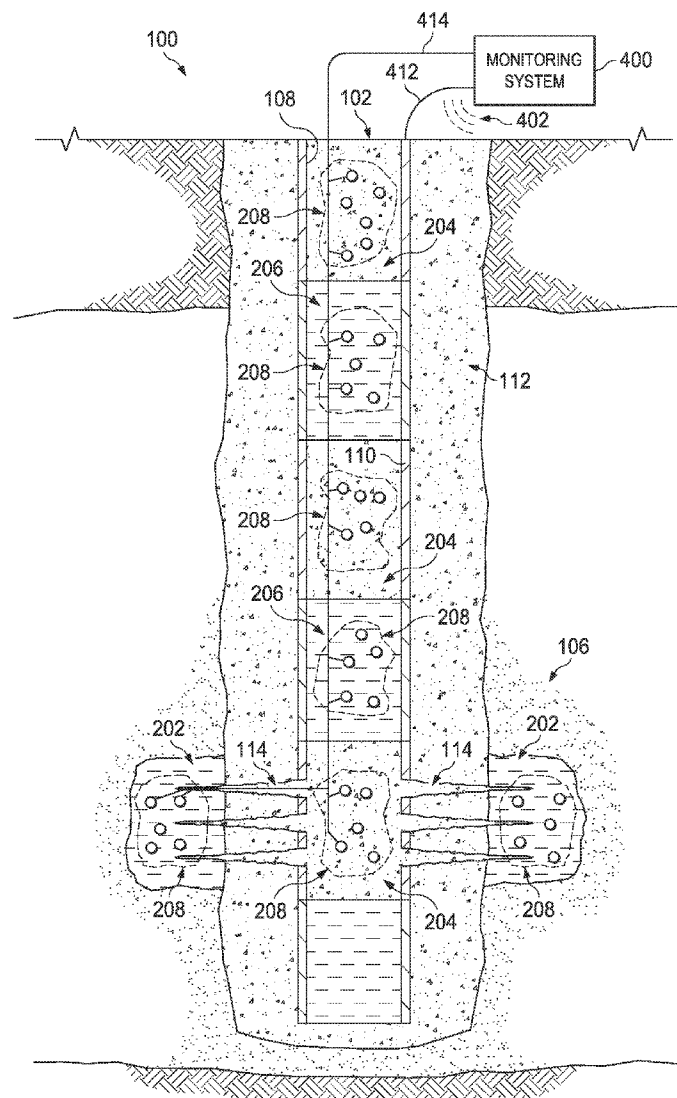


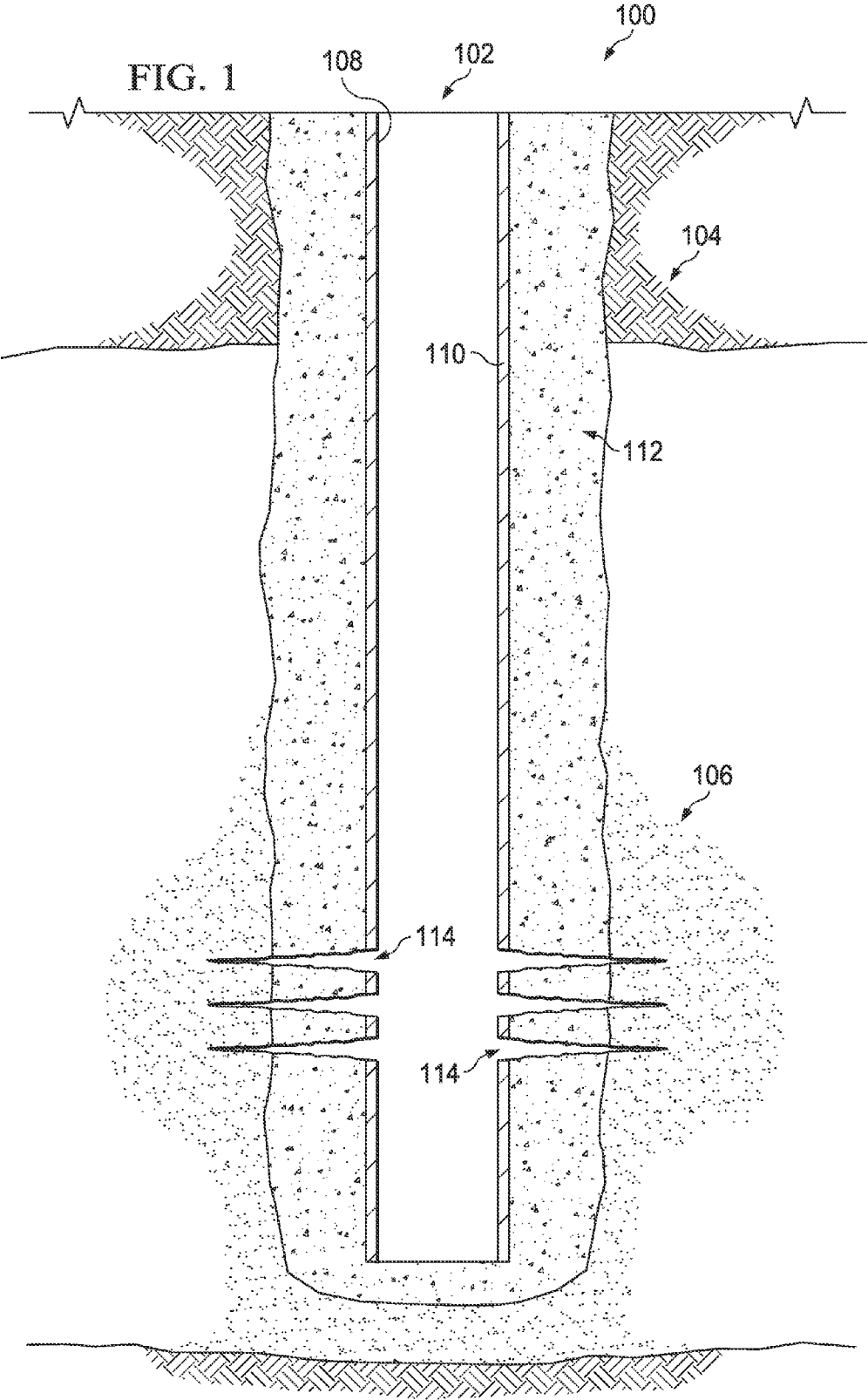


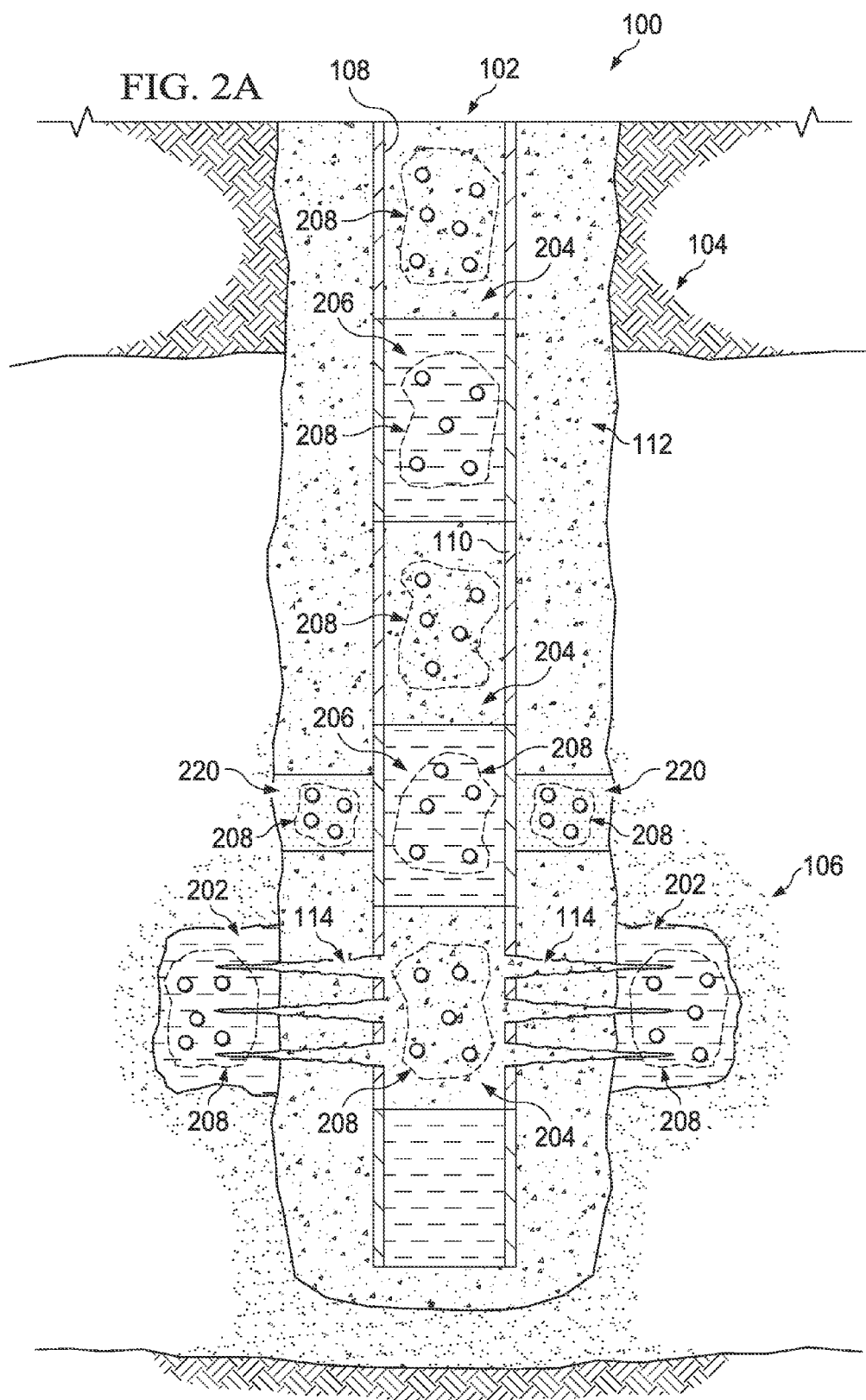
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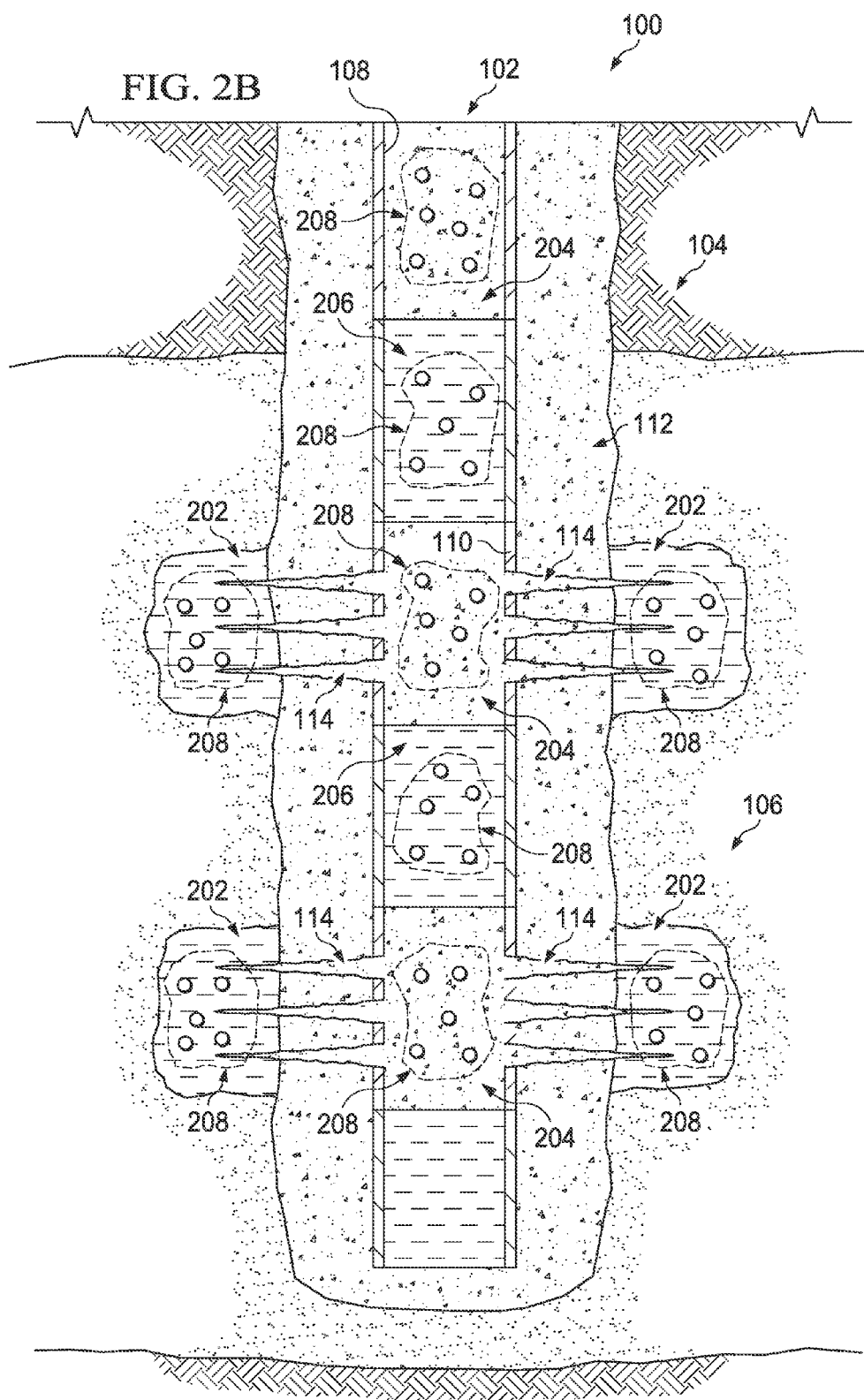
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Crow(10) **Pub. No.: US 2013/0299165 A1**(43) **Pub. Date: Nov. 14, 2013**(54) **METHODS AND SYSTEMS FOR LONG-TERM
MONITORING OF A WELL SYSTEM DURING
ABANDONMENT**(52) **U.S. Cl.**
USPC **166/250.08; 166/285; 166/66**(75) Inventor: **Walter Patrick Crow, Katy, TX (US)**(57) **ABSTRACT**(73) Assignee: **BP CORPORATION NORTH
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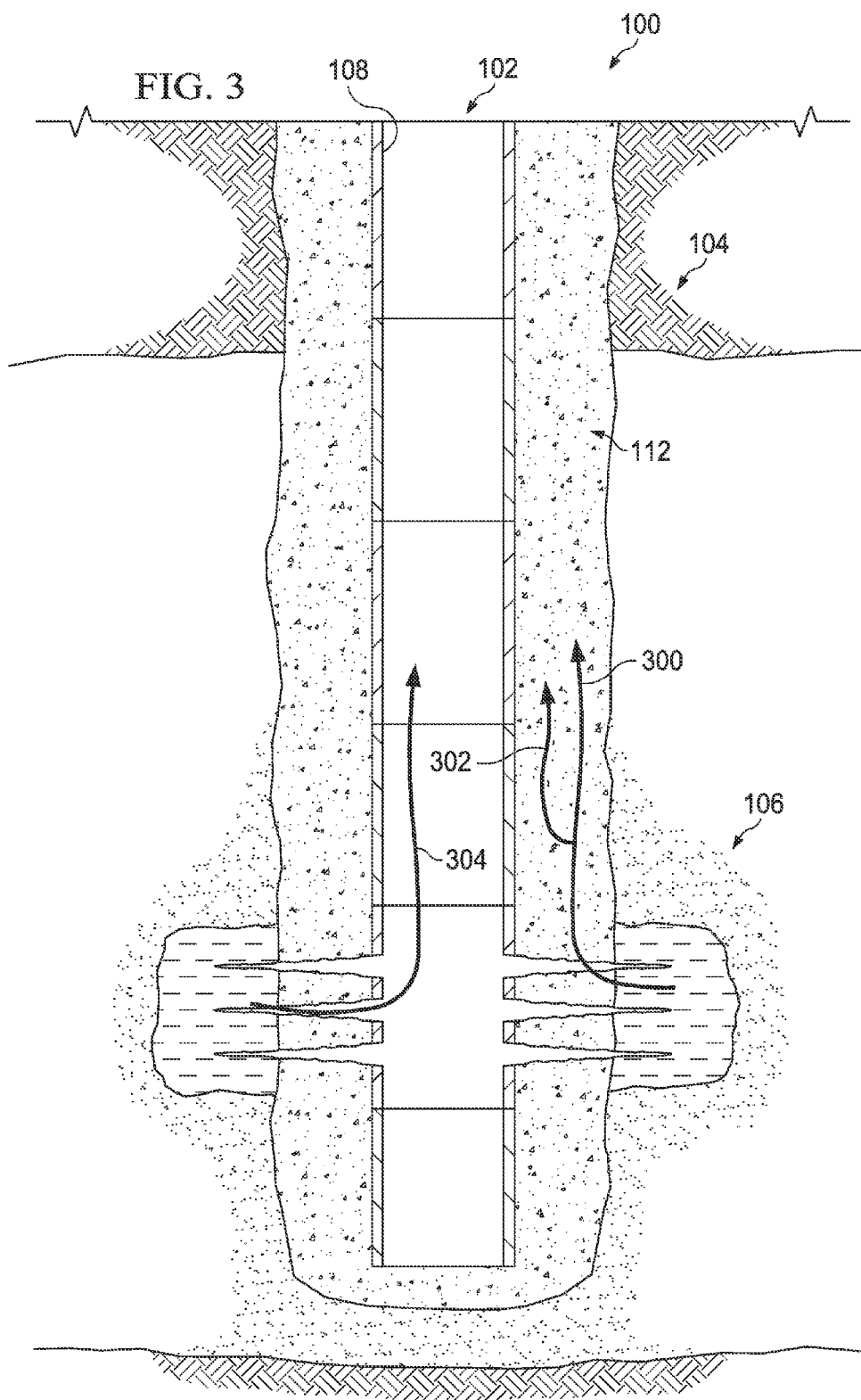
For long-term abandonment and monitoring of well systems, a series of barriers are formed within a formation and within a casing of a well to prevent materials from leaking from the well. Formation barriers are formed within the formation at the location of perforations in the casing and along the annulus. A series of casing barriers and fluid barriers are formed within the casing of the well. One or more sensors are formed within the barriers to monitor the conditions around the barriers over long periods of time. The sensors can be configured to measure the conditions around the one or more barriers during formation of the one or more barriers and over long periods of time after the one or more barriers are formed.

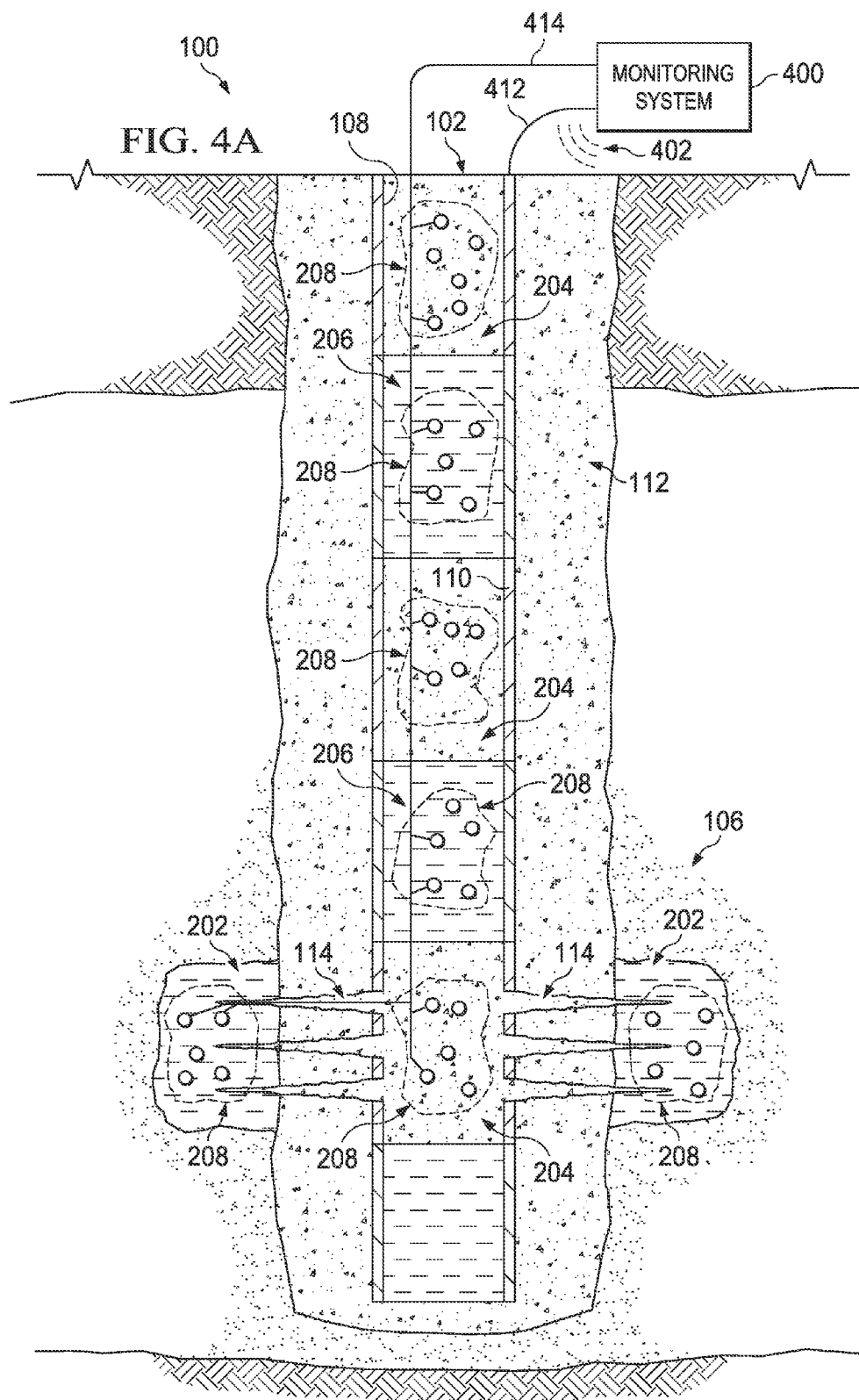












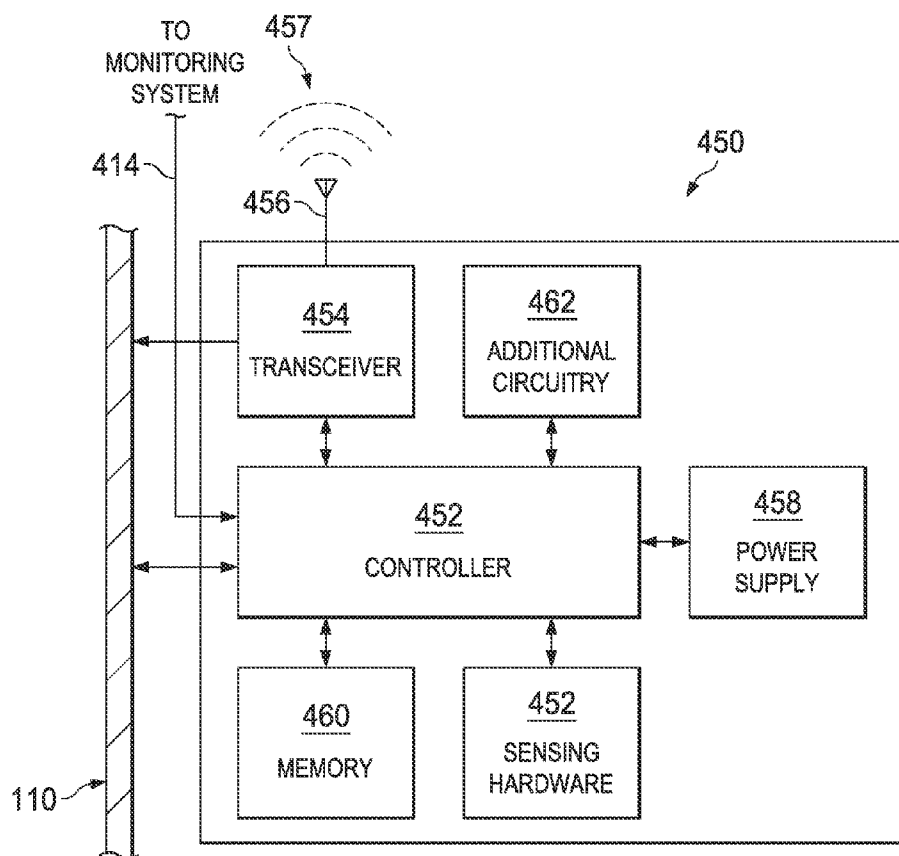


FIG. 4B

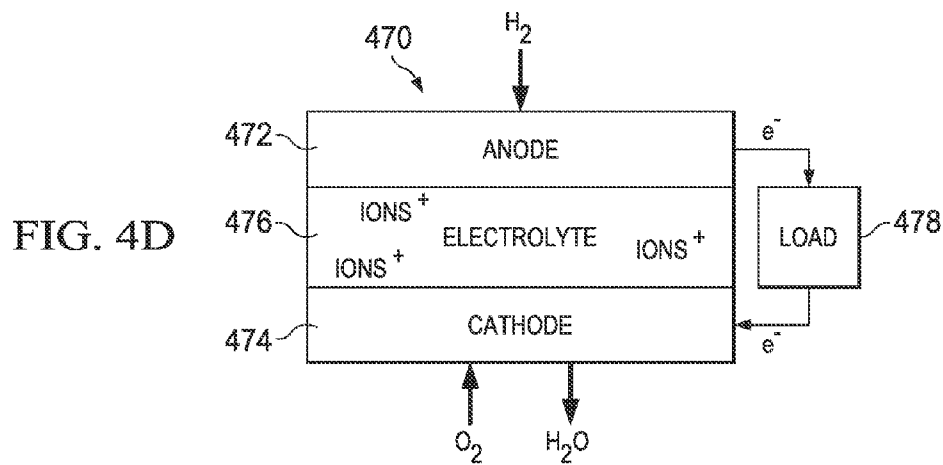


FIG. 4D

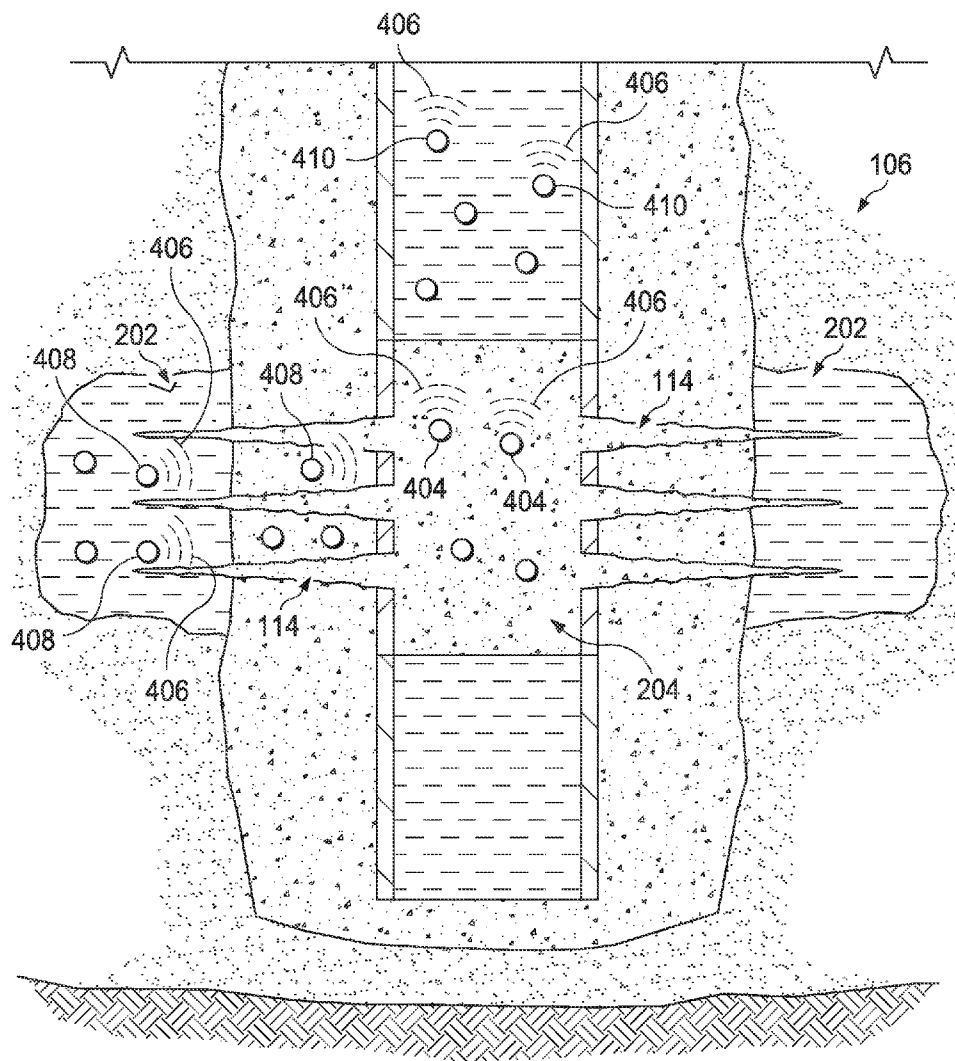


FIG. 4C

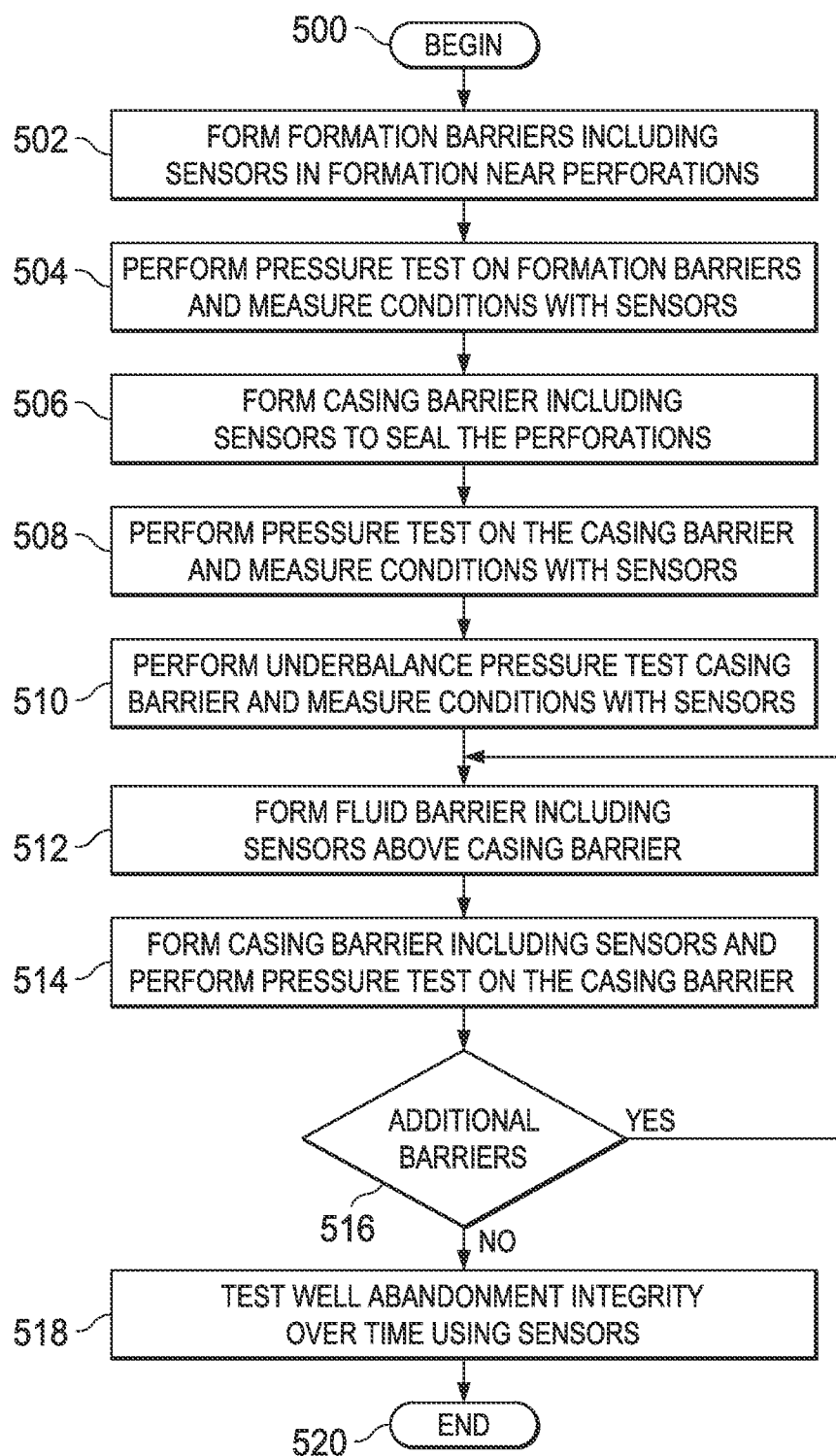
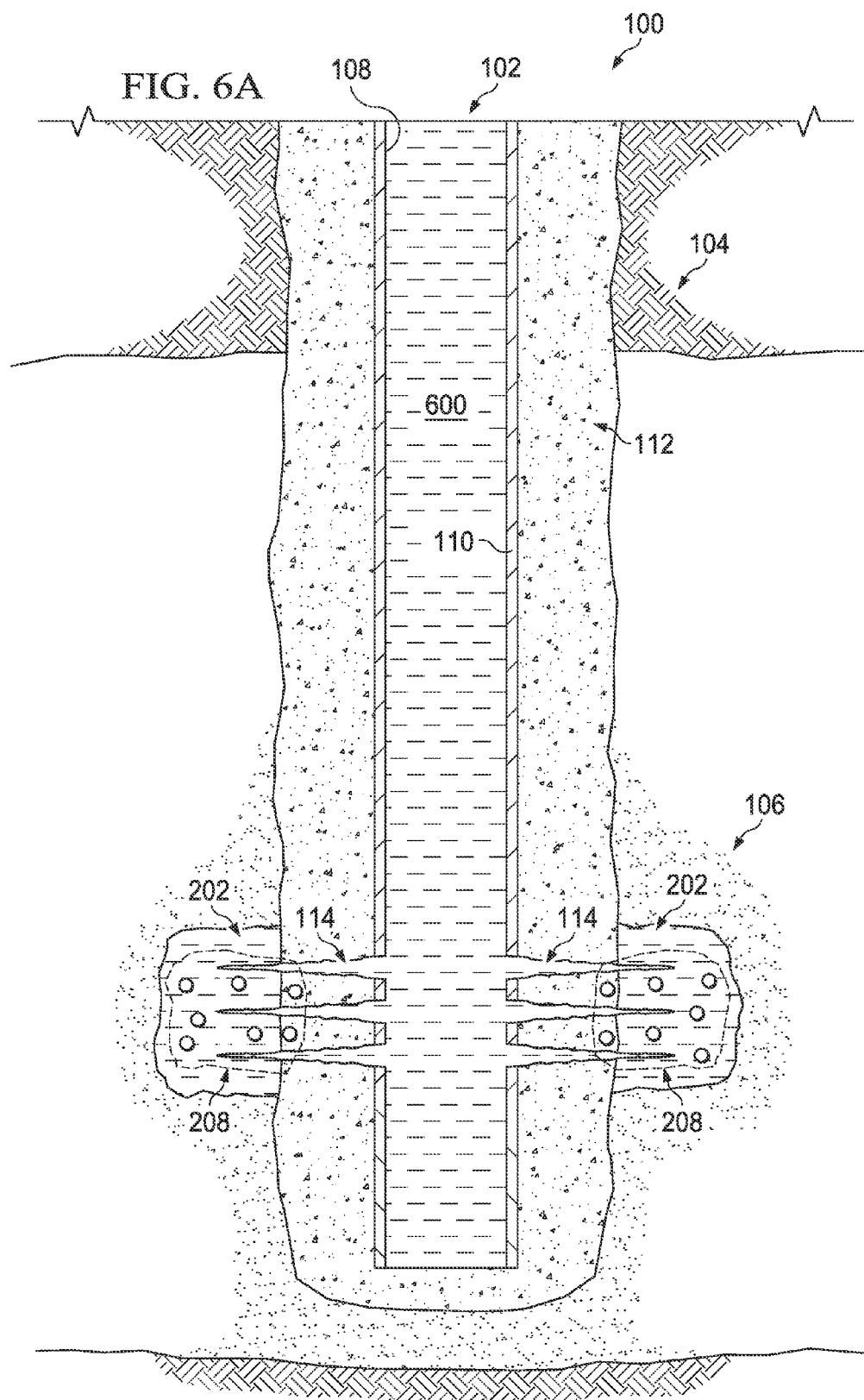
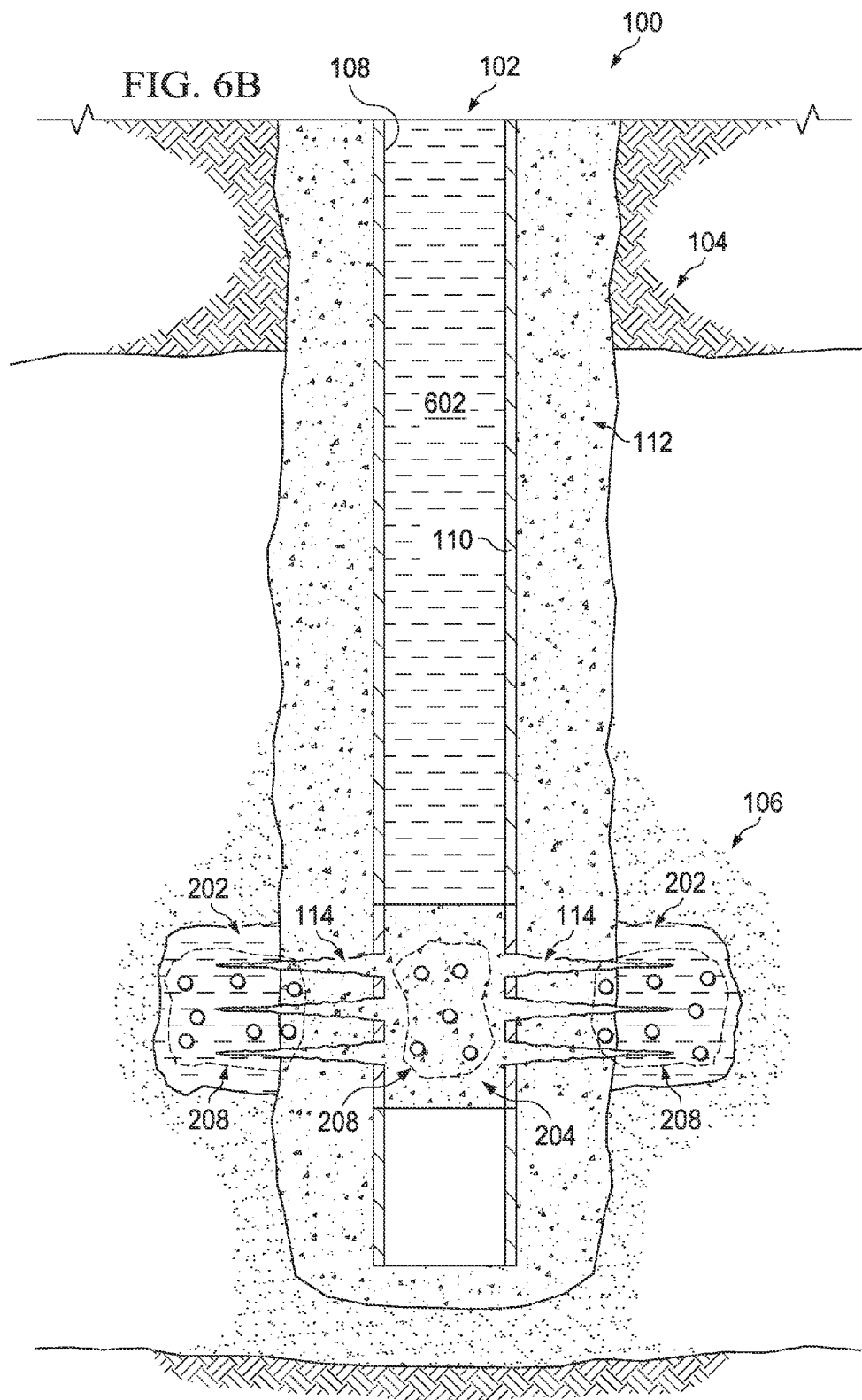
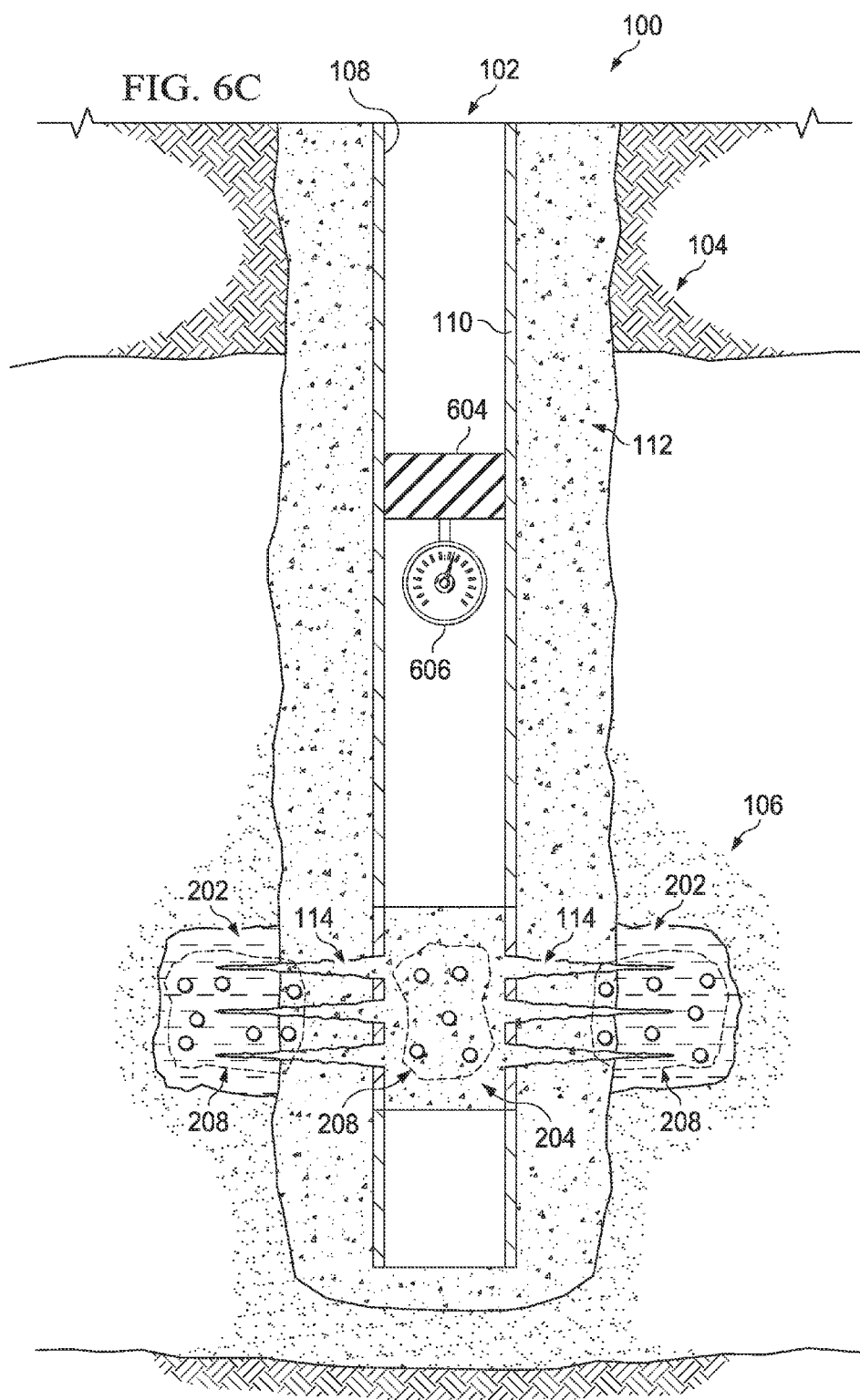
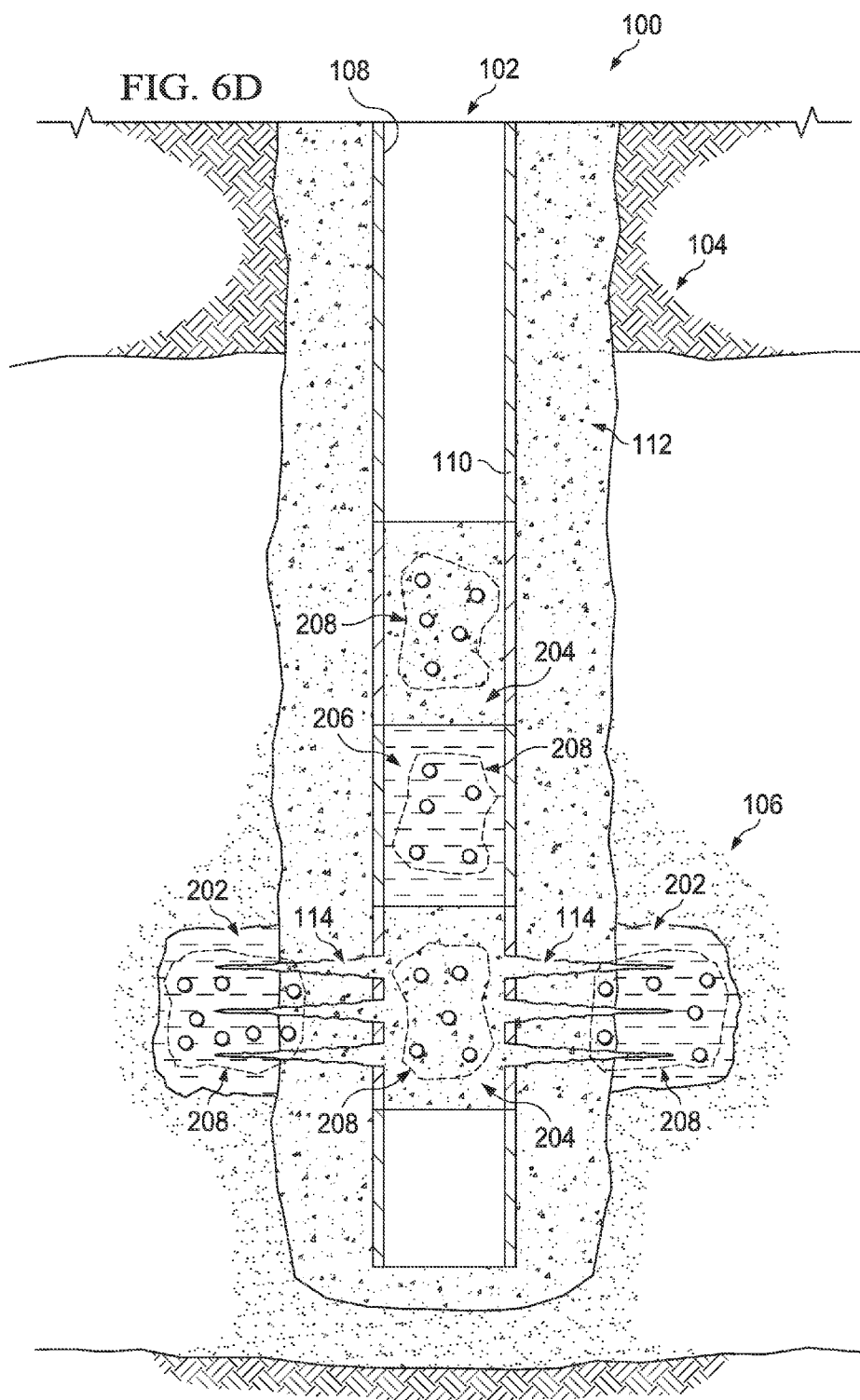


FIG. 5









METHODS AND SYSTEMS FOR LONG-TERM MONITORING OF A WELL SYSTEM DURING ABANDONMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] None.

FIELD

[0002] The present disclosure relates generally to well system abandonment and monitoring the well systems during the abandonment.

BACKGROUND

[0003] Many of the resources (oil, gas, water, etc.) utilized by today's societies are extracted from underground formations. To extract the resources, wells are created to access the formations and extract the resources. When the resources are depleted from the formation, the well can undergo abandonment procedures to close-off and secure the well for the long-term. Remaining amounts of the resources or other material used to extract the resource, for example, fluids and gases that are pumped into the formation to extract the resource, may still exist in the formation. These materials could possibly escape from the well if not properly abandoned. Likewise, after the resource has been extracted, the formation can be used for long-term storage of other materials, such as carbon dioxide (CO₂). In any case, the well can be sealed to prevent leakage of the materials that might impact the environment around the well.

[0004] As part of the abandonment procedures, the well can be monitored, over time, to ensure that materials are not leaking from the well. Current practice and regulations do not require monitoring the well after the abandonment is complete. For example, as the abandoned well ages, the materials used to seal the well can become compromised and fail. Likewise, conditions in the vicinity of the well can cause the materials to become compromised and fail, for example, shifting of the formation, subsurface tectonic stress change near the well, repressurization of the formation, and the like. Accordingly, after abandonment, the well needs to be monitored, long-term, to ensure that the abandonment procedures and materials are functioning and to identify any problems in order to address them before the abandonment procedures fail. Likewise, governments and governmental agencies can require that the abandoned well be monitored for relatively long periods of time. For example, the United States Environment Protection Agency requires monitoring for 50 years before assuming stewardship of an abandoned Class VI CO₂ sequestration well.

[0005] Accordingly, there is a need for reliable systems and procedures for abandoning a well, long-term, and reliably monitor the abandoned well, long-term.

SUMMARY

[0006] Embodiments of the present teachings relate to systems and methods for long-term abandonment and monitoring of well systems. According to embodiments, a series of barriers are formed within a formation and within a casing of a well to prevent materials from leaking from the well. Formation barriers are formed within the formation and the annulus at the location of perforations in the casing. Perforations could refer to any type of penetration or hole created in the

casing whether created by explosives or mechanical device. A series of casing barriers and fluid barriers are formed within the casing of the well.

[0007] According to embodiments, one or more sensors are formed within the barriers to monitor the conditions around the barriers over long periods of time. The sensors can be configured to measure the conditions around the one or more barriers during formation of the one or more barriers and over long periods of time after the one or more barriers are formed. The sensors are configured to include (or be connected to) one or more power supplies that allow the sensors to operate over long periods of time. The one or more power supplies can be power supplies included in the sensors or power supplies that are external to sensors, which remotely supply power to the sensors. For example, the sensors can include long life batteries, power supply that draws energy from the environment, inductive power sources that produce power from received electromagnetic signals, and external power supplies that are electrically coupled to the sensors. The sensors can also include components that allow monitoring systems to communicate with the sensors over long periods of time. The components can include electronic circuitry that allows the monitoring systems to communicate, wired and/or wirelessly, with the sensors in order to monitor the conditions in the well. Sensors could be configured of nanoparticle material that becomes an integral part of formation barrier or casing barrier.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Various features of the embodiments can be more fully appreciated, as the same become better understood with reference to the following detailed description of the embodiments when considered in connection with the accompanying figures, in which:

[0009] FIG. 1 is a generalized schematic diagram that illustrates components of a well system.

[0010] FIGS. 2A and 2B are generalized schematic diagrams that illustrate components of the well system including barriers utilized during abandonment, according to various embodiments.

[0011] FIG. 3 is a generalized schematic diagram that illustrates examples of leaks from which materials can escape from the well system.

[0012] FIGS. 4A, 4B, 4C, and 4D are generalized schematic diagrams that illustrate examples of systems and procedures for communicating with and powering sensors in the well system, according to various embodiments.

[0013] FIGS. 5 and 6A-6D are a flow diagram and generalized schematic diagrams that illustrate an example of a process for abandoning and monitoring a well, according to various embodiments.

DETAILED DESCRIPTION

[0014] For simplicity and illustrative purposes, the principles of the present teachings are described by referring mainly to exemplary embodiments thereof. However, one of ordinary skill in the art would readily recognize that the same principles are equally applicable to, and can be implemented in, all types of information and systems, and that any such variations do not depart from the true spirit and scope of the present teachings. Moreover, in the following detailed description, references are made to the accompanying figures, which illustrate specific exemplary embodiments. Elec-

trical, mechanical, logical and structural changes may be made to the exemplary embodiments without departing from the spirit and scope of the present teachings. The following detailed description is, therefore, not to be taken in a limiting sense and the scope of the present teachings is defined by the appended claims and their equivalents.

[0015] FIG. 1 illustrates components of a well system 100 including a well 102 formed in the earth 104 in order to extract resources from a formation 106, in which various embodiments can be practiced. While FIG. 1 illustrates various components contained in the well system 100, one skilled in the art will realize that FIG. 1 is exemplary and that additional components can be added and existing components can be removed.

[0016] As illustrated, the earth 104 can include the formation 106 that contains one or more resources. The resources can be any type of substance or combination of substances that can be extracted from or disposed into the formation 106, for example, hydrocarbons, (oil, natural gas, etc.), water, and the like. The formation 106 can be at various locations and under various conditions in the earth 104, for example, located on the surface of a land mass, located underwater in an ocean or lake, and the like. The formation 106 typically consists of rock and other materials in which the resource or disposed substance(s) resides.

[0017] To extract the resource, the well 102 can be created in the earth 104 to provide access to the formation 106. The well 102 can include a borehole 108. The borehole 108 can be a shaft that extends from the surface of the earth 104 down into the formation 106. The borehole 108 can be created utilizing any known and/or conventional drilling techniques and processes and can be any size and dimension required to access the formation 106.

[0018] To create the borehole 108 and extract the resource, a casing 110 can be placed in the borehole 108. The casing 110 can include one or more pipes that extend down the borehole 108 from the surface of the earth 104 into the formation 106. The one or more pipes can be formed of any material or combination of materials that are capable of withstanding the conditions in the borehole 108. During creation of the borehole 108, an annulus 112 can be formed around the casing 110. To secure the casing 110 and prevent the resource from escaping from the borehole 108, the annulus 112 can be filled with a material or combination of materials that secures the casing 110 and prevents leakage. For example, a cement layer can be formed in the annulus 112 that is composed of cement and other materials. To extract the resource from the formation 106, perforations 114 are formed that extend through the casing 110 and the annulus 112. The perforations 114 allow the resource to flow from the formation 106 into the casing 110. Over the lifetime of the well 102, the resource is removed from or injected for disposal in the formation 106 through the casing 110.

[0019] When the resource is depleted from the formation 106, the well 102 can undergo abandonment procedures to close-off and secure the well 102 for the long-term. During abandonment procedures, the borehole 108 can be sealed to prevent residual materials from escaping to the surface of the earth 104. For example, the formation 106 can include residual amounts of the resource or other material used to extract the resource, for example, fluids and gases that are pumped into the formation to extract the resource. Likewise, after the resource has been extracted, the formation 106 can be used for long-term storage of other materials, such as

carbon dioxide (CO₂) gas. In any case, the borehole 108 can be sealed to prevent leakage of the materials remaining or stored in the formation 106 that might impact the environment around the well 102.

[0020] As part of the abandonment procedures, the borehole 108 can be monitored, over time, to ensure that materials are not leaking from the borehole 108. For example, as the abandoned well ages, the materials used to seal the borehole 108 can become compromised and fail. Likewise, conditions in the vicinity of the formation 106 can cause the materials used to seal the borehole 108 to become compromised, for example, shifting of the rock of the formation 106, an earthquake near the well 102, and the like, and fail allowing materials in the formation 106 to migrate through and/or around the materials used to seal the borehole 108. Accordingly, after abandonment, the well 102 can be monitored, long-term, to ensure that the abandonment procedures and materials are functioning and to identify any problems in order to address the problems before the abandonment procedures fail. Likewise, governments and governmental agencies can require that the abandoned well be monitored for relative long periods of time. For example, the United States Environment Protection Agency requires monitoring for 50 years before assuming stewardship of an abandoned Class VI CO₂ sequestration well.

[0021] Embodiments of the present teachings relate to systems and methods for long-term abandonment and monitoring of the well system 100. FIGS. 2A and 2B illustrate components of the well system 100 including barriers utilized during abandonment, according to various embodiments. While FIGS. 2A and 2B illustrate various components contained in the well system 100, one skilled in the art will realize that FIGS. 2A and 2B are exemplary and that additional components can be added and existing components can be removed.

[0022] According to embodiments, one or more barriers can be formed in the formation 106 and the casing 110 to contain leakage of materials from the borehole 108. To monitor conditions around the barrier during and after formation, the one or more barriers can be formed to include sensors. The sensors can be configured to measure the conditions around the one or more barriers during formation of the one or more barriers and over long periods of time after the one or more barriers are formed.

[0023] As illustrated in FIG. 2A, a formation barrier 202 can be formed within the formation 106 in the area surrounding the perforations 114 to contain the flow of material out of the formation 106. The formation barrier 202 can be formed within the formation 106 adjacent to the perforations 114 in the casing 110 and the annulus 112. The formation barrier 202 can be a fluid that penetrates the rock matrix in the formation 106 to induce damage in the rock matrix near the perforation 114. The formation barrier 202 can be formed by introducing the fluid to the formation 106 through the perforations 114. The fluid can be a low-viscosity fluid that induces damage in the rock matrix of the formation 106 and that increases in fluid gel strength over time to create a barrier in the formation 106 adjacent to the perforations 114. For example, the fluid can be sodium silicate.

[0024] While FIG. 2A illustrates one formation barrier 202 being formed in the formation 106, one skilled in the art will realize that the well 102 can include multiple locations of perforations 114 in the casing 110 and the annulus 112 in order to extract resources from the formation 106 at multiple

locations. According to embodiments, a formation barrier **202** can be formed in the formation **106** at each location that includes perforations **114** in the casing **110** and the annulus **112** to access the formation **106**. For example, FIG. 2B illustrates the well system **100** which includes multiple locations of the perforations **114** and corresponding formation barriers **202** formed within the formation **106**.

[0025] According to embodiments, one or more casing barriers **204** can be formed within the casing **110** to contain the flow of materials out of the well **102**. The casing barriers **204** can be formed at any location within the casing **110**. For example, as illustrated, a series of casing barriers **204** can be formed at intervals within the casing **110** (e.g., a casing barrier **204** formed adjacent to the perforations **114** and two casing barriers **204** formed at higher intervals relative to the bottom of the borehole **108**). One skilled in the art will realize that any number of the casing barriers **204** can be formed at any position within the casing **110**.

[0026] The casing barriers **204** can be cement plugs that are formed within the casing **110** to contain the flow of materials from the well **102**. The cement plugs can be formed of a combination of cement and other materials that form a fluid and gas barrier in order to maintain integrity of the well **102** over long-periods of time. Cement plugs can be a blend of 55% Class G cement and 45% fresh water, plus additives to obtain desirable fluid and mechanical properties. Cement could be any one of the Class A, B, C, D, E, F, G or H. The casing barriers **204** can be formed to any dimensions and at any interval spacing within the casing **110** to prevent the escape of materials from the well **102**.

[0027] According to embodiments, fluid barriers **206** can be formed within the casing **110** between the casing barriers **204**. The fluid barriers **206** can be any type of material to further contain the flow of materials from the well **102**. For example, the fluid barriers **206** can be brine composed of sodium chloride. For example, brine mixture could be 68 pounds of sodium chloride per barrel of fresh water to obtain a fluid density of 9.4 pounds per gallon.

[0028] According to embodiments, annulus barriers **220** can be formed within the annulus **112**. As the well **102** ages during the production life and after abandonment, the cement within the annulus **112** may degrade. Accordingly, the annulus barriers **220** can be formed at any location in the annulus **112**. For example, the annulus barriers **220** can be formed in the annulus **112** at the location of the perforations **114** or other device that provides a pathway through the casing. Likewise, as illustrated in FIG. 2A, new perforations can be created in the annulus **112**, and the annulus barriers **220** can be formed at the location of the new perforations. For instance, the new perforations and the annulus barriers **220** can be formed at a location in the annulus **112** where leakage might likely occur.

[0029] The annulus barriers **220** can be formed of a combination of cement and other materials that form a fluid and gas barrier in order to maintain integrity of the annulus **112** over long-periods of time. The cement can be a blend of 55% Class G cement and 45% fresh water, plus additives to obtain desirable fluid and mechanical properties. The cement could be any one of the Class A, B, C, D, E, F, G or H. Likewise, the annulus barriers **220** can be formed on any material to contain the leakage of materials from the formation **106**, such as epoxy or resin systems. The annulus barriers **220** can be formed to any dimensions and at any interval spacing within the annulus **112** to prevent the escape of materials from the well **102**.

[0030] Both during the formation of the barriers and for the long term after abandonment, the well **102** and the barriers formed in the well **102** can be monitored to ensure that the material in the formation **106** is not leaking from the well **102**. For example, as the well **102** ages after abandonment, the barriers in the well **102** can begin to leak or conditions around the barriers can indicate a possible leak in the future. FIG. 3 illustrates several examples of leaks that can occur in the barriers. For example, the materials in the formation **106** can migrate out of the well **102** at a location **300** or location **302** external from the casing **110**. For example, the materials can migrate along interfaces between the rock in the formation **106** and the cement filling the annulus **112**, within the cement filling the annulus **112**, or between the casing **110** and the cement filling the annulus **112**. Likewise, for example, the materials can migrate out of the well **102** at a location **304** inside the casing **110**. For example, the barriers within the casing **110** can degrade over time and allow the materials from the formation **106** to flow through the barriers and out of the well **102**.

[0031] According to embodiments, to monitor the conditions in the well **102** both during the creation of the barriers and for the long term after abandonment, the formation barriers **202**, the casing barriers **204**, the fluid barriers **206**, and the annulus barriers **220** are formed to include sensors **208**. The sensors **208** are formed within the formation barriers **202**, the casing barriers **204**, the fluid barriers **206**, and the annulus barriers **220** to monitor the conditions within and around the formation barriers **202**, the casing barriers **204**, the fluid barriers **206**, and the annulus barriers **220**. The sensors **208** can be any type of sensors to measure the various conditions around the formation barriers **202**, the casing barriers **204**, the fluid barriers **206**, and the annulus barriers **220**. For example, the sensors **208** can include one or more or a combination of a pressure sensor, a temperature sensor, a force sensor, a stress sensor, a corrosion sensor, an acoustic sensor, a seismic sensor, a micro-gravity sensor, a resistance/conductivity sensor, and a chemical detection sensor.

[0032] While FIG. 2A illustrates the sensors **208** being formed in the formation barriers **202**, the casing barriers **204**, the fluid barriers **206**, and the annulus barriers **220**, the sensors **208** can be located at any location within the well **102**. For example, the sensors **208** can be located within the annulus **114**, within the casing **110**, at any location within the formation **106** and/or the earth **104**, etc. These sensors **208** can be placed or formed within the well **102** at the time of abandonment and/or at any time prior to or after abandonment.

[0033] According to embodiments, in order to measure the conditions, the sensors **208** will be powered over long periods of time even though well access is generally limited after abandonment. Likewise, communications will be maintained with the sensors **208** in order to read and retrieve the measurements made by the sensors **208**. FIGS. 4A-4D illustrate various examples of the sensor **208** and systems and procedures for powering the sensors **208** and communicating with the sensors **208**. One skilled in the art will realize that each procedure and system, described below, to power the sensors **208** and to communicate with the sensors **208** can be used alone or in any combination with other procedures and systems described below, according to the various embodiments. Additionally, one skilled in the art will realize the example 450 of the sensor **208** illustrated in FIG. 4B shows one example of the sensor **208** and examples of components that

can be included in the sensors 208. Any of the components illustrated in FIG. 4B can be removed and/or additional components can be added.

[0034] As illustrated in FIG. 4A, the well system 100 can include a monitoring system 400 to communicate with the sensors 208. The monitoring system 400 can be any type of electronic device that is capable of communicating with the sensors 208. For example, the monitoring system 400 can be a special purpose electronic device designed to communicate with the sensors 208. Likewise, for example, the monitoring system 400 can be a general purpose electronic device, e.g. general purpose computer, that can be programmed to communicate with the sensors 208. One skilled in the art will realize that monitoring system 400 can include multiple electronic devices that cooperate with the sensors 208 in order to monitor the conditions in the well 102.

[0035] As illustrated in FIG. 4B, the sensor 450 can include a controller 452. The controller 452 can be configured to include the necessary hardware and/or software to control the operation of the sensor 450. The sensor 450 can include sensing hardware 452. The sensing hardware 452 can be configured to detect the conditions in the proximity of the sensor 450. The sensing hardware 452 can be configured to detect conditions such as pressure, temperature, force, stress, corrosion, acoustic activity, seismic activity, a micro-gravity, resistance/conductivity, and presence of one or more chemical(s) or molecular compounds.

[0036] The sensing hardware 452 can be configured to detect a single condition or can be configured to detect multiple conditions in the proximity of the sensor 450.

[0037] In embodiments, the monitoring system 400 can utilize a variety of systems and process, both wired or wireless, to communicate with the sensors 208. For example, the monitoring system 400 can utilize a wireless signal 402 to communicate with the sensors 208. As such, the monitoring system 400 can include the necessary transmitters, receivers, antennas, etc. to communicate the wireless signals 402 to the sensors 208 and to receive signals from the sensors 208. Likewise, the sensors 208 can be configured to include the necessary transmitters, receivers, and antennas to receive the wireless signals 402 and communicate a signal back to the monitoring system 400.

[0038] For example, as illustrated in FIG. 4B, the sensor 450 can include a transceiver 454 and an antenna 456. The transceiver 454 and the antenna 456 can be configured to receive the wireless signals 402 from the monitoring system 400 and configured to transmit a wireless signal 457 to the monitoring system 400. The transceiver 454 can be configured to include any necessary hardware and/or software to communicate wirelessly with the monitoring system 400 utilizing any type of wireless protocol or procedure. For example, the transceiver 454 and the antenna 456 can be configured to transmit the wireless signal 457 utilizing electromagnetic radiation, such as radio waves, microwaves, etc. Likewise, for example, the transceiver 454 and the antenna 456 can be configured to transmit the wireless signal 457 utilizing other wireless communication forms, such as acoustic waves, seismic waves, etc. Accordingly, the monitoring system 400 can include the necessary hardware and/or software to receive and interpret the wireless signal 457.

[0039] In embodiments, the sensors 208, such as the sensor 450, can be configured to receive the wireless signals 402 directly from the monitoring system 400 and configured to transmit the wireless signal directly to the monitoring system

400. Likewise, the sensors 208, such as the sensor 450, can be configured to operate in conjunction to relay signals to and from the monitoring system 400. FIG. 4C is an expanded view of a portion of the well system 100 that illustrates the relay of wireless signals to and from the monitoring system 400, according to embodiments. As illustrated in FIG. 4C, one or more sensors 404 can be configured to receive signals 406 from other sensors, for example, one or more sensors 408 located lower within the well 102. The one or more sensors 404 can be configured to re-transmit the signals 406 to one or more sensors 410. The process can repeat until the signals 406 are received by the monitoring system 400. The same processes can be utilized to relay the wireless signals 402 from the monitoring system 400 to the sensors 208.

[0040] In embodiments, to enhance the wireless signal 402 and the wireless signals received from the sensors 208, the monitoring system 400 can be electrically coupled to the casing 110 by a wire 412. Likewise, the sensors 208 can be electrically coupled to the casing 110. For example, as illustrated in FIG. 4B, the controller 452 and/or the transceiver 454 of the sensor 450 can be electrically coupled to the casing 110. Because the casing 110 can be formed of a conducting material, the monitoring system 400 and the sensors 208 can utilize the casing 110 as an antenna or communication pathway to provide the wireless signal 402 (or wired electrical signals) to the sensors 208 and receive wireless signals (or wired electrical signals) from the sensors 208.

[0041] In embodiments, the monitoring system 400 can also be configured to communicate with the sensors 208 utilizing one or more wires 414. As illustrated in FIG. 4A, the monitoring system 400 and one or more of the sensors 208 can be coupled to the one or more wires 414 in order to exchange communications. For example, the controller 452 of the sensor 208 can be coupled to the one or more wires 414. During formation of the barriers, the one or more wires 414 can be coupled to the sensors 208 when the sensors 208 are formed within the barriers. The one or more wires 414 can be formed of any type of material and formed in any configuration that is capable carrying signals between the monitoring system 400 and the sensors 208. For example, the one or more wires 414 can be formed of one or more conducting materials and can optionally include insulating materials to carry an electrical signal between the monitoring system 400 and the sensors 208. Likewise, for example, the one or more wires 414 can be formed of optical materials to carry optical signals between the monitoring system 400 and the sensors 208.

[0042] One skilled in the art will realize that any number of the communication systems and processes described above can be utilized by the sensors 208. For example, a particular sensor 208 can utilize one or more of the communication systems and process described above. For instance, the sensor 450 can include the transceiver 454, can be coupled to the casing 110, or can be coupled to the wire 414, or any combination thereof. Likewise, the sensors 208 can utilize the same communication systems or processes and/or the sensors 208 can utilize different combinations of the communication systems and processes described above.

[0043] In embodiments, the sensors 208 can be powered by a power supply contained within the sensors 208. For example, the sensor 450 can include a power supply 458, which is electrically coupled to the controller. Likewise, the power supply 458 can be coupled to any of the components of the sensor 450. Additionally, while a single power supply is

illustrated, the sensor 450 can include multiple power supplies whether of the same or different type.

[0044] The power supply, for example, power supply 458, can be any type of power source that can power the sensors 208 for long periods of time. The power supply can be one or more batteries for supplying power to the sensors 208. For example, the power supply can be a long-term battery, such as NanoTritium™ battery manufactured by City Labs, Inc. and capable of operating over a 20 year life. Likewise, the power supply can be one more fuel cells for supplying power to the sensors 208. Likewise, the sensors 208 can include a power supply that draws power from the environmental conditions around the sensors 208, for example, thermal energy.

[0045] In embodiments, a fuel cell can be a device that converts chemical energy from a fuel into electricity through a chemical reaction. For example, the fuel cell can generate electricity through a chemical reaction of hydrogen or hydrocarbon(s) with oxygen or other oxidizing agent(s) that could be formed in the well 102, for example, in the formation barriers 202, the casing barriers 204, the fluid barriers 206, and/or the annulus barriers 220. FIG. 4D illustrates an example of a fuel cell 470, according to various embodiments. As illustrated in FIG. 4D, the fuel cell 470 can generate electricity through a chemical reaction of hydrogen (e.g. H₂) with oxygen (O₂) to produce electricity and water (H₂O) and/or other materials as a byproduct. The fuel cell 470 can include an anode 472, a cathode 474, and an electrolyte 476 located between the anode 472 and the cathode 474. In the fuel cell 470, a chemical reaction occurs at the interface between the anode 472 and the electrolyte 476, and a chemical reaction occurs at the interface between the cathode 474 and the electrolyte 476. The net result of the two chemical reactions is that fuel is consumed, H₂O or carbon dioxide (CO₂) is created, and an electric current is created, which can be used to power electrical devices (load 478), such as the circuitry of the sensors 208. At the anode 472 a catalyst oxidizes the fuel, H₂, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte 476 is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire to the load 478 creating the electric current. The ions travel through the electrolyte 476 to the cathode 474. Once reaching the cathode 474, the ions are reunited with the electrons and the two react with a third chemical, O₂, to create H₂O and/or CO₂.

[0046] In embodiments, the sensors 208 can include a power supply, for example, power supply 458, which receives a portion or all its power from external sources. For example, the sensors 208 can include a power supply that generates power from received electromagnetic waves. The monitoring system 400 can output a signal for power generation in the sensors 208. The sensors 208 can include inductive circuitry that induces a current in the sensors 208 when the signal is received from the monitoring system 400. For example, the antenna 456 and the transceiver 454 can be configured to convert signals received from the monitoring system 400 into electricity for use by the sensor 450. The monitoring system 400 can provide the power generation signal in a manner similar to the wireless signal 402. For example, the monitoring system 400 can transmit the signal directly to the sensors 208. Likewise, for example, the monitoring system 400 can utilize the casing 110 as an antenna for transmitting the power generating signal to the sensors 208. Further, as described above, one or more of the sensors 208 can include circuitry

that receives the power generating signal from the monitoring system 400 and relays a power generating signal to other sensors 208.

[0047] In embodiments, the sensors 208 can be powered by an external power source. The sensors 208 can be electrically coupled to an external power source via one or more electrically conducting wires, for example the one or more wires 414 or other separate wire(s). Likewise, the sensors 208 can be electrically coupled to other conducting media, such as the casing 110, to receive power from an external source. The monitoring system 400 can provide an electric current via the one or more wires to power the sensors 208. For example, as illustrated in FIG. 4B, the controller 452 of the sensor 450 can be electrically coupled to the one or more wires 414 and/or the casing 110. One skilled in the art will realize that any of the components of the sensor 450 can be coupled an external power source. Likewise, when power is provided externally to the sensors 208, the sensors 208 can include power storage hardware, such as rechargeable batteries and capacitors, to store the power received for the external sources.

[0048] In embodiments, the sensors 208 can include one more data storage devices to store software utilized by the sensors 208 and/or to store data measured by the sensors 208. For example, as illustrated in FIG. 4B, the sensor 450 can include a memory 460, which is coupled to the controller 452. The memory 460 can be any type volatile or non-volatile memory that can store data. The memory 460 can store data collected by the sensing hardware 452, can store software programs and/or data used by the components of the sensor 450, or any other type of data. While the sensor 450 illustrates a single memory 460, one skilled in the art will realize that the sensor 450 can include any number of memories whether the same or a different type. Likewise, for example, the sensors 450 can be configured to omit the memory 460. Additionally, one skilled in the art will realize that the memory 460 can be coupled to any of the components of the sensor 450.

[0049] The sensors 208 can include additional circuitry that aids in the operation of the sensors 208. For example, as illustrated in FIG. 4B, the sensor 450 can include additional circuitry 462. The additional circuitry 462 can be configured to aid in maintaining the life span of the power supply or perform other functions for the sensor 450. For instance, the additional circuitry 462 can include power-saving circuitry that powers down the sensors 450 when not in use. The power-saving circuitry can be configured to wake the sensors 450 periodically and/or in response to signals from the monitoring system 400. One skilled in the art will realize that the sensors 208 can include any additional circuitry to aid in powering the sensors 208 and extending the life time of the power supply in the sensors 208.

[0050] One skilled in the art will realize that the any number of the power supply systems and processes described above can be utilized by the sensors 208. For example, a particular sensor 208 can utilize one or more of the power supply systems and processes described above. Likewise, the sensors 208 can utilize the same power supply systems or methods and/or the sensors 208 can utilize different combinations of the power supply systems and methods described above. For instance, in a non-limiting example, a sensor 208 can include a long-term re-chargeable battery and inductive circuitry to re-charge the battery. Likewise, in another non-limiting example, a sensor 208 can be coupled to an external power supply and can include a battery as a backup. One skilled in

the art will realize that any combination of power supply systems and processes is possible.

[0051] As described above, in embodiments, the monitoring system 400 can be configured to provide the communication signals and external power to the sensors 208. One skilled in the art will realize that additional communication and power system can be used in combination with the monitoring system 400 to communicate with the sensors 208 and to power the sensors 208.

[0052] In embodiments, the monitoring system 400 can be configured to communicate with and provide power to one or more sensor that were placed in the well 102 prior to abandonment or after the abandonment procedures were completed. For example, one or more sensors may have been introduced into the well 102 during the production life of the well 102. Likewise, after abandonment is completed, one or more additional sensors can be added to the well 102. The monitoring system 400 can be configured to communicate with and provide power to one or more sensors that were introduced to the well 102 at any time utilizing the systems and procedures described above.

[0053] FIG. 5 and FIGS. 6A-6D are a flow diagram and generalized diagrams that illustrate an exemplary process by which the well system 100 can be abandoned and monitoring long term. In 500, the process can begin.

[0054] In 502, the formation barriers 202, which include the sensors 208, can be formed within the formation 106 near the perforations 114 or in the annulus. For example, as illustrated in FIG. 6A, the formation barrier 202 can be formed within the formation 106 adjacent to the perforations 114 in the casing 110 and the annulus 112. The formation barrier 202 can be a fluid that penetrates the rock matrix in the formation 106 to induce damage in the rock matrix near the perforation 114. The formation barrier 202 can be formed by introducing the fluid to the formation 106 through the perforations 114.

[0055] As the fluid is introduced to the formation 106, the sensors 208 can be added to the fluid so that the sensors 208 will be dispersed within the formation barriers 202, for example, near the perforations 114. If the sensors 208 are connected to one or more wires (e.g. the one or more wires 414), the sensors 208 can be coupled to the one or more wires prior to being introduced to the fluid. The one or more wires can be fed into the wellbore 108 as the sensors 208 are introduced into the wellbore 108 with the fluid. The fluid can be a low-viscosity fluid that induces damage in the rock matrix of the formation 106 and that increases in fluid gel strength over time to create a barrier in the formation 106 adjacent to the perforations 114.

[0056] In 504, a pressure test can be performed on the formation barriers 202, and the conditions can be measured by the sensors 208. For example, as illustrated in FIG. 6A, a material 600 can be introduced into the wellbore 108 that will apply a pressure on the formation barriers 202. The material 600 can be any type of fluid or gas that will create a pressure in the casing that is higher than the pressure in the formation 106. Once introduced, the measurements can be taken using the sensors 208 (or other sensors) to determine the conditions surrounding the formation barriers 202 and determine if the formation barriers 202 are leaking.

[0057] The pressure test can be performed under any suitable pressure or a suitable time period to determine if the formation barriers 202 are leaking. In a non-limiting example, the material 600 can be introduced into the casing 110, and a pressure can be applied to the material 600 to create

a pressure of approximately 2700 psi. While under pressure, the conditions can be measured for approximately 2 hours to approximately 24 hours to determine whether the formation barriers 202 are leaking. If the pressure stabilizes to within a defined percentage (e.g. approximately less than 10%) of the test pressure, the formation barrier 202 can be identified as functioning properly.

[0058] In 506, the casing barrier 204, which includes the sensors 208, can be formed in the casing 110 near the perforations 114. For example, as illustrated in FIG. 6B, the casing barrier 204 can be a cement plug that is formed within the casing 110 to prevent the flow of materials from the well 102. The cement plug can be formed of a combination of cement and other materials that form a fluid and gas barrier that can maintain integrity of the well 102 over long-periods of time. The casing barrier 204 can be formed to any dimensions and at any interval spacing within the casing 110 to prevent the escape of materials from the well 102.

[0059] As the cement and other materials are introduced to the casing 110 to form the casing barrier 204, the sensors 208 can be added to the cement so that the sensors 208 will be dispersed within the casing barrier 204. If the sensors 208 are connected to one or more wires (e.g. the one or more wires 414), the sensors 208 can be coupled to the one or more wires prior to being introduced to the cement. The one or more wires can be fed into the wellbore 108 as the sensors 208 are introduced into the wellbore 108 with the cement.

[0060] In 508, a pressure test can be performed on the casing barrier 204, and the conditions can be measured by the sensors 208. For example, as illustrated in FIG. 6B, a material 602 can be introduced into the wellbore 108 that will apply a pressure on the casing barrier 204. The material 602 can be any type of fluid or gas that will create a pressure in the casing 110 that is higher than the pressure in the formation 106. Once introduced, the measurements can be taken using the sensors 208 (or other sensors) to determine the conditions surrounding the casing barrier 204 and the formation barriers 202 and determine if the casing barrier 204 and/or the formation barriers 202 are leaking.

[0061] The pressure test can be performed under any suitable pressure or a suitable time period to determine if the casing barrier 204 is leaking. In a non-limiting example, the cement for the casing barrier 204 can be allowed to develop to approximately 80% of its final compressive strength. Then, the material 602 can be introduced into the casing 110, and a pressure is applied to the material 602 to create a pressure of approximate 2700 psi. While under pressure, the conditions can be measured for approximately 2 hours to approximately 24 hours to determine whether the casing barrier 204 is leaking. If the pressure stabilizes to within a defined percentage (e.g. approximately less than 10%) of the test pressure, the casing barrier 204 can be identified as functioning properly.

[0062] In 510, an under balance pressure test can be performed on the casing barrier 204, and the conditions can be measured with the sensors 208. For example, as illustrated in FIG. 6C, a packer 604 can be placed in the casing 110 above the casing barrier 204. The packer 604 can include a pressure sensor 606 to measure the pressure within the space between the packer 604 and the casing barrier 204. Then, the pressure within the space between the packer 604 and the casing barrier 204 can be reduced to a pressure less than the pressure in the formation 106. The conditions are then measured to determine if the casing barrier 204 and/or the formation barriers 202 are leaking.

[0063] The under balance pressure test can be performed under any suitable pressure or a suitable time period to determine if the casing barrier 204 and/or the formation barriers 202 are leaking. In a non-limiting example, the packer 604 can be placed within approximately 50 feet of the casing barrier 204. Then, the pressure within the space between the packer 604 and the casing barrier 204 can be reduced to a pressure less than the pressure in the formation 106, for example, 500 psi under balance. Then, the conditions can be measured for approximately 1 week to approximately 4 months to determine whether the casing barrier 204 and/or the formation barriers 202 are leaking. If the pressure stabilizes to within a defined percentage (e.g. approximately less than 10%) of the test pressure, the casing barrier 204 and the formation barriers 202 can be identified as functioning properly.

[0064] In 512, a fluid barrier 206, which includes sensors 208, can be formed above the casing barrier 204. The fluid barrier 206 can be any type of material to further prevent the flow of materials from the well 102. As illustrated in FIG. 6D, as the fluid is introduced to the casing 110 to form the fluid barrier 206, the sensors 208 can be added to the fluid so that the sensors 208 will be dispersed within the fluid barrier 206. If the sensors 208 are connected to one or more wires (e.g. the one or more wires 414), the sensors 208 can be coupled to the one or more wires prior to being introduced to the fluid. The one or more wires can be fed into the wellbore 108 as the sensors 208 are introduced into the wellbore 108 with the fluid.

[0065] In 514, a casing barrier 204, which includes the sensors 208, can be formed, and a pressure test can be performed on the casing barrier 204. As illustrated in FIG. 6D, the casing barrier 204 can be formed above the fluid barrier 206. The casing barrier 204, which is formed above the fluid barrier 206, can be formed in a manner as described above in 506. Likewise, a pressure test can be performed on the casing barrier 204, which is formed above the fluid barrier 206, as described above in 508.

[0066] In 516, additional barriers can be formed in the casing 110. For example, alternating fluid barriers 206 and casing barrier 204 can be formed until the desired number of barriers is created to prevent materials from leaking from the well 102.

[0067] In 518, after the barriers are formed and tested, the integrity of the abandonment of the well 102 can be monitored over time utilizing the sensors 208. For example, over time, the monitoring system 400 can communicate (and power) the sensors 208 to monitor the conditions around the formation barriers 202, casing barriers 204, and the fluid barriers 206.

[0068] The monitoring system 400 can communicate with the sensors periodically and/or on-demand to determine the conditions in the well 102.

[0069] In 520, the process can end, return to any point or repeat.

[0070] Additionally, in embodiments, one or more annulus barriers 220 can be formed in the annulus 112. The annulus barriers 220 can be formed during any stage described above or in a separate stage at any time during the process described above. The annulus barriers 220 can be formed at any location in the annulus 112. For example, the annulus barriers 220 can be formed in the annulus 112 at the location of the perforations 114. Likewise, as illustrated in FIG. 2A, new perforations can be created in the annulus 112, and the annulus

barriers 220 can be formed at the location of the new perforations. For instance, the new perforations and the annulus barriers 220 can be formed at a location in the annulus 112 where leakage might likely occur.

[0071] The annulus barriers 220 can be formed of a combination of cement and other materials that form a fluid and gas barrier in order to maintain integrity of the annulus 112 over long-periods of time. The cement can be a blend of 55% Class G cement and 45% fresh water, plus additives to obtain desirable fluid and mechanical properties. The cement could be any one of the Class A, B, C, D, E, F, G or H. Likewise, the annulus barriers 220 can be formed on any material to prevent the leakage of materials from the formation 106. The annulus barriers 220 can be formed to any dimensions and at any interval spacing within the annulus 112 to prevent the escape of materials from the well 102.

[0072] While the teachings have been described with reference to the exemplary embodiments thereof, those skilled in the art will be able to make various modifications to the described embodiments without departing from the true spirit and scope. The terms and descriptions used herein are set forth by way of illustration only and are not meant as limitations. In particular, although the method has been described by examples, the steps of the method may be performed in a different order than illustrated or simultaneously. Furthermore, to the extent that the terms “including”, “includes”, “having”, “has”, “with”, or variants thereof are used in either the detailed description and the claims, such terms are intended to be inclusive in a manner similar to the term “comprising.” As used herein, the terms “one or more of” and “at least one of” with respect to a listing of items such as, for example, A and B, means A alone, B alone, or A and B. Those skilled in the art will recognize that these and other variations are possible within the spirit and scope as defined in the following claims and their equivalents.

What is claimed is:

1. A method for abandoning a well system, the well system including a formation, a casing providing access to the formation, and an annulus formed around the casing, the method comprising:

forming, within the formation, a first barrier that comprises a first set of sensors located within the first barrier, wherein the first barrier is formed within the formation adjacent to perforations in the casing and the annulus; and

forming, within the casing, at least one additional barrier that comprises an additional set of sensors located within the at least one additional barrier.

2. The method of claim 1, the method further comprising: forming, within the annulus, at least one annulus barrier that comprises another set of sensors located within the annulus barrier.

3. The method of claim 1, wherein forming the first barrier comprises:

injecting a fluid into the formation through the perforations in the casing and the annulus, wherein the fluid induces damage in the formation and prevents migration of formation fluids to form the first barrier; and

introducing the first set of sensors into the fluid during injection, wherein the first set of sensors is introduced into the fluid in a manner to cause the first set of sensors to be dispersed within the first barrier adjacent to the perforations in the casing and the annulus.

4. The method of claim 3, wherein the fluid comprises a low-viscosity fluid that penetrates a rock matrix of the formation to damage the rock matrix and that prevents migration of formation fluids, over time, to form the first barrier.

5. The method of claim 1, wherein forming the at least one additional barrier comprises:

forming, within the casing, a second barrier that comprises a second set of sensors located within the second barrier.

6. The method of claim 5, wherein forming the second barrier comprises:

injecting cement into the casing, wherein the cement hardens to form the second barrier; and

introducing the second set of sensors into the cement during injection, wherein the second set of sensors is introduced into the cement in a manner to cause the second set of sensors to be dispersed within the second barrier.

7. The method of claim 5, wherein the second barrier is formed within the casing adjacent to the perforations in the casing and the annulus.

8. The method of claim 5, the method further comprising: forming, within the casing, a third barrier that comprises a third set of sensors located within the third barrier, wherein the third barrier is formed at a higher location in the casing relative to the second barrier.

9. The method of claim 8, wherein forming the third barrier comprises:

injecting cement into the casing, wherein the cement hardens to form the third barrier; and

introducing the third set of sensors into the cement during injection, wherein the third set of sensors is introduced into the cement in a manner to cause the third set of sensors to be dispersed within the third barrier.

10. The method of claim 1, the method further comprises: injecting a fluid between the second barrier and the third barrier; and

introducing a fourth set of sensors into the fluid during injection, wherein the fourth set of sensors is introduced into the fluid in a manner to cause the fourth set of sensors to be dispersed within the fluid.

11. The method of claim 1, wherein the first set of sensors comprises at least one of pressure sensor, a temperature sensor, a force sensor, a stress sensor, a corrosion sensor, an acoustic sensor, a seismic sensor, and a chemical detection sensor.

12. The method of claim 1, wherein the additional set of sensors comprises at least one of pressure sensor, a temperature sensor, a force sensor, a stress sensor, a corrosion sensor, an acoustic sensor, a seismic sensor, and a chemical detection sensor.

13. The method of claim 1, the method further comprising: testing an integrity of at least one of the first barrier and the at least one additional barrier.

14. The method of claim 13, wherein testing the integrity, comprises:

applying a positive pressure to at least one of the first barrier and the at least one additional barrier; and

measuring conditions around at least one of the first barrier and the at least one additional barrier using at least one of the first set of sensors and the additional set of sensors.

15. The method of claim 13, wherein testing the integrity, comprises:

applying a negative pressure to at least one of the first barrier and the at least one additional barrier; and

measuring conditions around at least one of the first barrier and the at least one additional barrier using at least one of the first set of sensors and the additional set of sensors.

16. A method for abandoning a well system, the well system including a formation, a casing providing access to the formation, and an annulus formed around the casing, the method comprising:

forming a set of barriers within the well system, wherein the set of barriers are formed to prevent leaking of fluid and gases from the well system; and

introducing, during formation of the set of barriers, a set of sensors to each barrier in the set of barriers, wherein the set of sensors is configured to monitor conditions around the set of barriers.

17. The method of claim 16, wherein forming the set of barriers comprises:

forming, within the formation, a first barrier that comprises a first set of sensors located within the first barrier, wherein the first barrier is formed within the formation adjacent to perforations in the casing and the annulus.

18. The method of claim 16, wherein forming the set of barriers comprises:

forming, within the casing, a second barrier that comprises a second set of sensors located within the second barrier.

19. The method of claim 18, wherein the second barrier is formed within the casing adjacent to the perforations in the casing and the annulus.

20. The method of claim 18, wherein forming the set of barriers comprises:

forming, within the casing, a third barrier that comprises a third set of sensors located within the third barrier, wherein the third barrier is formed at a higher location in the casing relative to the second barrier.

21. The method of claim 20, wherein forming the set of barrier comprises:

injecting a fluid between the second barrier and the third barrier; and

introducing a fourth set of sensors into the fluid during injection, wherein the fourth set of sensors is introduced into the fluid in a manner to cause the fourth set of sensors to be dispersed within the fluid.

22. The method of claim 16, the method further comprising:

testing, during formation, an integrity of at least one of the set of barriers using the set of sensors formed within the at least one of the set of barriers under test.

23. The method of claim 16, wherein forming the set of barriers comprises:

forming, within the annulus, an additional barrier that comprises an additional set of sensors located within the additional barrier.

24. A method for monitoring a well system, the well system including a formation, a casing providing access to the formation, and an annulus formed around the casing, the method comprising:

forming, within the well system, a set of barriers, each barrier in the set of barriers comprising a set of sensors, wherein the set of barriers are formed to prevent leaking of fluid and gases from the well system; and

monitoring at least one of the set of sensors to identify leaking in the well system.

25. The method of claim 24, wherein the at least one of the set of sensors is monitored during formation of the set of barriers to identify leaking in the well system.

26. The method of claim 24, wherein the at least one of the set of sensors is monitored after formation of the set of barriers to identify leaking in the well system.

27. The method of claim 24, wherein monitoring the at least one of the set of sensors comprises:

communicating with the at least one of the set of sensors with a wireless signal.

28. The method of claim 27, wherein the wireless signal is relayed to the at least one of the set of sensors by another sensor in the set of sensors.

29. The method of claim 24, the method further comprising:

powering the set of sensors.

30. The method of claim 29, wherein powering the set of sensors comprises introducing an electromagnetic signal to the set of sensors to induce power in the set of sensors.

31. The method of claim 29, wherein powering the set of sensors comprises introducing an electrical current to the set of sensors via wire.

32. A sensor for measuring condition in a well system during abandonment of the well system, comprising:

sensing hardware for measuring at least one condition in a well;

a power supply coupled to the sensing hardware and configured to power the sensing hardware; and communication hardware coupled to the sensing hardware and configured to communicate measurements of the at least one condition to a monitoring system.

33. The sensor of claim 32, further comprising: at least one wire coupled to the monitoring system.

34. The sensor of claim 33, wherein the at least one wire serves as a communication pathway to communicate the measurements of the at least one condition to the monitoring system.

35. The sensor of claim 33, wherein the at least one wire is coupled to an external power supply to power the sensor.

36. The sensor of claim 33, wherein the at least one wire is coupled to a casing in the well.

37. The sensor of claim 32, wherein the communication hardware comprises:

an antenna; and

a transceiver coupled to the antenna.

38. The sensor of claim 32, wherein the communication hardware is configured to power the sensor from electromagnetic waves received by the communication hardware.

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