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(54) Title: SOURCELESS DENSITY MEASUREMENT USING ACTIVATION

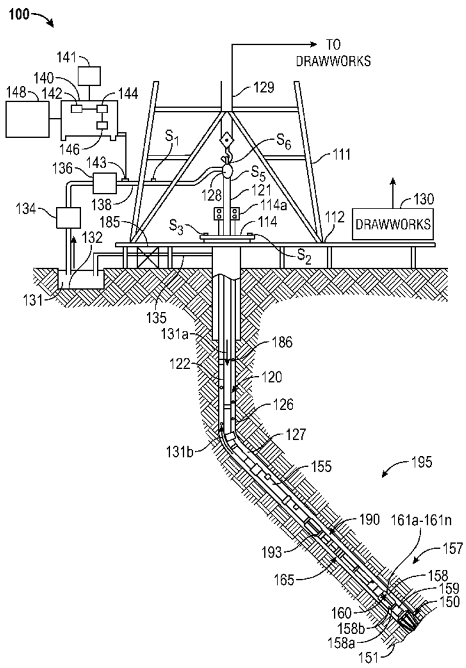

FIG. 1

(57) Abstract: The present disclosure relates to borehole logging methods and apparatuses for estimating at least one parameter of interest of an earth formation using nuclear radiation, particularly by detecting interactions between the earth formation and an activated radiation source. The method may include using nuclear radiation information from at least one nuclear radiation sensor to estimate a parameter of interest. The method may include separating a gross nuclear radiation count into separate nuclear radiation components. The method may also include activating a part of a downhole tool with neutron radiation. The apparatus may include at least one nuclear radiation sensor. The apparatuses may include an information processing device to perform the methods.

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TITLE: SOURCELESS DENSITY MEASUREMENT USING ACTIVATION

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 carrier 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 interest of an earth formation, comprising: estimating the at least one parameter of interest using a response from the volume of interest to radiation from at least one radionuclide on a carrier in a borehole in the earth formation, the at least one radionuclide being generated by neutron irradiation.

[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 carrier configured to be conveyed in a borehole in the earth formation; at least one radionuclide disposed on the carrier; and a sensor configured to produce a signal indicative of a response of the volume of interest to the at least one radionuclide.

[0006] Another embodiment according to the present disclosure may include a non-transitory computer-readable medium product having instructions thereon that, when executed, cause at least one processor to perform a method, the method comprising: estimating the at least one parameter of interest using a response from the volume of interest to radiation from at least one radionuclide on a carrier in a borehole in the earth formation, the at least one radionuclide being generated by neutron irradiation.

[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 graph of variation of nuclear densities with time under constant neutron radiation for one embodiment according to the present disclosure;

Fig. 5 shows a graph of nuclear radiation counts for sensors in different positions for one embodiment according to the present disclosure;

Fig. 6 shows a graph of nuclear radiation information before and after separation into radiation components for one embodiment according to the present disclosure; and

Fig. 7 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 of an earth formation using a radionuclide generated by neutron irradiation.

[0010] The application of neutrons may cause "activation" of specific nuclides (iron, silicon, and oxygen) that may be found in a downhole environment. The neutrons may cause some nuclides to be converted into radionuclides that are not stable. Radionuclides generally give off ionizing radiation, such as gamma rays, during their delayed decay. 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" 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 Logging-While-Drilling (LWD) tools, there may be a significant amount of iron in the tool structure. The significant portion of the iron, about 92%, may be iron-56. When iron-56 is irradiated by neutrons, the interaction of the neutrons with some iron-56 nuclides may be result in manganese-56 radionuclides. Manganese-56 may later decay and emit certain gamma rays.

The buildup of gamma emitting radionuclides in the downhole tool due to activation may reach asymptotic values, thus providing a constant gamma source.

[0012] In a typical logging environment, LWD tools stay in the borehole for extended time periods while exposed to a neutron source. The neutron source may include, but is not limited to, one or more of: a chemical neutron source and a pulsed neutron generator. Regular exposure to the neutron source may result in a stable radionuclide population in at least one part of a downhole tool that includes one or more radionuclides. The at least one part of the downhole tool may include a drill collar. The radionuclides in the at least one part of the downhole tool may emit nuclear radiation that may interact with the earth formation after the neutron source has been turned off. The interaction of the nuclear radiation from the radionuclides may result radiation emission from the earth formation.

[0013] In a non-limiting exemplary implementation, neutron logging may be performed using a three time bin configuration. During the first time bin, one or more nuclear radiation sensors may detect photons being emitted as a result of inelastic neutron scattering interactions, capture of thermal neutrons (neutrons that slowed down while the pulsed neutron generator is still on), and photons from radionuclides that go through delayed decay due to a volume of interest of an earth formation being exposed to neutron radiation. During the second time bin, the nuclear radiation sensor(s) may detect photons from neutron capture reactions and decay of radionuclides due to neutron activation. During the third time bin, the detector(s) may detect photons from the delayed decay of radionuclides produced through activation interactions. Activation interactions may generate radionuclides in the downhole tool and the earth formation. Since the logging tool is generally in motion, the buildup of radionuclides in the earth formation may be low relative to the buildup of radionuclides in the tool. The downhole tool may be exposed to neutrons for an extended period of time, since the neutron source may remain in close proximity to the tool during the logging operation.

[0014] Thus, after the neutron source is turned off and thermal neutrons disappeared due to capture and diffusion, one or more nuclear radiation sensors disposed on the downhole tool may detect radiation due to radionuclides in the tool and in the earth formation that have been activated by neutron irradiation. The radionuclides (and their corresponding nuclides) may be described as nuclide-radionuclide pairs formed by nuclear interactions, such that a radionuclide may be formed from a nuclide that has been exposed to neutron radiation. The nuclear interactions may include, but are not limited to, neutron-proton reactions (n,p) and thermal neutron capture (n,γ). The nuclide-radionuclide pairs may include, but are not limited to, one more of: (i) oxygen-16→nitrogen-16 (n,p), (ii) sodium-23→neon-23 (n,p), (iii) sodium-23→sodium-24 (n,γ), (iv) magnesium-24→sodium-24 (n,p), (v) aluminum-27→aluminum-28 (n,γ), (vi) aluminum-27→magnesium-27 (n,p), (vii) silicon-28→aluminum-28 (n,p), (viii) iron-56→manganese-56 (n,p), and (ix) iodine-127→iodine-128 (n,γ).

[0015] The one or more nuclear radiation sensors disposed along the downhole tool may be configured to generate a signal indicative of the nuclear radiation detected. The detected nuclear radiation may include gamma rays. Since a gamma ray count may include gamma rays from radionuclides of 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 radionuclide 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.

[0016] **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.

[0017] 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 $\mathbf{S_1}$ in line **138** provides information about the fluid flow rate. A surface torque sensor $\mathbf{S_2}$ and a sensor $\mathbf{S_3}$ 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 $\mathbf{S_5}$, while the sensor $\mathbf{S_6}$ provides the hook load of the drill string **120**.

[0018] 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.

[0019] 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.

[0020] 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 $\mathbf{S_1}$-$\mathbf{S_6}$ 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.

[0021] 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**.

[0022] 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.

[0023] 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. Suitable systems are also discussed in "Downhole Diagnosis of Drilling Dynamics Data Provides New Level Drilling Process Control to Driller", SPE 49206, by G. Heisig and J.D. Macpherson, 1998.

[0024] 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.

[0025] **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**. When neutron source **240** is turned on, emitted neutrons may generate radionuclides in the drill collar **230**. The drill collar **230** may then serve as a gamma radiation source. When the neutron source **240** is turned off and after delayed neutron emissions have stopped, the drill collar **230** may still be emitting nuclear radiation **250** into the earth formation **195**. The interaction with the nuclear radiation **250** and the earth formation **195** may result in a nuclear radiation response **260** from the formation. Nuclear radiation **260** may be the result of gamma ray scattering by the earth formation **195**. Detectors **210**, **220** may receive a nuclear radiation response **250** from the drill collar **230** and nuclear radiation **260** from the earth formation **195**. The accumulation of radionuclides in drill collar **230** is exemplary and illustrative only, as other components of the BHA **190** may accumulate radionuclides, including components that do not contain iron-56. In some embodiments, the nuclear detection module **200** may not include a neutron source **240**, and the radionuclides in the drill collar **230** may be generated by neutron irradiation by another neutron source located in the borehole **126** or at the surface.

[0026] **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 step **310**, neutron source **240** may be turned on to expose at least part of the drill collar **230** to neutron radiation. In step **320**, radionuclides build up in the drill collar **230** during neutron irradiation. The build-up of radionuclides may take place over one or more neutron irradiation cycles. In step **330**, the neutron source may be turned off. In step **340**, the drill collar **230** may expose the earth formation **195** to nuclear radiation emissions **250** due to the radionuclides. In step **350**, interaction with the nuclear radiation emissions **250** and the earth formation **195** may result in nuclear radiation response **260** from earth formation **195**. In step **360**, one or more nuclear radiation sensors **210**, **220** may generate signals in response to detected nuclear radiation emissions **250** and scattered nuclear radiation **260**. In step **370**, the signals representing nuclear radiation **250**,

260 may be separated into nuclear radiation components associated with each of the radionuclides. In step **380**, a parameter of interest of the formation may be estimated using at information about at least one nuclear radiation component of the earth formation **195**. In some embodiments, steps **310**-**330** may be performed at the surface prior to the nuclear detection module **200** being conveyed into the borehole **26**, and the irradiation of drill collar **230** may be performed using another neutron source.

[0027] 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. In some embodiments, separation into nuclear radiation components 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.

[0028] **FIG. 4** shows a set of curves indicating a buildup of several radionuclides that may be encountered during nuclear logging. As shown, the curve **400** for manganese-56, which is a byproduct of iron-56 and neutron reactions, reaches an asymptotic value around 10 hrs. The radionuclides may form a gamma ray source. The gamma ray source may be used to estimating the density of the earth formation.

[0029] **FIG. 5** shows a set of curves indicating the buildup of gamma ray counts detected, as three different detector distances from a neutron source, due to activation of nuclides over time. Curve **510** represents a gamma ray count from a detector closest to the neutron source. Curve **520** represents a gamma ray count from a middle detector. Curve **530** represents a gamma ray count from a detector furthest from the neutron source. In this example, background nuclear radiation may be observed from a tool where a pulsed neutron generator has operated for several hours. It may be observed that the gradual buildup of nuclear radiation counts may approach an asymptotic value around 10 hours. The dips **540** in the curves **510**, **520**, **530** may indicate the period where the neutron source may be turned off. Even when the pulsed neutron generator is off, there are photons being detected by the radiation sensors **210**, **220**. The detected photons may come from the tool and the components of the tool, such as a drill collar. When the tool has a large collar with high iron content, the neutron activation may cause a significant number of gamma photons to be emitted during the third time bin.

[0030] **FIG. 6** shows a chart showing an example of radiation information before and after separation into a plurality of radiation components. Curve **600** may represent a signal generated from at least one radiation detector before separation. Curves **610**, **620** may represent two radiation components, corresponding to two radionuclides (radionuclide A and radionuclide B), that may be realized by separation. In this example, the separation may be performed using time spectrum deconvolution, which is one non-limiting technique that may be used in a model for separating the radiation information into a plurality of radiation components. The curves **600**, **610**, **620** may be represented as:

$$N(t) = N_A e^{-\lambda_A t} + N_B e^{-\lambda_B t} \qquad (1)$$

where $N(t)$ is the nuclear density value over time estimated by the at least one radiation detector and represented in curve **600**, N_A is the nuclear density of radionuclide A at t=0, N_B is the nuclear density of radionuclide A at t=0, λ_A is the decay constant of radionuclide A, λ_B is the decay constant of radionuclide A, and t is time. Hence, $N_A e^{-\lambda_A t}$ may mathematically express curve **610** and $N_B e^{-\lambda_B t}$ may mathematically express curve **620**.

[0031] The density change over time for radionuclides A and B may be written as:

$$N_B = \frac{N_2 - N_1 e^{-\lambda_A(t_2-t_1)}}{e^{-\lambda_B t_2} - e^{-(\lambda_B-\lambda_A)t_1-\lambda_A t_2}};\quad N_A = N_1 e^{\lambda_A t_1} - N_B e^{-(\lambda_B-\lambda_A)t_1} \qquad (2)$$

where N_1 and N_2 are the nuclear densities (on curve **600**) at times t_1 and t_2.

Using values for N_1 , N_2, t_1, and t_2 from curve **600**, radiation contributions for radionuclides A and B may be separated into curves **610**, **620**, which may be represented as $N_A(t) = N_A e^{-\lambda_A t}$ and $N_B(t) = N_B e^{-\lambda_B t}$, respectively. While this example shows the separations of radiation information into two radiation components, this in no way limits the number of radiation components that may be separated out of the radiation information.

[0032] As shown in **FIG. 7**, certain embodiments of the present disclosure may be implemented with a hardware environment that includes an information processor **700**, a information storage medium **710**, an input device **720**, processor memory **730**, and may include peripheral information storage medium **740**. 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 **720** may be any information reader or user input device, such as data card reader, keyboard, USB port, etc. The information storage medium **710** stores information provided by the detectors. Information storage medium **710** 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 **710** stores a program that when executed causes information processor **700** to execute the disclosed method. Information storage medium **710** may also store the formation information provided by the user, or the formation information may be stored in a peripheral information storage medium **740**, 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 **700** may be any form of computer or mathematical processing hardware, including Internet based hardware. When the program is loaded from information storage medium **710** into processor memory **730** (e.g. computer RAM), the program, when executed, causes information processor **700** to retrieve detector information from either information storage medium **710** or peripheral information storage medium **740** and process the information to estimate a parameter of interest. Information processor **700** may be located on the surface or downhole.

[0033] 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 interest of an earth formation, comprising:
   estimating the at least one parameter of interest using a response from the volume of interest to radiation from at least one radionuclide on a carrier in a borehole in the earth formation, the at least one radionuclide being generated by neutron irradiation.
2. The method of claim 1, wherein the activated radiation source is at least part of a housing of a downhole tool.
3. The method of claim 1, wherein the at least one parameter of interest includes at least one of: (i) density, (ii) porosity, and (iii) fluid saturation of the volume of interest.
4. The method of claim 1, wherein the response includes gamma rays.
5. The method of claim 1, wherein the at least one radionuclide includes manganese-56.
6. The method of claim 1, further comprising:
   generating the at least one radionuclide using a neutron source.
7. The method of claim 6, wherein the neutron source includes a pulsed neutron generator.
8. The method of claim 1, wherein the response is estimated when a neutron flux in the volume of interest is substantially zero.
9. The method of claim 1, further comprising:
   generating information related to the response using a sensor in a borehole in the earth formation.
10. The method of claim 9, further comprising:
    separating the information into a plurality of radiation components using a model.
11. The method of claim 10, wherein at least one of the plurality of radiation components includes a time decay.

12. The method of claim 10, wherein the model includes at least one 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.
13. The method of claim 1, wherein estimating the at least one parameter of interest includes a time decay measurement technique.
14. The method of claim 1, further comprising:
    conveying the at least one radionuclide into the borehole.
15. An apparatus for estimating at least one parameter of interest of a volume of interest of an earth formation comprising:
    a carrier configured to be conveyed in a borehole in the earth formation;
    at least one radionuclide disposed on the carrier; and
    a sensor configured to produce a signal indicative of a response of the volume of interest to the at least one radionuclide.
16. The apparatus of claim 15, wherein the at least one radionuclide is at least part of a housing of a downhole tool.
17. The apparatus of claim 15, wherein the response includes gamma rays.
18. The apparatus of claim 15, wherein the at least one radionuclide includes manganese-56.
19. The apparatus of claim 15, further comprising:
    a neutron source configured to generate the at least one radionuclide.
20. The apparatus of claim 19, wherein the neutron source includes a pulsed neutron generator.
21. The apparatus of claim 19, wherein the response is estimated when a neutron flux in the volume of interest is substantially zero.
22. The apparatus of claim 15, further comprising:
    a processor configured to estimate the at least one parameter of interest using the signal.The apparatus of claim 22, wherein the at least one parameter of interest is density of the volume of interest.

23. A non-transitory computer-readable medium product having instructions thereon that, when executed, cause at least one processor to perform a method, the method comprising:

    estimating the at least one parameter of interest using a response from the volume of interest to radiation from at least one radionuclide on a carrier in a borehole in the earth formation, the at least one radionuclide being generated by neutron irradiation.

24. The non-transitory computer-readable medium product of claim 24 further comprising at least one of: (i) a ROM, (ii) an EPROM, (iii) an EEPROM, (iv) a flash memory, and (v) an optical disk.

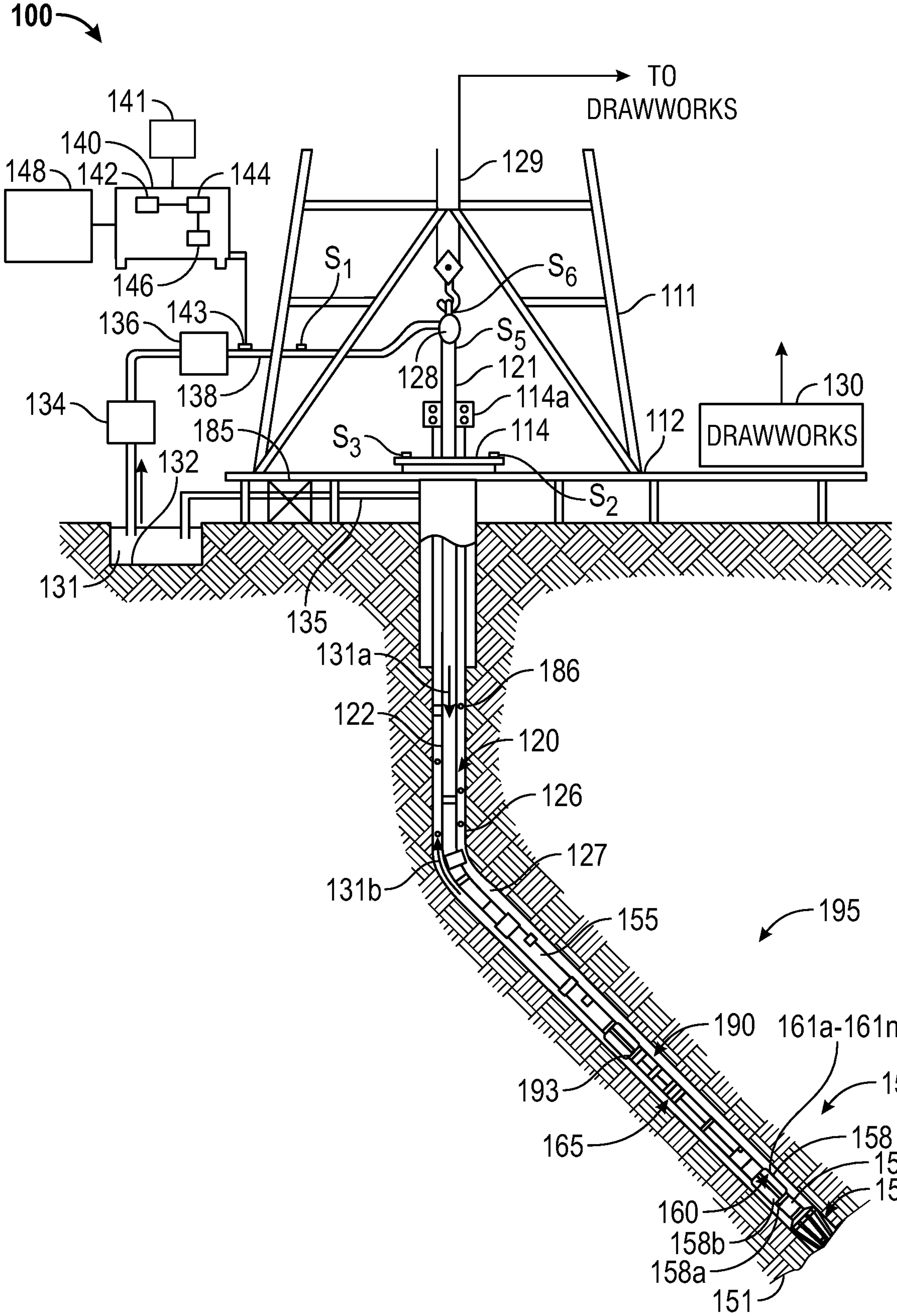
100
TO DRAWWORKS
141
140
142
144
148
129
146
S_1
S_6
111
143
136
S_5
138
128
121
134
114a
185
S_3
114
112
130
DRAWWORKS
132
S_2
131
135
131a
186
122
120
126
131b
127
155
195
190
161a-161n
193
157
165
158
159
150
160
158b
158a
151

FIG. 1

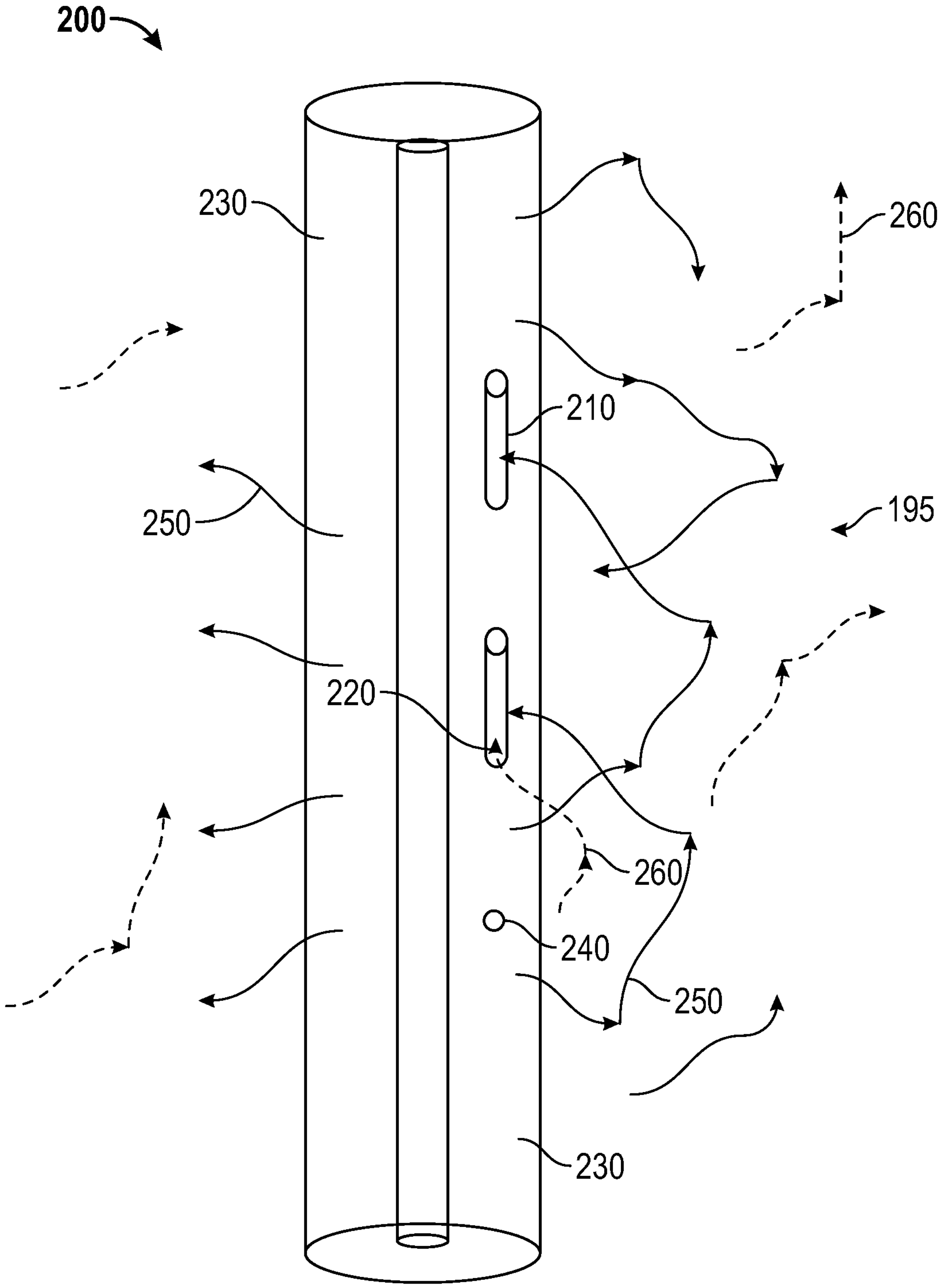

FIG. 2

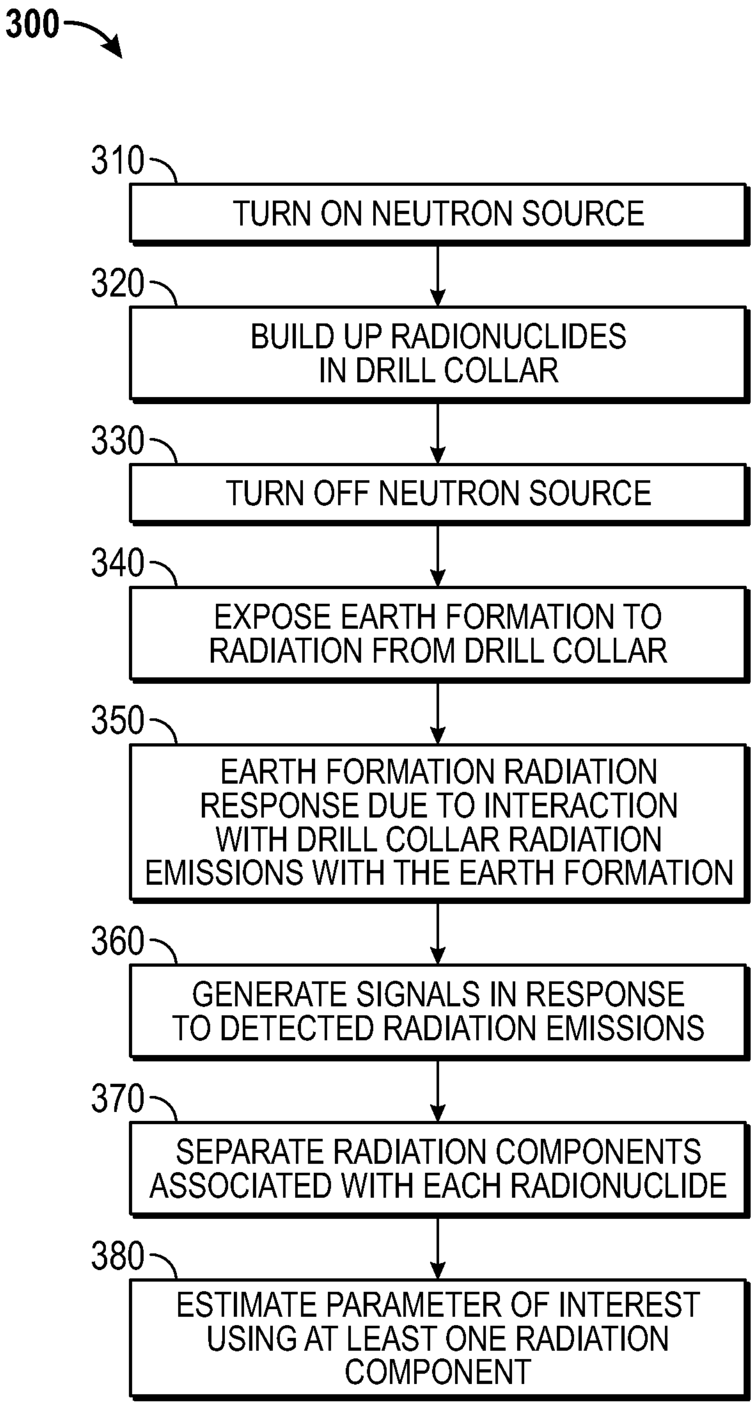
300
310
TURN ON NEUTRON SOURCE
320
BUILD UP RADIONUCLIDES IN DRILL COLLAR
330
TURN OFF NEUTRON SOURCE
340
EXPOSE EARTH FORMATION TO RADIATION FROM DRILL COLLAR
350
EARTH FORMATION RADIATION RESPONSE DUE TO INTERACTION WITH DRILL COLLAR RADIATION EMISSIONS WITH THE EARTH FORMATION
360
GENERATE SIGNALS IN RESPONSE TO DETECTED RADIATION EMISSIONS
370
SEPARATE RADIATION COMPONENTS ASSOCIATED WITH EACH RADIONUCLIDE
380
ESTIMATE PARAMETER OF INTEREST USING AT LEAST ONE RADIATION COMPONENT

FIG. 3

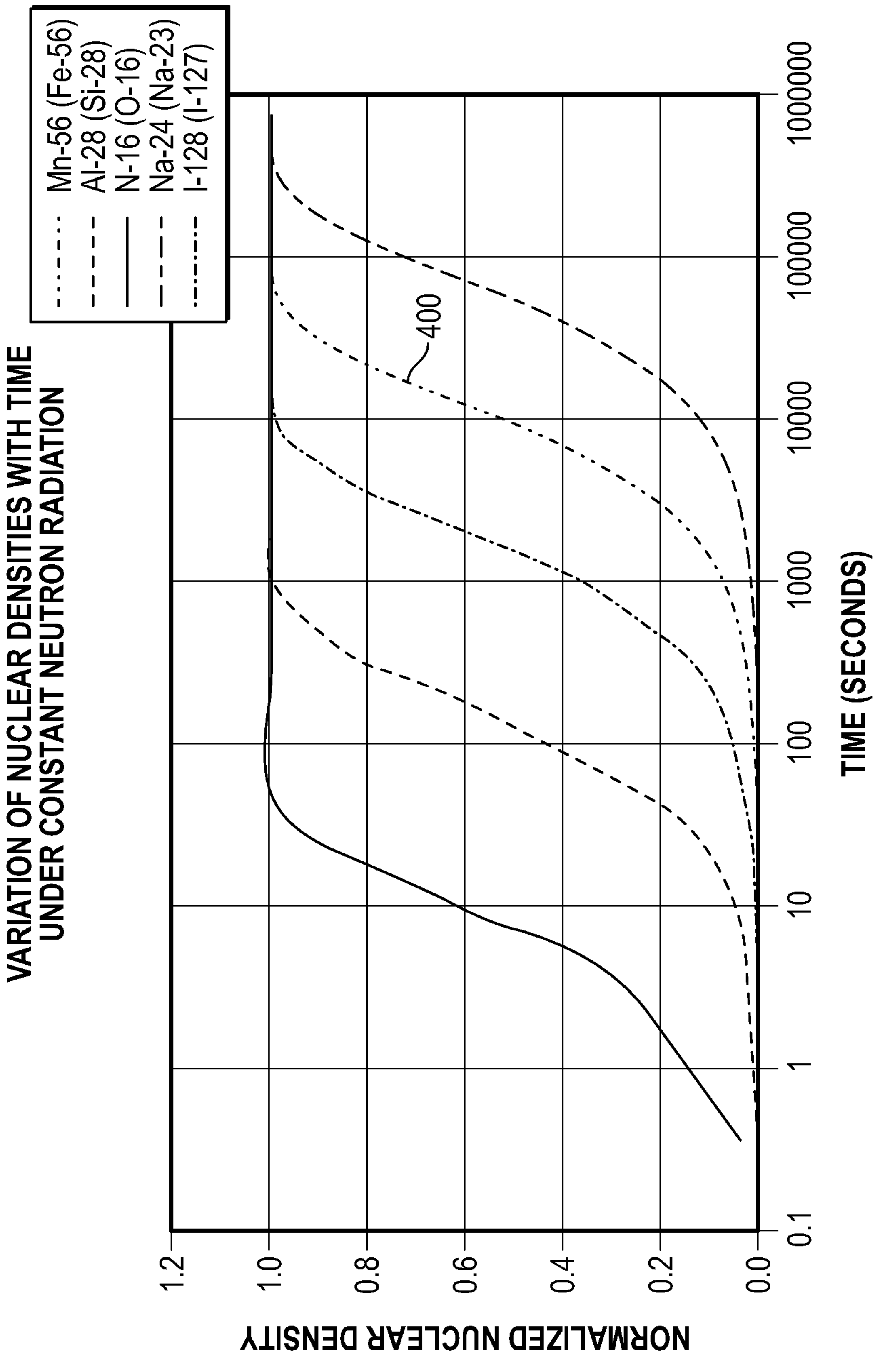
VARIATION OF NUCLEAR DENSITIES WITH TIME
UNDER CONSTANT NEUTRON RADIATION
Mn-56 (Fe-56)
Al-28 (Si-28)
N-16 (O-16)
Na-24 (Na-23)
I-128 (I-127)
400
NORMALIZED NUCLEAR DENSITY
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1
10
100
1000
10000
100000
1000000
TIME (SECONDS)

FIG. 4

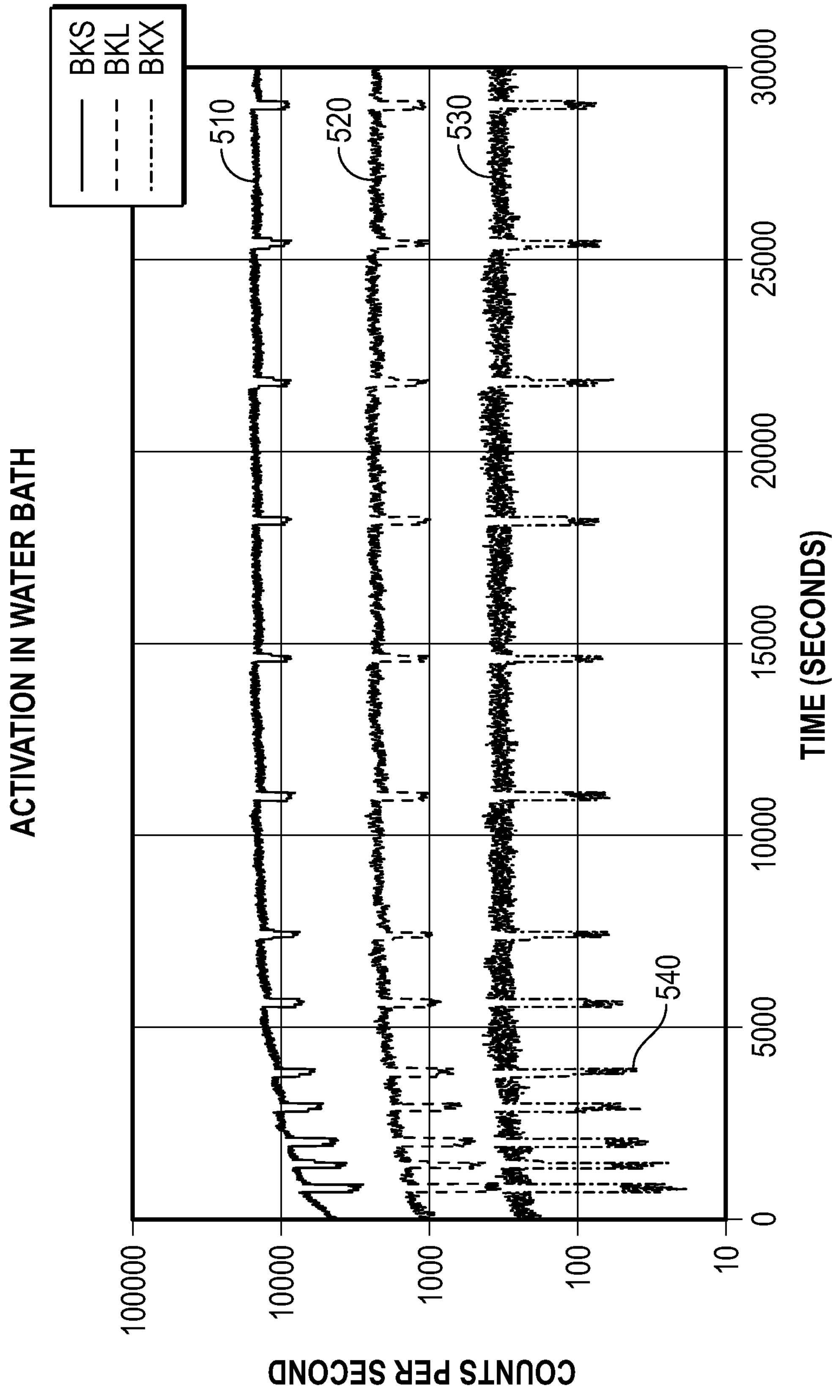
ACTIVATION IN WATER BATH
BKS
BKL
BKX
510
520
530
540
COUNTS PER SECOND
100000
10000
1000
100
10
0
5000
10000
15000
20000
25000
30000
TIME (SECONDS)

FIG. 5

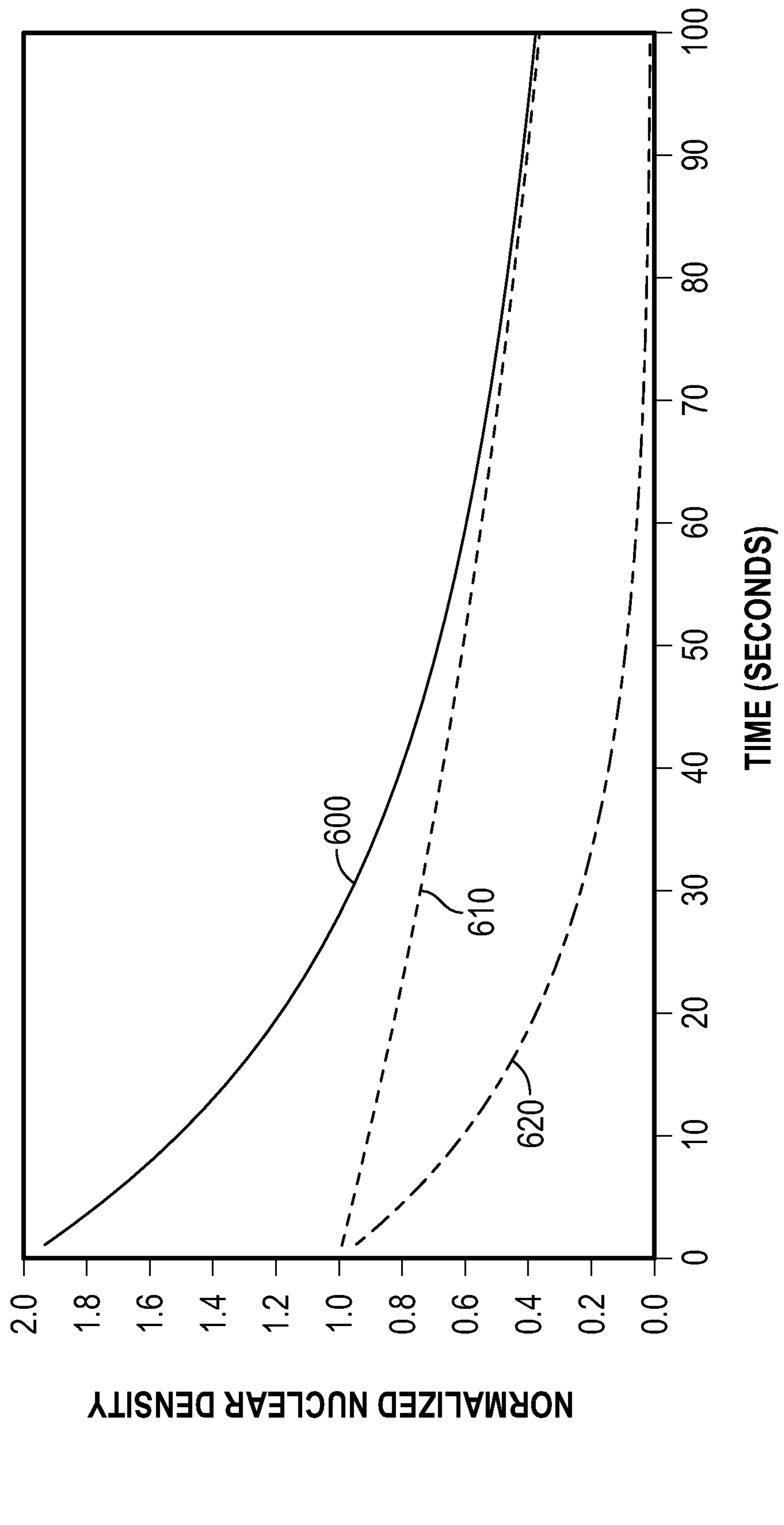
NORMALIZED NUCLEAR DENSITY
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70
80
90
100
TIME (SECONDS)
600
610
620

FIG. 6

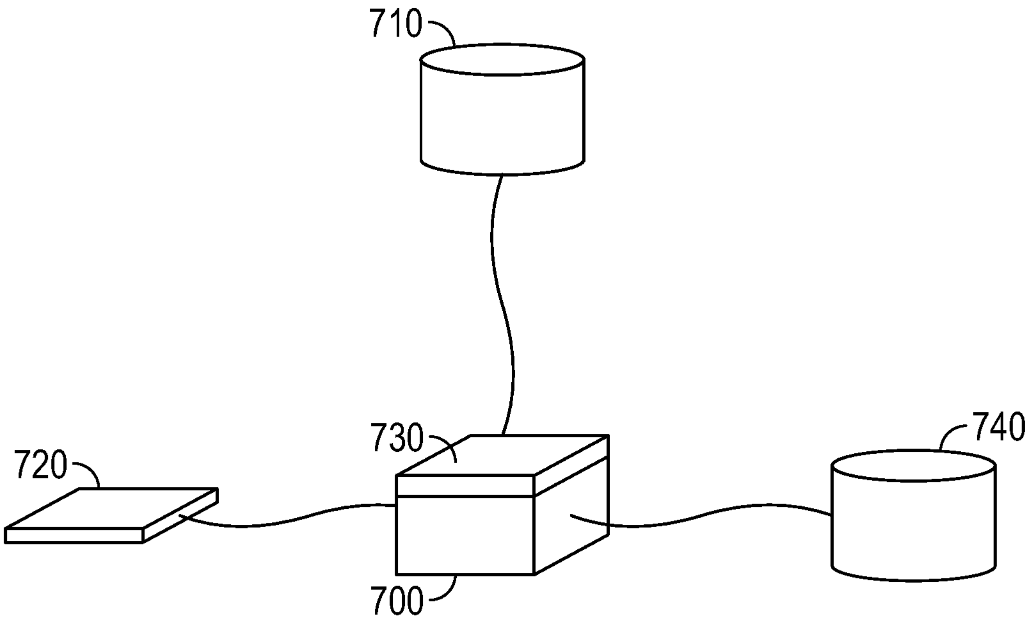

FIG. 7