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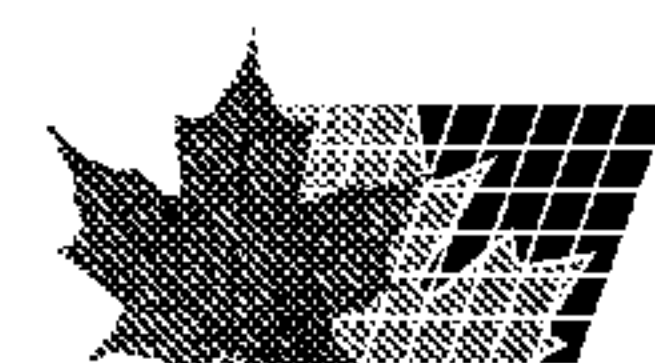
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DE FOND ET DES MESURES DE RESONANCE MAGNETIQUE NUCLEAIRE
(54) Title: ANTENNA CORE MATERIAL FOR USE IN MWD RESISTIVITY MEASUREMENTS AND NMR
MEASUREMENTS

(57) **Abrégé/Abstract:**

The present invention provides a novel use of a material having a high internal magnetostrictive damping and/or using material with explicitly low magnetostriction as an antenna core material for NMR and resistivity devices in a borehole. The probe structural geometry facilitates the use of material, which has a relatively low magnetic permeability.



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ANTENNA CORE MATERIAL FOR USE IN MWD RESISTIVITY MEASUREMENTS AND NMR MEASUREMENTS

Thomas Kruspe, Arcady Reiderman, Martin Blanz & Peter Rottengatter

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Field of the Invention

[0001] The present invention is related to the field of resistivity and nuclear magnetic resonance ("NMR") sensing apparatus. More specifically, the invention is related to a well logging apparatus having a powdered soft magnetic material core as a flux concentrator for sensing NMR properties within earth formations adjacent a wellbore.

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Description of the Related Art

[0002] NMR well logging instruments can be utilized for determining properties of earth formations including: the fractional volume of pore space, the fractional volume of mobile fluid filling the pore space and other petrophysical parameters. An NMR well logging instrument typically contains a permanent magnet to generate a static magnetic field in adjacent earth formations. The NMR well logging instrument typically includes a transmitting antenna assembly positioned near the magnet. The transmitting antenna assembly is shaped so that a pulse of radio frequency (RF) power conducted through the antenna assembly induces a RF magnetic field in the adjacent earth formation. The induced RF magnetic field is generally orthogonal to the static magnetic field, thereby creating appropriate conditions for NMR excitation in the formation.

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[0003] Following the RF antenna pulse, voltages representative of NMR conditions in the formation are induced in the receiving antenna. In particular, these voltages represent precessional rotation of hydrogen or other nuclei spin axes about the static magnetic field generated by the NMR well logging tool. NMR apparatus designs typically use the same antenna for transmitting and receiving along with de-coupling, receiving and protection circuitry.

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[0004] There are various known NMR well logging instruments proposed and/or

implemented for measuring NMR properties of substances, in particular, the properties of earth formations. One type of NMR instrument is described in U.S. Patent No. 4,710,713 to *Taicher* et al (*Taicher* '713 patent). Another type of NMR instrument is described in U.S. Patent No. 4,350,955 to *Jackson* et al. Both of these
5 NMR instruments represent early designs of well logging NMR instruments with the main focus on the magnet assembly. No provision was made in these early designs for the use of a soft magnetic material in the NMR probe for improving the efficiency of the RF antenna.

10 [0005] It was recognized in more recent NMR well logging tool designs that a soft magnetic material can be utilized as a magnetic flux concentrator to increase efficiency of generating and receiving RF signals. For example, the NMR well logging instruments using ferrite material as an essential element of the design are described in U.S. Patent No. 5,712,566, to *Taicher* et al (*Taicher* '566), in U.S. Patent
15 No. 5,644,231 to *Wignall*, in UK Patent Application GB 2 141 236 to *Clow*, et al. and in U.S. Patent No. 5,376,884 to *Sezginer*.

[0006] All prior designs known to the present inventors, however, explicitly or implicitly suggest ferrite as the soft magnetic material satisfying the requirements of
20 high permeability and negligible RF losses. Ferrite materials, however, suffer from a relatively low saturation flux density, typically in the range of 0.3 - 0.4 T. This relatively low saturation flux density results in core saturation when the ferrite core is placed near the NMR probe permanent magnet. NMR probe core saturation results in reduction of the core magnetic permeability which tends to increase core sensitivity to
25 temperature variations. A sintered ferrite material core tends to generate magnetostrictive ringing in a strong RF magnetic field. Elimination of this parasitic magnetostrictive ringing signal increases the complexity and cost of NMR antenna design.

30 [0007] A common limitation of the *Wignall*, *Taicher* '566, *Sezginer*, and *Clow* patent designs is the necessity of finding or creating a magnetic field low enough in a region

where the soft ferrite material can be positioned to avoid saturation. For example, the apparatus disclosed in the *Wignall* patent provides a soft magnetic ferrite material loaded in the antenna coil (a so called half-coax antenna). As described in the *Wignall* patent, the effectiveness of the ferrite material is substantially reduced by the strong magnetic field of the permanent magnet. The structure of the *Wignall* patent compensates for this reduction in effectiveness by providing a magnetic shield around the ferrite region. The shield comprises a shell of soft magnetic steel, which effectively provides a shunt path for static magnetic field in the region of the antenna. Implicitly, the steel shell is not saturated due to its sufficient saturation flux density and cross-sectional area. The necessity of creating a region of low static magnetic field places a serious constraint on the design of NMR probes. In particular it places limitations on the antenna core size, thereby reducing the efficiency of the antenna.

[0008] United States Patent 6,452,388 to *Reiderman* et al teaches the use of a soft magnetic core as part of an antenna assembly. Included in the teachings is a discussion of magnetostrictive ringing and possible remedies to reduce the ringing. The discussion on magnetostrictive ringing did not fully investigate the possible causes of this ringing and only partially discussed methods and materials for its reduction.

[0009] An alternate approach to reducing magnetostriction uses non-metallic soft magnetic materials (ferrites) as taught by *Prammer* et al. (US Patent 6,268,726). *Prammer* discloses the use of 1mm thick layers of ferrite in combination with 0.3mm layers of rubber or lead filled epoxy. The arrangement taught by *Prammer* has increased complexity and an increase of flux density and an accompanying risk of saturation in the ferrite layers. As the amount of ferrite needs to be reduced in the same volume, the efficiency of the antenna core is reduced.

[0010] Yet another method to reducing the ringing on NMR signals caused by magnetostriction in an antenna core is to provide a condition of substantially zero static field at the core material. In a zero static magnetic field, an oscillating stress

due to magnetostriction in a soft magnetic core produces substantially no changes in the net magnetization of the core. An NMR tool where this condition is satisfied is disclosed in US Patent 5,712,566 to *Taicher* and *Reiderman*. As taught therein, the antenna core is placed in a cylindrical hole at the center of a transversely magnetized magnet. While such a design is practical for wireline logging, it is difficult to do this with MWD logging tools.

[0011] US Patent 6,452,388 to *Reiderman* et al teaches the concept of using a soft magnetic material for an antenna core. However, the principles to be used in selecting suitable antenna core material for NMR applications were not fully explored therein. Also not specifically discussed therein was the use of antenna core material for resistivity measurements in earth formations and considerations therefor.

[0012] US Patent 5,138,263 to *Towle* having the same assignee as the present invention discloses a tool for evaluating electrical properties of an earth formation surrounding a borehole while drilling the borehole. The tool includes a housing for connecting upper and lower portions of a drillstring, a transmit antenna for generating electromagnetic waves at least two receiving antennas for receiving electromagnetic waves and magnetic elements associated with each of the antennas for electromagnetically coupling each of the antennas with the formation. The tool provides improved transmit efficiency and improved receiving sensitivity.

[0013] There are several disadvantages in using ferrite as an antenna core material for either resistivity measurements or for NMR measurements in a Measurement- while-Drilling (MWD) applications. First, ferrite is brittle. Ferrite cores can shatter under shock and vibration and to a certain extent degrade the performance of the core. This can be a serious problem in MWD applications due to the extreme conditions of vibration to which the core may be subjected. Physicists might say that the cracks are negligible; however in certain NMR measurements, it is important to maintain a rotational symmetry of the magnetic field (and the core). Core elements will break

not equally around the sensor.

[0014] In many MWD applications, deep resistivity measurements (i.e., measurements up to 10 m away from the borehole) are desirable so as to provide real time information about the position of a borehole relative to bed boundaries. Deep resistivity tools require operation at lower frequencies. At these lower frequencies, there may be problems with mechanical resonances of a ferrite core. It would be desirable to have antenna core material that is not susceptible to mechanical resonance. Finally, it would be desirable to have magnetic core material that is easy to fabricate into cores.

[0015] Thus, there is a need for an antenna core material that overcomes the limitations of prior art discussed above following a further evaluation of principles for selection of the core material. The present invention satisfies this need.

Summary of the Invention

[0016] The present invention is directed towards an core material suitable for use in downhole applications. One embodiment is for use in a nuclear magnetic resonance (NMR) logging apparatus for use in a borehole for determining properties of an earth formation surrounding the borehole. The apparatus comprises a magnet for inducing a static magnetic field in a region of interest in the earth formation. A transmitting antenna assembly is used for inducing a radio frequency magnetic field within the region of interest and producing signals from materials in the region of interest. A receiving antenna assembly is used for detecting said signals from said region of interest. At least one of the antenna assemblies includes a magnetic core formed from a material having high internal magnetostrictive damping and/or low magnetostriction. A suitable material having high internal damping is a non-conductive, powdered metal, soft magnetic material having a grain size sufficiently small to reduce intragranular power loss at the operating frequency of the RF magnetic field. The magnetic material may further have a grain size less than half a

wavelength of an acoustic wave at the frequency of the RF field.

5 [0017] A suitable material having high internal damping has a large area within a hysteresis loop associated with magnetostrictive deformation. A suitable material is powdered metal like Fluxtrol™.

[0018] In an optional embodiment of the invention, the same antenna is used as both the transmitting antenna and the receiving antenna.

10 [0019] The antenna core material may also be used on a resistivity measurement device.

[0019a] Accordingly, in one aspect of the present invention there is provided a nuclear magnetic resonance (NMR) logging apparatus for use in a borehole for determining
15 properties of an earth formation surrounding the borehole, the apparatus comprising:

(a) a magnet for inducing a static magnetic field in a region of interest in the earth formation;

(b) a transmitting antenna assembly for inducing a radio frequency magnetic field within said region of interest and producing signals from materials in the region of interest;
20 and

(c) a receiving antenna assembly for detecting said signals from said region of interest;

wherein at least one of the antenna assemblies includes at least one magnetic core formed from a non-ferritic material having low magnetostriction.

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[0019b] According to another aspect of the present invention there is provided a method of determining properties of an earth formation surrounding a borehole, the method comprising:

(a) using a magnet on a nuclear magnetic resonance (NMR) logging apparatus conveyed in the borehole for inducing a static magnetic field in a region of interest in the
30 earth formation;

(b) using a transmitting antenna assembly for inducing a radio frequency magnetic field within said region of interest and producing signals from materials in the region of interest; and

(c) using a receiving antenna assembly for detecting said signals from said region of interest;

the method further comprising using a core for at least one of the antenna assemblies formed from a non ferritic material having low magnetostriction.

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[0019c] According to yet another aspect of the present invention there is provided an apparatus for evaluating electrical properties of an earth formation surrounding a borehole, the apparatus comprising:

(a) a transmitting antenna assembly for conveying a radio frequency

10 electromagnetic field into said earth formation; and

(b) a receiving antenna assembly for receiving a signal resulting from interaction of said electromagnetic field with said earth formation;

wherein at least one of the antenna assemblies includes at least one of: (I) a magnetic core formed from a material having high internal magnetostrictive damping, and, (II) low

15 magnetostriction.

[0019d] According to yet another aspect of the present invention there is provided a method of determining a resistivity parameter of an earth formation surrounding a borehole, the method comprising:

20 (a) using a transmitting antenna assembly on a tool conveyed in said borehole for transmitting a radio frequency electromagnetic field into said earth formation;

(b) using a receiving antenna assembly for receiving a signal resulting from interaction of said electromagnetic field with said earth formation;

(c) using a core for at least one of the antenna assemblies for enhancing the
25 received signals, said core formed from a material having at least one of (I) high internal magnetostrictive damping, and, (II) low magnetostriction.

[0019e] According to yet another aspect of the present invention there is provided an apparatus for evaluating electrical properties of an earth formation surrounding a borehole,
30 the apparatus comprising:

(a) a transmitting antenna assembly for conveying an electromagnetic field into said earth formation; and

(b) a receiving antenna assembly for receiving a signal resulting from interaction of said electromagnetic field with said earth formation;

wherein at least one of said antenna assemblies includes at least one magnetic core formed from a non-ferritic powdered soft magnetic material having high saturation flux density and a non-conductive bonding agent, said magnetic core having a magnetic permeability μ_m less than 500 and wherein said saturation flux density is greater than about 0.4 T.

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[0019f] According to still yet another aspect of the present invention there is provided a method of making measurements of a parameter of interest of an earth formation comprising:

- (a) conveying a logging tool into a borehole in said earth formation;
- (b) using a transmitter antenna assembly on the logging tool for
- 10 conveying an electromagnetic field into the earth formation;
- (c) using a receiver antenna assembly for detecting signals resulting from interaction of said electromagnetic field with said earth formation, and
- (d) including in at least one of the antenna assemblies a magnetic core formed from a non-ferritic powdered soft magnetic material having high saturation
- 15 flux density and a non-conductive bonding agent, said magnetic core having a magnetic permeability less than 500 and a saturation flux density greater than about 0.4 T.

Brief Description of the Drawings

- 20 **[0020]** The application is best understood with reference to the following drawings wherein like numbers in different figures refer to like components
- Figure 1 is an illustration of a typical NMR tool deployed in a bore hole.
- Figure 2 is a cross-sectional view of a preferred embodiment of the present invention
- 25 illustrating the geometry of a preferred NMR probe using the preferred powdered soft magnetic material of the present invention;
- Figure 3 is a plot of the isoline for the RF field generated by a preferred embodiment of the present invention utilizing a powdered soft magnetic core;
- 30 Figure 4 is a plot of two isolines for the static field generated by a preferred embodiment of the present invention utilizing a powdered soft magnetic core;
- Figure 5 is a plot of the isoline for the RF field generated by the probe geometry of Figure 2 without utilizing a powdered soft magnetic core;
- 35 Figure 6 is a plot of two isolines for the static field generated by the probe geometry of Figure 1 without utilizing a powdered soft magnetic core;
- Figure 7 illustrates the isolines for the magnetic flux density of the static field exceeding 0.35 T illustrating that no contour lines appear at the antenna core region;
- Figure 8 illustrates the flux density value of 0.35 T as well below the saturation flux density of typical iron powdered soft magnetic materials; and

Figure 9 is an illustration of an alternative embodiment of the present invention.

Figure 10 shows the results of a ringing test of NMR probes using a ferrite flux guide as part of the antenna assembly.

Figure 11 shows the results of a ringing test of NMR probes using an amorphous metal ribbon or Fluxtrol™

Figure 12 shows the magnetostrictive hysteresis associated with Fluxtrol™

Figure 13 shows the magnetostrictive hysteresis associated with steel.

Figure 14 shows an exemplary resistivity measurement sensor suitable for use with the present invention.

Detailed Description of a Preferred Embodiment

[0021] The invention is first discussed with reference to use in a wireline NMR logging tool. **Fig. 1**, illustrates well logging tool string **1** having an NMR probe **2**, having antenna assembly **4** deployed in bore hole **3**. The NMR probe sends magnetic pulses into and receives signals from region of investigation **5** in formation **6**. **Fig. 1** is shown for purposes of showing an example of the orientation of a tool utilizing the present invention and is not intended to limit the use of the present invention to a particular application or orientation.

[0022] **Fig. 2** illustrates a cross section of an exemplary logging tool for use with the present invention, taken perpendicular to axis of elongation. The preferred embodiment of **Fig. 2**, comprises a probe **2**, moveable through a bore hole **3** for measuring nuclear magnetic resonance (NMR) properties of a formation **6** surrounding the bore hole. The preferred probe comprises an elongated permanent magnet **21**, having an axis of elongation extending parallel to the axis of elongation of the probe **2** and parallel to the longitudinal axis of the bore hole **3**. The axes of elongation are perpendicular to plane of **Fig. 2**. Permanent magnet **21** has magnetic dipole moment **25** perpendicular to the axes of elongation.

[0019] Preferred antenna assembly **10** has an axis of elongation generally parallel to the axis of the magnet **21**. The preferred antenna assembly **10** comprises soft

magnetic core **22** and flat wires **23** and **31**. Core **22** is preferably comprised of the preferred powdered soft magnetic material such as the commercially available MICROMETALS™ or FLUXTROL® iron powder materials and preferably comprises a ferromagnetic metal powder combined with an organic non-conductive binder, such as an epoxy resin. The particle size of the powder is small enough to appear transparent to the RF magnetic field. In the 0.5 –1.0 MHz frequency range, the preferred non-ferrite soft magnetic material exhibits acceptable RF losses, thereby causing negligible deterioration of the NMR antenna Q-factor. An alternative to the powdered soft-magnetic material is provided by a laminated stack of ferromagnetic material ribbons as flux guiding material. The ribbons made from soft-magnetic material, which have preferably a low magnetostriction, such as amorphous metal for instance METGLAS®, need to be isolated from each other. The orientation of the ribbons has to be in the direction of the magnetic flux and the thickness needs to be low compared to the skin-depth of the respectively frequency in order to minimize eddy-currents. Antenna assembly **10** has a magnetic dipole moment **35** in the plane perpendicular to the axis of elongation. The antenna dipole moment **35** is perpendicular to a line between the effective center of the magnet dipole moment **25** and the effective center of the antenna dipole moment. Thus, the antenna assembly **10** generates a RF magnetic field perpendicular to the magnetic field of the permanent magnet in the area in front of the probe in sensitive volume **24** which is defined by the magnetic field of the permanent magnet and the RF magnetic field parameters.

[0023] Specifically, the static magnetic field, for which the resonance condition exists, is proportional to the excitation and detection frequency of the apparatus; the proportionality factor (gyromagnetic ratio) is dependent on the kind of atomic nuclei used, e.g. protons (hydrogen nuclei). Similarly, the RF magnetic field have optimum amplitudes that are related to the RF pulse durations and a direction perpendicular to the static magnetic field.

[0024] For the preferred embodiment of the probe presented in Fig. 2, the sensitive volume **24** is close to the shape of an arc in a cross-sectional plane perpendicular to

the axis of elongation, the arc extending within a defined angle, typically 70 - 120 degrees, depending upon the particular geometry of the magnet and the RF antenna assembly. Since the volume of investigation **24** exists on one side of the probe of **Fig. 2**, it is referred to as a side looking NMR probe design. The preferred core material, however, can be utilized in applications other than side looking probes or NMR applications for formations adjacent a bore hole.

[0025] The preferred probe core uses a non ferrite powdered soft magnetic material core which exhibits a lower magnetic permeability than sintered ferrite cores. The preferred powdered soft magnetic core material's permeability μ_m is typically 20-200, in contrast to permeability in the range of 500-10000, for ferrite NMR cores operating in the same frequency range. However, the preferred probe performs as effectively as a ferrite soft magnetic material as explained below.

[0026] For a given current in RF antenna elements **23** and **31**, the antenna magnetic moment, and consequently the antenna RF magnetic field projected into the NMR volume of investigation **24** is proportional to the effective magnetic permeability of the preferred soft magnetic core. The effective magnetic permeability is calculated using the magnetic material permeability μ_m and a core demagnetizing factor, D as follows:

$$\mu = 1 + (\mu_m - 1) / ((\mu_m - 1) \cdot D + 1) \quad (1)$$

The demagnetizing factor can be estimated from the elliptic equivalent of the cross-section of the core **22**, as shown in **Fig. 2**, as follows:

$$D = S_x / (S_x + S_y) \quad (2)$$

[0027] As shown in **Fig. 2**, in **eqn. (2)**, S_x and S_y represent the elliptic equivalent dimensions in the horizontal and vertical dimensions respectively, in the plane of **Fig. 2**, for a preferred powdered soft magnetic material core **22** geometry. There are two limiting cases for equation (1), as follows:

$$(D)(\mu_m - 1) \ll 1 \text{ or } \mu = \mu_m; \text{ and} \quad (3)$$

(D)($\mu_m - 1$) $\gg 1$, which means $\mu = 1 + 1/D$ (independent of μ_m). (4)

The second limit of **eqn. (4)** corresponds to the situation where the effective magnetic permeability and antenna efficiency are substantially independent of the magnetic permeability of the material. The maximum available permeability of the preferred, non- ferrite soft magnetic iron powder materials for the frequency around 1MHz is about 20. If we require that $D (\mu_m - 1) > 5$, which means insignificant effective permeability loss compared to high permeability ferrite, then the effective permeability as defined by the equation (1) should be less than 5. This value for the effective permeability corresponds to the demagnetizing factor of more than 0.25 and the S_y/S_x ratio of less than 3.

[0028] In a preferred embodiment, using the preferred powdered soft magnetic material, a magnetic core shape is provided, having values for S_x and S_y , which ensure that the effective permeability of the core, μ as determined by the core proportions associated with the shape or core geometry does not exceed a value of 5. It is these relative proportions, rather than a particular shape that facilitate use of the preferred powdered core material. For known prior core geometric shapes, structures or designs, the effective magnetic permeability, dictated by the core shape, is greater than 5, which renders the preferred non ferrite powder soft magnetic material ineffective when compared to the performance of ferrite cores.

[0029] **Fig. 3** illustrates the isoline for the probe RF field when using the preferred soft magnetic material in the probe geometry of **Fig. 2**. **Fig. 4** illustrates the isoline **41** for the static magnetic field, when using the preferred magnetic material in the core **22** of the preferred probe geometry of **Fig. 2**. The distances shown in **Figs. 3** and **4** are normalized to a NMR probe cross sectional radius of 2". Isolines for field strengths of 0.021T and 0.0205T are shown in **Fig. 4**. **Figs. 5** and **6** illustrate the isolines for the static magnetic field **51** and the RF magnetic field **61** respectively, for the probe geometry of **Fig. 2**, without using the preferred powdered soft magnetic material in core **22**. Isolines for field strengths of 0.066T are shown in **Fig. 5** while

isolines for a field strength of 0.018T and 0.0175T are shown in **Fig. 6**. Comparison of the static magnetic field and RF magnetic field isolines of **Figs. 3 and 4** to the static magnetic field and RF magnetic field isolines of **Figs. 5 and 6**, demonstrates an improvement by a factor of 3 in the RF antenna efficiency and magnet field enhancement, for the probe design of **Fig. 2** using the preferred powdered soft magnetic core material. The reciprocity principle suggests that the probe of **Fig. 2**, using a soft magnetic material core, provides a three-fold gain in probe sensitivity in the receiving mode as well.

[0030] **Fig. 7** is a plot that was generated to show isolines for the magnetic flux density of the static magnetic field exceeding 0.35 T. None are seen. As it is clear from **Fig. 8**, presenting the magnetic hysteresis curve **B1** for the preferred core material, the flux density value of 0.35 T is well below the saturation flux density of the preferred core soft magnetic iron powder materials which is about 1.2T. This value typically exceeds the maximum flux density near the surface of the strongest permanent magnets (e.g., Sm₂Co₁₇), thereby enabling a new variety of geometric core designs, not previously useful in core designs, which required compensation for the limitations of ferrite cores.

[0031] **Fig. 9** illustrates an alternative embodiment of the present invention having two cores **92** and **93** and magnet **96**. Antenna flat wires **94** and **95** are located adjacent cores **92** and **93**, respectively. Magnet **96** has magnetic dipole **98**. Preferably both cores are made of the preferred soft core material. The antenna assembly of **Figure 9** generates a RF magnetic field perpendicular to the magnetic field of the permanent magnet in the area in front of the probe in sensitive volume **97**.

[0032] The limiting eqns. (1) and (2) and other geometric considerations, as well as the maximum effective permeability, as discussed in connection with use of the preferred powdered soft magnetic core material and core shape of **Fig. 2**, also apply to the alternative embodiment of the probe shown in **Fig. 9**. In the preferred embodiment, as shown in **Fig. 2**, the antenna dipole moment is perpendicular to a line

between an effective center of the magnet dipole moment and an effective center of the antenna dipole moment. In the alternative embodiment of **Fig. 9**, the permanent magnet has a magnetic dipole moment in a plane perpendicular to the axes of elongation and the antenna assembly has a dipole moment in a plane perpendicular to the axes of elongation and parallel to a line between the effective center of the magnet dipole moment and the effective center of the antenna dipole moment. In another alternative embodiment, the permanent magnet has a magnetic dipole moment in a plane perpendicular to the axes of elongation, the antenna assembly has a dipole moment in a plane perpendicular to the axes of elongation and the antenna dipole moment and the magnet dipole moment have coincident effective centers.

[0033] In addition to improving antenna efficiency, the flux concentration effect of the preferred powdered soft magnetic core provides the additional significant consequence of rendering the antenna assembly relatively insensitive to the conductivity of the permanent magnet. This insensitivity enables the use of relatively powerful conductive magnets, for example SmCo, to establish a larger static magnetic field, increasing the NMR signal and NMR signal-to-noise ratio.

[0034] The preferred powdered core material also reduces or substantially eliminates magnetostrictive ringing by virtue of the particulate structure of the preferred material. The magnetic particle size of the preferred core material (powder) is substantially smaller than the minimum wavelength for acoustic excitation associated with magnetostrictive ringing. Moreover, the epoxy binder does not efficiently transmit acoustic energy between particles.

[0035] The preferred powdered core magnetic and electrical characteristics are more stable than ferrite core characteristics in presence of temperature variations. This temperature stability is due to the fact that the magnetic and electrical characteristic of the preferred core is determined mainly by the shape of the core and the micro-geometry of the particulate structure (particle shape and volume packing density) of the preferred powdered material and substantially independent of the material of the

particles.

[0036] Using magnetic materials in the antenna as a magnetic core could cause problems with magneto-acoustic excitation due to the effect of magnetostriction. In ferromagnetic materials, there is a coupling between the elastic quantities and magnetism leading to a dependence of elastic energy on the magnetization of the material. This dependence results in a stress (and strain) when magnetization of the material changes. The stress is initially generated in the transmit mode of the antenna operation. The effect is most noticeable but not limited to the situation where the generated stress has the frequency of an acoustic resonance of a structural element of the soft magnetic core. Even without acoustic resonance during the RF pulse an acoustic wave packet is transmitted. This travels along the body of the NMR tool and gets reflected at mechanical interfaces. Therefore, at various times, reflected acoustic wave packets arrive back at the NMR sensor coil and cause interference. Conversely, if stress is applied to an unsaturated crystal, the local magnetization will change direction (and in most cases, the bulk magnetization will change its magnitude) in order to reduce the stress energy through the action of magnetostrictive strain. The change of magnetization corresponding to the oscillating stress will induce a spurious signal in the NMR antenna during the process of receiving the NMR spin echo signals.

[0037] Turning now to **Fig. 10**, shown are two sets of experimental data showing the spectral ringing of a ferrite flux guide. The abscissa is frequency (ranging from 460kHz to 540kHz) while the ordinate is the amplitude of the spectra in arbitrary units. The ringing is noticeable in the spectral band from about 490 kHz to 510kHz. The ferrite for which data are shown in **Fig. 10** has a high level of magnetostrictive ringing, which is quite normal for ferrite material.

[0038] Similar sets of experimental data are shown in **Fig. 11** for two different materials that are characterized by a low level of magnetostrictive ringing. The curve 151 corresponds to a stack of amorphous metal ribbons (discussed below) while the

curve **153** is for the material Fluxtrol® (#17) that is a powdered soft magnetic material of the type discussed above. It should be pointed out that the vertical scale in **Fig. 11** is from 0 – 25 units: this is much smaller than the range in **Fig. 10** that is from 0 – 3000 arbitrary units. These data show that the stack of amorphous metal ribbons and soft magnetic materials have a level of ringing that is two orders of magnitude less than ferrite.

[0039] It should be noted that Fluxtrol® has been used in the past, primary as flux concentrators for induction heating. This is brought out by the Fluxtrol® document downloaded from the website for Fluxtrol Manufacturing Company. What follows includes a discovery of a novel use for the material.

[0040] Turning now to **Fig. 12**, a hysteresis curve for a Fluxtrol® is shown. The abscissa is the current applied to a coil enclosing a sample of the material and the ordinate is the magnetostrictive deformation produced (in μm). The arrows in **Fig. 12** show that as the current is increased, the deformation is increased, but upon reducing the current, some residual deformation will remain. The large area within the hysteresis curve is an indication of high internal dissipation and damping. This is much larger than the hysteresis curve for a steel core shown in **Fig. 13**.

[0041] Turning now to **Fig. 13**, a hysteresis curve for steel is shown. The scales in **Fig. 13** are the same as the scales in **Fig. 12**., making it clear that there would be very little internal damping of acoustic waves in steel.

[0042] Typical metals used in soft magnetic cores have an acoustic wave velocity of the order of 6km/s. At an RF frequency of 500kHz, this gives a wavelength for acoustic waves of approximately 12 mm. In order to reduce intragranular electromagnetic RF losses, the grain sizes used in powdered cores are of the order of 0.01 – 0.1 mm. Hence selecting the grain size to minimize RF dissipation also makes the grain size much smaller than half the acoustic wavelength.

[0043] A second requirement is that the binding material should also provide electrical insulation and acoustic decoupling between metal particles. The necessity of having a sufficient quantity of binding material to provide electrical insulation and acoustic decoupling leads to a relatively low magnetic permeability. This low magnetic permeability limits the use of such materials to core configurations having a high demagnetization factor, e.g., as antenna cores.

[0044] We next discuss amorphous metals as fluxguides. Cooling certain molten metal alloys extremely rapidly to the solid state makes an amorphous metal. This material has specific properties depending on the actual composition of the alloy. Some of the materials such as METGLAS® 2705M from Allied Signal Inc. provide high magnetic permeability combined with low magnetostriction. Due to the manufacturing process it is only available in ribbons of about 2 inch times 0.8mil. In a preferred embodiment of the invention, a flux guide of a NMR antenna comprising a stack of amorphous metal ribbons with non-conductive interlayers is used. The interlayer should isolate the ribbons from each other and provide high acoustic damping and should absorb the remaining magnetostrictive ringing. In order to avoid eddy currents, the stack of laminates should be oriented in such a way that high frequency field lines do not cross the amorphous ribbon. A flux guide, of the type for which test results are shown in Fig. 11, is made of a stack of METGLAS® 2705M with Kapton® interlayer. Kapton® is a registered trademark of DuPont that generally covers a variety of polyamide films.

[0045] Amorphous metals and, specifically METGLAS® have been used in prior art as antenna cores. Examples of these are given in US Patents 5,220,338 and 5,220,339 to *Matsushita*. However, their use as antenna cores for an NMR apparatus and method with reduced magnetostrictive ringing are believed to be novel.

[0046] The present invention has been discussed above using a wireline logging tool of *Reiderman* as an example. The present invention is equally applicable for use with

Measurement-while-drilling logging (MWD) tools. For example, US Patent 6215304 to *Slade* teaches the use of ferrite members for an antenna core for MWD applications. As discussed therein, the core has to be split up into a plurality of separate members with gaps in-between to avoid resonance effects. Instead of gapped ferrite elements, materials of the present invention may be used in a preferred embodiment of a MWD NMR logging tool such as that of *Slade*..

[0047] We next discuss use of the present invention in a MWD resistivity tool. Specifically, the antenna core of the present invention may be used with an electromagnetic formation evaluation tool such as that disclosed in U.S. Patent No. 5,138,263 to *Towle*., having the same assignee. It is to be noted that the device of *Towle* is only for exemplary purposes, and that the antenna core material of the present invention may be used with any MWD formation evaluation device that requires the transmission and/or reception of electromagnetic signals indicative of properties of earth formations.

[0048] Referring to FIG. 14 (prior art) a tool 311 of the present invention includes a longitudinally extending cylindrical housing 312. The housing 312 has an inner diametral surface 314 defining a longitudinal bore through the housing and has an outer diametral surface 316. A circumferential groove 318 is defined in the outer diametral surface 316.

[0049] Six magnetic elements 324 are secured within groove 318. Each of the magnetic elements 324 is C-shaped and has a curvilinear body 326 extending from a first end 328 to a second end 330. Each of the magnetic elements 324 is oriented so that the first and second ends 328, 330 are longitudinally aligned with the rotational axis of the tool housing 312 and face radially outwardly from the housing 312.

[0050] The magnetic elements 324 may comprise an material having a relative magnetic permeability of about 10 or greater. The magnetic elements 324 described in

the *Towle* patent comprise powdered iron or ferrite. The present invention envisages use of the soft magnetic material described in the *Reiderman* patent and any of the materials described above with respect to the NMR logging tool

5 [0051] An antenna loop 332 circumferentially surrounds housing 312 and is secured with the circumferential groove 318 by supports 334. The antenna loop 332 may comprise a single turn of wire or multiple turns of wire. Preferably, the antenna loop comprises a wire element 336 within a tubular electrostatic shield 338. Preferably, the electrostatic shield 338 comprises a beryllium copper alloy.

10 [0052] An elastomer layer 340 fills circumferential groove 318, is bonded to the housing 312 and surrounds the antenna loop 332 and magnetic elements 324 to protect the antenna loop 332 and magnetic elements 324 from impact and moisture. Preferably, the elastomeric layer comprises a nitrile rubber composition.

15 [0053] The resistivity measurements may be made for both propagation resistivity tools as well as for induction tools as the terms are understood in the art. In propagation resistivity tools, measurements are made of amplitude and/or phase differences for received electromagnetic signals for two different transmitter-receiver
20 distances. These differences are indicative of the resistivity of earth formations. For induction tools, currents are induced in earth formations by the transmitter and the resulting induced currents in the receiver are indicative of the resistivity of earth formations. In a general sense, for both induction and propagation resistivity tools, the receiver antenna receives signals resulting from interaction of a generated
25 electromagnetic signal with the earth formation. Any of the materials discussed above with reference to the wireline NMR logging tool may be used for the antenna core.

30 [0054] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be

embraced by the foregoing disclosure.

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AMENDED CLAIMS

[received by the International Bureau on 12 February 2004 (12.02.04);
original claims 1 and 10 amended; remaining claims unchanged]

- 1 1. A nuclear magnetic resonance (NMR) logging apparatus for use in a
2 borehole for determining properties of an earth formation surrounding the
3 borehole, the apparatus comprising:
4 (a) a magnet for inducing a static magnetic field in a region of interest in
5 the earth formation;
6 (b) a transmitting antenna assembly for inducing a radio frequency
7 magnetic field within said region of interest and producing signals
8 from materials in the region of interest; and
9 (c) a receiving antenna assembly for detecting said signals from said
10 region of interest;
11 wherein at least one of the antenna assemblies includes at least one magnetic
12 core formed from a non-ferritic material having low magnetostriction.
13
- 1 2. The NMR logging apparatus of claim 1 wherein said material has a
2 high internal damping and further comprises a powdered soft magnetic
3 material.
4
- 1 3. The NMR logging apparatus of claim 2 wherein the powdered soft magnetic
2 material is non-conductive and has a maximum grain size to
3 substantially reduce intragranular power loss at a frequency of said radio
4 frequency magnetic field.
5
- 1 4. The NMR logging apparatus of claim 2 wherein the powdered soft
2 magnetic material has a maximum grain size less than half the wavelength of an
3 acoustic wave having a frequency of said radio frequency magnetic field.
4
- 1 5. The NMR logging apparatus of claim 1 wherein said material has a
2 high internal damping and further has a large area within a hysteresis loop
3 associated with magnetostrictive deformation of the material.
4
- 1 6. The NMR logging apparatus of claim 2 wherein said at least one antenna

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2 core further comprises a non-conductive bonding agent having substantial
3 acoustic decoupling between grains.

4

1 7. The NMR logging apparatus of claim 1 wherein said logging apparatus is
2 adapted to be conveyed on one of (i) a wireline, and, (ii) a drilling tubular.

3

1 8. The NMR logging apparatus of claim 1 wherein said material has a low
2 magnetostriction and comprises an amorphous metal.

3

1 9. The NMR logging apparatus of claim 1 wherein the transmitting antenna
2 assembly and the receiving antenna assembly are the same.

3

1 10. A method of determining properties of an earth formation surrounding a
2 borehole, the method comprising:

3 (a) using a magnet on a nuclear magnetic resonance (NMR) logging
4 apparatus conveyed in the borehole for inducing a static magnetic field
5 in a region of interest in the earth formation;

6 (b) using a transmitting antenna assembly for inducing a radio frequency
7 magnetic field within said region of interest and producing signals
8 from materials in the region of interest; and

9 (c) using a receiving antenna assembly for detecting said signals from said
10 region of interest;

11 the method further comprising using a core for at least one of the antenna
12 assemblies formed from a non ferritic material having low magnetostriction.

13

1 11. The method of claim 10 wherein said material has a high internal damping,
2 the method further comprising using a powdered soft magnetic material as
3 said material with high internal damping.

4

1 12. The method of claim 11 further comprising selecting the powdered soft
2 magnetic material to be substantially non-conductive and having a maximum

- 3 grain size to substantially reduce intragranular power loss at a frequency of
4 said radio frequency magnetic field.
5
- 1 13. The method of claim 11 further comprising selecting the powdered soft
2 magnetic material as having a maximum grain size less than half a
3 wavelength of an acoustic wave having a frequency of said radio frequency
4 magnetic field.
5
- 1 14. The method of claim 10 wherein said material has high internal damping, the
2 method further comprising selecting said material as having a large area
3 within a hysteresis loop associated with magnetostrictive deformation of the
4 material.
5
- 1 15. The method of claim 11 further comprising using in said at least one antenna
2 core a non-conductive bonding agent having substantial acoustic decoupling
3 between grains.
4
- 1 16. The method of claim 10 further comprising conveying said NMR logging
2 apparatus into said borehole on one of (i) a wireline, and, (ii) a drilling
3 tubular.
4
- 1 17. The method of claim 10 wherein said material has a low magnetostriction, the
2 method further comprising selecting an amorphous metal for use as said
3 material.
4
- 1 18. The method of claim 10 further comprising using the same antenna for the
2 transmitting antenna and the receiving antenna.
3
- 1 19. An apparatus for evaluating electrical properties of an earth formation
2 surrounding a borehole, the apparatus comprising:
3 (a) a transmitting antenna assembly for conveying a radio frequency

- 4 electromagnetic field into said earth formation; and
- 5 (b) a receiving antenna assembly for receiving a signal resulting from
- 6 interaction of said electromagnetic field with said earth formation;
- 7 wherein at least one of the antenna assemblies includes at least one of: (I) a
- 8 magnetic core formed from a material having high internal magnetostrictive
- 9 damping, and, (II) low magnetostriction.
- 10
- 1 20. The apparatus of claim 19 wherein said material has a high internal damping
- 2 and further comprises a powdered soft magnetic material.
- 3
- 1 21. The apparatus of claim 20 wherein the powdered soft magnetic material is
- 2 non-conductive and has a maximum grain size to substantially reduce
- 3 intragranular power loss at a frequency of said radio frequency magnetic field.
- 4
- 1 22. The apparatus of claim 20 wherein the powdered soft magnetic material has a
- 2 maximum grain size less than half a wavelength of an acoustic wave having a
- 3 frequency of said radio frequency magnetic field.
- 4
- 1 23. The apparatus of claim 19 wherein said material has a high internal damping
- 2 and further has a large area within a hysteresis loop associated with
- 3 magnetostrictive deformation of the material.
- 4
- 1 24. The apparatus of claim 20 wherein said at least one antenna core further
- 2 comprises a non-conductive bonding agent having substantial acoustic
- 3 decoupling between grains.
- 4
- 1 25. The apparatus of claim 19 wherein said apparatus is adapted to be conveyed
- 2 on one of (i) a wireline, and, (ii) a drilling tubular.
- 3
- 1 26. The apparatus of claim 19 wherein said material has a low magnetostriction
- 2 and comprises an amorphous metal.

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3

1 27. A method of determining a resistivity parameter of an earth formation
2 surrounding a borehole, the method comprising:

3 (a) using a transmitting antenna assembly on a tool conveyed in said
4 borehole for transmitting a radio frequency electromagnetic field into
5 said earth formation;

6 (b) using a receiving antenna assembly for receiving a signal resulting
7 from interaction of said electromagnetic field with said earth
8 formation;

9 (c) using a core for at least one of the antenna assemblies for enhancing
10 the received signals, said core formed from a material having at least
11 one of (I) high internal magnetostrictive damping, and, (II) low
12 magnetostriction.

13

1 28. The method of claim 27 wherein said material has a high internal damping,
2 the method further comprising using a powdered soft magnetic material as
3 said material with high internal damping.

4

1 29. The method of claim 28 further comprising selecting the powdered soft
2 magnetic material to be substantially non-conductive and having a maximum
3 grain size to substantially reduce intragranular power loss at a frequency of
4 said radio frequency magnetic field.

5

1 30. The method of claim 28 further comprising selecting the powdered soft
2 magnetic material as having a maximum grain size less than half a wavelength
3 of an acoustic wave having a frequency of said radio frequency magnetic
4 field.

5

1 31. The method of claim 27 wherein said material has high internal damping, the
2 method further comprising selecting said material as having a large area
3 within a hysteresis loop associated with magnetostrictive deformation of the

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4 material.

5

1 32. The method of claim 28 further comprising using in said at least one antenna
2 core a non-conductive bonding agent having substantial acoustic decoupling
3 between grains.

4

1 33. The method of claim 27 wherein said material has a low magnetostriction, the
2 method further comprising selecting an amorphous metal for use as said
3 material.

4

1 34. The method of claim 27 wherein said tool is conveyed into the borehole on
2 one of (i) a wireline, and, (ii) a drilling tubular.

3

1 35. An apparatus for evaluating electrical properties of an earth formation
2 surrounding a borehole, the apparatus comprising:

3 (a) a transmitting antenna assembly for conveying an electromagnetic
4 field into said earth formation; and

5 (b) a receiving antenna assembly for receiving a signal resulting from
6 interaction of said electromagnetic field with said earth formation;

7 wherein at least one of said antenna assemblies includes at least one magnetic
8 core formed from a non-ferritic powdered soft magnetic material having high
9 saturation flux density and a non-conductive bonding agent, said magnetic
10 core having a magnetic permeability μ_m less than 500 and wherein said
11 saturation flux density is greater than about 0.4 T.

12

1 36. The apparatus of claim 35, wherein the magnetic core further comprising
2 dimensions which are related to the direction of an RF magnetic field
3 produced by the transmitter coil and to the magnetic permeability of the
4 powdered soft magnetic material.

5

1 37. The apparatus of claim 35 wherein the powdered soft magnetic material is

2 conductive and has a maximum grain size to substantially prevent
3 intragranular power loss of said transmitted electromagnetic signal.

4
1 38. The apparatus of claim 35 wherein an effective demagnetizing factor of the
2 magnetic core in a direction of the radio frequency magnetic field
3 substantially exceeds the inverse magnetic permeability of the powdered soft
4 magnetic material.

5
1 39. The apparatus of claim 36, wherein the core has an effective permeability, μ ,
2 less than 5, as defined by a first equation,

$$\mu = 1 + (\mu_m - 1) / ((\mu_m - 1) \cdot D + 1),$$

4 wherein D, the demagnetizing factor can be estimated from an elliptic
5 equivalent of the cross-section of the core, as defined by a second equation,
6 $D = S_x / (S_x + S_y)$,

7 wherein S_x and S_y represent the elliptic equivalent dimensions in horizontal
8 and vertical dimensions respectively, in a plane the core.

9
1 40. The apparatus as defined in claim 35 wherein the powdered soft magnetic
2 material possesses a maximum magnetic permeability given a predetermined
3 maximum RF antenna power loss.

4
1 41. The apparatus of claim 35 wherein said flux density is greater than that of a
2 magnetic core consisting primarily of ferrite.

3
1 42. The apparatus of claim 35 wherein the magnetic core further comprises
2 relative dimensions that are related to the direction of the RF magnetic field
3 and to the magnetic permeability of the powdered soft magnetic material.

4
1 43. A method of making measurements of a parameter of interest of an earth
2 formation comprising:

3 (a) conveying a logging tool into a borehole in said earth formation;

- 4 (b) using a transmitter antenna assembly on the logging tool for
 5 conveying an electromagnetic field into the earth formation;
 6 (c) using a receiver antenna assembly for detecting signals resulting from
 7 interaction of said electromagnetic field with said earth formation, and
 8 (d) including in at least one of the antenna assemblies a magnetic core
 9 formed from a non-ferritic powdered soft magnetic material having
 10 high saturation flux density and a non-conductive binding agent, said
 11 magnetic core having a magnetic permeability μ_m less than 500 and a
 12 saturation flux density greater than about 0.4T.
 13

- 1 44. The method of claim 43 further comprising selecting dimensions for the
 2 magnetic core which are related to the direction of the magnetic field and to
 3 the magnetic permeability of the powdered soft magnetic material.
 4
 1 45. The method of claim 43 further comprising selecting relative dimensions for
 2 the magnetic core which are related to the direction of the magnetic field and
 3 to the magnetic permeability of the powdered soft magnetic material.
 4
 1 46. The method of claim 43 wherein the powdered soft magnetic material is
 2 conductive, the method further comprising selecting a maximum grain size for
 3 the soft magnetic material to substantially prevent intragranular power loss of
 4 said radio frequency magnetic field.
 5
 1 47. The method of claim 43 wherein an effective demagnetizing factor of the
 2 magnetic core in the direction of the magnetic field substantially exceeds the
 3 inverse magnetic permeability of the powdered soft magnetic material.
 4
 1 48. The method of claim 47, wherein the core has an effective permeability, μ ,
 2 less than 5, as defined by a first equation,
 3
$$\mu = 1 + (\mu_m - 1) / ((\mu_m - 1) \cdot D + 1),$$

 4 wherein D, the demagnetizing factor can be estimated from an elliptic

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5 equivalent of the cross-section of the core, as defined by a second equation,

6
$$D = S_x / (S_x + S_y),$$

7 wherein S_x and S_y represent the elliptic equivalent dimensions in horizontal
8 and vertical dimensions respectively, in a plane the core.

9

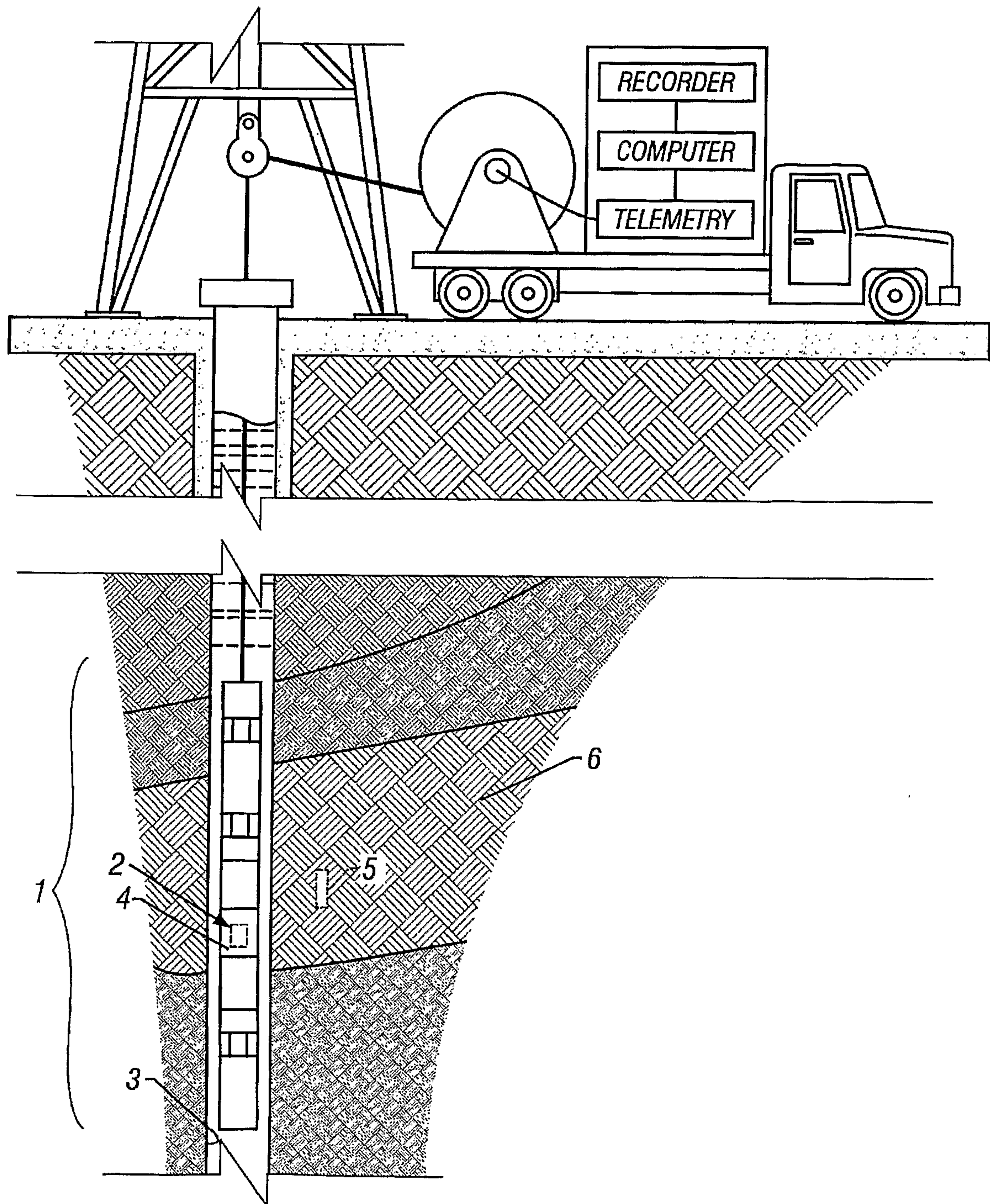
1 49. The method of claim 43, wherein the powdered soft magnetic material
2 possesses a maximum magnetic permeability given a predetermined
3 maximum RF antenna power loss.

4

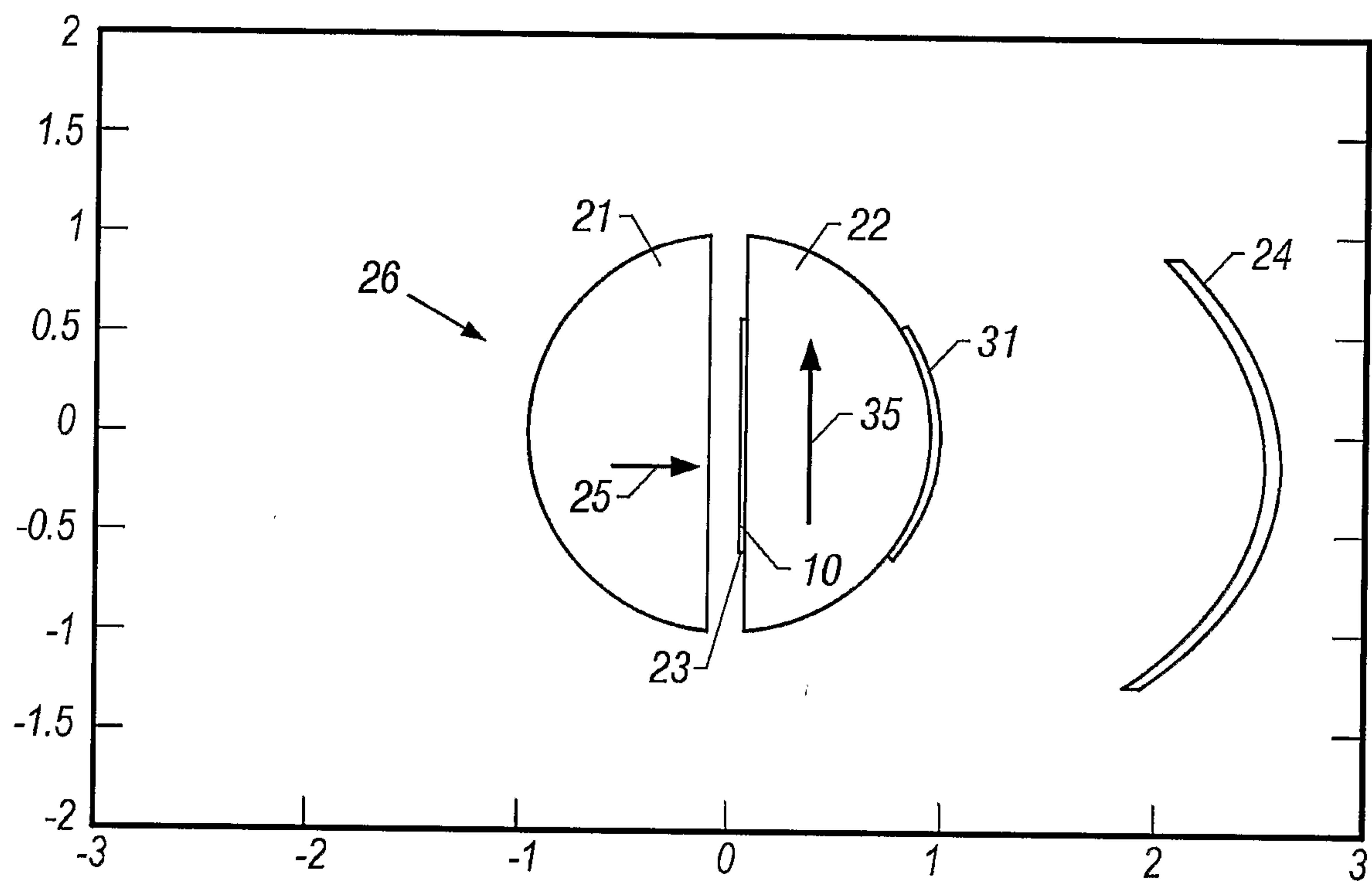
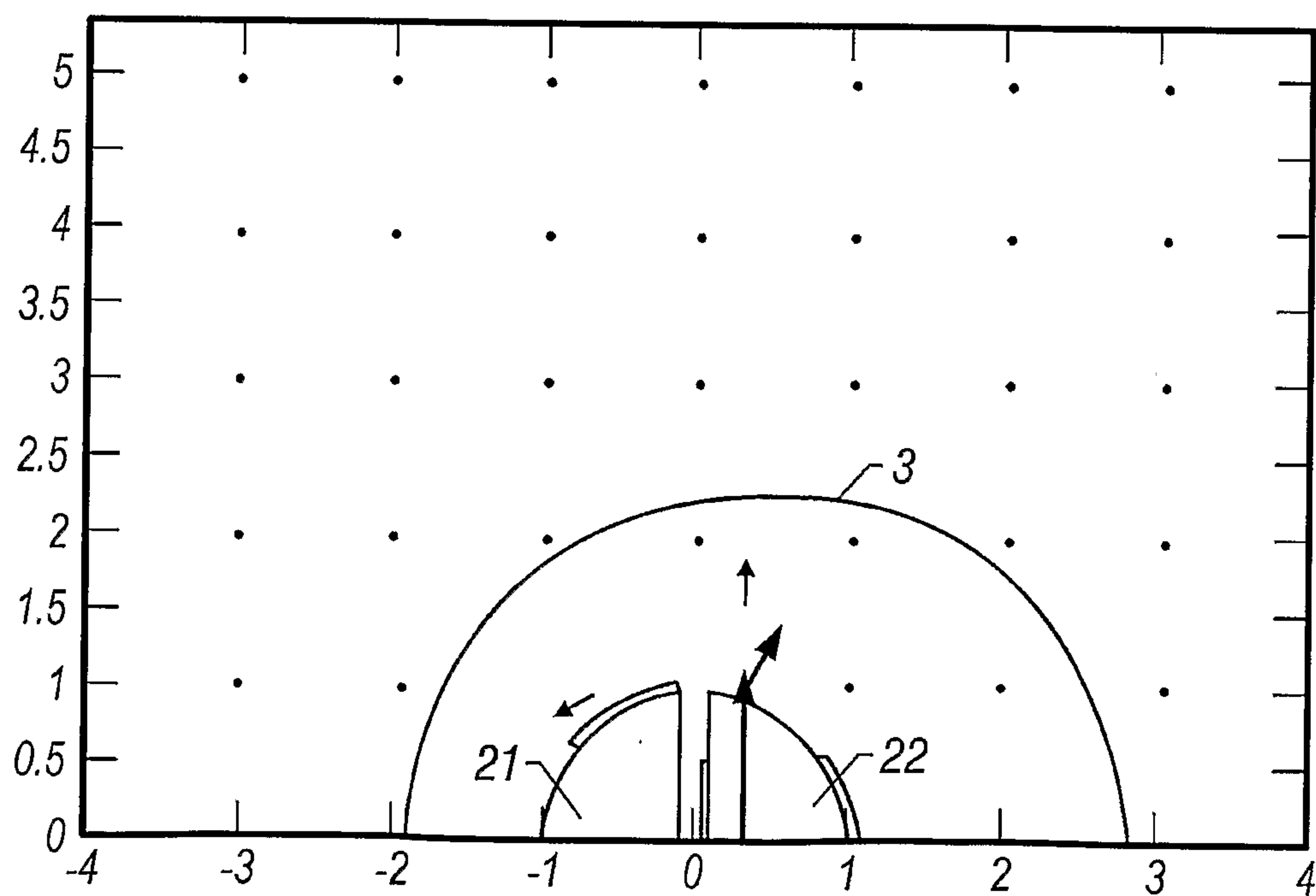
1 50. The method of claim 43, wherein the magnet and the antenna possess an
2 elongation direction, the radio frequency magnetic field and the static
3 magnetic field being perpendicular to the elongation direction.

4

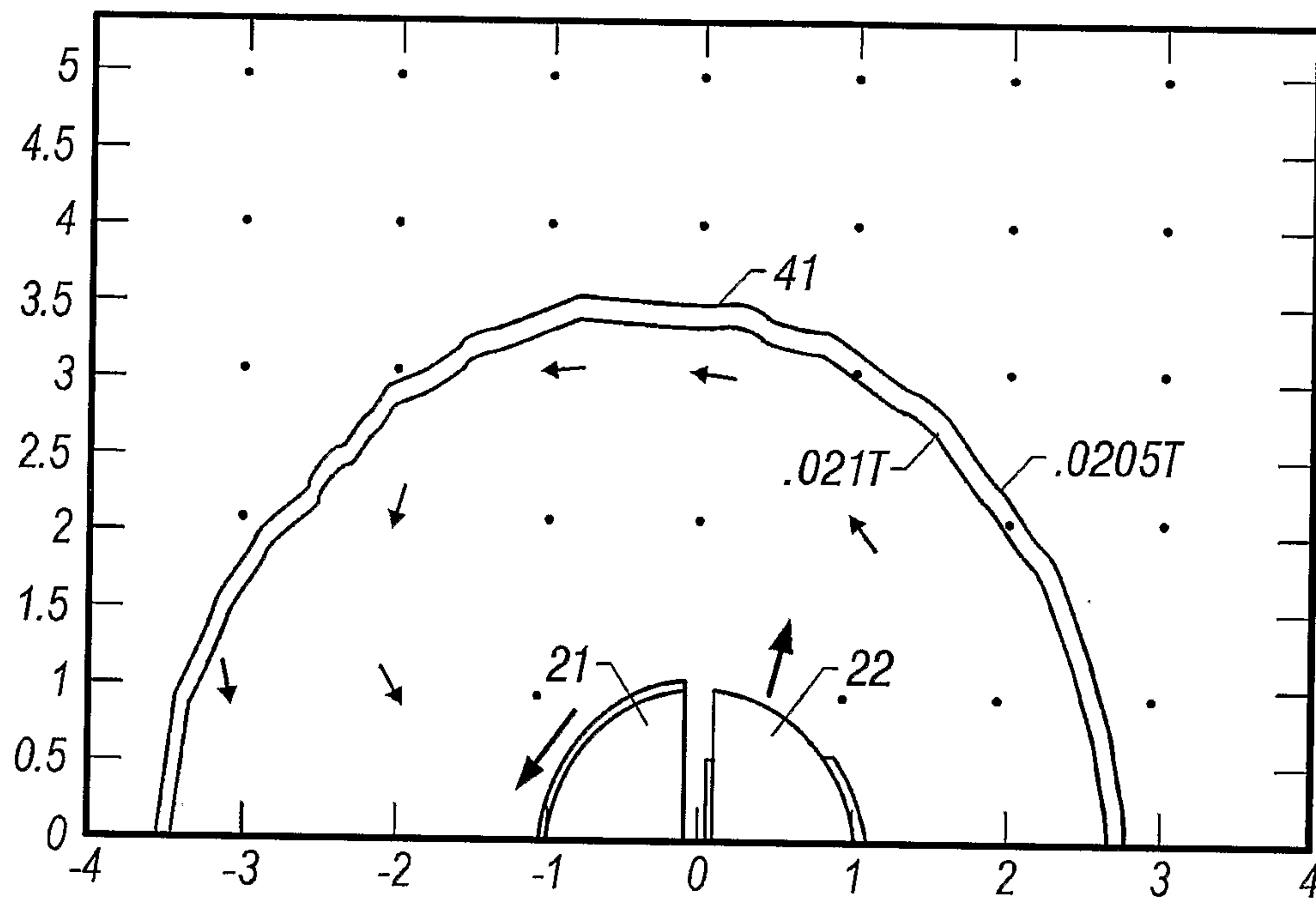
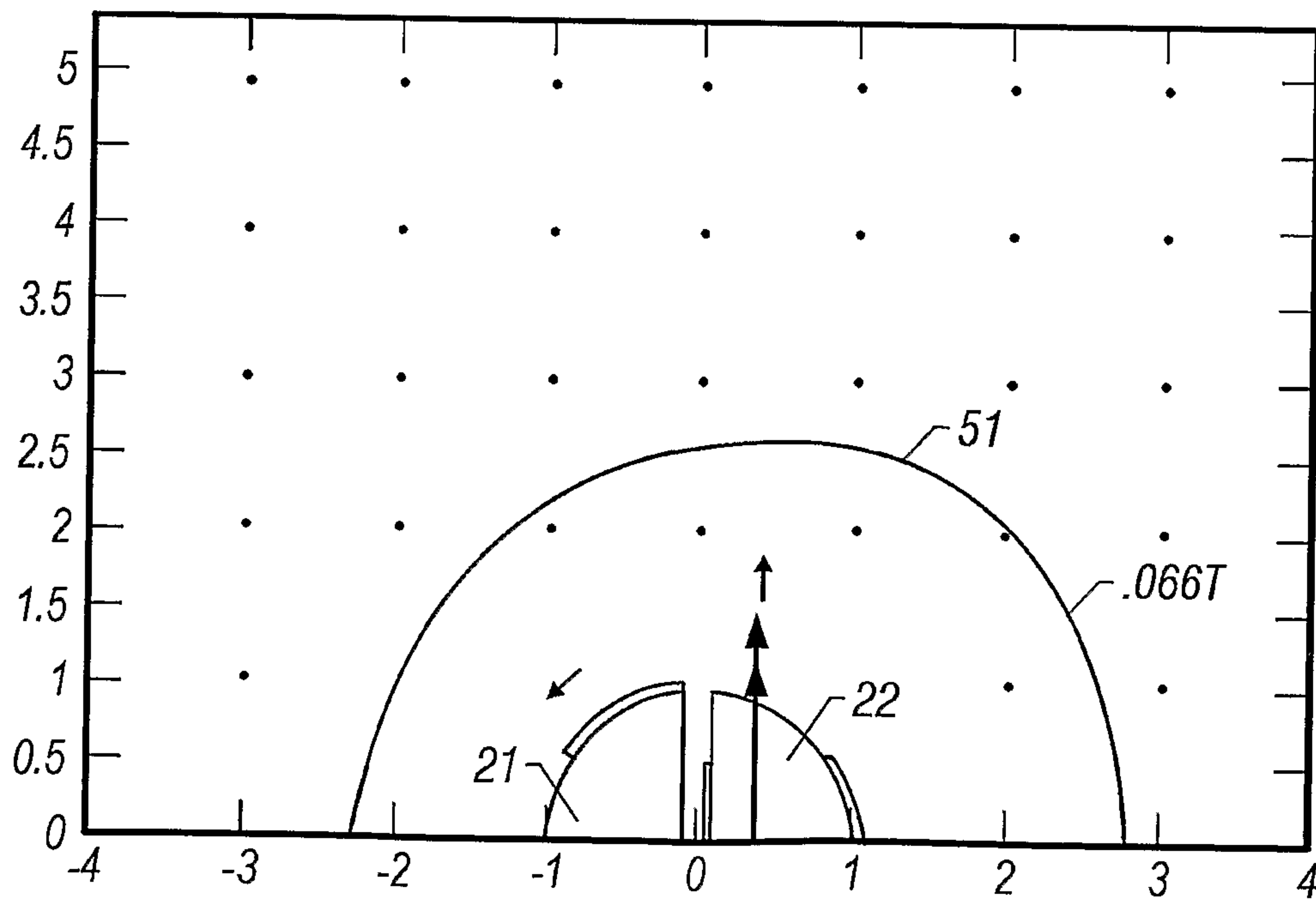
1/8

**FIG. 1**

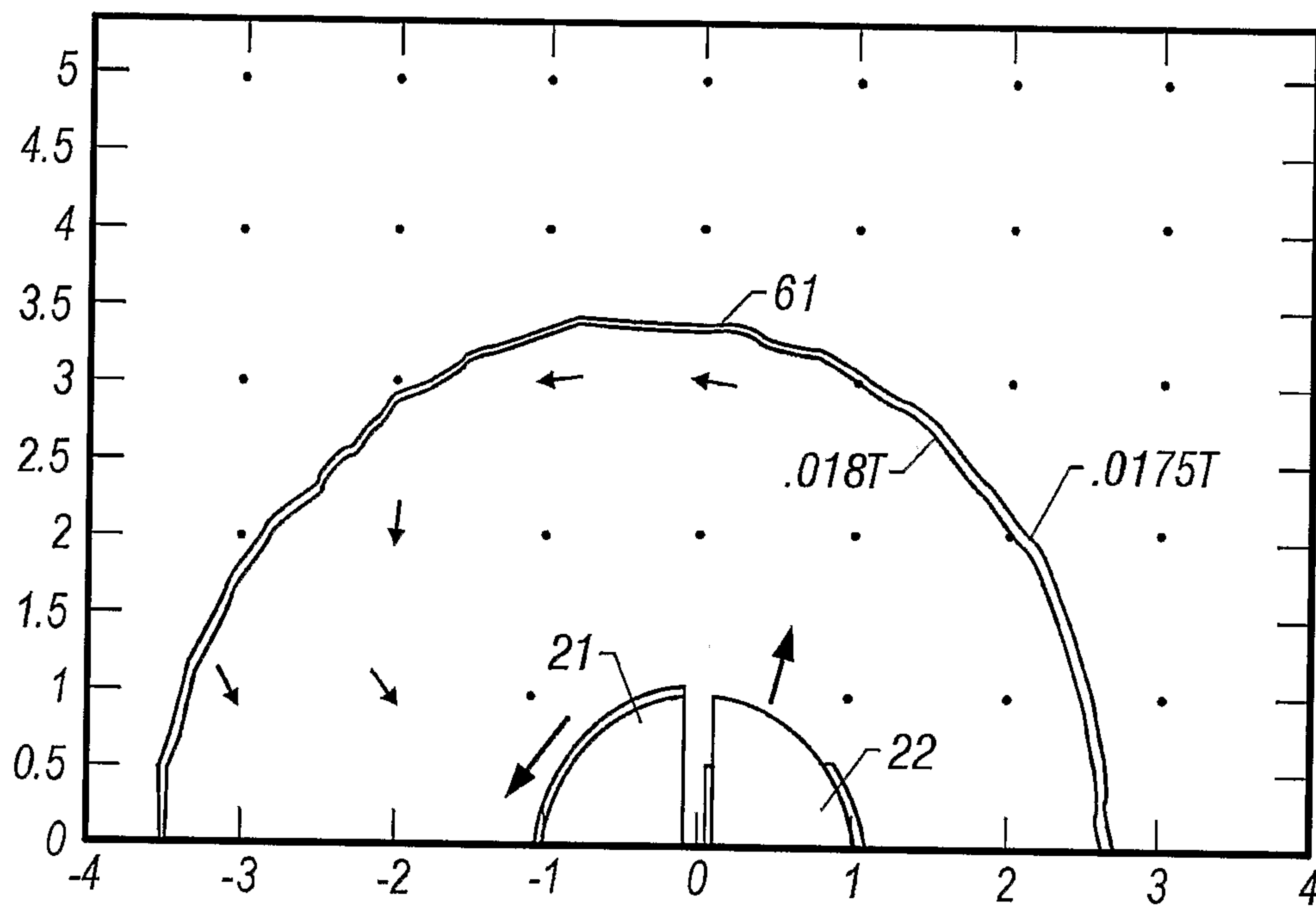
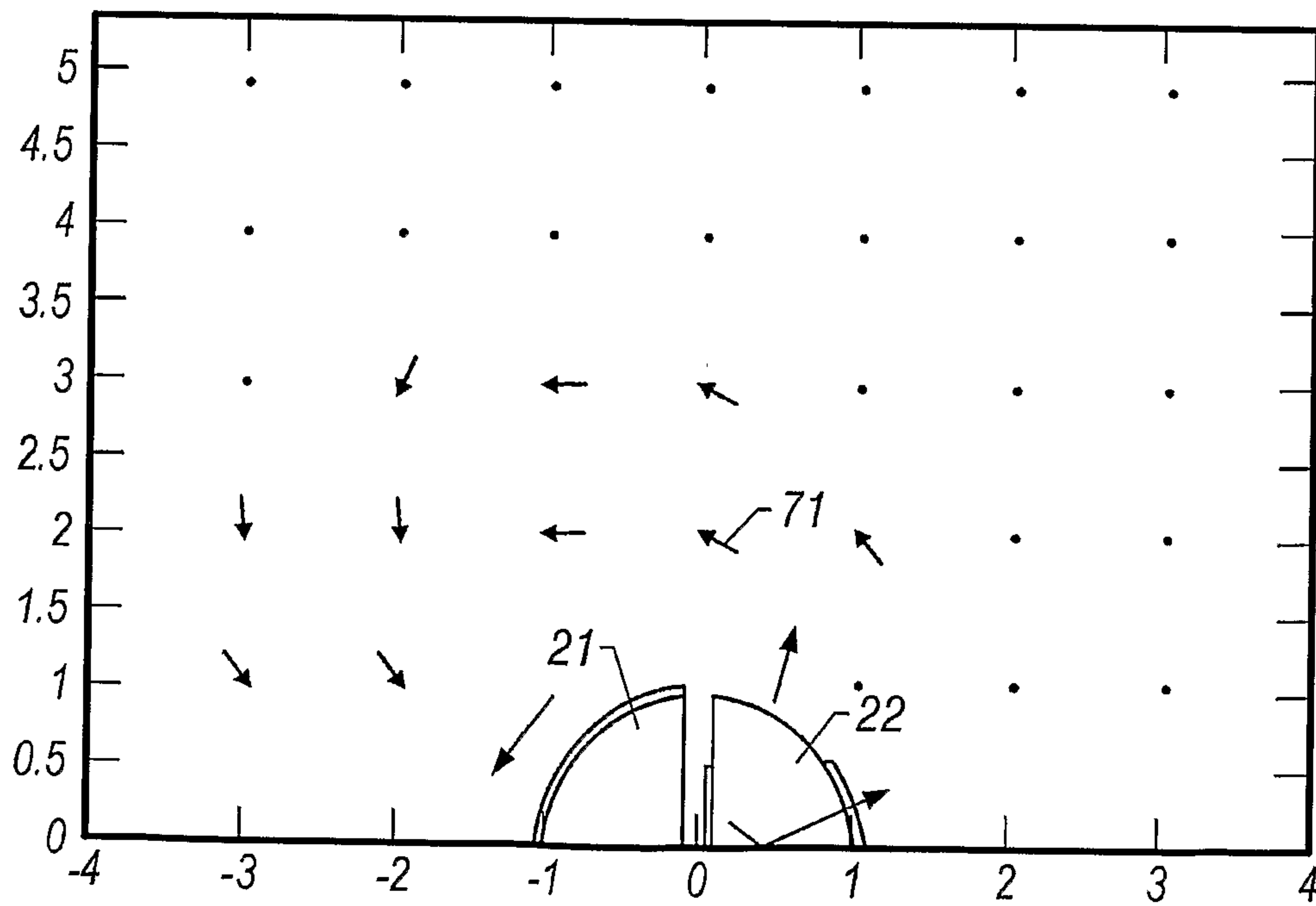
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**FIG. 2****FIG. 3**

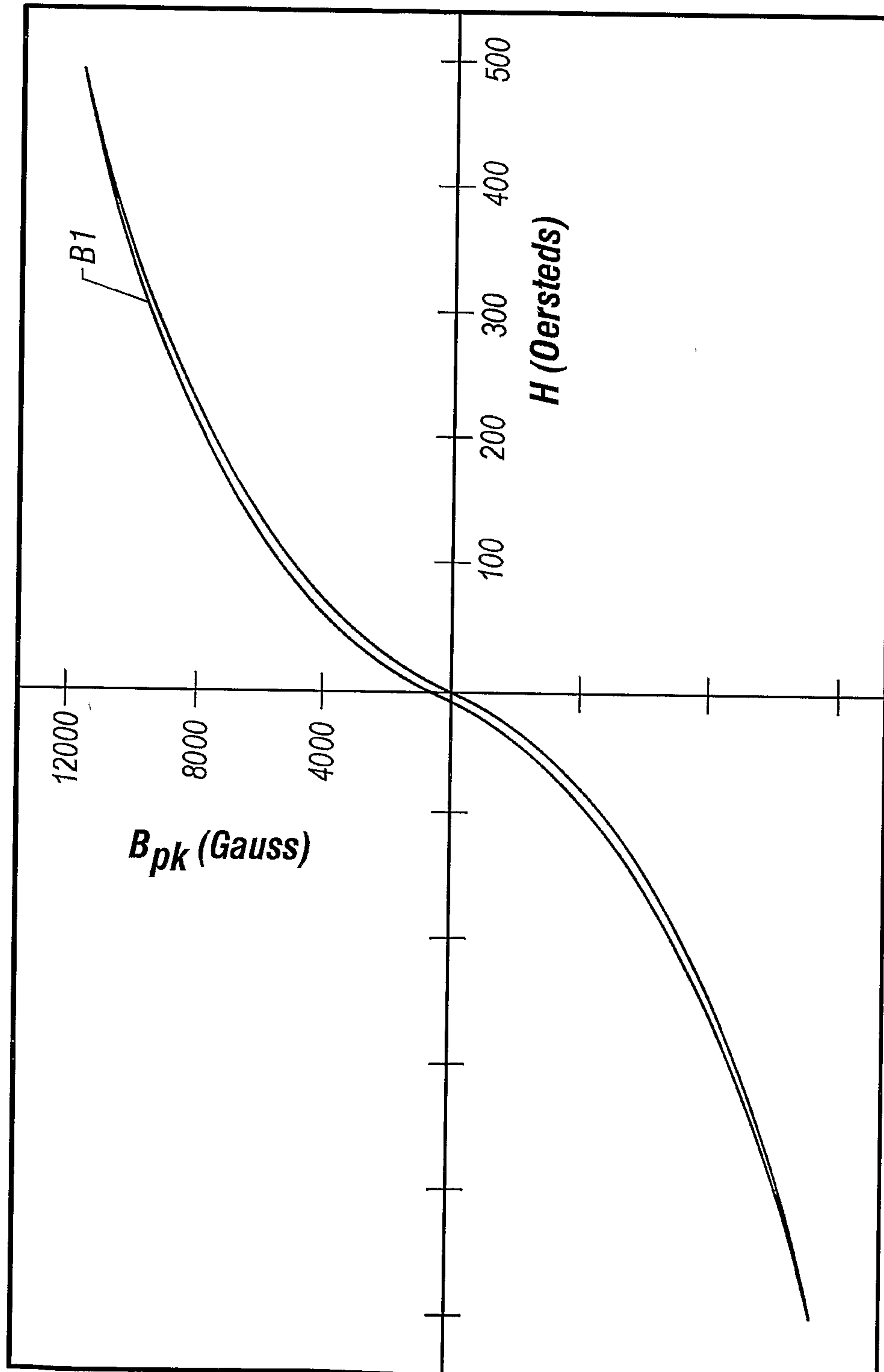
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**FIG. 4****FIG. 5**

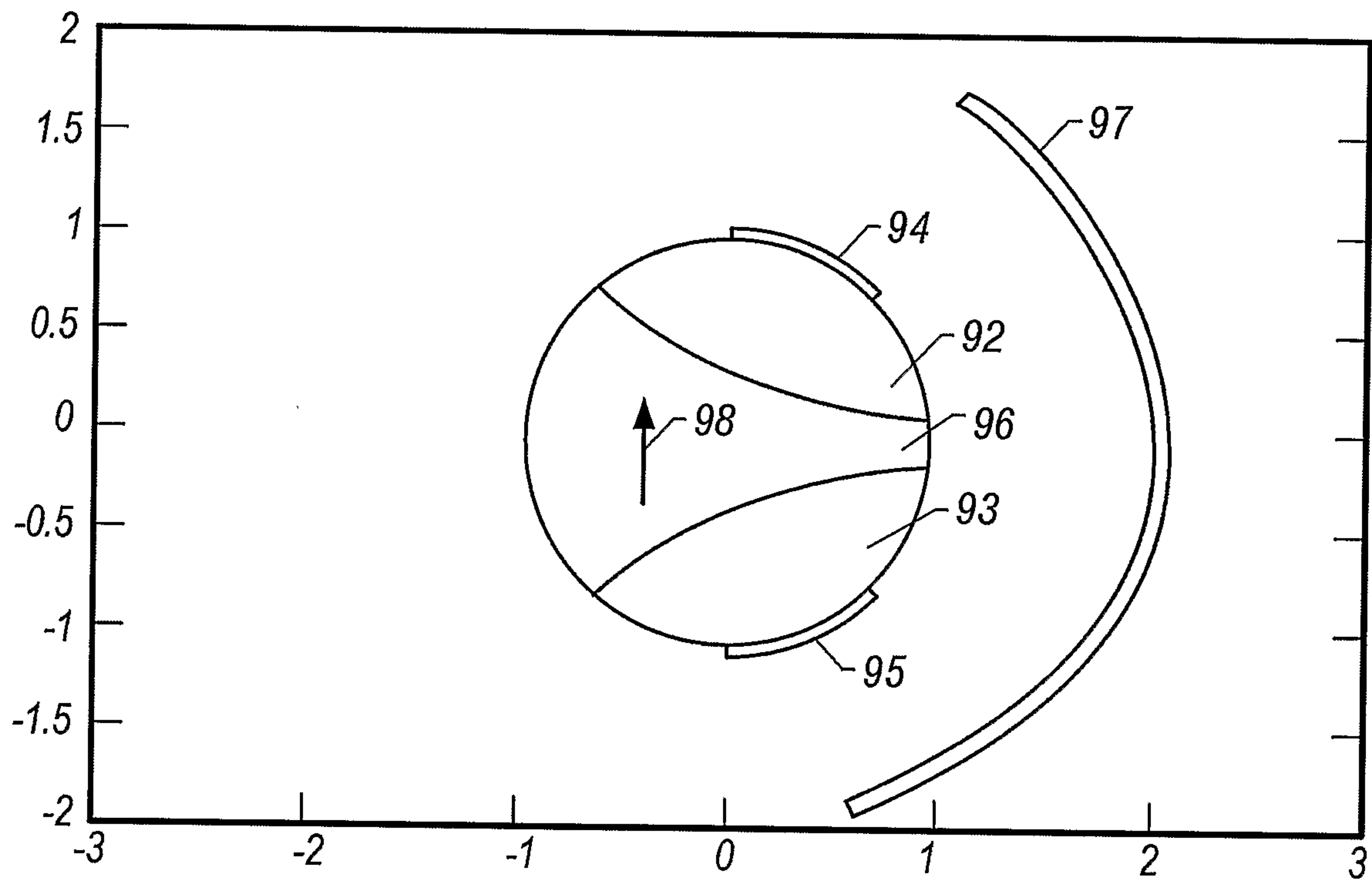
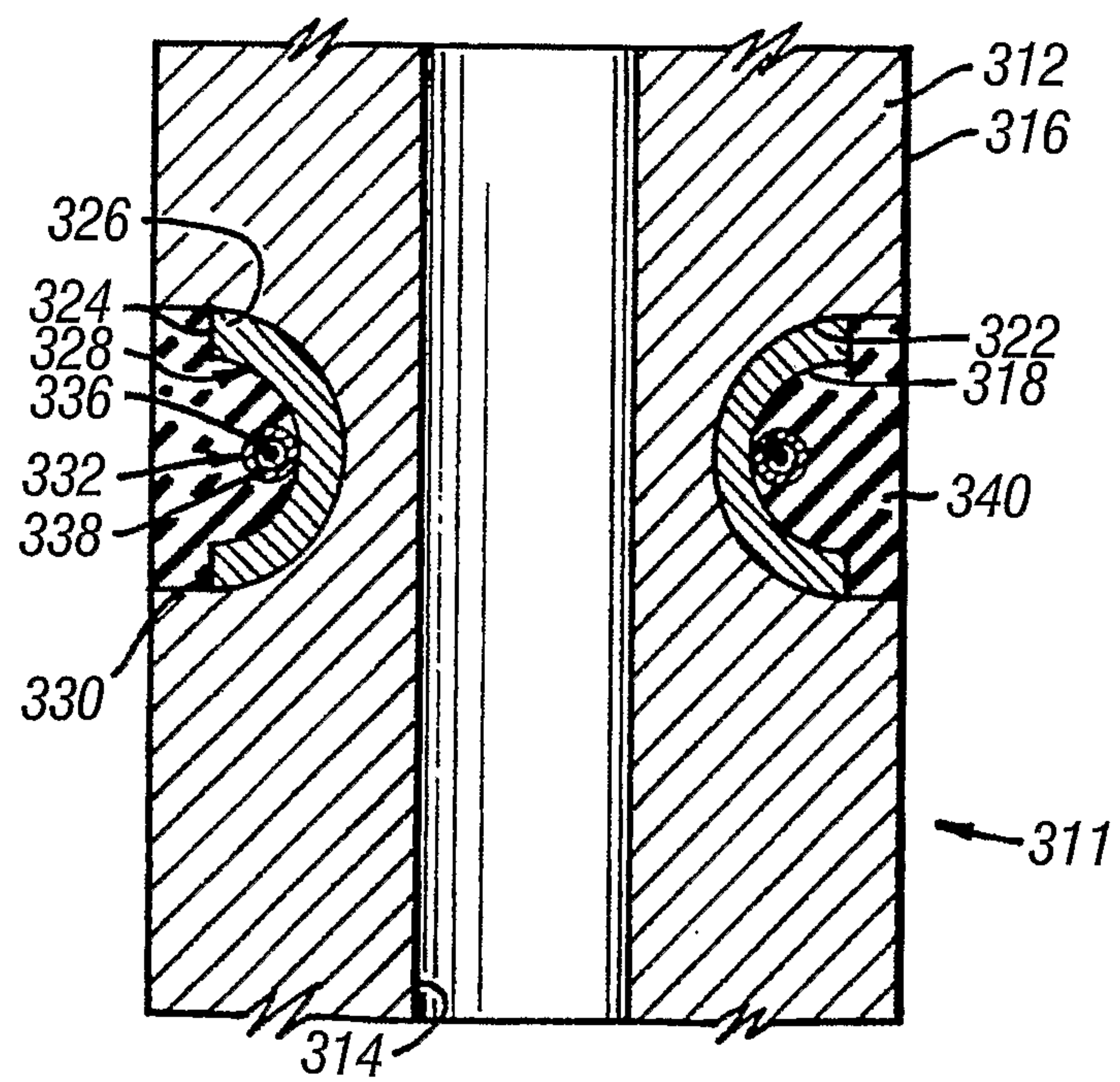
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**FIG. 6****FIG. 7**

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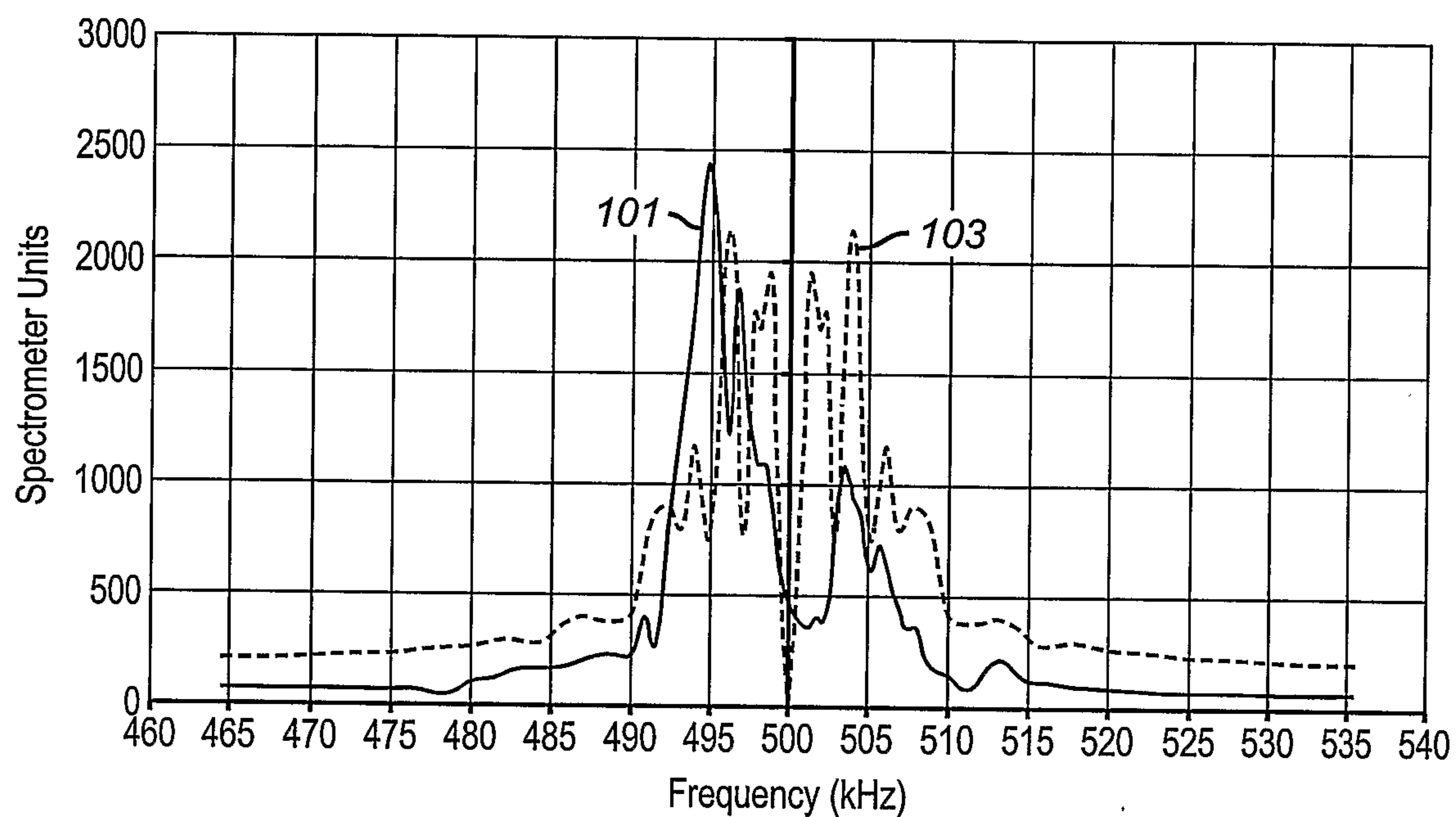
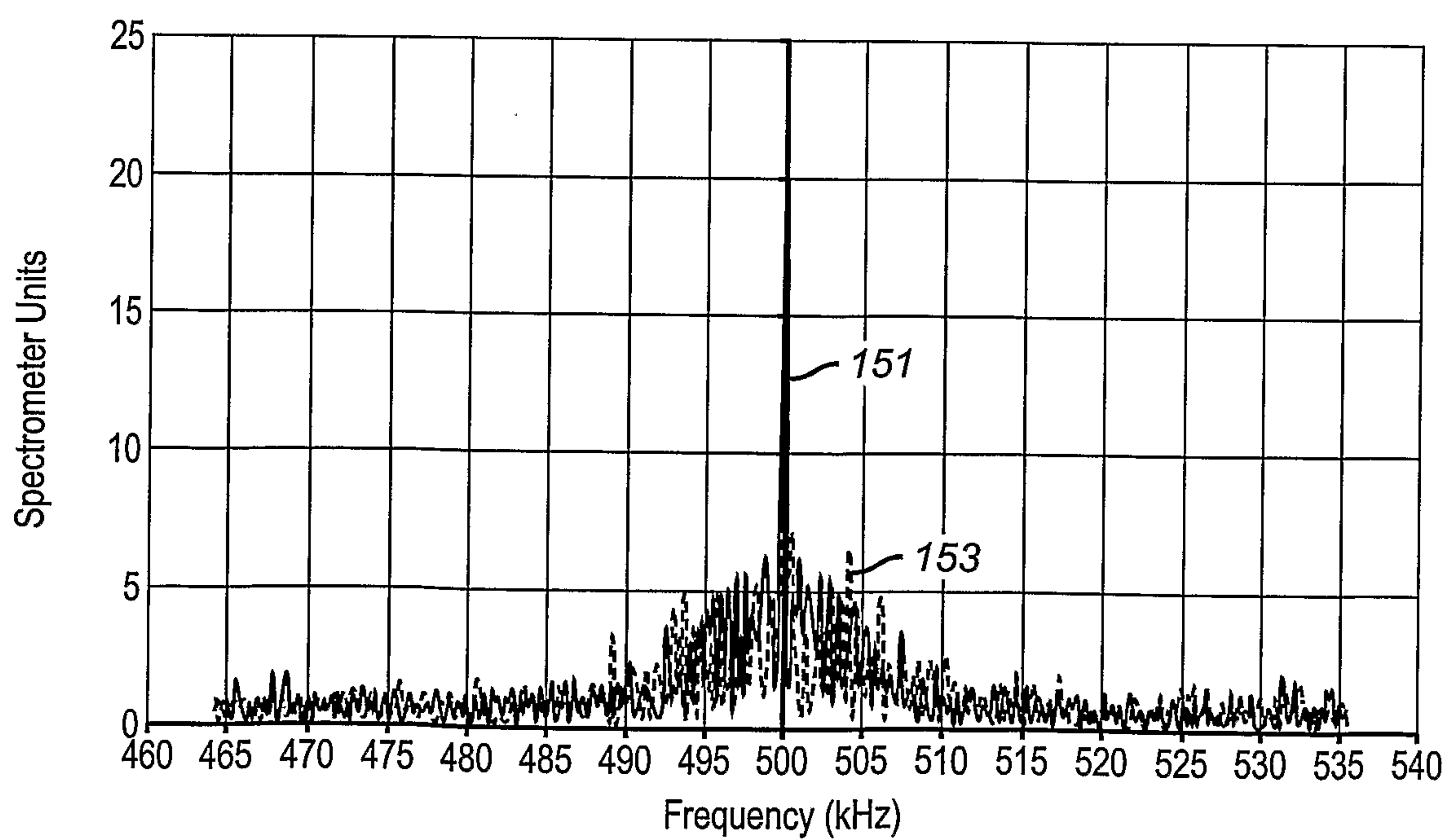
**FIG. 8**

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**FIG. 9****FIG. 14**

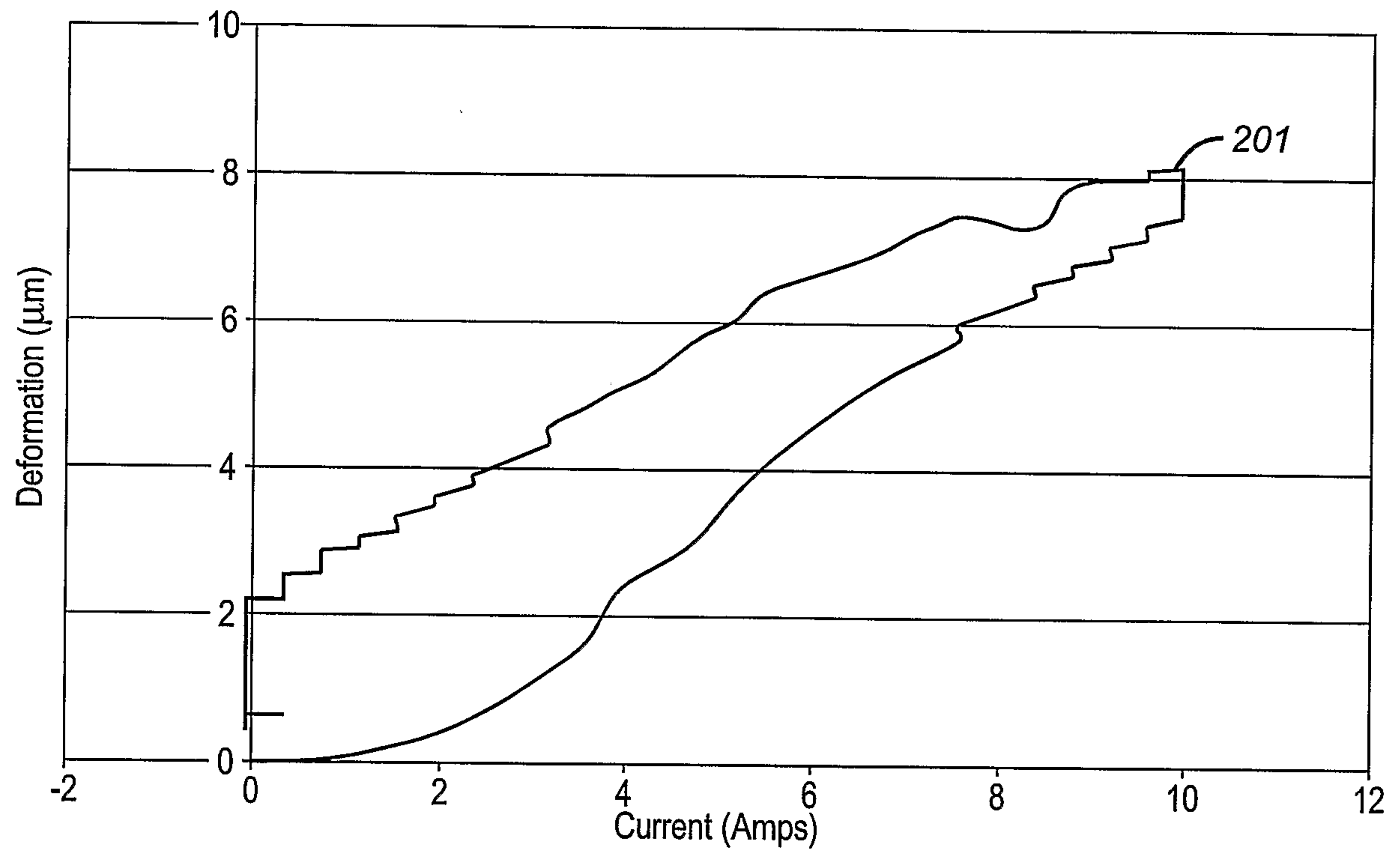
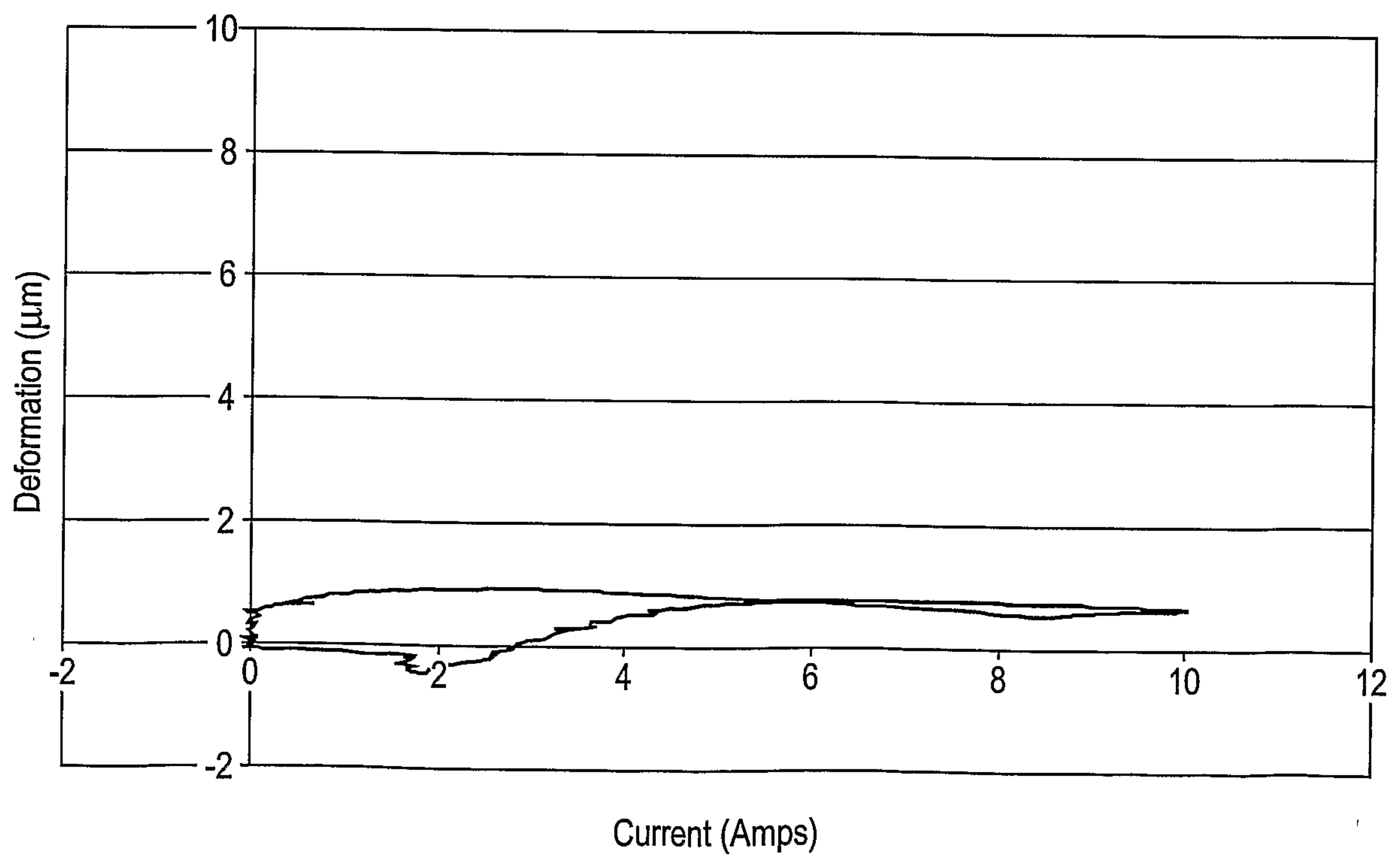
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**FIG. 10****FIG. 11**

+

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**FIG. 12****FIG. 13**