

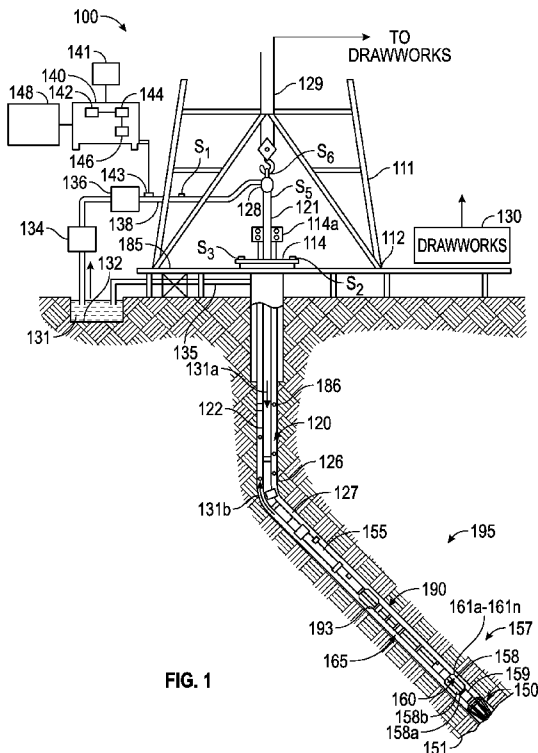


- (51) International Patent Classification:
E21B 47/09 (2012.01) G01V 5/04 (2006.01)
- (21) International Application Number:
PCT/US2014/037467
- (22) International Filing Date:
9 May 2014 (09.05.2014)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
13/892,951 13 May 2013 (13.05.2013) US
- (71) Applicant: **BAKER HUGHES INCORPORATED**
[US/US]; P.o. Box 4740, Houston, TX 77210 (US).
- (72) Inventor: **INANC, Feyzi**; 6526 Loblolly Vista Drive,
Spring, TX 77389 (US).
- (74) Agent: **CROWLEY, Michael**; Baker Hughes Incorporated,
Intellectual Property Counsel, P.O. Box 4740, Houston,
TX 77210-4740 (US).

- (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: SOURCELESS DENSITY MEASUREMENTS WITH NEUTRO INDUCED GAMMA NORMALIZATION



(57) Abstract: Methods, systems, devices, and products for estimating at least one parameter of interest of a volume of an earth formation, including density, porosity, and fluid saturation of the volume. Methods may include normalizing radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume. The nuclear source may be in the volume. Radiation emissions may be generated by neutron irradiation of at least one nuclide in the volume. The correction factor may be determined using any of nuclear density of the at least one nuclide; an estimated concentration of the at least one nuclide in the volume; or a parameter relating to concentration of the nuclide in the volume. The emissions may include gamma rays.

WO 2014/186222 A1

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

Published:

— *with international search report (Art. 21(3))*

**SOURCELESS DENSITY MEASUREMENTS WITH
NEUTRON INDUCED GAMMA NORMALIZATION****Inventor: INANC, Feyzi****FIELD OF THE DISCLOSURE**

[0001] This disclosure generally relates to borehole logging methods and apparatuses for estimating formation properties using nuclear radiation based measurements.

BACKGROUND OF THE DISCLOSURE

[0002] Oil well logging has been known for many years and provides an oil and gas well driller with information about the particular earth formation being drilled. In conventional oil well logging, during well drilling and/or after a well has been drilled, a nuclear radiation source and associated nuclear radiation sensors may be conveyed into the borehole and used to determine one or more parameters of interest of the formation. A rigid or non-rigid conveyance device is often used to convey the nuclear radiation source, often as part of a tool or a set of tools, and the carrier may also provide communication channels for sending information up to the surface.

SUMMARY OF THE DISCLOSURE

[0003] In aspects, the present disclosure is related to methods and apparatuses for estimating at least one parameter of interest of a volume of interest of an earth formation using nuclear radiation based measurements.

[0004] One embodiment according to the present disclosure may include a method of estimating at least one parameter of interest of a volume of an earth formation. Methods may include normalizing radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume. The nuclear source may be in the volume. Radiation emissions may be generated by neutron irradiation of at least one nuclide in the volume. The correction factor may be determined using any of nuclear density of the at least one nuclide; an estimated concentration of the at least one nuclide in the volume; or a parameter relating to concentration of the nuclide in the volume. The emissions may include gamma rays.

[0005] Another embodiment according to the present disclosure may include an apparatus for estimating at least one parameter of interest of a volume of interest of an earth formation comprising: a processor configured to normalize radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume.

[0006] Another embodiment according to the present disclosure may include a non-transitory computer-readable medium product for estimating at least one parameter of interest of a volume of an earth formation, comprising instructions disposed on the medium that, when executed by a processor, cause the at least one processor to: normalize radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume.

[0007] Examples of the more important features of the disclosure have been summarized rather broadly in order that the detailed description thereof that follows may be better understood and in order that the contributions they represent to the art may be appreciated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a detailed understanding of the present disclosure, reference should be made to the following detailed description of the embodiments, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

Fig. 1 shows a schematic of a downhole tool deployed in a borehole along a drill string according to one embodiment of the present disclosure;

Fig. 2 shows a schematic of a nuclear sensor module for one embodiment according to the present disclosure;

Fig. 3 shows a flow chart for a method for one embodiment according to the present disclosure;

Fig. 4 shows a flow chart for a method for one embodiment according to the present disclosure; and

Fig. 5 shows a schematic of an apparatus for implementing one embodiment of the method according to the present disclosure.

DETAILED DESCRIPTION

[0009] In aspects, this disclosure relates to estimating at least one parameter of interest of a volume of interest using radiation induced by neutron irradiation. In some aspects, this disclosure relates to estimating a parameter of interest related to a volume from normalized radiation information. The volume may include an earth formation, such as, for example, an earth formation surrounding a borehole. The parameter of interest may be a physical characteristic of the volume, such as, for example, density.

[0010] Following neutron irradiation of the earth formation, interactions between the neutrons and nuclides in the formation may produce radiation (e.g., gamma rays). The application of neutrons may cause “activation” of specific nuclides (e.g., carbon, silicon, and oxygen) that may be found in a downhole environment. The activated nuclides may emit ionizing radiation, such as gamma rays. The term “activation” relates to the conversion of a normally stable nuclide into a radionuclide through a nuclear process, such as, but not limited to, neutron-proton (n,p) reactions and radiative capture (n, γ). Depending on the radionuclide, the delayed decay spectrum may have characteristics that allow the radionuclide to be used as a nuclear radiation source. Herein, the term “nuclear radiation” and “radiation emission” includes particle and non-particle radiation emitted by atomic nuclei during nuclear processes (such as radioactive decay and/or nuclear bombardment), which may include, but are not limited to, photons from neutron inelastic scattering and from neutron thermal capture reactions, neutrons, electrons, alpha particles, beta particles, and pair production photons.

[0011] For example, in typical downhole applications, there may be a significant amount of oxygen in the volume surrounding the borehole and in the borehole. A significant portion of the oxygen may be an oxygen-16 nuclide. When oxygen-16 is irradiated by neutrons, the interaction of the neutrons with the oxygen-16 nuclide may result in a nitrogen-16 radionuclide which may emit certain gamma rays. In another mode, fast neutrons can inelastically scatter from oxygen-16 nuclei and increase the nuclear energy states. This may result in a gamma emission so that the nucleus can go back to stable energy state. One or more nuclear radiation sensors disposed along the downhole tool may be configured to generate a signal indicative of nuclear radiation detected. The detected nuclear radiation may include gamma rays. Gamma rays (or other

radiation emissions) resulting from neutron irradiation of nuclides in the formation may subsequently undergo interactions with the atoms making up the formation, before some of the gamma rays reach a detector. The flux of those gamma rays reaching a detector is therefore attenuated by the formation.

[0012] Conventional density measurements determine the count rates of the radiation that were emitted by a well characterized gamma ray source. The detected count rates are understood to correspond to the density of the formation. Through comparison of source intensity and the measured gamma ray intensity, a density value is estimated. Conventional density measurements in nuclear logging are based on having a very stable (predictable) radiation source with a substantially constant intensity. The source is unitary. For example, pre-existing gamma ray density measurement systems may utilize a point source of gamma rays, such as a Cesium-137 pill. The source emissions are therefore known or directly measureable. Small errors in the gamma ray source intensity value may be sufficient to corrupt the resulting density measurements.

[0013] Aspects of the present disclosure may relate to nuclear logging (e.g., nuclear density logging) using at least one radiation source apart from the tool. The radiation source may be a gamma ray source in the earth formation, such as nuclides irradiated by neutrons. Neutrons may interact with nuclides throughout the formation. Thus, in the present disclosure, the source may be spatially distributed in the formation. The source (and the source's radiation emissions) may be lithology dependent, and therefore unstable. As a result, variation in the count rates may thus be attributable to density of the formation, but may also be attributable to variation in the lithology of the formation and / or variation in borehole fluid types.

[0014] Aspects of the present disclosure may further relate to normalizing radiation information, such as emission rates (e.g., gamma ray count rates), relating to radiation emissions from a spatially distributed source in an earth formation. Normalizing the radiation information may be carried out using a correction factor determined using an estimated lithology of the volume. Normalization may adjust radiation information to be used for density measurements by mitigating effects of variations in the lithology and fluids in both formation and borehole. After normalization

of the radiation information, it is certain that changes seen are due to density variations in the formation.

[0015] Each of the embodiments herein may be used in a variety of settings in both drilling and non-drilling environments. In some implementations, the disclosed embodiments may be used as part of a drilling system. **FIG. 1** is a schematic diagram of an exemplary drilling system **100** that includes a drill string having a drilling assembly attached to its bottom end that includes a steering unit according to one embodiment of the disclosure. **FIG. 1** shows a drill string **120** that includes a drilling assembly or bottomhole assembly (BHA) **190** conveyed in a borehole **126**. The drilling system **100** includes a conventional derrick **111** erected on a platform or floor **112** which supports a rotary table **114** that is rotated by a prime mover, such as an electric motor (not shown), at a desired rotational speed. A tubing (such as jointed drill pipe **122**), having the drilling assembly **190**, attached at its bottom end extends from the surface to the bottom **151** of the borehole **126**. A drill bit **150**, attached to drilling assembly **190**, disintegrates the geological formations when it is rotated to drill the borehole **126**. The drill string **120** is coupled to a drawworks **130** via a Kelly joint **121**, swivel **128** and line **129** through a pulley. Drawworks **130** is operated to control the weight on bit (“WOB”). The drill string **120** may be rotated by a top drive (not shown) instead of by the prime mover and the rotary table **114**. Alternatively, a coiled-tubing may be used as the tubing **122**. A tubing injector **114a** may be used to convey the coiled-tubing having the drilling assembly attached to its bottom end. The operations of the drawworks **130** and the tubing injector **114a** are known in the art and are thus not described in detail herein.

[0016] A suitable drilling fluid **131** (also referred to as the “mud”) from a source **132** thereof, such as a mud pit, is circulated under pressure through the drill string **120** by a mud pump **134**. The drilling fluid **131** passes from the mud pump **134** into the drill string **120** via a desurger **136** and the fluid line **138**. The drilling fluid **131a** from the drilling tubular discharges at the borehole bottom **151** through openings in the drill bit **150**. The returning drilling fluid **131b** circulates uphole through the annular space **127** between the drill string **120** and the borehole **126** and returns to the mud pit **132** via a return line **135** and drill cutting screen **185** that removes the drill cuttings **186** from the returning drilling fluid **131b**. A sensor S_1 in line **138** provides information about the fluid flow rate. A surface torque sensor S_2 and a sensor S_3 associated with the drill string **120**

respectively provide information about the torque and the rotational speed of the drill string **120**. Tubing injection speed is determined from the sensor **S₅**, while the sensor **S₆** provides the hook load of the drill string **120**.

[0017] In some applications, the drill bit **150** is rotated by only rotating the drill pipe **122**. However, in many other applications, a downhole motor **155** (mud motor) disposed in the drilling assembly **190** also rotates the drill bit **150**. The rate of penetration (ROP) for a given BHA largely depends on the WOB or the thrust force on the drill bit **150** and its rotational speed.

[0018] The mud motor **155** is coupled to the drill bit **150** via a drive shaft disposed in a bearing assembly **157**. The mud motor **155** rotates the drill bit **150** when the drilling fluid **131** passes through the mud motor **155** under pressure. The bearing assembly **157**, in one aspect, supports the radial and axial forces of the drill bit **150**, the down-thrust of the mud motor **155** and the reactive upward loading from the applied weight-on-bit.

[0019] A surface control unit or controller **140** receives signals from the downhole sensors and devices via a sensor **143** placed in the fluid line **138** and signals from sensors **S₁-S₆** and other sensors used in the system **100** and processes such signals according to programmed instructions provided to the surface control unit **140**. The surface control unit **140** displays desired drilling parameters and other information on a display/monitor **141** that is utilized by an operator to control the drilling operations. The surface control unit **140** may be a computer-based unit that may include a processor **142** (such as a microprocessor), a storage device **144**, such as a solid-state memory, tape or hard disc, and one or more computer programs **146** in the storage device **144** that are accessible to the processor **142** for executing instructions contained in such programs. The surface control unit **140** may further communicate with a remote control unit **148**. The surface control unit **140** may process data relating to the drilling operations, data from the sensors and devices on the surface, data received from downhole, and may control one or more operations of the downhole and surface devices. The data may be transmitted in analog or digital form.

[0020] The BHA **190** may also contain formation evaluation sensors or devices (also referred to as measurement-while-drilling ("MWD") or logging-while-drilling

("LWD") sensors) determining resistivity, density, porosity, permeability, acoustic properties, nuclear-magnetic resonance properties, formation pressures, properties or characteristics of the fluids downhole and other desired properties of the formation **195** surrounding the BHA **190**. Such sensors are generally known in the art and for convenience are generally denoted herein by numeral **165**. The BHA **190** may further include a variety of other sensors and devices **159** for determining one or more properties of the BHA **190** (such as vibration, bending moment, acceleration, oscillations, whirl, stick-slip, etc.) and drilling operating parameters, such as weight-on-bit, fluid flow rate, pressure, temperature, rate of penetration, azimuth, tool face, drill bit rotation, etc.) For convenience, all such sensors are denoted by numeral **159**.

[0021] The BHA **190** may include a steering apparatus or tool **158** for steering the drill bit **150** along a desired drilling path. In one aspect, the steering apparatus may include a steering unit **160**, having a number of force application members **161a-161n**, wherein the steering unit is at partially integrated into the drilling motor. In another embodiment the steering apparatus may include a steering unit **158** having a bent sub and a first steering device **158a** to orient the bent sub in the wellbore and the second steering device **158b** to maintain the bent sub along a selected drilling direction.

[0022] The drilling system **100** may include sensors, circuitry and processing software and algorithms for providing information about desired dynamic drilling parameters relating to the BHA, drill string, the drill bit and downhole equipment such as a drilling motor, steering unit, thrusters, etc. Exemplary sensors include, but are not limited to drill bit sensors, an RPM sensor, a weight on bit sensor, sensors for measuring mud motor parameters (e.g., mud motor stator temperature, differential pressure across a mud motor, and fluid flow rate through a mud motor), and sensors for measuring acceleration, vibration, whirl, radial displacement, stick-slip, torque, shock, vibration, strain, stress, bending moment, bit bounce, axial thrust, friction, backward rotation, BHA buckling, and radial thrust. Sensors distributed along the drill string can measure physical quantities such as drill string acceleration and strain, internal pressures in the drill string bore, external pressure in the annulus, vibration, temperature, electrical and magnetic field intensities inside the drill string, bore of the drill string, etc. Suitable systems for making dynamic downhole measurements include COPILOT, a downhole measurement system, manufactured by BAKER HUGHES INCORPORATED.

[0023] The drilling system **100** can include one or more downhole processors at a suitable location such as **193** on the BHA **190**. The processor(s) can be a microprocessor that uses a computer program implemented on a suitable non-transitory computer-readable medium that enables the processor to perform the control and processing. The non-transitory computer-readable medium may include one or more ROMs, EPROMs, EAROMs, EEPROMs, Flash Memories, RAMs, Hard Drives and/or Optical disks. Other equipment such as power and data buses, power supplies, and the like will be apparent to one skilled in the art. In one embodiment, the MWD system utilizes mud pulse telemetry to communicate data from a downhole location to the surface while drilling operations take place. The surface processor **142** can process the surface measured data, along with the data transmitted from the downhole processor, to evaluate formation lithology. While a drill string **120** is shown as a conveyance system for sensors **165**, it should be understood that embodiments of the present disclosure may be used in connection with tools conveyed via rigid (e.g. jointed tubular or coiled tubing) as well as non-rigid (e. g. wireline, slickline, e-line, etc.) conveyance systems. The drilling system **100** may include a bottomhole assembly and/or sensors and equipment for implementation of embodiments of the present disclosure on either a drill string or a wireline. A point of novelty of the system illustrated in **Fig. 1** is that the surface processor **142** and/or the downhole processor **193** are configured to perform certain methods (discussed below) that are not in prior art.

[0024] **FIG. 2** shows a nuclear detection module **200** that may be incorporated in BHA **190**, such as along with evaluation sensors **165** according to one embodiment of the present disclosure. The nuclear detection module **200** may include one or more sensors **210, 220** configured to detect nuclear radiation disposed along a drill collar **230**. The one or more nuclear radiation sensors **210, 220** may be spaced at different distances along the drill collar **230** apart from a neutron source **240**. The radiation source **240** may be controllable in that the radiation source may be turned “on” and “off” while in the wellbore (or at the surface), as opposed to a radiation source that is “on” continuously. The measurements performed using this type of radiation may be referred to as “sourceless” measurements since they employ a source that may be turned off, as opposed to a continuously emitting chemical radiation source. When neutron source **240** is turned on, emitted neutrons may induce gamma ray emissions **250** in the earth formation **195**. The gamma ray emitting nuclides **250** in the earth formation **195** may then serve as a

spatially distributed radiation emission source, e.g., a gamma radiation source. When the neutron source **240** is turned off and after delayed neutron emissions have stopped, the radionuclides formed through nuclear reactions **250** may still be emitting nuclear radiation **260** into the earth formation **195**. The interaction with the nuclear radiation **260** and the earth formation **195** may result in a nuclear radiation response **270** from the formation. Nuclear radiation response **270** may be the result of gamma ray scattering by the earth formation **195**. Detectors **210**, **220** may receive a nuclear radiation response **270** (e.g., scattered nuclear radiation) from the earth formation **195**. In some embodiments, the nuclear detection module **200** may not include a neutron source **240**, and the radionuclides in the earth formation **195** may be generated by neutron irradiation by another neutron source located in the borehole **126** or at the surface.

[0025] While a drill string is shown as a conveyance system for nuclear detection module **200**, it should be understood that embodiments of the present disclosure may be used in connection with tools conveyed via rigid (e.g. jointed tubular or coiled tubing) as well as non-rigid (e. g. wireline, slickline, e-line, etc.) conveyance systems.

[0026] Neutron source **240** may be any neutron generator, including, but not limited to, a pulsed neutron generator and a chemical neutron source. The nuclear radiation sensors **210**, **220** may include detectors configured to detect gamma rays. In some embodiments, the at least one parameter of interest may include density.

[0027] In contrast to existing density measurements, the gamma ray source is not a point source but a spatially distributed source (e.g., radionuclides **250**). Prompt gamma ray emission rate from thermal capture and inelastic scattering nuclear reactions can be expressed as a product of nuclear density, microscopic cross section and neutron flux as shown below,

$$S = \gamma N \sigma(E) \Phi(E) \quad (1)$$

where S is the gamma ray emission rate, γ is the number of gamma photons emitted per each specific nuclear reaction, N is nuclear density of the nuclide that neutrons are interacting with, $\sigma(E)$ is microscopic cross section for the given reaction type and the nuclide, $\Phi(E)$ is neutron flux. Some of those parameters vary with the energy of the incident neutron.

[0028] As shown in this equation, nuclear density of the nuclides targeted by neutrons play a direct role in prompt gamma ray emission. One typical nuclear reaction for a very fast 14 MeV neutron emitted by a pulsed neutron generator is inelastic scattering with the nuclides present in the target material.

[0029] In an earth formation, oxygen is an element that is typically present in large amounts, and an oxygen-16 nuclide has a sufficiently large inelastic scattering cross section, $\sigma(E)$, to generate significant amounts of prompt gamma rays from inelastic scattering reactions. In some cases, a significant amount of carbon (or other elements) may also be present in the formation. Additionally, a large portion of oxygen and carbon gamma rays may have energy in the 4-8 MeV range, so pair production is a significant interaction mechanism that is specific to the material in the formation.

[0030] Density measurements via nuclear logging benefit from a stable radiation source. Having a stable gamma ray source using gamma rays from a spatially distributed source, e.g., neutron inelastic scattering reactions and thermal capture reactions initiated by neutron irradiation of nuclides in the formation, requires stability of the parameters in equation (1). A stable neutron flux may be reasonably maintained over the logging period - it is possible to monitor the pulsed neutron source and account for any variations. Microscopic reaction cross section, $\sigma(E)$, is a property of the nuclide and does not change. Number of photons emitted per nuclear reaction, γ , does not change either. However, nuclear density changes with the formation lithology. Thus, the formation mineral type, porosity, fluid in the pore space, and fluid in the borehole affect the density measurements.

Table 1. Oxygen and Carbon Nuclear Density in Various Formation Materials

Mineralogy	Oxygen Nuclear Density ($\times 10^{22}$)	Carbon Nuclear Density ($\times 10^{22}$)
Quartz (SiO_2)	5.31	---
0.8 Quartz + 0.2 Water (v/v)	4.92	---
0.8 Quartz + 0.2 Oil (v/v)	4.25	0.69
0.8 Quartz + 0.2 Methane (v/v)	4.25	0.15
Calcium Carbonate (CaCO_3)	4.90	1.63
0.8 CaCO_3 + 0.2 Water (v/v)	4.58	1.31
0.8 CaCO_3 + 0.2 Oil (v/v)	3.92	2.00
0.8 CaCO_3 + 0.2 Methane (v/v)	3.92	1.46
Kaolinite	5.50	---
Illite	4.90	---
Smectite	5.20	---

[0031] Table 1 shows the variation of oxygen and carbon with respect to various formation materials. For example, there might be approximately a 7% change in oxygen nuclear density between pure sandstone and 20pu water-saturated rocks. For a similar case that has oil rather than water, that change may be 20%. In contrast with the water-saturated case, oil-saturated rock will have carbon that may not be found in the pure quartz rock.

[0032] Calcium carbonate mineralogy may be another example. Three common clays, kaolinite, illite and smectite have significant amounts of oxygen. Those clays are

likely to generate more oxygen gamma rays compared to higher porosity water saturated rocks.

[0033] As is readily apparent from the varying nuclear density values in Table 1, providing a constant gamma ray source in the formation for use in density measurements via neutron irradiation is not practical. Because conventional density measurements rely on change between the gamma ray source intensity values and the recorded gamma ray intensity values, obtaining accurate estimations of density (or related parameters of interest) may be problematic. Thus, normalization of the radiation information to compensate for nuclear density variability may be beneficial to increase accuracy of estimating a parameter of interest.

[0034] Since gamma count rates are originally driven by the inelastic scattering interactions between neutrons and elements of the formation, the necessary normalization factors may be determined from the concentration of oxygen, carbon and other relevant elements in the system, which may be estimated from predicted lithology, or more specifically, predicted mineralogy. A tool such as the Baker Hughes Formation Lithology eXplorer ('FLeX') tool can be used to provide such data.

[0035] Normalization may be carried out using predicted formation lithology established from neutron induced gamma spectroscopy, porosity, or NMR logs, or the like, either individually or in combination. Predicted formation lithology may include predicted formation mineralogy, porosity and fluids. It is well known to estimate the nuclear density of oxygen, carbon and other relevant elements in dependence upon such information.

[0036] FIG. 3 shows a flow chart 300 for estimating at least one parameter of interest of the earth formation according to one embodiment of the present disclosure. In optional step 310, neutron source 240 may be turned on to expose at least part of the earth formation 195 to neutron radiation. In step 320, the earth formation is exposed to prompt gamma rays the emitted through nuclear reactions. In step 330, interaction with the nuclear radiation emissions 260 and the earth formation 195 may result in nuclear radiation response 270 from earth formation 195. In step 340, detection occurs when one or more nuclear radiation sensors 210, 220 may generate radiation information in the form of signals in response to detected nuclear radiation emissions 260 and nuclear

radiation responses **270**. In step **350**, the signals representing nuclear radiation **260**, **270** may be normalized by applying a correction factor. The correction factor may be determined in dependence upon an estimated lithology of the formation containing the radionuclide and a model relating nuclear density and lithology. In step **360**, a parameter of interest of the formation may be estimated using information relating to at least one nuclear radiation component of the earth formation **195**.

[0037] Since a gamma ray count may include gamma rays from multiple elements, the gamma ray count information may be separated using a model into gamma ray components associated with each element. Herein, “information” may include raw data, processed data, analog signals, and digital signals. In some embodiments, the model may include, but is not limited to, one or more of: (i) a mathematical equation, (ii) an algorithm, (iii) an energy spectrum deconvolution technique, (iv) a stripping technique, (v) an energy spectrum window technique, (vi) a time spectrum deconvolution technique, and (vii) a time spectrum window technique. The gamma ray component for at least one nuclide may be used to estimate at least one parameter of interest of the earth formation. The at least one parameter of interest may include, but is not limited to, one or more of: (i) density, (ii) porosity, and (iii) fluid saturation. A description for some embodiments estimating the at least one parameter of interest follows below.

[0038] In some embodiments, estimation of the parameter of interest may involve applying a model. The model may include, but is not limited to, (i) a mathematical equation, (ii) an algorithm, (iii) an energy spectrum deconvolution technique, (iv) an energy spectrum stripping technique, (v) an energy spectrum window technique, (vi) a time spectrum deconvolution technique, (vii) a time spectrum window technique, or a combination thereof.

[0039] **FIG. 4** shows a flow chart **400** for determining a correction factor according to one embodiment of the present disclosure. In optional step **410**, lithology-related measurements are obtained. Lithology related measurements may include spectral gamma ray measurements, porosity related measurements, NMR logging measurement, and so on. In step **420**, a processor may be used to predict mineralogy of the formation using the obtained measurements. Prediction of lithology from such information is very well known in the prior art. See, for example, the methods as described in “A New

Pulsed Neutron Sonde for Derivation of Formation Lithology and Mineralogy” by Pemper et al, “The Direct Measurement of Carbon in Wells Containing Oil and Natural Gas Using a Pulsed Neutron Mineralogy Tool” by Pemper et al, and US 8101907 B2 to Jacobi et al. Methods as disclosed in US Patent application publication 2011/0218735 to Han et al may also be used.

[0040] Natural gamma ray measurements may be subjected to an elemental analysis to give an estimate of K, Th, and U. Pulsed neutron measurements may be subject to an elemental analysis to give other elements such as Ca, Cl, Fe, Mg, Si, and S. The outputs of the elemental analyses, density measurements, and porosity measurements may be input to a constrained optimization module in a processor. The output of the constrained optimization module may be the mineralogy. Quadratic programming may include a quadratic objective function of the form $g^T x + \frac{1}{2} x^T H x$. Other constraints may include bound constraints ($bl \leq x \leq bu$), linear constraints ($Ax \leq b$) and non-linear constraints ($C(x) \leq 0$). Here, g is the gradient of f at the current point x , f is the objective function, H is the Hessian matrix (the symmetric matrix of second derivatives). An objective function is minimized at each sample (depth) of the logs independently of the other depths. The objective function may be a summation from i to k of the value $(\text{Logdata}_i - f_i (\text{component volumes}))^2 / \text{Var}_i$. There are a total of k input logs which may include density, porosity, and photoelectric factor (PE) as well as the logs from elemental analysis. The function f_i relates the mineralogy at each depth to the value of the i -th log. The weighting function Var_i gives different weights to the different logs depending upon their accuracy. Generally speaking, density and porosity measurements have the largest weights.

[0041] In step **430**, a processor may use the predicted mineralogy of the formation to estimate relevant nuclear density values. In step **440**, a processor may calculate a correction factor using the relevant nuclear density values.

[0042] Methods of the present disclosure may include determining the concentration in the system (e.g., the formation and borehole fluid) of significant nuclides such as, for example, oxygen and carbon. This may be carried out using a neutron induced gamma ray mineralogy measurement obtained along with the density measurement system. The same can also be achieved by measuring sourceless density and using an existing mineralogy log from a previous logging run. In both cases, it is

possible to estimate a total oxygen concentration and a total carbon concentration in the system. Since the oxygen and carbon amount is linearly correlated with the gamma ray source to be used for density measurements, the oxygen, carbon and any other relevant element concentration measurement may be used to normalize the gamma ray source. The methods herein may occur in real-time using a tool that has both density and neutron induced gamma mineralogy systems on board. Alternatively, a sourceless density log may be processed subsequent to the logging run with mineralogy data sufficient to estimate oxygen content, carbon content, and / or any other relevant element content for normalizing the gamma ray source. Either embodiment enables removal of all other variables from the measurement except the formation density.

[0043] As shown in **FIG. 5**, certain embodiments of the present disclosure may be implemented with a hardware environment that includes an information processor **500**, a information storage medium **510**, an input device **520**, processor memory **530**, and may include peripheral information storage medium **540**. The hardware environment may be in the well, at the rig, or at a remote location. Moreover, the several components of the hardware environment may be distributed among those locations. The input device **520** may be any information reader or user input device, such as data card reader, keyboard, USB port, etc. The information storage medium **510** stores information provided by the detectors. Information storage medium **510** may be any standard computer information storage device, such as a ROM, USB drive, memory stick, hard disk, removable RAM, EPROMs, EAROMs, EEPROM, flash memories, and optical disks or other commonly used memory storage system known to one of ordinary skill in the art including Internet based storage. Information storage medium **510** stores a program that when executed causes information processor **500** to execute the disclosed method. Information storage medium **510** may also store the formation information provided by the user, or the formation information may be stored in a peripheral information storage medium **540**, which may be any standard computer information storage device, such as a USB drive, memory stick, hard disk, removable RAM, or other commonly used memory storage system known to one of ordinary skill in the art including Internet based storage. Information processor **500** may be any form of computer or mathematical processing hardware, including Internet based hardware. When the program is loaded from information storage medium **510** into processor memory **530** (e.g. computer RAM), the

program, when executed, causes information processor **500** to retrieve detector information from either information storage medium **510** or peripheral information storage medium **540** and process the information to estimate a parameter of interest. Information processor **500** may be located on the surface or downhole.

[0044] A “spatially distributed source” may comprise a multitude of sources collectively. For example, the spatially distributed source may be spread throughout the formation. A source with “substantially constant intensity” may not change during logging, or the source intensity variation may be sufficiently small such that it is negligible with regard to estimation of density, porosity, or other parameter of interest. An “interaction” may be described as an event causing a change in energy and direction of incident radiation (e.g., a gamma ray) prior to measurement of the radiation and absorption of the radiation. An “interaction” may induce emission of secondary radiation as well (e.g. emission of a secondary neutron and/or gamma ray). Normalizing may refer to adjusting values measured on different scales to a notionally common scale, so that variation in the values corresponds to a variation of single factor. Formation lithology may include formation mineral type, porosity, and fluid in the pore space. Mineralogy may include the chemical composition and structure of minerals in the formation.

[0045] Herein, the term “information” may include, but is not limited to, one or more of: (i) raw data, (ii) processed data, and (iii) signals. The term “conveyance device” as used above 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 conveyance devices include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other conveyance device examples include casing pipes, wirelines, wire line sondes, slickline sondes, drop shots, downhole subs, BHA's, drill string inserts, modules, internal housings and substrate portions thereof, self-propelled tractors. As used above, the term “sub” refers to any structure that is configured to partially enclose, completely enclose, house, or support a device. The term “information” as used above includes any form of information (Analog, digital, EM, printed, etc.). The term “information processing device” herein includes, but is not limited to, any device that transmits, receives, manipulates, converts, calculates, modulates, transposes, carries, stores or otherwise utilizes information. An information

processing device may include a microprocessor, resident memory, and peripherals for executing programmed instructions. The “correction factor” may be applied in additive (or subtractive) or multiplicative fashion to the radiation information.

[0046] While the foregoing disclosure is directed to the one mode embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations be embraced by the foregoing disclosure.

CLAIMS

What is claimed is:

1. A method of estimating at least one parameter of interest of a volume of an earth formation, comprising:

normalizing radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume.

2. The method of claim 1, wherein the radiation emissions are generated by neutron irradiation of at least one nuclide in the volume.

3. The method of claim 1, wherein the correction factor is determined using nuclear density of at least one nuclide in the volume.

4. The method of claim 1, wherein the correction factor is determined using an estimated concentration of at least one nuclide in the volume.

5. The method of claim 1, wherein the correction factor is determined using a parameter relating to concentration of at least one nuclide in the volume.

6. The method of claim 1, wherein the at least one parameter of interest comprises density.

7. The method of claim 1, wherein the emissions include gamma rays.

8. The method of claim 1, further comprising estimating the at least one parameter of interest using the normalized radiation information.
9. The method of claim 2, wherein the neutron irradiation is carried out using a pulsed neutron generator.
10. The method of claim 1, further comprising:
generating the radiation information using a sensor in a borehole in the earth formation.
11. The method of claim 1, wherein the radiation information relates to a radiation emission rate from the spatially distributed nuclear source.
12. An apparatus for estimating at least one parameter of interest of a volume of an earth formation, comprising:
at least one processor configured to normalize radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume.
13. A non-transitory computer-readable medium product for estimating at least one parameter of interest of a volume of an earth formation, comprising:
instructions disposed on the medium that, when executed by a processor, cause the at least one processor to:
normalize radiation information relating to radiation emissions from a spatially distributed nuclear source and indicative of a property of the earth volume using a correction factor determined using an estimated lithology of the volume.

14. The non-transitory computer-readable medium product of claim 13, wherein the radiation emissions are generated by neutron irradiation of at least one nuclide in the volume.

15. The non-transitory computer-readable medium product of claim 13, wherein the instructions further comprise instructions for determining the correction factor using nuclear density of at least one nuclide in the volume.

16. The non-transitory computer-readable medium product of claim 13, wherein the instructions further comprise instructions for determining the correction factor using an estimated concentration of at least one nuclide in the volume.

1/3

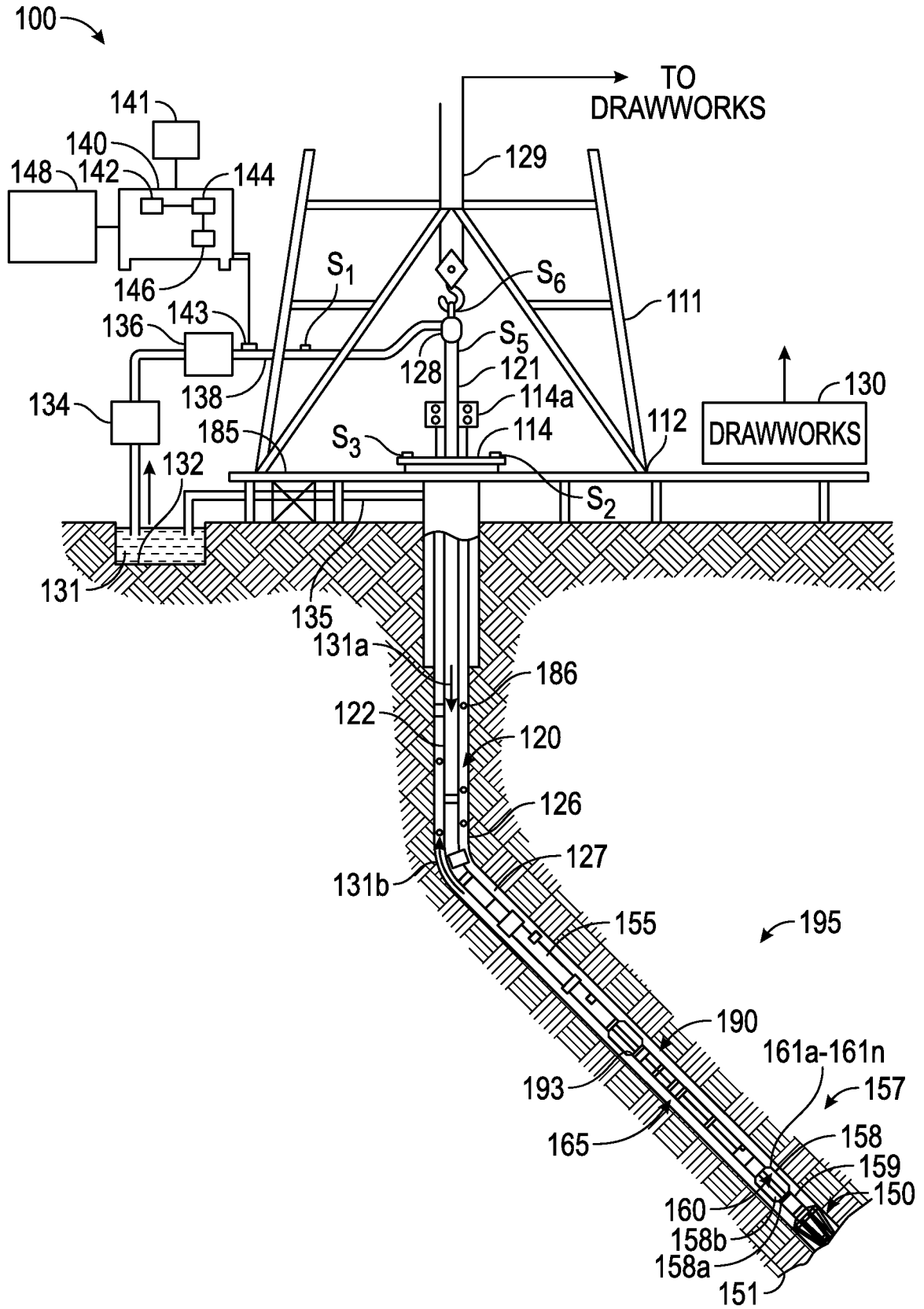


FIG. 1

2/3

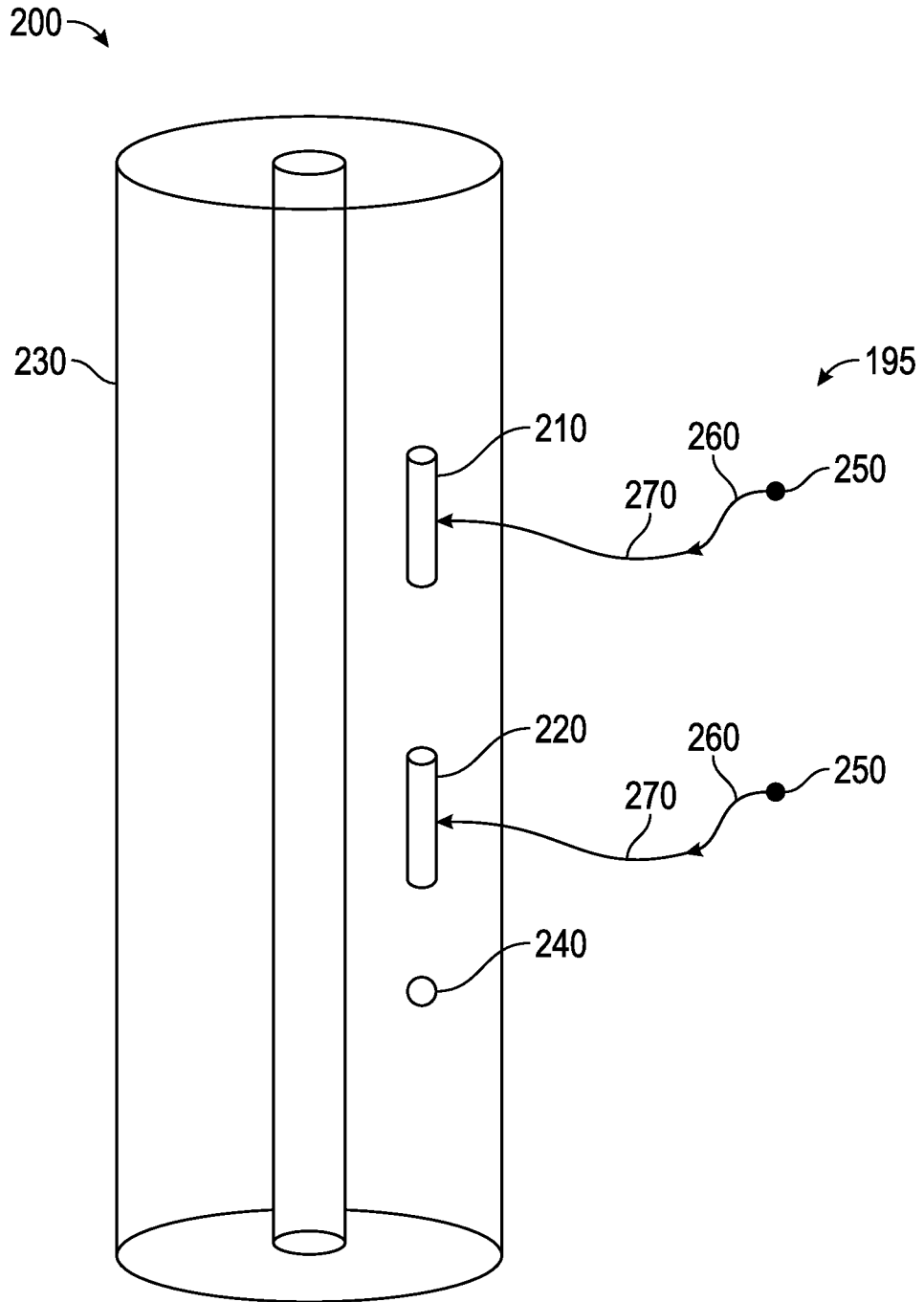


FIG. 2

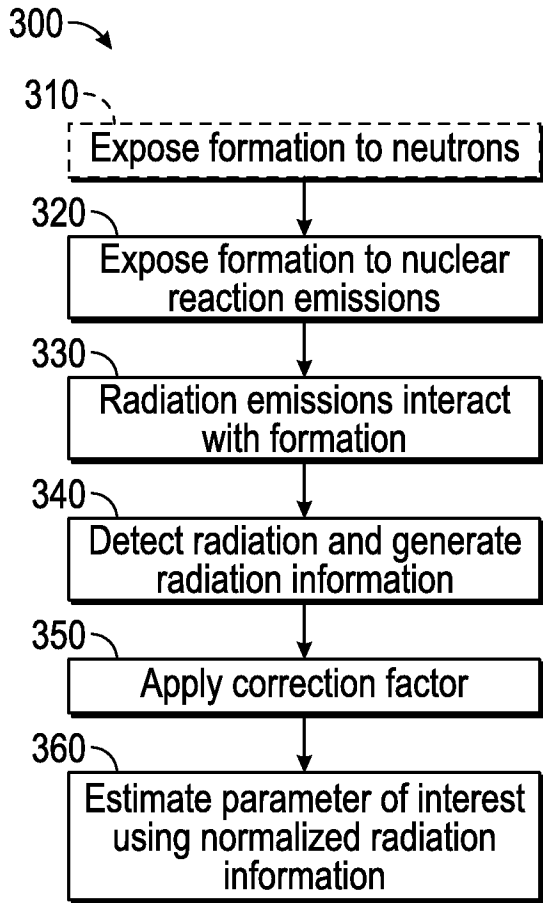


FIG. 3

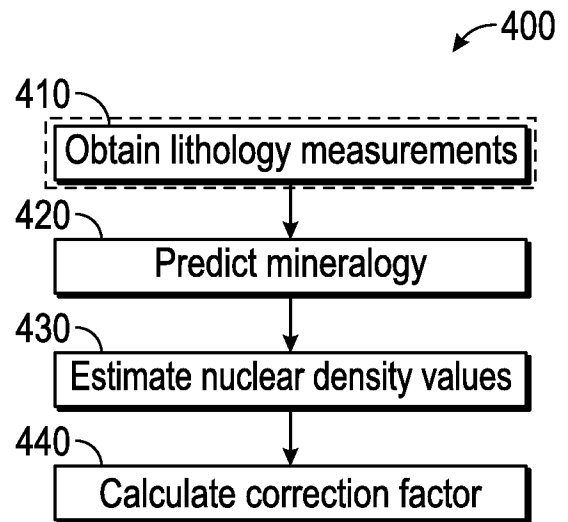


FIG. 4

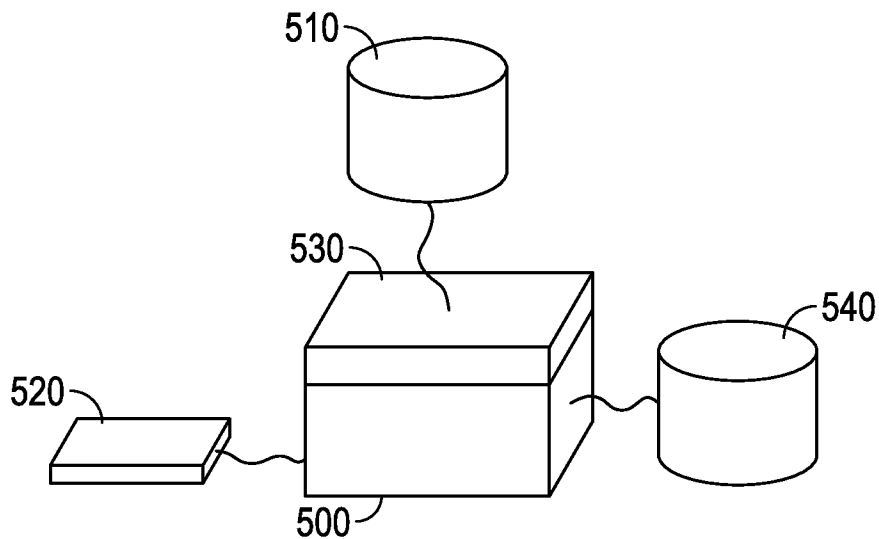


FIG. 5

A. CLASSIFICATION OF SUBJECT MATTER**E21B 47/09(2006.01)i, G01V 5/04(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 47/09; G06F 17/10; G12B 13/00; G01V 5/04; G01V 5/12; G01V 5/10

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: earth formation, volume, radiation information, spatially distributed nuclear source, correction factor, nuclide, and gamma ray

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2011-0191030 A1 (ROBERTS, LOREN P.) 04 August 2011 See paragraphs [0008], [0023], [0026]-[0028], [0032] and figures 1-5.	1-16
Y	US 2007-0246649 A1 (JACOBI et al.) 25 October 2007 See paragraphs [0046], [0050]-[0051], [0098] and figures 1, 2B.	1-16
A	US 2011-0218735 A1 (HAN et al.) 08 September 2011 See paragraphs [0024]-[0026] and figure 1.	1-16
A	US 2010-0314535 A1 (ZHANG et al.) 16 December 2010 See paragraphs [0050], [0059]-[0060] and figures 9-11.	1-16
A	US 2011-0257948 A1 (MCDANIEL et al.) 20 October 2011 See paragraphs [0039], [0041]-[0043] and figures 2-3.	1-16

 Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family


Date of the actual completion of the international search

16 September 2014 (16.09.2014)

Date of mailing of the international search report

17 September 2014 (17.09.2014)

Name and mailing address of the ISA/KR


 International Application Division
 Korean Intellectual Property Office
 189 Cheongsu-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
 Republic of Korea

Facsimile No. +82-42-472-7140

Authorized officer

LEE, Jong Kyung

Telephone No. +82-42-481-3360



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/037467

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011-0191030 A1	04/08/2011	GB 201214333 D0	26/09/2012
		GB 2494954 A	27/03/2013
		NO 20120829 A	14/08/2012
		US 8700333 B2	15/04/2014
		WO 2011-094686 A2	04/08/2011
		WO 2011-094686 A3	17/11/2011
US 2007-0246649 A1	25/10/2007	CA 2646307 A1	01/11/2007
		CA 2646307 C	23/07/2013
		CN 101501531 A	05/08/2009
		EA 200802137 A1	30/10/2009
		EP 2008125 A2	31/12/2008
		GB 0818092 D0	05/11/2008
		GB 2450444 A	24/12/2008
		GB 2450444 B	09/03/2011
		US 8101907 B2	24/01/2012
		WO 2007-123996 A2	01/11/2007
		WO 2007-123996 A3	18/12/2008
		US 2011-0218735 A1	08/09/2011
WO 2011-109182 A3	17/11/2011		
US 2010-0314535 A1	16/12/2010	US 8598510 B2	03/12/2013
		WO 2010-144579 A2	16/12/2010
		WO 2010-144579 A3	07/04/2011
		WO 2010-144579 A4	26/05/2011
US 2011-0257948 A1	20/10/2011	AU 2009-314273 A1	20/05/2010
		CA 2738824 A1	20/05/2010
		CN 102209834 A	05/10/2011
		EP 2352901 A1	10/08/2011
		MX 2011004722 A	01/09/2011
		RU 2011123779 A	20/12/2012
		RU 2483210 C2	27/05/2013
		US 2009-090505 A1	09/04/2009
		US 7933718 B2	26/04/2011
		US 8392120 B2	05/03/2013
		WO 2010-056605 A1	20/05/2010