation properties 20 via a wire to power the neutron source 23, e.g., when the neutron source is a pulsed neutron generator, and may also provide operating power to the photodetectors 27 and 31. Data D is transmitted to a computing device, such as a personal computer or server having a database to store and generate formation characteristic data based on the data collected by the SS detector 24 and the LS detector 25. The computing device may include a processor and another suitable electronics, and may be disposed at any desired location, such as at surface location or a downhole location.

[0020] The intensity of gamma rays produced by the neutron reaction with B10 nuclei is proportional to the intensity of the thermal neutron flux passing through the detectors 24 or 25. Since the characteristics of the thermal neutron cloud 41 correspond to characteristics of the geological formation 10, the intensity of gamma rays produced in neutron reaction with B10 nuclei provides information about the characteristics of the geological formation 10. Since the boron peak in the measured spectrum includes the gamma ray signal generated in a neutron reaction with B10 nuclei, detecting and measuring the boron peak provides information about the thermal neutron cloud 41 and the geological formation 10. In particular, the ratio of the intensity of gamma rays formed in neutron reaction with B10 nuclei in layer 29 of the SS detector 24 to the intensity of gamma rays formed in neutron reaction with B10 nuclei in layer 33 of the LS detector 25 corresponds to a porosity of the formation 10, as demonstrated by formula (1).

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

[0021] In equation (1), R is a ratio of gamma ray intensities,  $GI_{xx}$  is the gamma ray intensity emitted in neutron reaction with layers of B10 coatings 34 and 35 detected of a respective SS or LS detector 24 or 25,  $FTN_{xx}$  is a flux of thermal neutrons passing through the respective SS or LS detector 24 or 25,  $n(Z_x)$  is the concentration of thermal neutrons in a point of detector location  $Z_x$ , and  $f(\rho)$  is a function of the formation porosity.

[0022] FIG. 2 illustrates a gamma ray spectrum measured by a gamma ray detector with a B10 isotope coating exposed to the thermal neutrons. Line 53 represents gamma rays generated by the neutron reaction with B10 nuclei in the B10 isotope coating, which has a peak C. The gamma ray intensity at peak C is around  $E_\gamma=0.478\text{MeV}$ . Line 52 represents gamma rays born due to the annihilation of the positrons generated within the crystal of the detector, and the gamma ray intensity of a corresponding peak B is around  $E_\gamma=0.511\text{ MeV}$ . Line 51 includes lines 52 and 53, as well as background radiation. Peak A corresponds to the combined peaks B and C. Detecting the characteristics of the peak B provides information about the thermal neutron cloud 41 and the geological formation 10.

[0023] In the example shown in FIG. 2, the intensity of B peak was extracted from measured gamma ray spectra through spectra decomposition using exponential background and 3 Gaussian peaks (one for unidentified low energy peak and 2 for peaks at energy  $E_\gamma=0.478\text{ MeV}$  and  $E_\gamma=0.511\text{ MeV}$ ) for better convergence of the fit (see Fig 2). The intensity of A peak was equal to the sum of intensities of peak B and peak C in the fit.

[0024] FIG. 3 shows the dependence of a ratio of peak A intensities  $GI_{SS}/GI_{LS}$  extracted from the gamma ray spectra measured by the SS detector 24 and LS detector 25 of the assembly 20 in the case when assembly was equipped with pulsed neutron generator and was located in the sandstone and limestone formations of different porosity when pore space was filled with water. As illustrated in FIG. 3, the apparent porosity has a correlated relationship with the calculated ratio of the gamma ray intensity detected by the SS and LS detectors 24 and 25. In particular, as the ratio of intensities of peak A (i.e.,  $GI_{SS}/GI_{LS}$ ) increases, the apparent porosity also increases. In FIG. 3, line 54 corresponds to limestone formations of different porosity and line 55 corresponds to sandstone formations of different porosities. Accordingly, the apparent porosity of each type of formation may be determined by calculating the ratio of the intensities of peak A in gamma ray spectra detected by the SS and LS detectors 24 and 25.

[0025] FIG. 4 illustrates an embodiment of a gamma ray measurement system 42 configured to operate the detection assembly 22.

[0026] The gamma ray measurement system 42 includes the measurement unit 22, a computing device 43, and a communication line 45 to transmit detected gamma ray data from the measurement unit 22 to the computing device 43. The computing device 43 includes an input terminal 44 to receive the gamma ray data from the measurement unit 22, and a processor, memory, and supporting logic to convert the detected data to information about a geological formation. The input terminal 44 is one of a wired port, such as a conductive lead connected to a wire, or a wireless port, such as an antenna. Likewise, the communication line 45 is one of a wire and air through which wireless data signals propagate.

[0027] The computing device 43 is configured to receive the detected gamma ray data and calculates formation characteristics, such as a porosity of the formation, based at least upon the portion of the gamma ray data corresponding to gamma rays generated when neutrons interact with the coating of the detectors 24 and 25, as discussed above.

[0028] FIG. 5 illustrates a method of calculating formation characteristics according to an embodiment of the present invention. In operation 61, the formation analysis assembly 20 is inserted into a bore hole. In operation 62, the neutron emitter 23 emits neutrons, and a neutron cloud 41 is generated around the neutron emitter 23 and the measurement unit 22. In operation 63, the SS detector 24 and the LS detector 25 detect gamma rays generated when neutrons in the neutron cloud 41 react with a coating or layer (e.g., a B10 coating) on each of the SS detector 24 and the LS detector 25. In operation 64, a ratio of gamma ray intensities formed in neutron reaction with B10 material and detected by the SS detector 24 and the LS detector 25 is calculated. In operation 65, a formation characteristic, such as porosity, is calculated based on the calculated ratio of gamma ray intensities in operation 64. Although FIG. 5 illustrates an embodiment in which each of operations 61-65 are performed, according to alternative embodiments one or more operations may be omitted, or additional operations may be performed.

[0029] In support of the teachings herein, various analysis components may be used, including a digital and/or an analog system. The computing device and the detection assembly may have components such as a processor, storage media, memory, input, output, communications link, user interfaces, software programs, signal processors (digital or analog) and other such components (such as resistors, capacitors, inductors and others) to provide for operation and analyses of the apparatus and methods disclosed herein in any of several manners well appreciated in the art. It is considered that these teachings may be, but need not

be, implemented in conjunction with a set of computer executable instructions stored on a computer readable medium, including memory (ROMs, RAMs), optical (CD-ROMs), or magnetic (disks, hard drives), or any other type that when executed causes a computer to implement the method of the present invention. These instructions may provide for equipment operation, control, data collection and analysis and other functions deemed relevant by a system designer, owner, user or other such personnel, in addition to the functions described in this disclosure.

[0030] Further, various other components may be included and called upon for providing for aspects of the teachings herein. For example, a power supply (e.g., at least one of a generator, a remote supply and a battery), cooling unit, heating unit, motive force (such as a translational force, propulsional force or a rotational force), magnet, electromagnet, sensor, electrode, transmitter, receiver, transceiver, antenna, controller, optical unit, electrical unit or electromechanical unit may be included in support of the various aspects discussed herein or in support of other functions beyond this disclosure.

[0031] It will be recognized that the various components or technologies may provide certain necessary or beneficial functionality or features. Accordingly, these functions and features as may be needed in support of the appended claims and variations thereof are recognized as being inherently included as a part of the teachings herein and a part of the invention disclosed.

[0032] While the invention has been described with reference to exemplary embodiments, it will be understood that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications will be appreciated to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

## CLAIMS

1. A method of calculating a formation characteristic, comprising:  
measuring with at least two detectors, spaced apart from each other, an intensity of gamma rays; and  
calculating the formation characteristic by calculating a ratio of the intensity of the gamma rays detected by the two detectors.
2. The method of claim 1, wherein measuring the intensity of the gamma rays includes measuring gamma rays generated by neutrons reacting with a boron isotope B10, cadmium or samarium.
3. The method of claim 2, wherein measuring the intensity of gamma rays includes measuring a spectrum peak intensity of gamma rays generated by neutrons reacting with the boron isotope B10, cadmium or samarium.
4. The method of claim 2, wherein each of the at least two detectors is covered by a separate layer of B10 isotope, cadmium or samarium.
5. The method of claim 1, wherein each of the at least two detectors includes a scintillation crystal and a light detector, and  
the intensity of the gamma rays is measured by measuring light emitted by the scintillation crystal when gamma rays react with the scintillation crystal material.
6. The method of claim 1, wherein the formation characteristic is porosity.
7. The method of claim 6, wherein the porosity is calculated according to the formula:

$$\frac{GI_{SS}}{GI_{LS}} = f(\rho),$$

where  $GI_{SS}$  and  $GI_{LS}$  each represent a gamma ray intensity created in a neutron reaction with a material covering the at least two detectors and detected by a respective one of the at least two detectors, and  $f(\rho)$  is a function of the porosity of the formation.

8. The method of claim 7, wherein the material is a B10 isotope, cadmium or samarium.
9. A gamma ray measurement system, comprising:  
a neutron source;  
a first detector;  
a second detector; and

a computing device configured to receive from the first and second detectors detection signals corresponding to a detected gamma ray intensity of each of the first and second detectors, and configured to calculate a formation characteristic based on a ratio of a gamma ray intensity detected by the first detector to a gamma ray intensity detected by the second detector.

10. The gamma ray detection system of claim 9, wherein at least one of the first and second detectors is coated in a layer of boron isotope B10, cadmium or samarium.

11. The gamma ray detection system of claim 10, wherein each of the first detector and the second detector includes a scintillation crystal and a photodetector to detect gamma radiation, and

the B10 isotope, cadmium or samarium coating surrounds an outer circumference of the scintillation crystal and an end of the crystal facing the neutron source.

12. The gamma ray detection system of claim 11, wherein the scintillation crystal is one of an NaI,  $\text{LnBr}_3\text{:Ce}$ , GYSO, YAP or BGO crystal.

13. The gamma ray detection system of claim 9, wherein the neutron source and the first and second detectors are co-linear.

14. The gamma ray detection system of claim 9, wherein the neutron source and the first and second detectors are laterally adjacent to each other.

15. A method of measuring a characteristic of an earth formation, the method comprising:

covering at least two detectors with a layer of a boron isotope B10, cadmium or samarium;

inserting the at least two detectors and a neutron source into a borehole;

emitting neutrons from the neutron source;

detecting gamma rays generated by a reaction of the B10 isotope, cadmium or samarium and neutrons; and

calculating the characteristic of the formation by detecting a ratio of intensities of gamma rays detected by the at least two detectors.

16. The method of claim 15, wherein the characteristic is porosity.

17. The method of claim 15, wherein the at least two detectors and the neutron source are arranged co-linearly.

18. The method of claim 17, wherein one of the at least two detectors is located between another of the at least two detectors and the neutron source.

19. The method of claim 15, wherein the at least two detectors and the neutron source are arranged laterally adjacent to each other.

20. The method of claim 15, wherein detecting the ratio of intensities of gamma rays includes detecting a ratio of spectrum peak intensities of gamma rays detected by the at least two detectors.

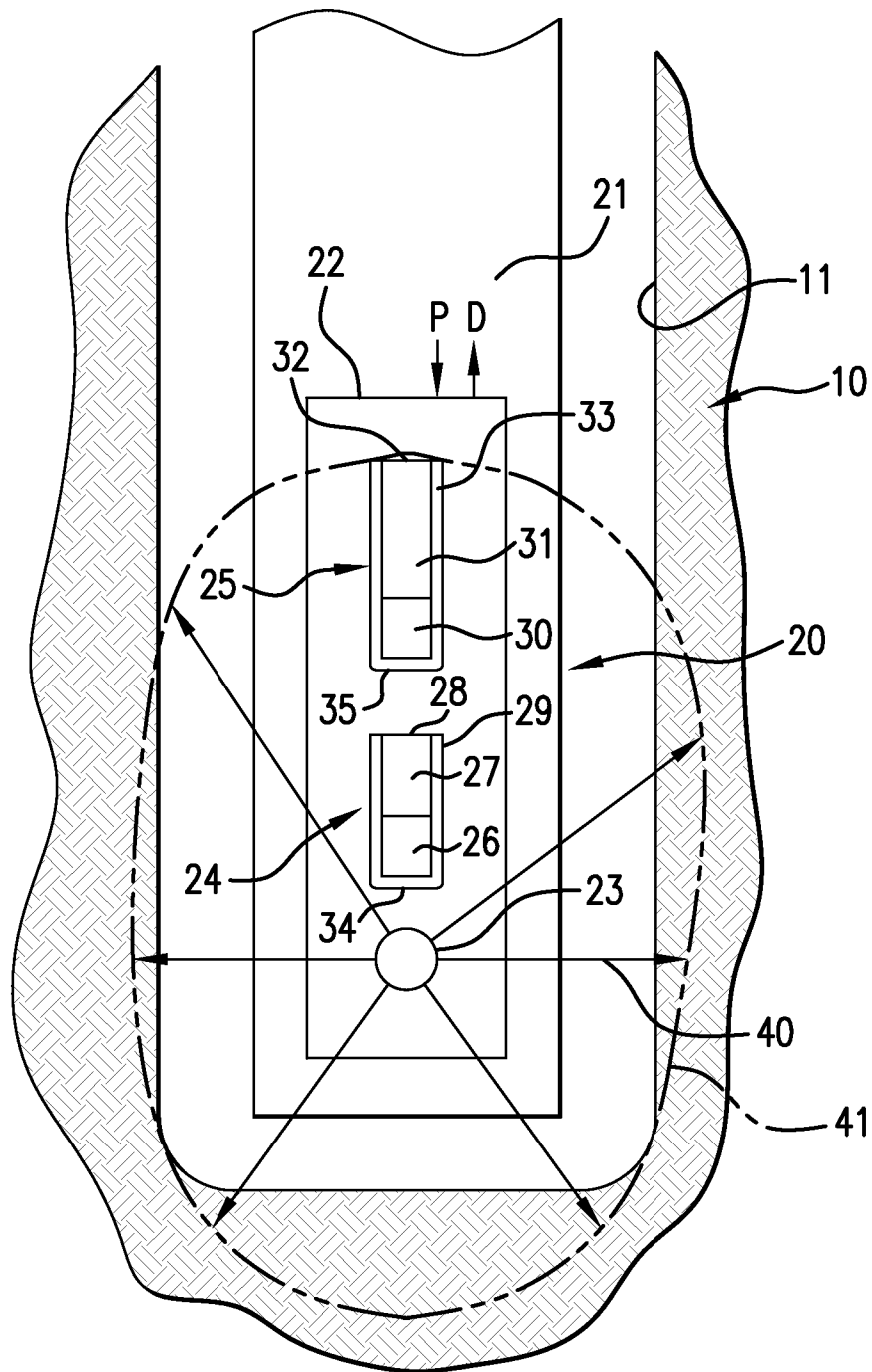


FIG.1

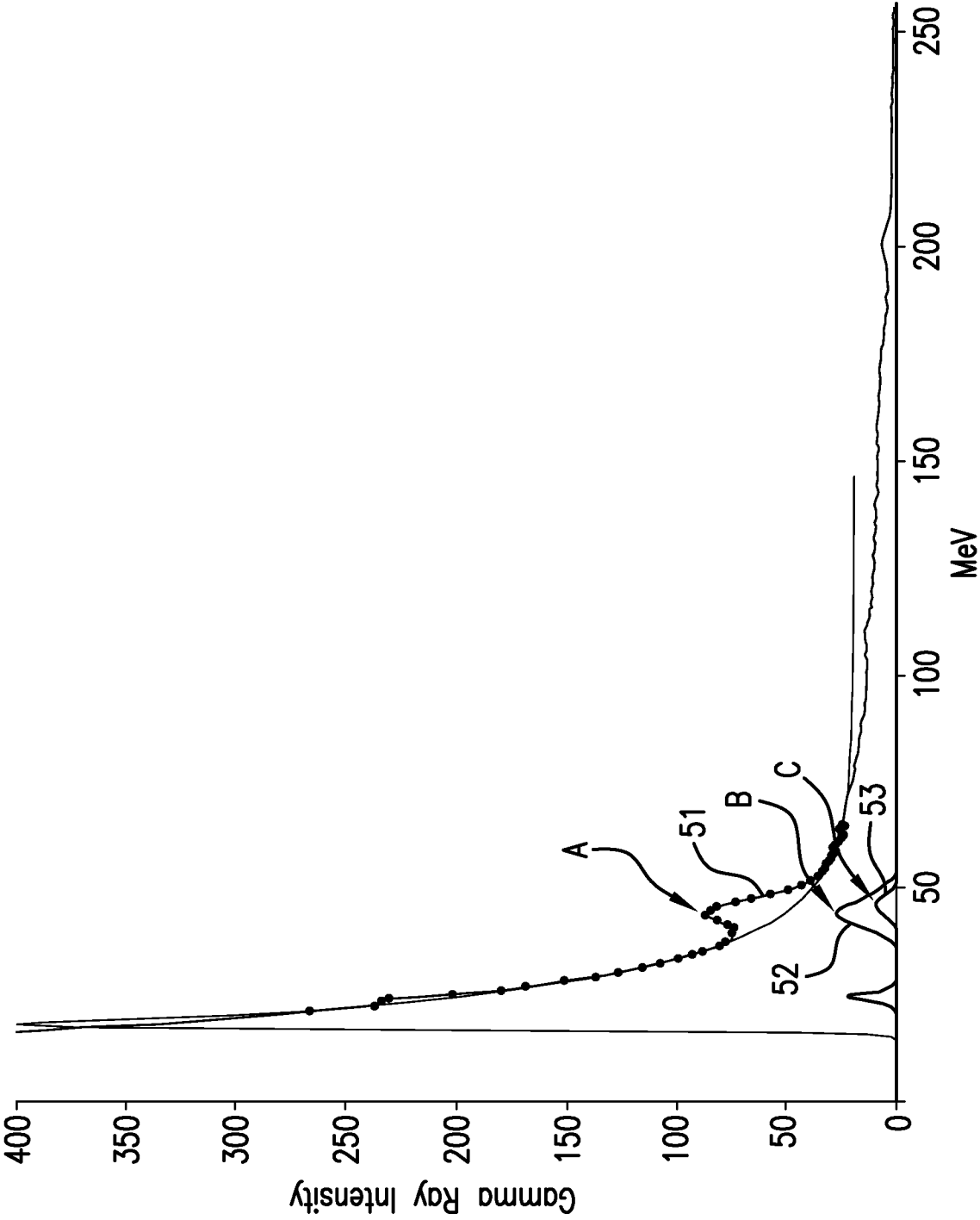


FIG. 2

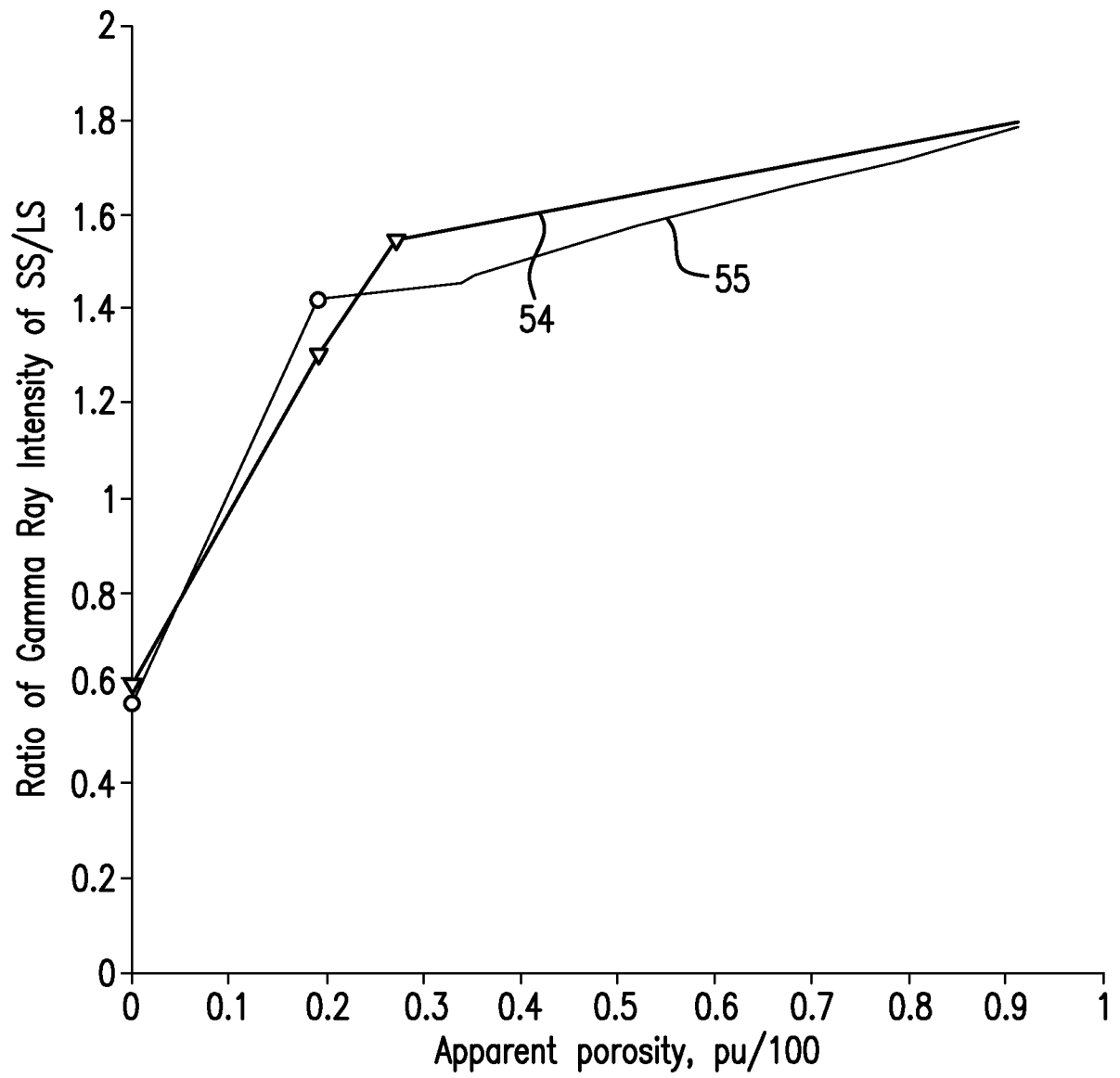


FIG.3

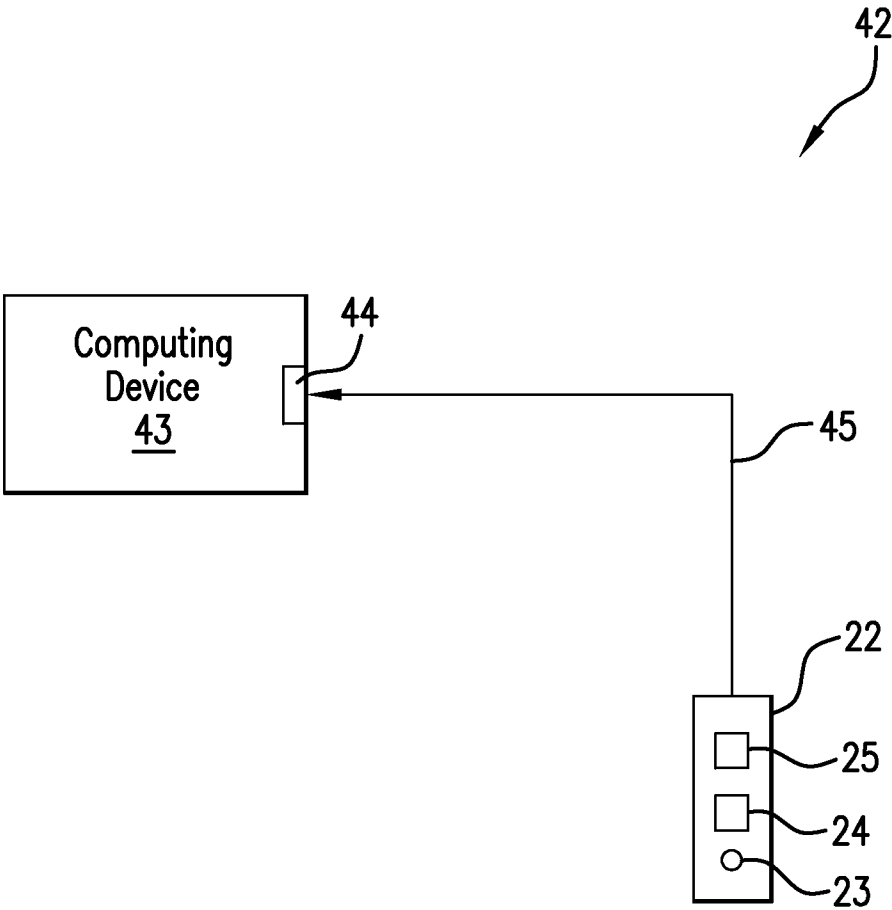


FIG.4

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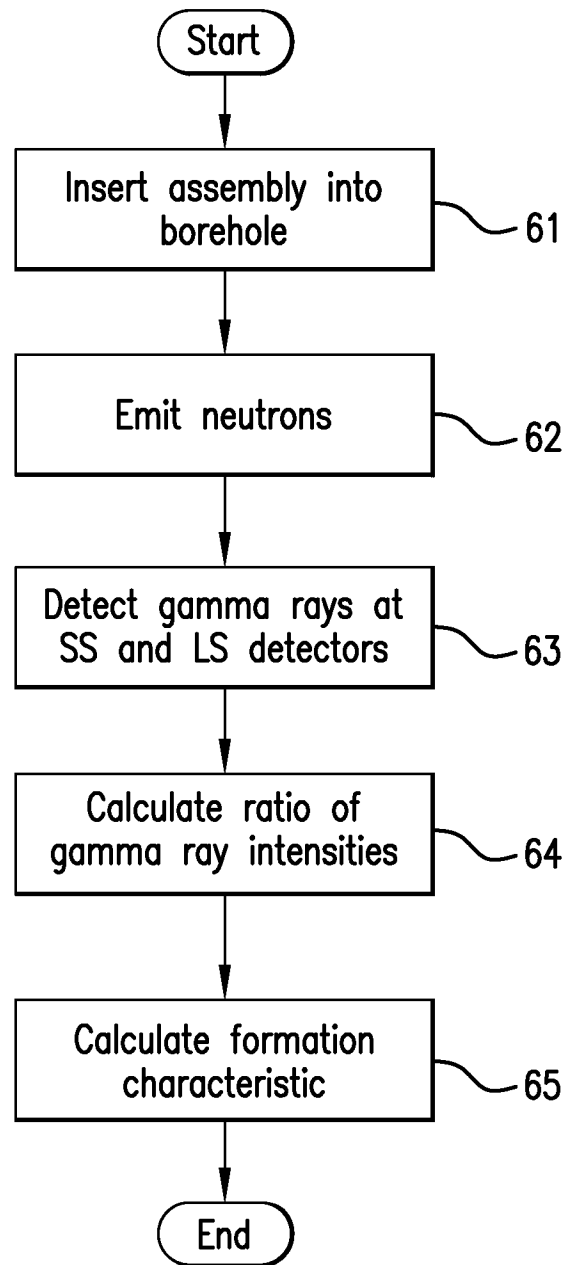


FIG.5

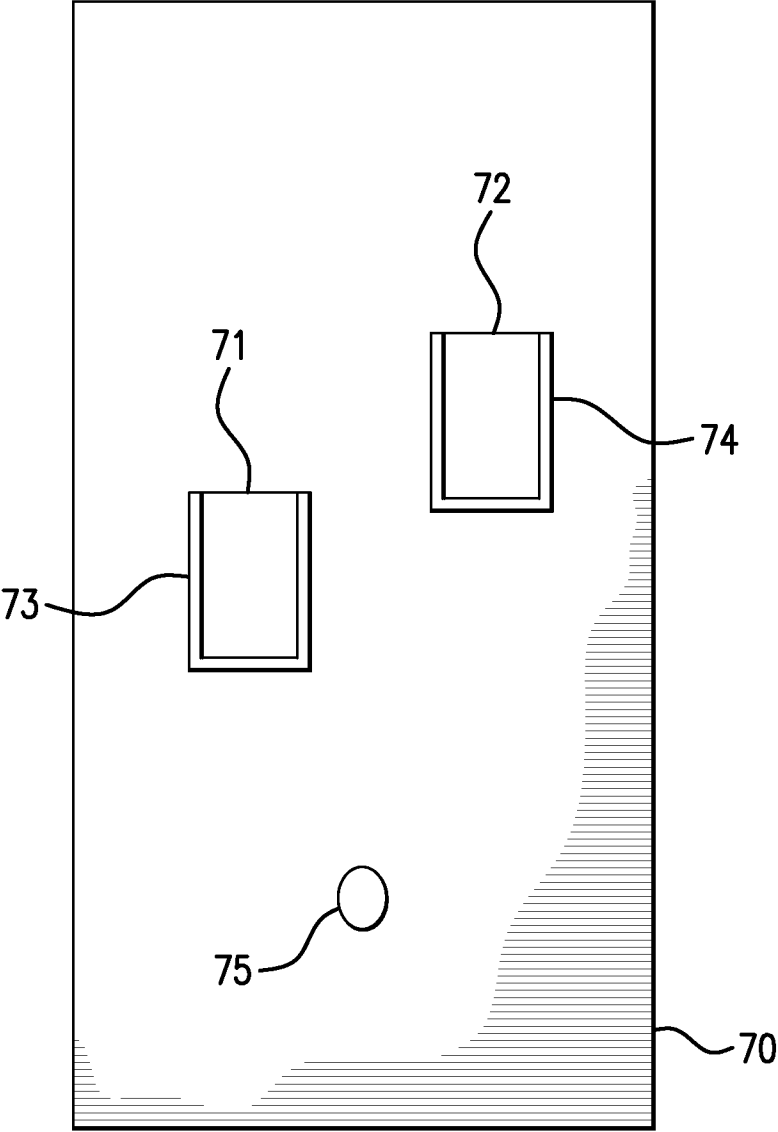


FIG. 6