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METHOD AND APPARATUS FOR NMR SATURATION

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BACKGROUND OF THE DISCLOSURE

5 1. Field of the Disclosure

[0001] The present disclosure relates generally to determining geological properties of subsurface formations using Nuclear Magnetic Resonance ("NMR") methods for logging wellbores, particularly the use of saturation pulse sequences in the presence of axial tool motion for dual wait time and T_1 saturation recovery measurements.

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2. Description of the Related Art

[0002] A variety of techniques are utilized in determining the presence and estimation of quantities of hydrocarbons (oil and gas) in earth formations. These methods are designed to determine formation parameters, including among other things, the resistivity, porosity and permeability of the rock formation surrounding the wellbore drilled for recovering the hydrocarbons. Typically, the tools designed to provide the desired information are used to log the wellbore. Much of the logging is done after the well bores have been drilled. More recently, wellbores have been logged while drilling, which is referred to as measurement-while-drilling (MWD) or logging-while-drilling (LWD).

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[0003] One recently evolving technique involves utilizing Nuclear Magnetic Resonance (NMR) logging tools and methods for determining, among other things, porosity, hydrocarbon saturation and permeability of the rock formations. The NMR logging tools are utilized to excite the nuclei of the liquids in the geological formations surrounding the wellbore so that certain parameters such as spin density, longitudinal relaxation time (generally referred to in the art as T_1) and transverse relaxation time (generally referred to as T_2) of the geological formations can be measured. From such measurements, porosity, permeability and hydrocarbon saturation are determined, which provides valuable information about the make-up of the geological formations and the amount of extractable hydrocarbons.

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[0004] The NMR tools generate a uniform or near uniform static magnetic field in a region of interest surrounding the wellbore. NMR is based on the fact that the nuclei

of many elements have angular momentum (spin) and a magnetic moment. The nuclei have a characteristic Larmor resonant frequency related to the magnitude of the magnetic field in their locality. Over time the nuclear spins align themselves along an externally applied magnetic field. This equilibrium situation can be disturbed by a pulse of an oscillating magnetic field, which tips the spins with resonant frequency within the bandwidth of the oscillating magnetic field away from the static field direction. The angle θ through which the spins exactly on resonance are tipped is given by the equation:

$$\theta = \gamma B_1 t_p \quad (1),$$

where γ is the gyromagnetic ratio, B_1 is the effective field strength of the oscillating field and t_p is the duration of the RF pulse.

[0005] After tipping, the spins precess around the static field at a particular frequency known as the Larmor frequency ω_0 , given by

$$\omega_0 = \gamma B_0 \quad (2)$$

where B_0 is the static field intensity. At the same time, the spins return to the equilibrium direction (i.e., aligned with the static field) according to an exponential decay time known as the spin-lattice relaxation time or T_1 . For hydrogen nuclei, $\gamma/2\pi = 4258$ Hz / Gauss, so that a static field of 235 Gauss would produce a precession frequency of 1 MHz. T_1 of fluid in pores is controlled totally by the molecular environment and is typically ten to one thousand milliseconds in rocks.

[0006] At the end of a $\theta = 90^\circ$ tipping pulse, spins on resonance are pointed in a common direction perpendicular to the static field, and they precess at the Larmor frequency. However, because of inhomogeneities in the static field due to the constraints on tool shape, imperfect instrumentation, or microscopic material heterogeneities, each nuclear spin precesses at a slightly different rate. Hence, after a time long compared to the precession period, but shorter than T_1 , the spins will no longer be precessing in phase. This de-phasing occurs with a time constant that is commonly referred to as T_2^* if it is predominantly due to the static field inhomogeneity of the apparatus, and as T_2 if it is due to properties of the material.

[0007] The receiving coil is designed so that a voltage is induced by the precessing spins. Only that component of the nuclear magnetization that is precessing in the plane perpendicular to the static field is sensed by the coil. After a 180° tipping pulse (or an "inversion pulse"), the spins on resonance are aligned opposite to the static field and the "precession" consists of a slow return along the static field axis to the equilibrium direction. Hence, a signal will be generated after a 90° tipping pulse, but not after a 180° tipping pulse in a generally uniform magnetic field.

10 [0008] Saturation in NMR means "destroying all magnetization". Saturation is needed within Dual Wait Time (DTW) and T_1 saturation recovery measurements. In the field of NMR the term T_1 is called the longitudinal relaxation time while the term T_2 is the transverse relaxation time. The DTW comprises two NMR echo trains, one starting with full magnetization after a long wait time TW (e.g. 6 s or more), the other
15 starting after a shorter wait time of e.g. TW = 1 s. If the NMR echoes of the two sequences are different then this is caused by formation components with $T_1 > \text{approx. } 0.5 \text{ s}$. The DTW method, therefore, provides some information about T_1 . For the method to work it is important that for the sequence with TW = 1 s, this sequence starts with zero magnetization, also called saturation. See, for example, U.S.
20 6,331,775 to *Thern et al.*, having the same assignee as the present disclosure and the contents of which are incorporated herein by reference. An aperiodic saturation sequence (APS) works well where the logging tool is stationary (*W. Dietrich et. al, Z. Anal. Chem. 279, 177-181 (1976)*). If, on the other hand, the logging tool moves between the application of the saturation sequence and the following NMR echo
25 sequence, then the saturated region is not coincident with the region where the NMR echoes come from. As a consequence, the saturation is not effective, and DTW measurements give wrong answers.

[0009] The use of wide-band saturation pulses that are relatively insensitive to lateral tool motion has been discussed in prior art. Not addressed in prior art is the issue of movement of the logging tool along the borehole axis. This can be a problem for a rate of penetration (ROP) greater than 20 m/h, depending upon the configuration of the logging tool. It should be noted that all the examples and discussions herein are specific to the NMR tool described in **FIG. 2**. With more elaborate wide-band

saturation sequences, the problem can be overcome and effective saturation becomes possible even in excess of ROP = 100 m/h.

SUMMARY OF THE DISCLOSURE

5 [0010] One embodiment of the disclosure is an apparatus for evaluating an earth formation. The apparatus includes a downhole assembly configured to be conveyed in a borehole; a magnet arrangement on a tool on the downhole assembly configured to generate a static magnetic field in the earth formation; at least one radio-frequency (RF) coil on the downhole assembly configured to generate an RF field in the earth
10 formation; and a processor configured to activate the at least one RF coil with a first pulse sequence which substantially saturates nuclear spins in a region of the earth formation, activate the at least one RF coil with a second pulse sequence that generates at least one signal from the region of substantial saturation and generates substantially no signal from outside the region, wherein there is an axial movement of
15 the tool between a start time of the first pulse sequence and an end time of the second pulse sequence.

[0011] Another embodiment of the disclosure is a method of evaluating an earth formation. The method includes conveying a downhole assembly in a borehole; using
20 a magnet arrangement on a tool on the downhole assembly to generate a static magnetic field in a region of the earth formation ; using at least one radio-frequency (RF) coil to generate an RF field in the earth formation; and activating the at least one RF coil with a first pulse sequence which substantially saturates nuclear spins in the region and with a second pulse sequence that generates at least one signal from the
25 region of substantial saturation of spins and generates no signal from outside the region, wherein there is an axial movement of the tool between a start time of the first pulse sequence and an end time of the second pulse sequence.

[0012] Another embodiment of the disclosure is a computer-readable medium
30 accessible to a processor. The medium includes instructions which enable the processor to determine a property of an earth formation selected from (I) a longitudinal relaxation time T_1 of the formation, (II) a transverse relaxation time T_2 of the formation, and (III) a fluid content of the formation using at least one signal from an earth formation acquired by a nuclear magnetic resonance tool following

application of: a static magnetic field in the earth formation during an axial motion of the tool, a first radio frequency (RF) pulse sequence which substantially saturates nuclear spins in a region of the earth formation, and a second pulse sequence that generates the at least one signal from the region, wherein the second pulse sequence
 5 generates substantially no signal from outside the region.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The present disclosure is best understood with reference to the accompanying
 10 figures in which like numerals refer to like elements and in which:

- FIG. 1** shows a measurement-while-drilling tool suitable for use with the present disclosure;
- FIG. 2** (Prior Art) shows a sensor section of a measurement-while-drilling device suitable for use with the present disclosure;
- 15 **FIG. 3** shows the nuclear magnetization as a fraction of the equilibrium magnetization one second after an aperiodic saturation sequence;
- FIG. 4** shows the sensitive volume of the exemplary logging tool at two time instances with an axial displacement;
- FIG. 5** shows the voxels of the sensitive volume of figure 4 sorted according
 20 to their B_0 field and B_1 field component that is orthogonal to B_0 ;
- FIG. 6** shows voxels of the shifted sensitive volume of figure 4 sorted according to their B_0 field and B_1 field component that is orthogonal to B_0 ;
- FIG. 7** shows the average B_1 component that is orthogonal to B_0 for each B_0 in figure 5;
- 25 **FIG. 8** shows the average B_1 component that is orthogonal to B_1 for each B_0 in figure. 6;
- FIG. 9** shows a variable frequency pulse;
- FIG. 10** shows the Fourier transform of the pulse of figure 9 and the frequency spectrum of a simple rectangular pulse;
- 30 **FIG. 11** shows the remaining magnetization after the variable frequency pulse;
- FIG. 12A** shows quadratic phase modulation in discrete 90° steps as in-phase and quadrature signals;

FIG. 12B shows quadratic phase modulation in discrete 90° steps as amplitude and phase;

FIG. 13 shows the frequency spectra of the quadratic phase modulation and of a simple rectangular pulse;

5 **FIG. 14** shows a comparison of the efficiency of the different saturation methods;

FIG. 15 shows a flow chart of methodologies that are used in designing the operational parameters of the tool;

10 **FIG. 16** shows a detail of the transmitter and receiver coil arrangement for one embodiment of the disclosure;

FIG. 17 shows the transmitting antenna coil and field configuration for another embodiment of the disclosure; and

FIG. 18 shows the disposition of a saturating coil in the antenna arrangement of Figure 17.

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DETAILED DESCRIPTION OF THE DISCLOSURE

[0014] **FIG. 1** shows a schematic diagram of a drilling system **10** with a drillstring **20** carrying a drilling assembly **90** (also referred to as the bottomhole assembly, or "BHA") conveyed in a "wellbore" or "borehole" **26** for drilling the wellbore. The

20 drilling system **10** includes a conventional derrick **11** erected on a floor **12** which supports a rotary table **14** that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drillstring **20** includes a tubing such as a drill pipe **22** or a coiled-tubing extending downward from the surface into the borehole **26**. The drillstring **20** is pushed into the wellbore **26** when a drill pipe **22** is

25 used as the tubing. For coiled-tubing applications, a tubing injector, such as an injector (not shown), however, is used to move the tubing from a source thereof, such as a reel (not shown), to the wellbore **26**. The drill bit **50** attached to the end of the drillstring breaks up the geological formations when it is rotated to drill the borehole **26**. If a drill pipe **22** is used, the drillstring **20** is coupled to a drawworks **30** via a

30 Kelly joint **21**, swivel **28**, and line **29** through a pulley **23**. During drilling operations, the drawworks **30** is operated to control the weight on bit, which is an important parameter that affects the rate of penetration. The operation of the drawworks is well known in the art and is thus not described in detail herein. During drilling operations, a suitable drilling fluid **31** from a mud pit (source) **32** is circulated under pressure

through a channel in the drillstring **20** by a mud pump **34**. The drilling fluid passes from the mud pump **34** into the drillstring **20** via a desurger (not shown), fluid line **38** and Kelly joint **21**. The drilling fluid **31** is discharged at the borehole bottom **51** through an opening in the drill bit **50**. The drilling fluid **31** circulates uphole through the annular space **27** between the drillstring **20** and the borehole **26** and returns to the mud pit **32** via a return line **35**. The drilling fluid acts to lubricate the drill bit **50** and to carry borehole cutting or chips away from the drill bit **50**. A sensor **S₁** typically placed in the line **38** provides information about the fluid flow rate. A surface torque sensor **S₂** and a sensor **S₃** associated with the drillstring **20** respectively provide information about the torque and rotational speed of the drillstring. Additionally, a sensor (not shown) associated with line **29** is used to provide the hook load of the drillstring **20**.

[0015] In one embodiment of the disclosure, the drill bit **50** is rotated by only rotating the drill pipe **22**. In another embodiment of the disclosure, a downhole motor **55** (mud motor) is disposed in the drilling assembly **90** to rotate the drill bit **50** and the drill pipe **22** is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction.

[0016] In an exemplary embodiment of **FIG. 1**, the mud motor **55** is coupled to the drill bit **50** via a drive shaft (not shown) disposed in a bearing assembly **57**. The mud motor rotates the drill bit **50** when the drilling fluid **31** passes through the mud motor **55** under pressure. The bearing assembly **57** supports the radial and axial forces of the drill bit. A stabilizer **58** coupled to the bearing assembly **57** acts as a centralizer for the lowermost portion of the mud motor assembly.

[0017] In one embodiment of the disclosure, a drilling sensor module **59** is placed near the drill bit **50**. The drilling sensor module contains sensors, circuitry and processing software and algorithms relating to the dynamic drilling parameters. Such parameters typically include bit bounce, stick-slip of the drilling assembly, backward rotation, torque, shocks, borehole and annulus pressure, acceleration measurements and other measurements of the drill bit condition. A suitable telemetry or communication sub **72** using, for example, two-way telemetry, is also provided as illustrated in the drilling assembly **90**. The drilling sensor module processes the

sensor information and transmits it to the surface control unit **40** via the telemetry system **72**.

5 [0018] The communication sub **72**, a power unit **78** and an MWD tool **79** are all connected in tandem with the drillstring **20**. Flex subs, for example, are used in connecting the MWD tool **79** in the drilling assembly **90**. Such subs and tools form the bottom hole drilling assembly **90** between the drillstring **20** and the drill bit **50**. The drilling assembly **90** makes various measurements including the pulsed nuclear magnetic resonance measurements while the borehole **26** is being drilled. The
10 communication sub **72** obtains the signals and measurements and transfers the signals, using two-way telemetry, for example, to be processed on the surface. Alternatively, the signals can be processed using a downhole processor in the drilling assembly **90**.

[0019] The surface control unit or processor **40** also receives signals from other
15 downhole sensors and devices and signals from sensors S_1 - S_3 and other sensors used in the system **10** and processes such signals according to programmed instructions provided to the surface control unit **40**. The surface control unit **40** displays desired drilling parameters and other information on a display/monitor **42** utilized by an operator to control the drilling operations. The surface control unit **40** typically
20 includes a computer or a microprocessor-based processing system, memory for storing programs or models and data, a recorder for recording data, and other peripherals. The control unit **40** is typically adapted to activate alarms **44** when certain unsafe or undesirable operating conditions occur.

25 [0020] A suitable device for use of the present disclosure is disclosed in U.S. 6,215,304 to *Slade*, the contents of which are fully incorporated herein by reference. It should be noted that the device taught by *Slade* is for exemplary purposes only, and the method of the present disclosure may be used with many other NMR logging devices, and may be used for wireline as well as MWD applications.

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[0021] Referring now to **FIG. 2**, the tool has a drill bit **107** at one end, a sensor section **102** behind the drill head, and electronics **101**. The sensor section **102** comprises a magnetic field generating assembly for generating a B_0 magnetic field (which is substantially time invariant over the duration of a measurement), and an RF

system for transmitting and receiving RF magnetic pulses and echoes. The magnetic field generating assembly comprises a pair of axially spaced main magnets **103, 104** having opposed pole orientations (i.e. with like magnetic poles facing each other), and three ferrite members **109, 110** axially arranged between the magnets **103, 104**. The ferrite members are made of "soft" ferrite which can be distinguished over "hard" ferrite by the shape of the BH curve which affects both intrinsic coercivity (H_j the intersection with the H axis) and initial permeability (μ_i , the gradient of the BH curve in the unmagnetized case). Soft ferrite μ_i values typically range from 10 to 10000 whereas hard ferrite has μ_i of about 1. Therefore the soft ferrite has large initial permeability (typically greater than 10, preferably greater than 1000). The RF system comprises a set of RF transmit antenna and RF receive antenna coil windings **105** arranged as a central "field forming" solenoid group **113** and a pair of outer "coupling control" solenoid groups **114**. This is shown in more detail in **FIG. 16**.

[0022] As discussed in *Slade*, the central "field forming" solenoid group **1613** comprises three positively wound transmit coil winding groups and two receive coil winding groups all wound in the same sense. Each winding group comprises a number of solenoidal turns. **FIG. 16** shows one of the two outer transmit coil winding groups **1681** (the other being located on the opposite side of centre plane **1680**), half of the central transmit coil winding group **1682** (the other half being located on the opposite side of centre plane **1680**), and one of the two receive coil winding groups **1686** (the other being located on the opposite side of centre plane **1680**).

[0023] Each "coupling control" solenoid group **1614** comprises a pair of receive coil winding groups **1683, 1684** wound in the same sense as the field forming winding groups and a transmit coil winding group **1685** wound in the opposite sense. All coils in both groups allocated to the transmit coil are series connected as are all those allocated to the receive coil. The coil and number of turns positions are selected to produce substantially uniform axially oriented RF flux across the sensitive volume, thus creating conditions for NMR, whilst simultaneously cancelling the mutual inductance of the transmit and receive coils. The system of "zero-coupling coils" is described in EP-A-0837338 of *Slade*. Furthermore, as also described in *Slade* '388, the design of the twin RF coil system is such that it does not generate any NMR signal

within the borehole region (for example, from vestigial borehole lobes).

Consequently, the present disclosure does not require the use of gradient coils to cancel the borehole signal. The importance of having three transmit coils in the central "field forming group" will be discussed below.

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[0024] The tool has a mud pipe **160** with a clear central bore **106** and a number of exit apertures **161-164** to carry drilling mud to the bit **107**, and the main body of the tool is provided by a drill collar **108**. Drilling mud is pumped down the mud pipe **160** by a pump **121** returning around the tool and the entire tool is rotated by a drive **120**.

10 Coiled tubing or a drillstring may be used for coupling the drive to the downhole assembly.

[0025] The drill collar **108** provides a recess **170** for RF transmit antenna and RF receive antenna coil windings **105**. Gaps in the pockets between the soft ferrite members are filled with non-conducting material **131, 135** (e.g: ceramic or high temperature plastic) and the RF coils **113, 114** are then wound over the soft ferrite members **109, 110**. The soft ferrites **109, 110** and RF coil assembly **113, 114** are pressure impregnated with suitable high temperature, low viscosity epoxy resin (not shown) to harden the system against the effects of vibration, seal against drilling fluid at well pressure, and reduce the possibility of magnetoacoustic oscillations. The RF coils **113, 114** are then covered with wear plates **111** typically ceramic or other durable non-conducting material to protect them from the rock chippings flowing upwards past the tool in the borehole mud.

25 [0026] Because of the axisymmetric magnet configuration, the device of *Slade* has an axisymmetric magnetic field and region of investigation **112** that is unaffected by tool rotation. Use of the ferrite results in a region of investigation that is close to the borehole. This is not a major problem on a MWD tool because there is little invasion of the formation by borehole drilling fluids prior to the logging. The region of investigation is within a shell with a radial thickness of about 20 mm and an axial length of about 50 mm. The gradient within the region of investigation is less than 2.7 G/cm. It is to be noted that these values are for the *Slade* device and, as noted above, the method of the present disclosure may also be used with other suitable NMR devices

[0027] Generally, the geometry of the NMR measurement device gives rise to a volume in the earth formation where the B_0 field has the correct strength to fulfill a resonance condition and in which an RF field can be presented with a substantial strength and orientation to reorient nuclear spins within the volume. This volume is often referred to as the sensitive volume. For a tool in motion, as the tool moves axially, the volume containing those protons excited by the excitation pulse (first pulse of the echo sequence) moves away from the sensitive volume. Hence, the number of spins available to contribute to the subsequent NMR signal is reduced with each subsequent echo. As a consequence, those echoes obtained later in an echo sequence with axial tool motion appear smaller compared to those echoes obtained later in an echo sequence acquired with no tool motion. "Later echoes" does not mean that only the last echoes of a sequence are affected. In fact, the loss of signal starts right at the beginning of a sequence and develops over time in a unique pattern.

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[0028] The magnet configuration of **FIG. 2** produces a somewhat inhomogeneous static magnetic B_0 field. Measured in the axial direction, this field has a minimum at the center of the NMR sensor and increases in magnitude to a maximum at the magnets. The result of this configuration on a volume of formation being traversed in an axial direction is that during constant axial motion the formation first comes close to one of the magnets and is magnetized by this higher field. As the NMR sensor center moves closer, the effective B_0 field decreases. But the formation "remembers" the earlier higher magnetization and only gradually decays, with the time constant T_1 , towards the minimum equilibrium magnetization B_0 field located in the center.

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[0029] The simplest possibility of NMR saturating is by a single 90° RF pulse. But any subsequent pulse will generate an NMR echo. In addition, the adjustment of the pulse length or height is critical. Considering that in the logging tool described above, the B_1 field is quite inhomogeneous, and B_1 is not everywhere orthogonal to B_0 , it becomes obvious that a single 90° pulse is too simple. Historically, a train of pulses has been used with the idea in mind that whatever z magnetization is left by the previous pulse is turned into the xy plane by the following pulse and hence z magnetization is destroyed. For simplicity, equal wait times have been used between the pulses, i.e. a periodic pulse sequence. This works well for solid materials where

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the transverse relaxation time T_2 is usually orders of magnitude shorter than the longitudinal relaxation time T_1 . There is a snag, though, with this method when applied to liquids with long T_2 : By any two succeeding pulses an echo is created - just at the time where a third pulse is applied. As the third pulse is applied during the
 5 echo when the spins in the xy plane are focused, this pulse turns the xy magnetization into z. This is undesirable. Wolfgang Dietrich (*Dietrich 1976*) suggested an aperiodic sequence where the interpulse times form a geometric sequence of decreasing times.

[0030] An aperiodic saturation sequence (APS) of this kind was simulated for the
 10 logging tool of **FIG. 2**. The APS comprises eight RF pulses with reducing interpulse times 6400 μ s, 3200 μ s, 1600 μ s, 800 μ s, 400 μ s, 200 μ s, 100 μ s. To increase the efficiency even more the phases are cycled as 0°, 180°, 90°, 270°, 0°, 180°, 90° and 270°. Hence the total duration of this sequence is 12.7 ms plus 8 times the length of the RF pulses.

15 [0031] This saturation sequence is effective when the logging tool is stationary, it becomes increasingly ineffective during fast drilling with high ROP. **FIG. 3** shows the nuclear magnetization **301** as a fraction of the equilibrium magnetization 1 second after the aperiodic saturation sequence. The magnetization (ordinate) as a fraction of
 20 equilibrium magnetization is plotted against ROP (abscissa) in m/h. We see that for zero ROP, the saturation is perfect (magnetization is zero). For ROP of 100 m/h the saturation is inefficient and more than half of the equilibrium magnetization is left.

[0032] An outflow effect is the reason why the saturation of **FIG. 3** does not work
 25 well during axial movement. For example, at 100 m/h the tool moves about 30 mm within the wait time of 1 s, or otherwise expressed after 1 s the saturated region has moved by 30 mm relative to the NMR tool. The voxels saturated have to a large degree moved to regions with lower or higher B_0 field while new unsaturated
 formation has moved into the sensitive region. This new formation was not saturated
 30 because at the time when the saturation pulses were applied this formation was exposed to higher or lower B_0 field, outside the bandwidth of the saturation. The solution of the problem is therefore to use wide-band saturation. There are many different ways to achieve this and is discussed with reference to **FIG. 15**.

[0033] The shape of the sensitive NMR volume is determined **1501**. This is the volume where B_0 is close to the resonant B_0 . "Close" means within the equivalent bandwidth of RF pulses and NMR receiver. See **FIG. 4** below for an example. Depending upon the wait time TW and max ROP, the SV in the magnetic field map is shifted **1503** by a distance "d" in the direction of movement. This is also illustrated above in **FIG. 4**. Next, for the shifted SV for all volume elements (voxels) B_0 and B_{1n} , are determined **1505**, where B_{1n} is the component of B_1 that is orthogonal to B_0 . The voxels of the shifted sensitive volume are sorted into a 2-dimensional map **1507** of horizontal axis B_0 and vertical axis B_{1n} . This is illustrated in **FIG. 6**. A weighted average of B_{1n} is calculated **1509** for every B_0 , the weights being the B_1 components of the receiver coil that are orthogonal to B_0 . The weights take care of the receiver coil sensitivity for a particular voxel of the SV. See for example **FIG. 8**. Let's call the resulting function $A(B_0)$. Next, $A(B_0)$ is inverted **1511** to get $f(B_0) = 1/A(B_0)$, where $f(B_0)$ is the now the optimized frequency spectrum that we have to apply for saturation. For efficient NMR saturation, this frequency spectrum is applied with every RF pulse of the earlier described aperiodic pulse sequence (APS). This will saturate spins in a region that includes the original **1501** and shifted **1503** regions,

[0034] There are at least three ways to apply the frequency spectrum determined above for NMR saturation. These are:

- A. **Frequency modulation.** This may be done with variable sweep rate and amplitude, variable sweep rate with constant amplitude, and fixed sweep rate with variable amplitude. All of these can be continuous or in discrete steps (applies to frequency and amplitude).
- B. **Phase modulation.** This may be done with variable phase change rate and variable amplitude, sometimes referred to as complex amplitude modulation (for example to minimize power as described in US 6,686,737 to *Kruspe et al.*, having the same assignee as the present disclosure). This may also be done with variable phase change rate and constant amplitude. This may be done with a quadratic phase change rate and variable amplitude (discussed below). All of these can be continuous or in discrete steps (applies to phase and amplitude).

C. Other methods, e.g. stochastic pulsing.

The use of stochastic pulsing (having a low power requirement) is discussed in US 7,015,694 to *Blumich* having the same assignee as the present disclosure.

Frequency sweeps and phase modulation can be designed to do exactly the same, the only difference being the implementation. It should further be noted that a broad band saturation using a B_0 sweep as discussed in U.S. 6,844,728 to *Speier et al.* is equivalent to a frequency sweep. Hence the methods discussed here of a tailor made
 5 frequency sweep are also applicable to saturation methods using a B_0 sweep. In the following embodiments, only methods that work with constant amplitude RF pulses are discussed.

[0035] Turning to **FIG. 4**, the sensitive region of the NMR tool discussed above is
 10 shown by **401**. The abscissa is distance from the borehole axis, and the ordinate is distance along the borehole axis. The sensitive region **403** corresponds to a displacement of the region **401** by a distance 'd'.

[0036] For the efficiency of the RF pulse only the B_1 component that is orthogonal to
 15 B_0 is meaningful. **FIG. 5** shows all the voxels **501** of the sensitive volume (**401** in **FIG. 4**) now sorted according to their B_0 field and B_1 field component that is orthogonal to the B_0 field. The abscissa is the B_0 field in arbitrary units. Similarly, the ordinate is the B_1 component that is orthogonal to the B_0 field. The line **503** is the reference B_1 field at the nominal radius of the region of investigation and $z = 0$ and is
 20 repeated as **603**, **705** and **805** in **FIGS. 6 to 8** respectively. **FIG. 6** shows an equivalent plot of all the voxels **601** of the shifted sensitive volume, (**403** in **FIG. 4**), now sorted according to their B_1 field component that is orthogonal to the B_0 field. **603** is the reference B_1 field.. Next, shown in **FIGS. 7-8** are average orthogonal B_1 values versus B_0 field. **701** is the simple average for the unshifted sensitive volume,
 25 **703** is a weighted average with weights proportional to the orthogonal B_1 component, and **705** is the reference B_1 value. **801** is the simple average for the shifted sensitive volume, **803** is a weighted average with weights proportional to the orthogonal B_1 component, and **805** is the reference B_1 value.

30 [0037] **FIG. 8** shows that the orthogonal B_1 average varies by a factor of 4 over the B_0 fields of the shifted sensitive volume. This means that for best saturation at the highest B_0 field (most right in the figure), the RF intensity must be 4 times of that at the peak of the curve. In one embodiment, pulses with constant amplitude are used. To vary the intensity of the frequency spectrum we can then choose the appropriate

length of irradiation at each frequency. We must, however consider that the longer the irradiation at a specific frequency is, the smaller the bandwidth at that frequency will become. Hence, the longer the pulse components the closer the frequency spacing must be. One tailored example is shown by **901** in **FIG. 9**. The abscissa is time and the ordinate is frequency. **FIG. 10** shows the frequency spectrum **1001** of the pulse **901**. The abscissa is the frequency. **1003** shows for comparison the magnitude of the frequency distribution of a simple rectangular pulse at the nominal NMR frequency. The nominal NMR frequency is the NMR resonance frequency for a spot in the formation that is at the nominal radius at $z = 0$.

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[0038] For the simulation results below, it is assumed that $|B_1|$, or equivalently, the transmit current is independent of the frequency. This may not be true in a real NMR tool. Such an effect is not considered in the simulation but is easy to handle.

15 [0039] Turning now to **FIG. 11**, simulation results are shown for the pulse **901**. The curve **1101** is for the pulse **901** implemented as an aperiodic pulse sequence with phases of 0° , 180° , 90° , -90° , 0° , 180° , 90° , and -90° . We note that the residual magnetization after the tailored variable-frequency saturation with an aperiodic pulse sequence is less than 4% of total equilibrium, compared with about 55% in **FIG. 3**.

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[0040] As an alternative to frequency modulation, phase modulation may be used. If continuous phase modulation is possible, a pulse can be generated that is completely equivalent to the frequency modulated pulse **901**. We discuss here a specific implementation in which phase modulation is limited to steps of 90° . Even with this crude limitation, it is possible to construct a wideband pulse.

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[0041] A phase modulated signal can be written as $\cos(\omega t + \phi(t))$. If the phase is constant, we get the signal $\cos(\omega t + \phi)$, a signal with constant angular frequency ω . If the phase change is linear in time, then $\phi(t) = ct$, and we get the

30 signal $\cos(\omega t + ct) = \cos((\omega + c)t)$, i.e., a constant shift of the frequency by an amount c compared to the unmodulated signal. If the phase change is quadratic in time $\phi(t) = ct^2$, we get the signal $\cos(\omega + ct)t$, a signal with an offset frequency ct , of

which the offset frequency is constantly increasing in time. This is a linear frequency sweep.

[0042] Subject to the limitation of 90° step changes in phase, the implementation of an approximate quadratic phase change in time is shown in **FIGS. 12A, 12B**. **1201** and **1203** show the in-phase and quadrature signals, while **1251** and **1253** show the amplitude and phase respectively. The frequency spectrum is shown in **FIG. 13** by the curve **1301** while **1303** is the spectrum of a rectangular pulse.

[0043] Turning next to **FIG. 14**, a comparison is shown between the efficiencies of the simple rectangular pulse **1401**, the variable frequency pulse **1405** of **FIG. 9**, and the stepped phase modulation, an approximation of quadrature phase modulation, **1403** of **FIGS. 12A, 12B**. The efficiency of the stepped-phase modulation **1403** in **FIG. 14** is better than that of the rectangular pulse **1401** but worse than that of the tailored frequency sweep **1405**. The efficiency of the stepped-phase modulation can be improved, though. This is possible by deviating from the simple quadratic phase change with the aim to get a frequency spectrum that is not “rectangular” like **1301** in **FIG. 13** but rather has a shape more like **1001** in **FIG. 10**.

[0044] In view of the discussion above, the advantages of having an RF coil just for saturation purposes becomes clear. The RF coil for saturation purposes may be the same as or in addition to the RF coil that is used for transmitting and receiving signals. An advantage of having a saturation coil separate from the receive coil is that it is possible to have the saturation field stronger and more orthogonal to the static field.

[0045] Referring now to **FIG. 16**, the advantage of the structure of the “field forming” solenoid group is discussed. While not contemplated by *Slade*, a number of modifications may be made in view of the above disclosure. To address the problem due to the limited bandwidth of the transmit antenna we can use the plurality of transmit coils for the saturation pulses. Each antenna can be tuned to a different frequency. A further advantage is that these antenna(s) can be closer to the region where saturation is wanted; this improves at the same time the orthogonality between B_1 and B_0 fields, increasing the effectiveness of these saturation antenna(s) even

more. In addition, the excitation of the transmit coils on the opposite sides of the center plane can be made asymmetric, so that saturated region is larger in the direction of tool motion than in the opposite direction. Using appropriate modeling techniques, it is also possible to dynamically alter the B_1 field based upon an average
5 rate of penetration of the drillbit.

[0046] Turning now to **FIG. 17**, an NMR tool is shown with one of the permanent magnets **103**, the center line **1680**, the antenna core **109** and a transmit coil **1701**. The B_0 field direction is given by the solid arrows **1703** and the RF field lines are given by
10 the double arrows **1705**. Also shown in the figure is the region between the dotted contour lines **1711** that needs to be saturated in order for a good NMR signal. With tool motion, this region will move into the region between the lines **1713**. It can be seen that orthogonality is satisfied in region between the lines **1713** but is not satisfied in the region between the lines **1711** (the region for saturation).

15

[0047] **FIG. 18** shows, in addition to the tool of Figure 17, a saturation coil **1801**. There is now good orthogonality between the RF field lines **1805** of the saturation coil and the B_0 lines **1703**.

20 [0048] Data acquired by the NMR logging tool may be used using known methods to determine formation properties such as porosity, a T_2 distribution, a T_1 distribution, and a permeability, and to record the determined formation properties on a suitable medium. As noted above, saturation using the methods disclosed herein is particularly useful when followed by a DTW for determination of T_1 -affected T_2
25 distributions and fluid typing, and by a saturation recovery sequence for determination of T_1 distributions. These methods are not discussed here.

[0049] The disclosure has been described with reference to a NMR device that is part of a BHA conveyed on a drillstring. The disclosure is equally applicable for NMR
30 devices conveyed on coiled tubing, wireline, and slickline as part of a logging string. Collectively, the logging string and the BHA may be referred to as a downhole assembly. The control described herein may be done using a downhole processor and the results stored on a suitable memory downhole or telemetered to the surface. Alternatively, the data may be stored on a downhole memory and processed when the

BHA is tripped out of the borehole. With improved telemetry capability, it should be possible to telemeter the NMR measurements to a surface location and do the processing there.

- 5 **[0050]** Implicit in the processing of the data is the use of a computer program *implemented on a suitable machine readable medium* that enables the processor to perform the control and processing. The machine readable medium may include ROMs, EPROMs, EAROMs, Flash Memories and Optical disks.
- 10 **[0051]** While the foregoing disclosure is directed to the specific embodiments of the disclosure, various modifications will be apparent to those skilled in the art.

CLAIMS

What is claimed is:

- 1 1. An apparatus for evaluating an earth formation, the apparatus comprising:
 - 2 a downhole assembly configured to be conveyed in a borehole;
 - 3 a magnet arrangement on a tool on the downhole assembly configured
 - 4 to generate a static magnetic field in the earth formation;
 - 5 at least one radio-frequency (RF) coil on the downhole assembly
 - 6 configured to generate an RF field in the earth formation; and
 - 7 a processor configured to:
 - 8 (i) activate the at least one RF coil with a first pulse sequence
 - 9 which substantially saturates nuclear spins in a region of the
 - 10 earth formation, and
 - 11 (ii) activate the at least one RF coil with a second pulse sequence
 - 12 that generates at least one signal from the region of substantial
 - 13 saturation of spins and generates substantially no signal from
 - 14 outside the region;
 - 15 wherein there is an axial movement of the tool between a start time of
 - 16 the first pulse sequence and an end time of the second pulse sequence.
- 17 2. The apparatus of claim 1 wherein the processor is further configured to:
 - 1 use the at least one signal to estimate at least one of: (I) a longitudinal
 - 2 relaxation
 - 3 time T_1 of the formation, (II) a transverse relaxation time T_2 of the formation,
 - 4 and
 - 5 (III) a fluid content of the formation.
- 6 3. The apparatus of claim 1 wherein the processor is further configured to alter a
- 7 frequency spectrum of at least one pulse in the first pulse sequence using a
- 8 shape of the region and a static magnetic field B_0 in the region for a resonance
- 9 condition.
- 10 4. The apparatus of claim 3 wherein the processor is further configured to alter
- 11 the frequency spectrum of at least one pulse in the pulse sequence by further

- 3 using a component of the RF magnetic field B_1 that is substantially orthogonal
4 to the static magnetic field B_0 .
5
- 1 5. The apparatus of claim 3 wherein the first pulse sequence comprises an
2 aperiodic pulse sequence.
3
- 1 6. The apparatus of claim 5 wherein the aperiodic pulse sequence further
2 comprises pulses with phase selected from the group consisting of: (i) 0° , (ii)
3 90° , (iii) 180° , and (iv) 270° .
4
- 1 7. The apparatus of claim 1 wherein the processor is further configured to alter a
2 frequency spectrum of at least one pulse of the first pulse sequence by at least
3 one of: (i) a frequency modulation, (ii) a phase modulation, and (iii) stochastic
4 pulsing.
5
- 1 8. The apparatus of claim 1 wherein the at least one RF coil further comprises a
2 first RF coil configured to generate the second pulse sequence and a second
3 RF coil configured to receive the at least one signal.
4
- 1 9. The apparatus of claim 1 wherein the at least one RF coil further comprises a
2 first RF coil which substantially saturates the nuclear spins in the region and a
3 second RF coil which is used to generate the at least one signal, and wherein
4 the first RF coil is configured to operate at a frequency different from a
5 frequency of the second RF coil.
6
- 1 10. The apparatus of claim 1 wherein the downhole assembly is configured to be
2 conveyed into the borehole on a conveyance device selected from: (i) a
3 wireline, and (ii) a drilling tubular.
4
- 1 11. A method of evaluating an earth formation, the method comprising:
2 conveying a downhole assembly in a borehole;
3 using a magnet arrangement on a tool on the downhole assembly to
4 generate a static magnetic field in a region of the earth formation;

5 using at least one radio-frequency (RF) coil to generate an RF field in
 6 the region; and
 7 activating the at least one RF coil with:
 8 (i) a first pulse sequence which substantially saturates nuclear
 9 spins in the region, and
 10 (ii) a second pulse sequence that generates at least one signal from
 11 the region of substantial saturations of spins and generates
 12 substantially no signal from outside the region;
 13 wherein there is an axial movement of the tool between a start time of the
 14 first pulse sequence and an end time of the second pulse sequence.

15
 1 12. The method of claim 11 further comprising:

2 using the at least one signal to estimate at least one of: (I) a longitudinal
 3 relaxation time T_1 of the formation, (II) a transverse relaxation time T_2 of the
 4 formation, and (III) a fluid content of the formation.

5
 1 13. The method of claim 11 further comprising altering a frequency spectrum of at
 2 least one pulse in the first pulse sequence using a shape of the region and a
 3 static magnetic field B_0 in the region for a resonance condition.

4
 1 14. The method of claim 13 further comprising altering the frequency spectrum of
 2 at least one pulse in the first pulse sequence by further using a component of
 3 the RF magnetic field B_1 that is substantially orthogonal to the static magnetic
 4 field B_0 .

5
 1 15. The method of claim 13 further comprising using, for the first pulse sequence
 2 an aperiodic pulse sequence.

3
 1 16. The method of claim 15 further comprising modulating the pulses of the
 2 aperiodic pulse sequence with a phase selected from the group consisting of:
 3 (i) 0° , (ii) 90° , (iii) 180° , and (iv) 270° .

4

- 1 17. The method of claim 11 further comprising altering a frequency spectrum of at
2 least one pulse in the first pulse sequence by at least one of: (i) a frequency
3 modulation, (ii) a phase modulation, and (iii) stochastic pulsing.
4
- 1 18. The method of claim 11 further comprising using a first RF coil to generate
2 the second pulse sequence and a second RF coil to receiver the at least one
3 signal.
4
- 1 19. The method of claim 11 further comprising using a first RF coil operated at a
2 first frequency for substantially saturating the nuclear spins in the region and
3 using a second RF coil operated at a second frequency for generating the at
4 least one signal.
5
- 1 20. A computer-readable medium accessible to a processor, the medium
2 comprising instructions which enable the processor to determine a property of
3 an earth formation selected from (I) a longitudinal relaxation time T_1 of the
4 formation, (II) a transverse relaxation time T_2 of the formation, and (III) a
5 fluid content of the formation using at least one signal from an earth formation
6 acquired by a nuclear magnetic resonance (NMR) tool following application
7 of:
8 (a) a static magnetic field in the earth formation during an axial motion of
9 the NMR tool,
10 (b) a first radio frequency (RF) pulse sequence which substantially
11 saturates nuclear spins in a region of the earth formation, and
12 (c) a second pulse sequence that generates the at least one signal from the
13 region, wherein the second pulse sequence generates substantially no
14 signal from outside the region.
15
- 1 21. The medium of claim 20 further comprising at least one of: (i) ROM, (ii) and
2 EPROM, (iii) an EARAM, (iv) a flash memory, and (v) an optical disk.
3

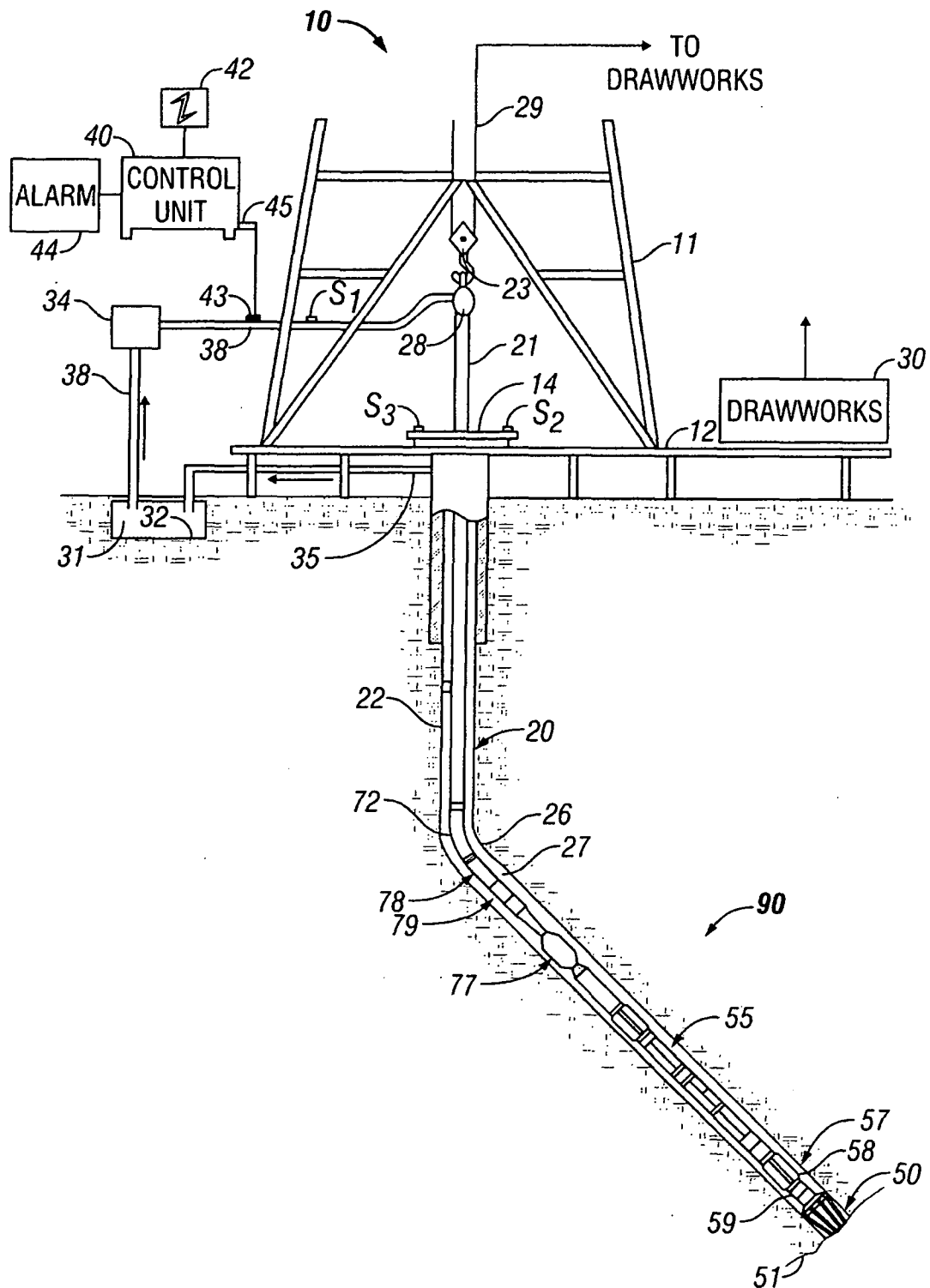


FIG. 1
(Prior Art)

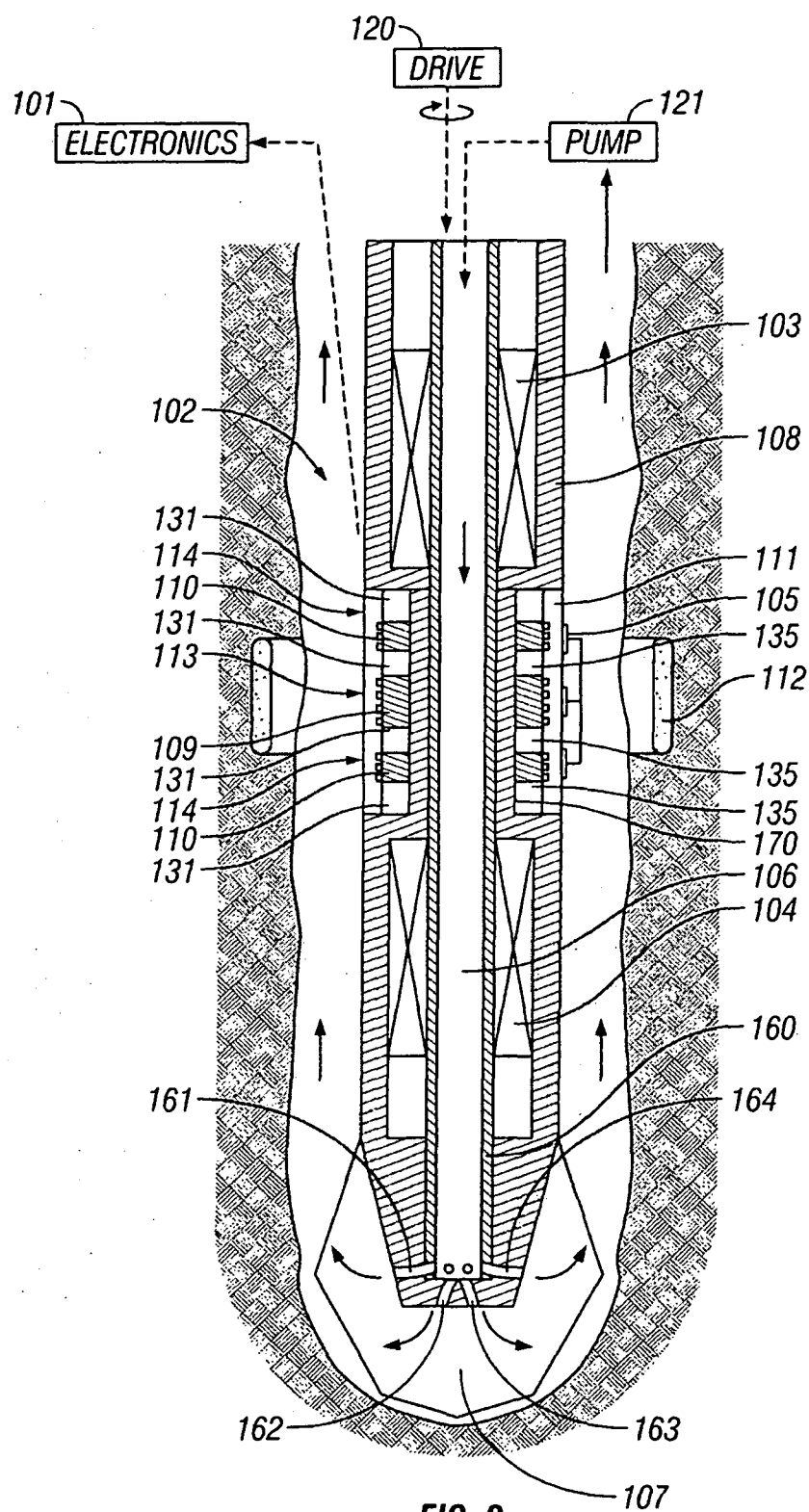


FIG. 2
(Prior Art)

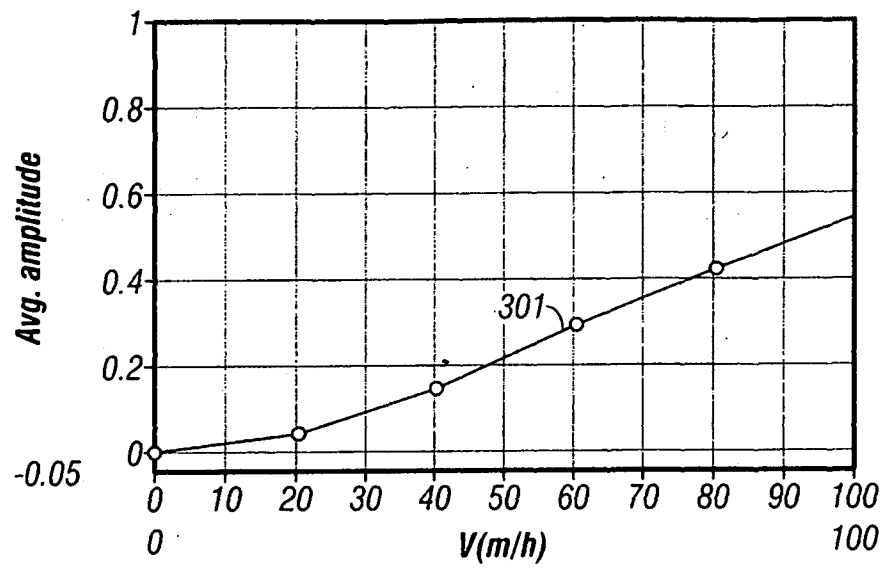


FIG. 3

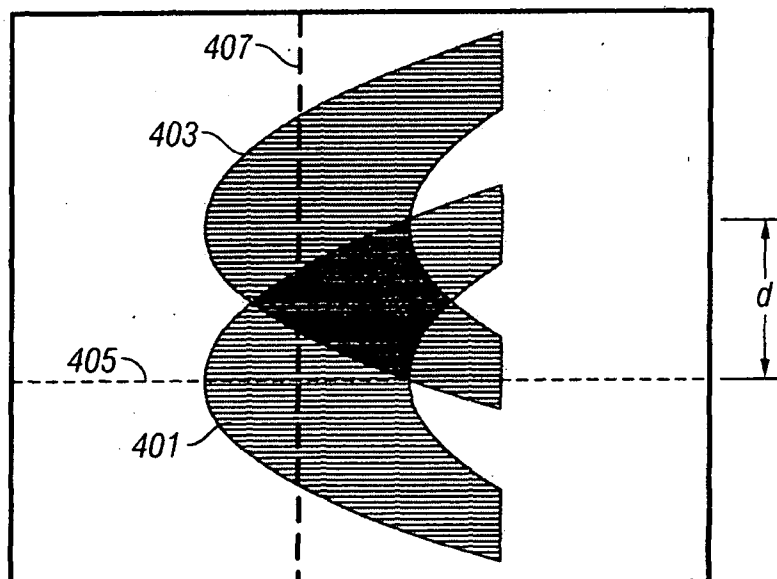


FIG. 4

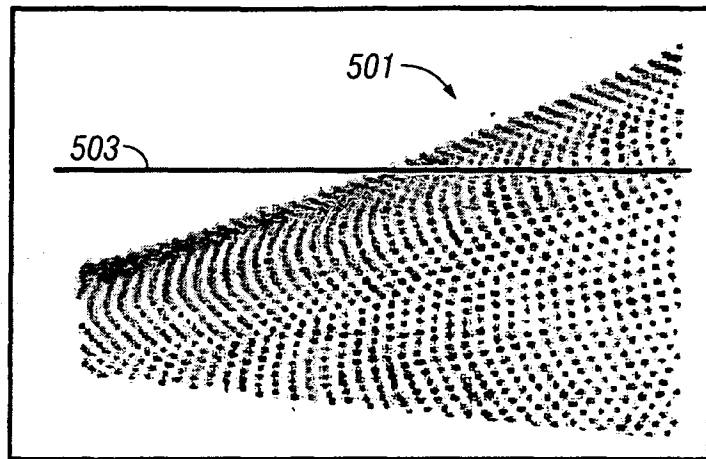


FIG. 5

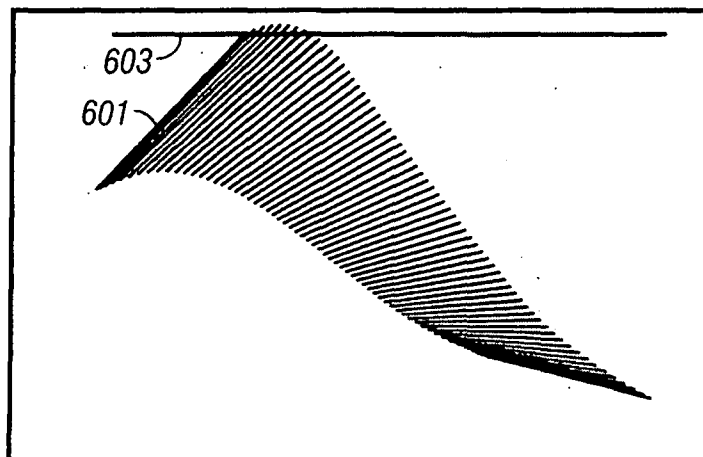


FIG. 6

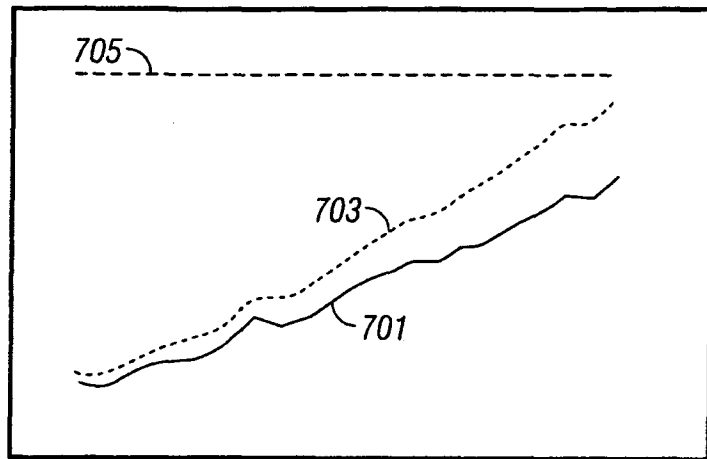


FIG. 7

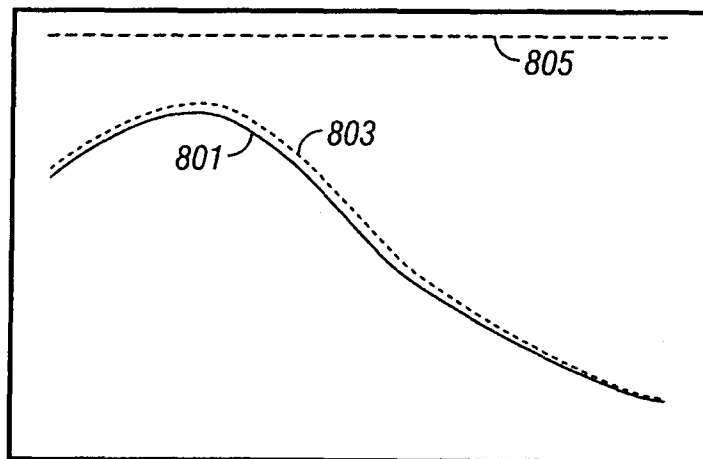


FIG. 8

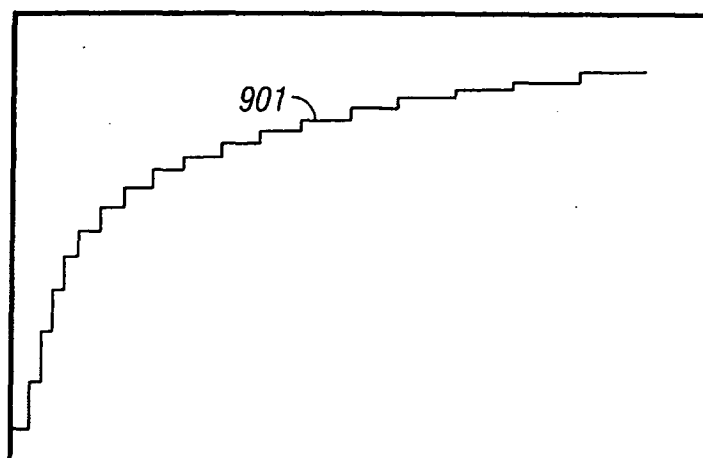


FIG. 9

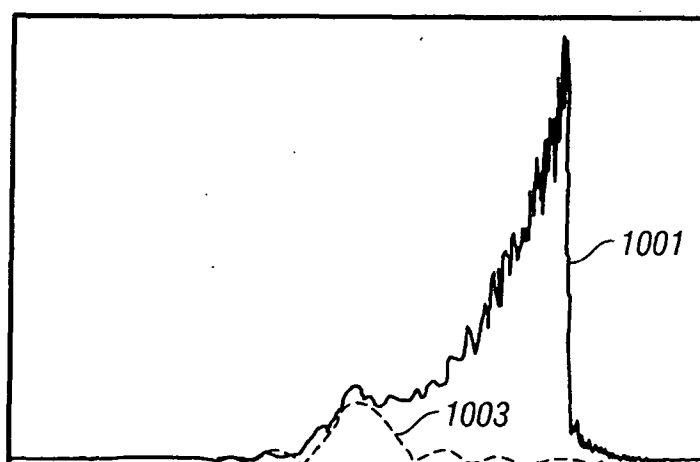


FIG. 10

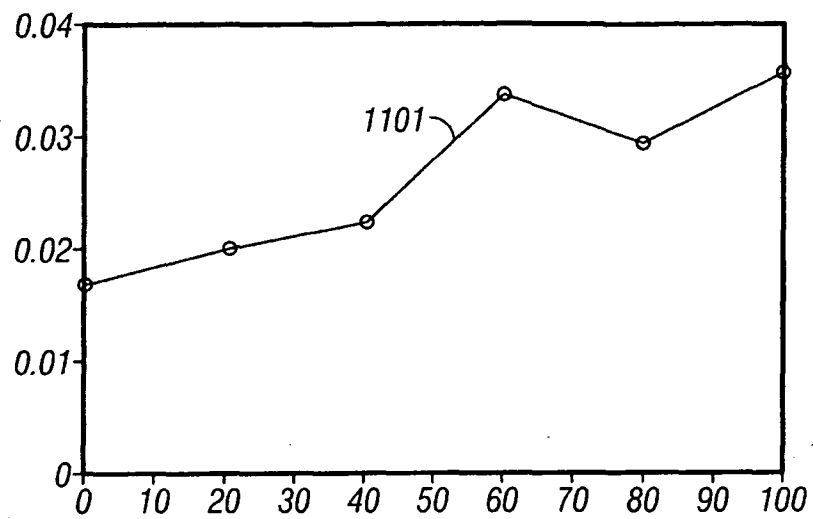


FIG. 11

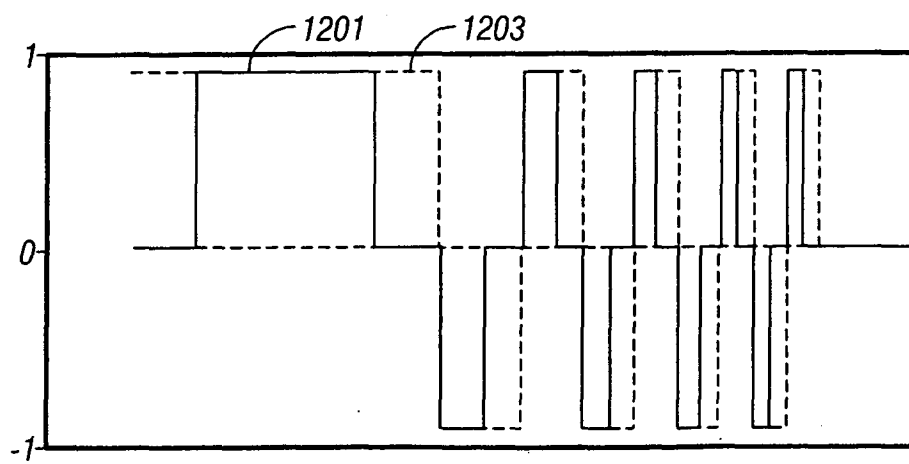


FIG. 12a

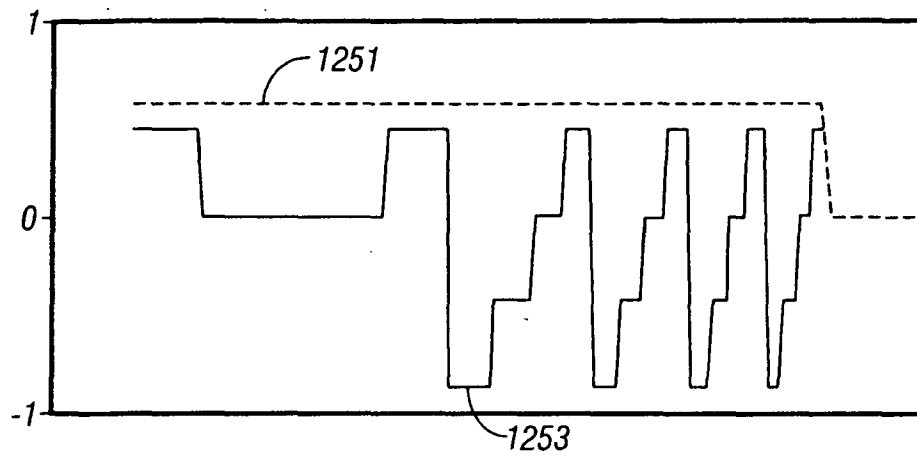


FIG. 12b

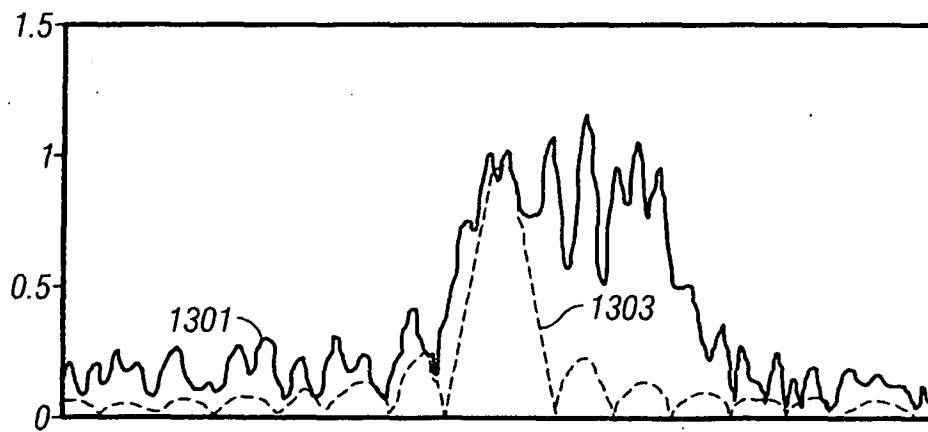


FIG. 13

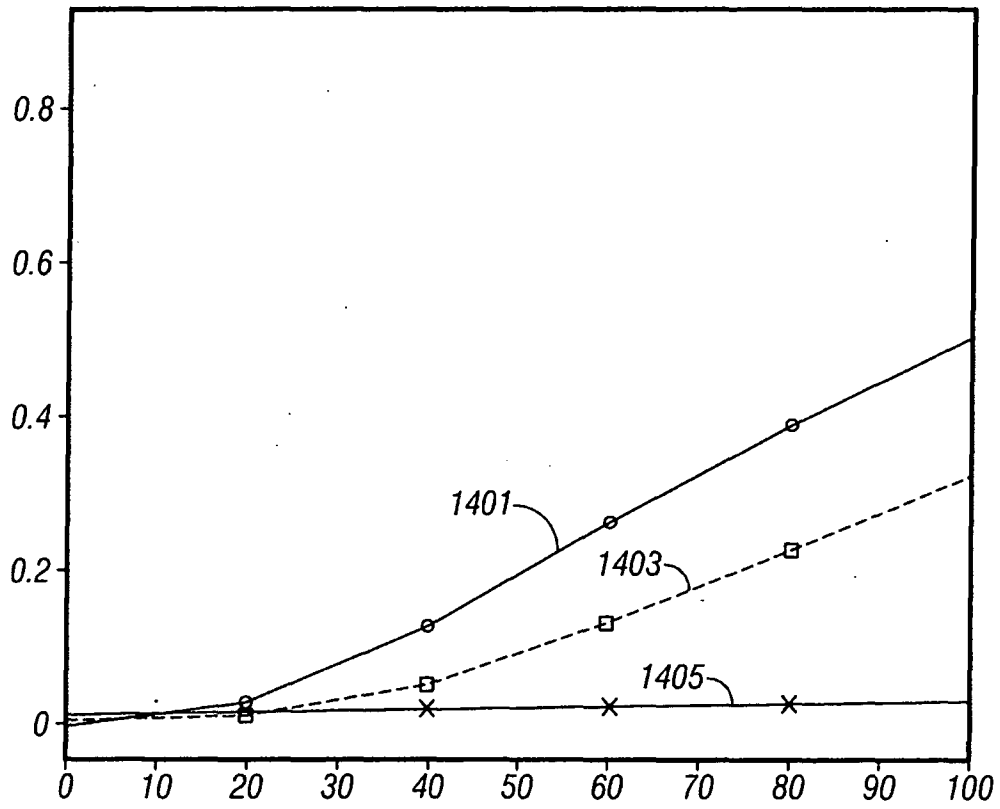


FIG. 14

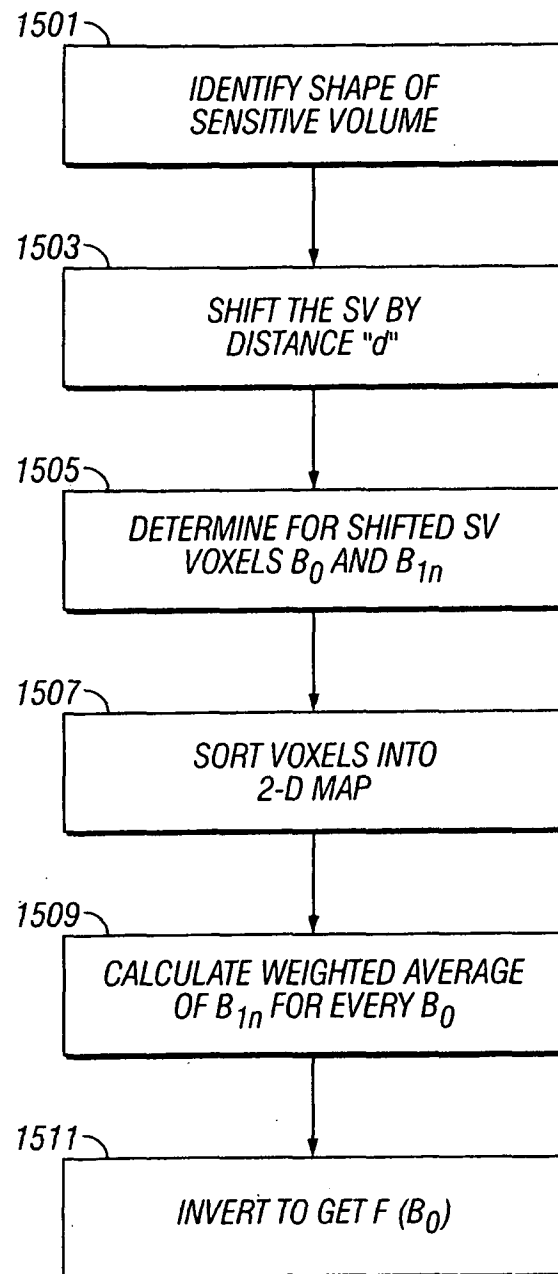


FIG. 15

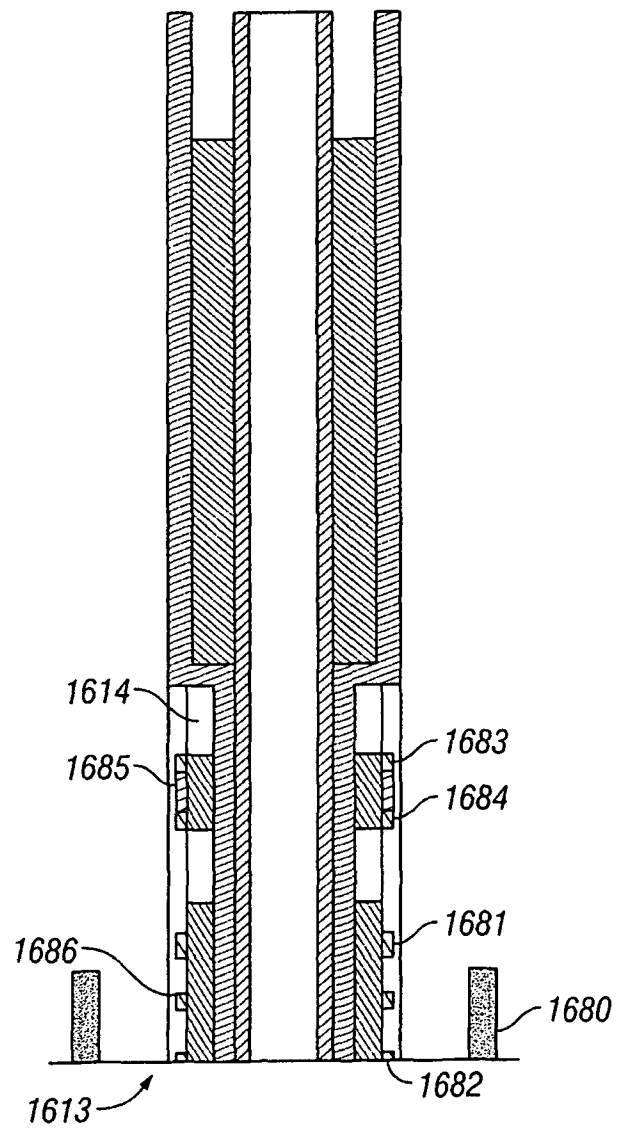


FIG. 16

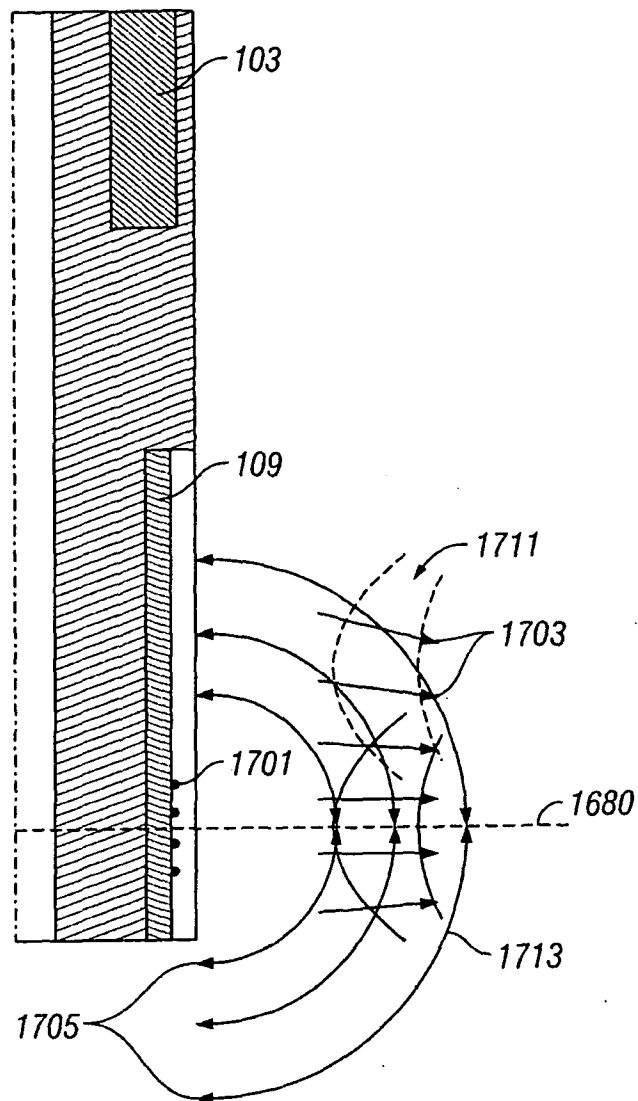


FIG. 17

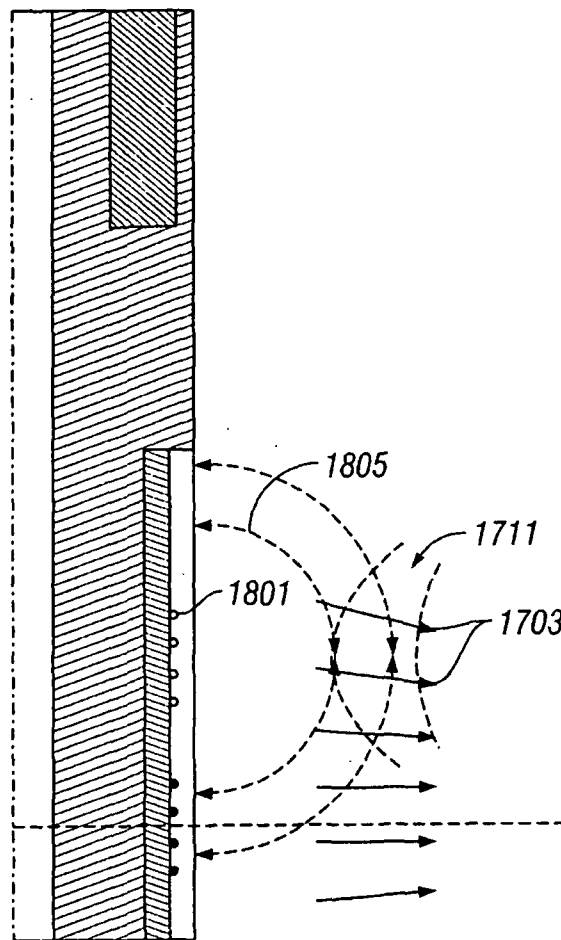


FIG. 18