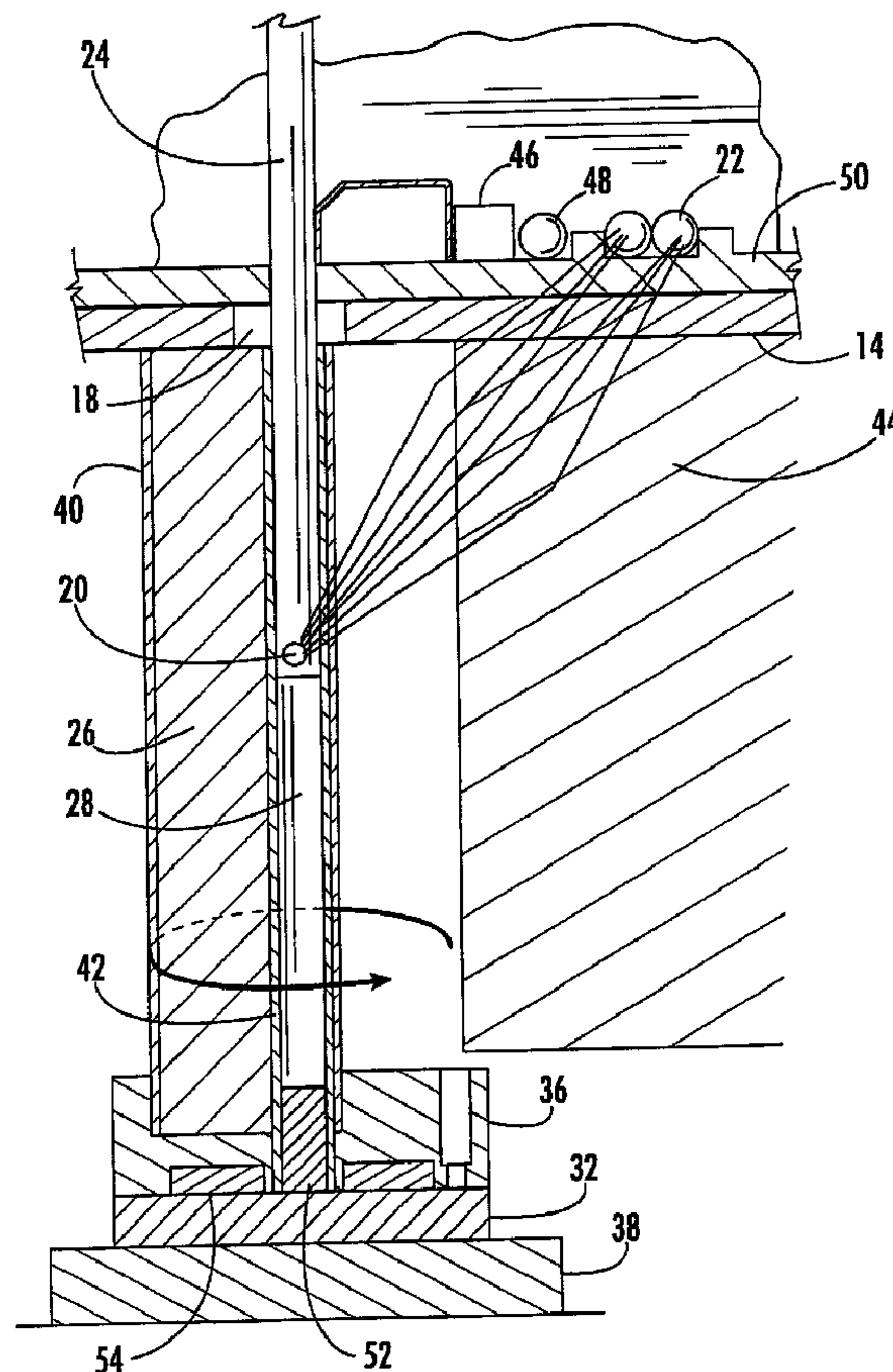




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(57) Abrégé/Abstract:

The present invention is directed to a method and apparatus for calibrating nuclear gauges and confirming gauge calibrations that provide the accuracy of multiple block calibration methods without requiring multiple standardized calibration blocks of known



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density. The apparatus includes a support for receiving a nuclear gauge of the type having a radiation source and a radiation detector and a variable radiation filter operatively associated with the support for providing variable attenuation of radiation emitted from the radiation source. The variable radiation filter includes a block having an eccentrically located cavity and positioned for rotation about the central axis of the cavity. The filter may further include a fixed mass for further attenuating radiation discharge by the radiation source such that the energy spectrum produced by the filter substantially matches the energy spectrum of a solid block of material, such as a standardized calibration block.

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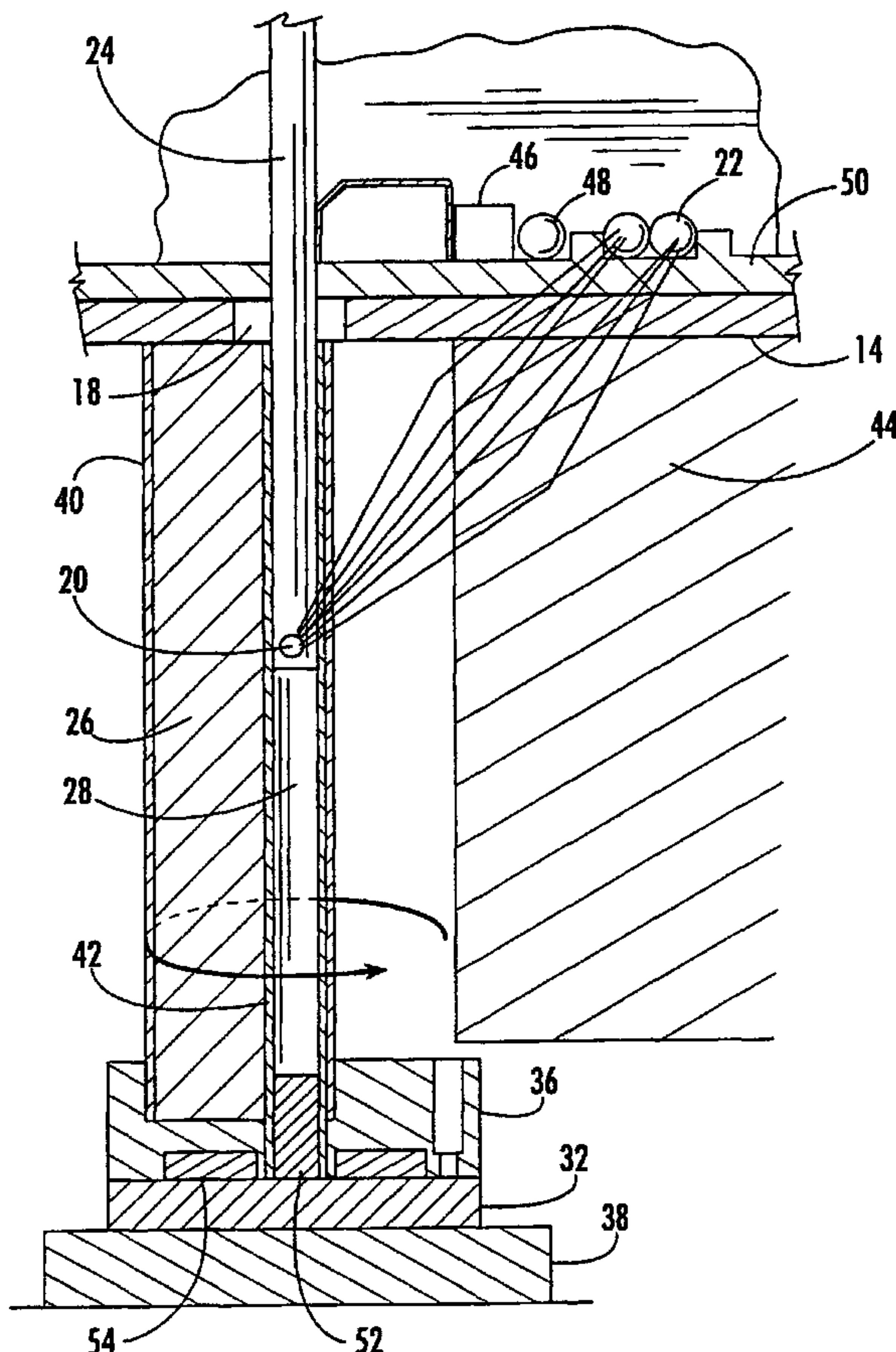
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(54) Title: APPARATUS AND METHOD FOR CALIBRATION OF NUCLEAR GAUGES



(57) Abstract: The present invention is directed to a method and apparatus for calibrating nuclear gauges and confirming gauge calibrations that provide the accuracy of multiple block calibration methods without requiring multiple standardized calibration blocks of known density. The apparatus includes a support for receiving a nuclear gauge of the type having a radiation source and a radiation detector and a variable radiation filter operatively associated with the support for providing variable attenuation of radiation emitted from the radiation source. The variable radiation filter includes a block having an eccentrically located cavity and positioned for rotation about the central axis of the cavity. The filter may further include a fixed mass for further attenuating radiation discharge by the radiation source such that the energy spectrum produced by the filter substantially matches the energy spectrum of a solid block of material, such as a standardized calibration block.

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APPARATUS AND METHOD FOR CALIBRATION OF NUCLEAR GAUGES

FIELD OF THE INVENTION

The present invention relates to the calibration and calibration confirmation of nuclear gauges and, more particularly, relates to a method of calibrating such gauges without standardized calibration blocks.

BACKGROUND OF THE INVENTION

Nuclear radiation gauges are used to determine density and/or moisture content of soils, asphalt, and similar materials. Examples of such gauges are described in U.S. Patent No. 2,781,453 and U.S. Patent No. 3,544,793. In many instances, these gauges have become the industry standard because of their non-destructive testing capability and endurance. The American Society for Testing and Materials (ASTM) has established testing standards for using nuclear gauges to measure density and moisture content. The testing standards are designated D 2922-05 (density) and D 3017-05 (moisture). The number "05" in these two standards indicates the year (2005) that they were last updated.

Nuclear density gauges currently in use, for example, the Troxler Model 3400 and 4400 series gauges manufactured by the Assignee of the present invention, employ a nuclear radiation source, typically a mono-energetic source, that discharges gamma radiation into the test specimen and a radiation detector, typically a Geiger Mueller tube, that measures the scattered radiation.

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The gamma radiation interacts with matter in the test specimen, either by losing energy and changing direction (Compton interactions) or by terminating (photoelectric interactions). Consequently, the gamma radiation detected
5 by the radiation detector has a continuous energy spectrum.

These gauges are designed to operate both in a "backscatter" mode and in a direct transmission mode. The radiation source is vertically moveable from a backscatter position where it resides within the gauge housing to a
10 series of direct transmission positions where it is inserted into small holes or bores in the test specimen. The gamma radiation received by the radiation detector is related to the density of the test medium by an expression of the following form.

$$CR = A \exp(-BD) - C$$

Equation 1

where:

5 CR = count ratio (the accumulated photon count normalized to a reference standard photon count for purposes of eliminating long term effects of source decay and electronic drift),

D = density of test specimen, and

A, B, and C are constants.

10 The gauges are factory calibrated to arrive at values for constants A, B, and C for each gauge at each source depth position. The factory calibration procedure is a time-consuming iterative process, which may require several hours, or even days, to complete. In order to determine values for the three calibration parameters of the above equation, count measurements must be taken using at least three
15 materials of different densities at each radiation source position. Typically, the three materials are solid blocks of aluminum, magnesium and a laminate of magnesium and aluminum. In some instances, as many as five calibration blocks of material have been employed in order to take into account the distinct mass attenuation coefficients of different soils. Thus, the standard factory calibration
20 methods, often referred to as the three-block or five-block calibration methods, require a large number of individual counts in order to complete the calibration. For example, a gauge having a twelve-inch radiation source rod with seven different radiation source depth positions requires a minimum of twenty-one separate counts using the three-block calibration method. Each count is taken for a
25 predetermined period of time, with longer periods of time producing greater precision. For example, for some gauge models, a typical count period for calibration is about four minutes for a direct transmission mode and about eight to twenty minutes for backscatter mode. Once all the counts are accumulated, values for the calibration parameters A, B, and C are calculated for each radiation source
30 position.

The above-described calibration method is both time consuming and labor intensive because it requires numerous counts and movement of the gauge to positions overlying a plurality of blocks. The requirement that the gauge be moved

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from block-to-block also makes it difficult to fully automate the calibration process. Additionally, each standardized calibration block occupies a relatively large volume of space and weighs over 300 pounds, making them
5 unwieldy and poorly suited for portability.

Further, in normal use, nuclear gauges undergo stress that can change the source-detector geometry of the gauge. Changes in geometry, as well as other factors, affect the gauge response such that, after a period of time,
10 there is a need for recalibration of the gauge to arrive at new values for the constants A, B, and C. The standard practice in the industry has been to return the gauge to the factory, or to a regional calibration center, where the factory calibration process described above is repeated.
15 Thus, the gauge user must go without the use of the gauge for a period of time while the gauge is recalibrated.

Efforts have been made to shorten the calibration process by using fewer standardized calibration blocks. For instance, in U.S. Patent No. 4,587,623, a calibration
20 process using only two blocks is disclosed. This disclosed method relies on the assumption that the constant B, for a given radiation source position, does not change during the life of the gauge. However, the two-block method does sacrifice some accuracy since constant B may change slightly
25 during the life of the gauge. Further, the two-block method still requires numerous counts and movement of the gauge between two heavy standard calibration blocks.

A calibration method using only one standard calibration block is disclosed in U.S. Patent No. 4,791,656.
30 The one-block method involves a collection of counts from a single calibration block and the use of statistically

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derived relationships between the count rate actually obtained from the calibration block to the count rates historically obtained from at least two different calibration blocks of other known densities. By using such

5 historically derived relationships, the expected calibration count rates for the other blocks can be estimated and used to calculate the equation parameters described above.

Although the one-block method reduces the number of experimental counts that must be taken, it still requires

10 the use of at least one heavy standardized calibration block. When using the one-block method, it is also generally advisable to confirm the calibration by

testing the gauge on at least one other calibration block of substantially different density. A three block calibration process would still be required if the gauge failed to pass quality control/quality assurance tests. Further, by relying on the historically derived data, the one-block method assumes that, at a given source rod depth, there is a set of strong linear relationships that relate the magnesium, magnesium/aluminum and aluminum counts to one another. Some gauges, however, do not adhere to these relationships in a consistent manner. Such gauges would require a full three-block calibration process to ensure an adequate calibration. Finally, the one-block calibration procedure is only appropriate for calibrating gauges of identical construction as the gauges used to generate the historical data. So a one-block calibration process would be impossible for a new model or style of gauge because of the absence of historical data.

International application PCT/US98/12091 discloses a validation and calibration apparatus for a nuclear gauge that comprises an absorption element positioned within an enclosure, wherein the absorption element is capable of simulating the photon count associated with a material of known density.

There remains a need for a new method of calibrating and confirming the calibration of nuclear gauges that is less time-consuming, less labor-intensive, and suitable for both initial factory calibrations and recalibrations by the gauge user at locations remote from the factory.

SUMMARY OF THE INVENTION

The present invention is directed to a method and apparatus for calibrating nuclear gauges that provides the accuracy of multiple block calibration methods without requiring multiple standardized calibration blocks of known density. Using the apparatus of the present invention, a nuclear gauge may be calibrated at each radiation source depth position without moving the gauge between multiple calibration blocks. Instead, the apparatus of the present invention utilizes a variable radiation filter capable of simulating the radiation attenuation of numerous materials of varying densities. In a preferred embodiment, the variable radiation filter simulates the density of multiple materials of known density, such as solid calibration blocks, and also attenuates the incident gamma radiation in such a way that the resulting energy spectra incident upon the gamma ray detectors

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substantially match the energy spectra of the materials of known density.

According to one aspect the invention provides an apparatus for calibrating a nuclear gauge having a radiation
5 source and a radiation detector, comprising: a support having a lateral support surface for receiving and supporting the underside of the nuclear gauge of the type having the radiation source located in a vertically moveable source rod and a radiation detector, said support having an
10 opening therein positioned for receiving the vertically moveable source rod therethrough; and a radiation filter capable of producing an energy spectrum incident upon the radiation detector that substantially matches the energy spectrum of at least one solid block of material, wherein
15 said radiation filter has a setting that simulates a known density when exposed to a 662 keV radiation source, said setting producing a ratio of total counts detected to counts with energy over 300 keV of at least 70% of the same ratio produced by the solid block of material of the known
20 density, as measured by a 1-inch by 1-inch NaI scintillation detector, said filter comprising a block of a radiation attenuating material of predetermined shape located beneath said support and mounted for movement relative to said support to present a variable extent of radiation
25 attenuation to the radiation detector of the nuclear gauge, and a fixed mass operatively positioned adjacent to the radiation detector and beneath said support to further attenuate radiation emitted from the radiation source of the nuclear gauge.

30 The ratio may be about 80% of the ratio produced by a solid block of material of the known density.

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In one embodiment the block has a vertical cavity therein positioned beneath the opening of the support and adapted for receiving the source rod of the nuclear gauge, the cavity being eccentrically located within the

5 predetermined shaped block. The block may be mounted for rotation relative to the support and, in particular, for rotation about the central axis of the cavity. A motorized drive cooperating with the block may be used to effect the rotation.

10 In one embodiment the block is cylindrical.

A rotatable platform may be positioned beneath the block for imparting rotational movement thereto such that the block presents a variable extent of radiation attenuation to the radiation detector of the nuclear gauge
15 upon rotation of the block.

The support may additionally include a guide operatively positioned to guide a nuclear gauge into a position wherein the source rod of the gauge is overlying the opening.

20 The fixed mass may comprise one or more plates each constructed of material selected from the group consisting of aluminum, magnesium, lead, polyethylene, cadmium, tungsten, graphite and combinations thereof.

In one embodiment, the variable radiation filter
25 has a setting that simulates the density of magnesium, wherein the setting produces a ratio of total counts detected/counts with energy over 300 keV of at least about 4.0 at a radiation source depth of 2 inches measured by a 1-inch by 1-inch NaI scintillation detector. The ratio
30 is at least about 4.5 in some embodiments. Using the same

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magnesium setting at a radiation source depth of 8 inches, the setting produces a ratio of total counts detected/counts with energy over 300 keV of at least about 3.5, measured by a 1-inch by 1-inch NaI scintillation detector. The ratio is
5 at least about 4.0 in some embodiments.

Another aspect of the present invention provides a method of calibrating a nuclear density gauge, comprising the steps of: providing the nuclear gauge having a radiation detector and a radiation source located in a vertically
10 moveable source rod; providing a calibration apparatus having a lateral support surface for receiving and supporting the underside of the nuclear gauge and a radiation filter located beneath the support surface, the filter being capable of producing an energy spectrum
15 incident upon the radiation detector that substantially matches the energy spectrum of at least one solid block of material, wherein said radiation filter has a setting that simulates a known density when exposed to a 662 keV radiation source, said setting producing a ratio of total
20 counts detected to counts with energy over 300 keV of at least 70% of the same ratio produced by a solid block of material of the known density, as measured by a 1-inch by 1-inch NaI scintillation detector, and wherein the radiation filter comprises a block of a radiation attenuating material
25 of predetermined shape located beneath said support and mounted for movement relative to said support to present a variable extent of radiation attenuation to the radiation detector of the nuclear gauge, and a fixed mass operatively positioned adjacent to the radiation detector to further
30 attenuate radiation emitted from the radiation source of the nuclear gauge; placing the nuclear gauge on the lateral support surface; positioning the radiation source of the nuclear gauge at a predetermined source depth position; and

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obtaining an accumulated count of scattered radiation with the nuclear gauge while on the apparatus.

The method may further include the step of adjusting the variable radiation filter to provide a
5 different extent of radiation attenuation and obtaining a second accumulated count of scattered radiation with the nuclear gauge in the same position on the stand. The variable radiation may be adjusted to provide further different extents of radiation attenuation and further
10 accumulated counts of scattered radiation may be obtained. For example, three or five different extents of radiation attenuation may be used to obtain a corresponding number of accumulated counts of scattered radiation.

The source rod may be repositioned to a different
15 source position while the gauge remains in position on the stand. In this manner, the gauge may be calibrated by obtaining accumulated counts of scattered radiation at each source depth position. Using the method of an embodiment of the present invention, the

nuclear gauge may be calibrated at each source depth position by adjusting the variable radiation filter to provide one or more different extents of radiation attenuation and obtaining corresponding accumulated counts of scattered radiation without moving the gauge from the lateral support surface.

5

BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

10 Figure 1 is a perspective view of an embodiment of the calibration apparatus of the present invention with a nuclear gauge positioned thereon;

Figure 2 is a cross-sectional side view of an embodiment of the calibration apparatus of the present invention having a nuclear gauge positioned thereon;

15 Figures 3A-3C illustrate various positions of the variable radiation filter of the calibration apparatus; and

Figure 4 is a graphical comparison of the gamma ray energy spectra produced by a calibration block and two embodiments of the apparatus of the present invention.

20

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Figure 1 is a perspective view of the calibration apparatus **10** of the present invention having a nuclear gauge **12** placed thereon. As shown in Figure 2, the nuclear gauge **12** comprises both a radiation source **20** and a radiation detector **22**. The calibration apparatus **10** of the present invention may be used to calibrate nuclear gauges **12** in both backscatter mode and direct transmission modes. The particular type or configuration of the nuclear gauge **12** is not of critical

importance to the present invention. As a result, the calibration apparatus **10** may be used with a variety of different nuclear gauges **12**. In one commonly used configuration for a nuclear gauge, the radiation source **20** is mounted in a vertically moveable source rod **24**, as shown in Figures 1 and 2. The nuclear gauge **12** may
5 also include the capacity to measure moisture content. This type of gauge, as shown in Figure 2, also contains a neutron source **46** and a neutron detector **48** within the nuclear gauge housing **50**.

The apparatus **10** of the present invention includes a support **14** for receiving a nuclear gauge **12**. The support **14** has a lateral surface **15**, which
10 receives and supports the underside of the nuclear gauge **12**. The support **14** has an opening **18** that allows the vertically movable source rod **24** to descend freely. The support **14** includes a guide **17** in the form of abutments or rails, which is designed to guide the gauge **12** into proper placement on the support.

Below the opening **18** of the support **14** is a variable radiation filter **16**.
15 The variable radiation filter **16** is operatively associated with the support **14** and located with respect to the nuclear gauge **12** so as to attenuate radiation emitted from the radiation source **20**. The variable radiation filter **16** of the present invention is capable of varying the extent of radiation attenuation, thereby simulating the radiation scattering of a plurality of materials having different
20 densities. In a preferred embodiment, the variable radiation filter **16** comprises a mass of substantially uniform density mounted for movement relative to the support **14** in order to present a variable extent of radiation attenuation to the radiation detector **22** of the nuclear gauge **12**. The filter **16** could be moved in various ways to provide the variable extent of radiation attenuation without
25 departing from the present invention. As a non-limiting example, the filter **16** could be moved linearly in a longitudinal or transverse direction between the radiation source **20** and the radiation detector **22**. In the embodiment shown, the moveable mass is a block **26** of predetermined shape mounted for rotation relative to the support **14**. The predetermined shape of the block **26** is preferably
30 cylindrical, but other shapes may be used without departing from the present invention. In one embodiment, the block **26** comprises a cylinder having a diameter of about two to about four inches.

By presenting a variable extent of radiation attenuation, the block **26** is

capable of simulating the density of numerous materials, including traditional calibration blocks, such as magnesium or aluminum blocks. The block 26 simulates density by producing the same approximate count rate as produced by the material to be simulated at a given radiation source 20 depth. The block 26
5 also shields the user from exposure to excessive radiation.

Preferably, the block 26 has a cavity 28 positioned beneath the opening 18 in the support 14. The cavity 28 is eccentrically located within the block 26 and positioned to receive the vertically movable source rod 24. Preferably, the cavity 28 is deep enough to accommodate a standard length source rod 24. For instance,
10 the cavity 28 is preferably deep enough to accommodate a source rod 24 capable of descending to a depth of 12 inches. Alternatively, the size of the block 26 can be reduced by allowing the block to move vertically with the source rod 24 such that the block only surrounds the portion of the rod containing the radiation source 20. The rotational axis of the block 26 is coincident with the rotational axis of the
15 cavity 28. As shown in Figures 3A-3C, due to the eccentric location of the cavity 28 within the block 26, rotation of the block around the central axis of the cavity changes the amount of block material disposed between the radiation source 20 in the source rod 24 and the radiation detector 22 located within the housing 50 of the nuclear gauge 12. The change in the amount of material disposed between the
20 radiation source 20 and the radiation detector 22 creates a corresponding change in extent of radiation attenuation provided by the variable radiation filter 16.

In one embodiment, the block 26 comprises an outer hollow aluminum cylinder 40 and an inner hollow aluminum cylinder 42. The inner hollow aluminum cylinder 42 defines the cavity 28 of the block 26. The space between
25 the inner cylinder 42 and the outer cylinder 40 is filled with a radiation attenuating material, such as lead or tungsten. In the embodiment shown, the block 16 surrounds the radiation source 20, thereby providing shielding to prevent exposure of the user to excessive radiation.

Preferably, the block 26 is mounted on a base plate 36. The base plate 36
30 includes a ring-shaped lead shield 54 that surrounds the cavity 28 in the block 26. Further, a lead plug 52 is preferably located in the end of the cavity 28 located in the base plate 36. The lead ring 54 and lead plug 52 provide shielding to prevent excessive radiation discharging through the bottom of the calibration apparatus 10

when the source rod 24 is extended into the cavity 28.

In a preferred embodiment, the base plate 36 is mounted on a rotating platform 32. The rotating platform 32 allows rotational movement of the block 26/base plate 36 assembly. The rotating platform 32 is mounted on a platform support 38 and may be manually operated or include a motorized drive 62.

In one embodiment, a magnetic switch 33 is placed adjacent to the rotating platform 32. A magnet 35 is located on the outer surface of the rotating platform 32. The magnetic switch 33 is operatively connected to the motorized drive 62 such that rotation of the block 26/base plate 36 assembly may be stopped when the magnetic switch senses the proximity of the magnet 35. Thus, in the motorized embodiment of the present invention, the magnetic switch 33 allows orientation of the block 26 to an initial starting point. This enables the degree of rotation of the block 26 to be measured using a known reference point.

The variable radiation filter 16 preferably further includes a fixed mass 44. The fixed mass 44 is operatively positioned adjacent to the radiation detector 22 in order to further attenuate radiation emitted from the radiation source 20 of the nuclear gauge 12. Any given material produces a unique spectrum of energy when radiation is scattered therethrough. Even dissimilar materials having approximately the same density will produce different energy spectra when radiation is introduced into the material. The presence of the fixed mass 44 facilitates matching the energy spectrum of the variable radiation filter 16 to the energy spectrum produced by solid blocks of material, such as calibration blocks or field test materials such as asphalt. This allows more accurate simulation of the radiation scattering effect produced by traditional calibration blocks of known density, such as aluminum or magnesium blocks. The fixed mass 44 also shields the user from exposure to excessive radiation.

The block 26 is capable of simulating count rates associated with blocks of known density; however, in some embodiments, the block does not contain the proper material and volume to simulate the energy spectra of a solid block of known density. Each radiation detector 22, such as Geiger Mueller tube, has a different energy dependent efficiency function. For instance, a given detector 22 may exhibit strong detection sensitivity in the energy range of 200 keV to 300 keV and poor detection sensitivity in the energy range of 50 keV to 150 keV. The

energy detection efficiency of the detector **22** impacts the accuracy of the gauge **12** calibration. If a gauge **12** is calibrated using an apparatus that simulates the count rates, but not the energy spectra, of traditional calibration blocks, the gauge may not receive an accurate calibration because of the difference between the detection efficiency of the “master gauge” used to prepare the density settings of the calibration apparatus **10** and the gauge to be calibrated. Using the fixed mass **44**, the calibration apparatus **10** is capable of simulating both the count rate and the energy spectrum of a traditional calibration block, which enables the apparatus to reliably calibrate any gauge, regardless of energy detection efficiency.

The fixed mass **44** is much lighter than the solid blocks traditionally used to calibrate nuclear gauges **12** of the type contemplated by the present invention. Thus, the entire calibration apparatus **10** of the present invention is much lighter and more easily transportable. The calibration apparatus **10** may weigh as little as one third to one tenth of the weight of a standardized calibration block constructed of magnesium.

In a preferred embodiment, the fixed mass **44** comprises at least one plate constructed of a material selected from the group consisting of aluminum, magnesium, lead, polyethylene, graphite, cadmium, tungsten and combinations thereof, including composite or laminate structures. For example, the fixed mass **44** may include a plurality of planar magnesium and polyethylene plates affixed together to form a block-like mass. In one configuration, the fixed mass **44** comprises a combination of polyethylene and magnesium plates stacked side-by-side in the following order: polyethylene, magnesium, magnesium, magnesium, magnesium, and polyethylene. The polyethylene blocks are preferably about 3 inches thick with a width of about 9 inches and a height of about 11.5 inches. The magnesium blocks are preferably about one inch thick with a width of about 10 inches and a height of about 11.5 inches. In one embodiment, the fixed mass **44** further includes a cadmium plate or sheet (not shown) located above the magnesium and polyethylene plates and directly underneath the radiation support **14** in the approximate area of the radiation detector **22**. However, many different configurations of the fixed mass **44** are possible. For instance, the number of plates, material of construction, shape of the plates and the position of each plate relative to the other plates may be adjusted as required to substantially match the

desired energy spectrum.

To arrive at a workable configuration for the fixed mass **44**, an energy spectrum analyzer, such as a scintillation detector-based multi-channel analyzer (MCA), may be employed to plot the unique energy spectrum of a given material.

- 5 For example, a NaI scintillator coupled to a photomultiplier tube manufactured by Canberra may be utilized to measure the energy spectrum of a standardized calibration block. Once the spectrum is known, the fixed mass **44** may be adjusted to substantially match the energy spectrum of the calibration block.

Substantial matching of an energy spectrum is defined in terms of the ratio
10 of total counts detected (C1)/counts with energy over 300 keV (C2) or the total-to-peak ratio defined as total counts detected (C1)/counts in the 662 keV peak (C3). These ratios assume the use of a 662 keV radiation source **20** (i.e. Cs-137). Further, these ratios are typically dependent on the geometry and type of detector used to measure the energy spectrum. The ratios used herein are based on the use
15 of a 1-inch by 1-inch NaI scintillation detector.

At a radiation source **20** depth of 2 inches and at a density setting corresponding to a magnesium block, the ratio C1/C2 should be at least about 4.0, preferably at least about 4.5, and most preferably at least about 4.75. At a radiation source **20** depth of 4 inches and at a density setting corresponding to a magnesium
20 block, the ratio C1/C2 should be at least about 3.5, preferably at least about 4.0, and most preferably at least about 4.4. At a radiation source **20** depth of 8 inches and at a density setting corresponding to a magnesium block, the ratio C1/C2 should be at least about 3.5, preferably at least about 4.0, and most preferably at least about 4.2.

25 The C1/C2 ratio calculated for a given source **20** depth and density setting of the apparatus **10** may also be compared to the C1/C2 ratio calculated using a calibration block having the same density. Preferably, for a given simulated density setting, the C1/C2 ratio calculated using the apparatus **10** (at any radiation source **20** depth) should be at least 70% of the C1/C2 ratio calculated using a
30 calibration block having the same density. Most preferably, the C1/C2 ratio calculated using the apparatus **10** should be at least 80% of the C1/C2 ratio calculated using a calibration block of the same density. For example, if a setting of the block **26** simulates the density of magnesium, the C1/C2 ratio calculated at

any radiation source **20** depth for that setting should be at least 70% of the same ratio calculated using a magnesium calibration block.

As shown in Figure 1, in one embodiment, the calibration apparatus **10** of the present invention is supported on a lower platform **60**. The calibration
5 apparatus **10** of the present invention may further include wheels **58** for enhancing the transportability of the apparatus or handles (not shown) for lifting the apparatus.

In operation, a nuclear gauge **12** is first used to obtain a standard count as recommended by the gauge manufacturer. The nuclear gauge **12** is then placed
10 onto the calibration apparatus **10** with the source rod **24** exposed to the opening **18** in the support **14**. The nuclear gauge **12** is precisely placed using the guide **17**, which allow the source rod **24** and the cavity **28** within the block **26** to be precisely aligned. The source rod **24** is then placed at the desired calibration depth, either a backscatter mode where the source rod remains above the block **26** or a direct
15 transmission mode where the source rod enters the cavity **28** of the block **26**.

The block **26** is then rotated using the rotating platform **32** to a predetermined position that provides the radiation attenuation that corresponds to a known density. The rotation may be accomplished manually or by motorized drive
20 **62**. If adjusted manually, markings, such as precise detents, may be made on the apparatus, such as on the platform support **38**, so that the block **26** may be precisely rotated to predetermined settings. If motorized, a computer **64** may be operatively coupled to the motorized drive **62** and used to input a specific density that the calibration apparatus **10** has been prepared to simulate. The computer **64** would then operate the motorized drive **62** and rotate the block **26** to a position or
25 setting known to simulate the desired density.

One or more accumulated counts of scattered radiation may then be measured using the process suggested by the manufacturer of the nuclear gauge **12**. After each count is measured, the block **26** is rotated to another predetermined setting corresponding to another known density. If a one-block calibration method
30 is used, a single accumulated count of scattered radiation taken using a single predetermined setting of the block **26** is sufficient to calibrate the nuclear gauge **12** at that source depth position. Similarly, two accumulated counts of scattered radiation could be collected using two predetermined settings of block **26** and used

in a two-block calibration method, in conjunction with the known value of constant B, to calibrate the nuclear gauge **12** at a given source depth position. Finally, three or more accumulated counts of scattered radiation may be measured and used to calculate the three constants found in Equation 1. Thus, the calibration apparatus **10** of the present invention may be used to perform a one-block, two-block, or any other multiple block calibration method. If a one-block calibration method is used, it is preferable to confirm the accuracy of the calibration by obtaining at least one additional accumulated count using at least one additional predetermined setting of block **26**. For example, one of the confirmation processes described below may be used to confirm the accuracy of the calibration. Each count may be taken for a period of time recommended by the gauge manufacturer. Typically, for calibration, a count is taken over a four-minute period for direct transmission modes and between eight and twenty minutes for backscatter mode.

Preferably, the accumulated counts are input into a curve-fitting routine whereby the calibration constants of Equation 1 are calculated. This data could be loaded either manually or via an RS-232 interface into a computational device. The computational device could be embodied in a separate hand-held calculator, a computer integrated into the calibration apparatus **10**, or the microprocessor of the nuclear gauge **12**. The new constants may then be loaded into the gauge **12**. For example, if a computer **64** is used, the computer may be used to input the constants into the gauge **12** via port **27**.

Depending on which calibration method is being employed, the required number of accumulated counts of scattered radiation may be obtained at each additional radiation source depth. Thus, the entire procedure described above may be repeated for each depth setting of the radiation source **20**. For example, the above procedure may be repeated in the backscatter mode, two-inch direct transmission mode, four-inch direct transmission mode, and the like. Due to the finite extent of the block **26**, slight differences in the density measurement are perceived between different radiation source depths using the same block setting or orientation. These differences can be accounted for by assigning slightly different densities to each radiation source depth position for each block setting. This simplified approach requires preparation of only three block settings to enable the calibration apparatus **10** to perform a three-block calibration method and is

particularly suitable for manual operation of the present invention where the block is adjusted to each setting by the user.

Alternatively, if it is desired that the calibration apparatus **10** simulate a specific density value at all radiation source depths, the density measurements may be equalized at a predetermined value by assigning a slightly different block orientation or position to each radiation source depth. For example, if the calibration apparatus **10** is designed to simulate the density values of a magnesium calibration block, an aluminum calibration block and a magnesium/aluminum laminate calibration block, a separate block orientation or position may be assigned to each radiation source depth for each desired density so that the calibration apparatus **10** simulates the same three density values at each radiation source depth. Since a greater number of block orientations are required, this method is particularly suited for automated operation of the present invention where a computer-controlled motorized drive **62** adjusts the block to each setting.

The calibration apparatus **10** may also be used to confirm or verify the calibration accuracy of a gauge **12** at periodic intervals in order to quickly ascertain whether the gauge is continuing to operate within predetermined quality control parameters. The calibration confirmation/verification method is similar to the calibration method described above. The calibration confirmation generally utilizes one, two or three points, depending on the density range that the gauge **12** encounters during use. If the gauge **12** is only used to measure a narrow range of densities, a one-point confirmation process is appropriate. A gauge application requiring a broader range of densities may require a two-point confirmation method. If the gauge **12** routinely measures densities over the entire dynamic range of the gauge calibration, a three-point confirmation is desirable.

In a one-point confirmation method, the gauge **12** is placed on the apparatus **10** of the present invention and the source rod **24** is lowered to the desired radiation source depth. The block **26** is rotated to a predetermined setting corresponding to a density that is within or near the narrow range of densities measured by the gauge **12**. An accumulated count is taken for a predetermined count period. Typically, the count period is about one to about four minutes for calibration confirmation. The density measured by the gauge **12** is then compared to the accepted density value of the predetermined setting of the block **26** and the

difference is evaluated using a quality control/quality assurance limit. For example, a typical quality control limit is about 1.0 lb/ft^3 . If the difference between the measured and accepted density values is greater than the quality control limit, the gauge **12** fails the calibration confirmation and should be recalibrated. If the difference is within the quality control limit, the operation of the gauge **12** is acceptable and calibration is not required.

In the two-point confirmation method, two predetermined settings of the block **26** are used and two accumulated count measurements are taken. Preferably, the setting corresponding to the highest density value and the setting corresponding to the lowest density value are used. As with the one-point calibration, the difference between the accepted density value and the measured density is evaluated using a quality control limit.

The three-point confirmation method utilizes three predetermined settings of the block **26**. The three settings are preferably spread out over the entire dynamic range of the original gauge calibration. As with the one and two-point confirmations, accumulated counts are taken at each setting and the corresponding densities are compared to the accepted density values for each setting. The difference between the measured density and the accepted density is evaluated using a quality control limit as described above.

In order to prepare the calibration apparatus **10**, at least three settings corresponding to at least three known densities must be determined so that the calibration apparatus may be used in a one, two, or three-block calibration method. To determine the densities corresponding to the settings of the apparatus **10**, a “master” gauge is used. The master gauge should be calibrated using the standardized calibration blocks used in the traditional three-block calibration method. Preferably, the master gauge is of the same type as the gauges that will be calibrated using the apparatus **10**. Preferably, the master gauge is calibrated using longer count periods and stricter quality control/quality assurance limits. For example, during calibration of the master gauge, counting periods of approximately twenty minutes, rather than four minutes, may be utilized in direct transmission mode. Further, the measured density values are preferably evaluated using a strict quality control limit. For example, the quality control limit may

require that the master gauge must fall within 0.2% of the accepted density value for each standardized calibration block.

In order to determine the settings for each calibration apparatus **10**, the block **26** is rotated to a first position. The master gauge is placed on the calibration apparatus **10**. An accumulated count of scattered radiation is measured using the procedure recommended by the gauge manufacturer. The block **26** may then be rotated to a second position in order to simulate a second extent of radiation attenuation. The master gauge is then used to take a second accumulated count of scattered radiation reading. The above steps may be repeated for as many settings as desired. Preferably, at least three settings are prepared for each calibration apparatus **10**.

Since the calibration constants of the master gauge are known, the densities corresponding to the accumulated count readings may be calculated. In this manner, each rotational setting of the block **26** is associated with a known density. Note that it is preferable to choose the settings of the block **26** in such a manner as to provide a wide range of known densities. By using a wide range of densities, the accuracy of the calibration provided by the calibration apparatus **10** will be improved. For example, when using the three-block method, standardized blocks of magnesium, aluminum, and a block of laminated magnesium and aluminum are often used. The use of both magnesium and aluminum provides a good range of densities. Thus, while it is not necessary to exactly match the settings of the block **26** to the densities of known calibration blocks, such as magnesium calibration blocks, it is preferable to duplicate the approximate range provided by the use of aluminum and magnesium blocks.

Additionally, as discussed above, the accuracy of the calibration apparatus **10** is improved when a fixed mass **44** is used to substantially simulate the energy spectrum generated by radiation scattering through a block of solid material. Since traditional calibration blocks, such as magnesium and aluminum, are available and the energy spectrum associated with such blocks may be easily plotted using a spectrum analyzer, it is advisable to roughly match the densities simulated by the apparatus **10** to the densities of blocks having known energy spectrums. The fixed mass **44** may then be adjusted to substantially match the known energy spectra of materials having the same approximate density as the density simulated by the

calibration apparatus **10**. Thus, both the simulated count rates and energy spectrum of each predetermined setting will substantially match the count rates and energy spectrum of a known material commonly used for nuclear gauge calibration, resulting in better calibration accuracy and precision.

5 Since the master gauge is calibrated using blocks whose gravimetric densities are measured using instruments calibrated with NIST standards, the traceability of the densities associated with the settings of the block **26** are substantially equivalent to the traceability of densities assigned to commonly used standardized calibration blocks. Thus, there is no loss in calibration accuracy by
10 using the calibration apparatus **10** of the present invention.

For nuclear gauges **12** that also measure moisture content, the calibration apparatus **10** may also be used to calibrate the moisture content measurement of the gauge. The relationship between moisture content and the thermal neutron count ratio is given by the following linear equation.

15

$$R = E + FM$$

Equation 2

where,

20 R is the thermal neutron count ratio (ratio of actual count to standard count),

M is the moisture content of the test specimen, and

E and F are constants.

To obtain values for the two constants, two accumulated count readings are required. For calibration, the nuclear gauge **12** is first placed on the support **14**. A
25 first accumulated count reading is taken while the gauge **12** is in position on the support **14**. A moisture plate (not shown) may then be placed between the gauge **12** and the support **14** to provide a different moisture content reading. The moisture plate may be constructed of any suitable material capable of simulating a certain amount of moisture content, such as polyethylene. A second accumulated
30 count reading is taken while the gauge **12** is in position on the moisture plate. The moisture content values corresponding to the two accumulated counts may be determined by first obtaining accumulated counts using a 'master' gauge that has been previously calibrated using traditional moisture calibration blocks. For

example, the master gauge may be calibrated using the calibration standards described in U.S. Patent No. 4,152,600. The two accumulated counts collected using the gauge to be calibrated are then used to calculate new values for the constants E and F by solving Equation 2.

- 5 Alternatively, the calibration may be accomplished without the moisture plate by assuming an accumulated neutron count corresponding to a moisture content of 0. For any given gauge type or design, the accumulated neutron count corresponding to a moisture content of 0 will be relatively constant. A second accumulated count is taken while the gauge 12 is in position on the support 14.
- 10 Using the assumed count and the accumulated count, new values for the two constants are calculated using Equation 2.

Example 1

- A master gauge, model M3440 manufactured by Troxler Electronic
- 15 Laboratories of Research Triangle Park, NC, was used to assign densities to three calibration apparatus orientations, designated O1, O2, and O3. Before using the master gauge, the calibration and stability of the gauge were verified. The assigned densities for the three orientations for a 4-inch source position were 109.9 (O1), 135.5 (O2), and 162.9 lbs/ft³ (O3).

- 20 A standard count was taken for a test gauge, model M3430 manufactured by Troxler Electronic Laboratories. The standard count was 2725. The test gauge was placed on the calibration apparatus of the present invention with the source rod in 4-inch mode. Counts were accumulated for each apparatus orientation: O1, O2, and O3. Each count was taken over a four-minute period. The three accumulated
- 25 counts acquired for the three orientations were 4398 (O1), 2620 (O2), and 1552 (O3). The same gauge was also calibrated using standardized calibration blocks. The calibration constants determined using the calibration apparatus are compared to the calibration constants determined using standardized calibration blocks in Table 1.

- 30 To determine the difference between the two calibrations, the values for A, B, and C calculated using the calibration blocks and the standard count were used to determine the ratio R (counts/standard counts) for a given density. The density

equivalent for the calibration performed with the calibration apparatus of the present invention was then determined using the same R value and the values for A, B, and C calculated using the calibration apparatus. The density difference ($\Delta\rho$) between the two calibrations equals the absolute value of $(\rho_{cb} - \rho_{ca})$, wherein ρ_{cb} is density determined using the constants calculated from calibration blocks and ρ_{ca} is density determined using the constants calculated from the calibration apparatus. If the values of A, B, and C were identical for the two calibration methods, the density difference should be zero. The density difference between the two calibrations at 125 lbs/ft³ was 0.10 lbs/ft³. The density difference for the range 110 to 165 lbs/ft³ in 5 lbs/ft³ steps was calculated in a similar way with an average $\Delta\rho$ of 0.27 lbs/ft³ over the entire range, indicating that the calibration apparatus of the present invention is capable of substantially matching the calibration accuracy provided by calibration blocks.

15

Table 1

Method	A	B*1000	C
Calibration Apparatus	16.8349	1.3651	-0.0920
Calibration Blocks	17.0467	1.3776	-0.1084

Example 2

The gamma-ray spectra received by the Geiger Mueller tubes of a nuclear density/moisture gauge was analyzed for various materials in both backscatter and direct transmission gamma-ray source positions. Spectra were acquired using a 1-inch by 1-inch NaI scintillation detector coupled to a photomultiplier tube. A Troxler model 3430 gauge without the neutron source, ³He detector, Geiger Mueller tubes, and gauge electronics was used. The active volume of the detector, i.e. the 1-inch by 1-inch NaI crystal, was placed at the middle of the area in the gauge base where the two Geiger Mueller tubes are normally placed. A 2-inch thick lead block was placed next to the NaI detector as a shield to prevent gamma rays hitting the crystal directly. It was discovered that each material-depth configuration has a unique gamma-ray spectrum.

Figure 4 compares the spectra produced by a magnesium calibration block

(with the radiation source **20** at a depth of four inches) with the spectra produced by two embodiments of the present invention. For each embodiment, a block **26** setting that simulates the density value of magnesium ($\sim 110 \text{ lbs/ft}^3$) at a radiation source depth of four inches was used. The solid line represents the energy spectrum of the magnesium calibration block. The double dash line represents the energy spectrum produced by the calibration apparatus **10** of the present invention without a fixed mass **44**. The single dash line represents the energy spectrum produced by the calibration apparatus **10** of the present invention with a fixed mass **44**. If the variable filter **16** of the calibration apparatus **10** cannot substantially match the energy spectrum of the material of known density that the apparatus is simulating, two gauges can read different densities (2 to 8 lbs/ft^3 apart) for the same block **26** setting. Experimentally, it has been determined that the connection between energy spectrum and differences in density readings between gauges results from the fact that two Geiger Mueller tubes can have different energy dependent gamma-ray detection efficiencies. As shown in Figure 4, the apparatus **10** with the fixed mass **44** more closely approximates the energy spectrum of the magnesium block.

Tables 2-10 list the energy spectra data obtained using the 1-inch by 1-inch NaI scintillation detector coupled to a photomultiplier tube. The tables list data for 2-inch mode (Tables 2-4), 4-inch mode (Tables 5-7), and 8-inch mode (Tables 8-10). In each case, the count readings were taken using a magnesium calibration block and using a setting on the apparatus **10** that simulates the density of magnesium. For each depth mode, the tables show the relationships between peak height at low energy and peak height at 662 keV, total counts and counts over 300 keV, and total counts and counts in the 662 keV peak. As indicated by the data, the calibration apparatus **10** with the fixed mass **44** is capable of producing an energy spectrum that substantially matches the energy spectrum produced by the calibration block.

Table 2 (2-inch source depth)

Device	Peak Height @ Low Energy (H1)	Peak Height at 662 KeV (H2)	Ratio (H1/H2)
Calibration Block	62,244 @ 110 keV	1,869	33.3
Apparatus with fixed mass	52,707 @ 120 keV	2,568	20.5
Apparatus without fixed mass	44,421 @ 190 keV	6,371	6.9

Table 3 (2-inch source depth)

Device	Total Counts (C1)	Counts with Energy > 300 keV (C2)	Ratio (C1/C2)
Calibration Block	2,182,002	366,214	6.0
Apparatus with fixed mass	2,135,249	439,588	4.9
Apparatus without fixed mass	1,948,889	548,740	3.6

Table 4 (2-inch source depth)

Device	Total Counts (C1)	Counts in the 662 keV peak (C3)	Ratio (C1/C3)
Calibration Block	2,182,002	7,488	291.7
Apparatus with fixed mass	2,135,249	11,873	180.9
Apparatus without fixed mass	1,948,889	52,174	37.4

Table 5 (4-inch source depth)

Device	Peak Height @ Low Energy (H1)	Peak Height at 662 KeV (H2)	Ratio (H1/H2)
Calibration Block	60,960 @ 110 keV	3,719	16.4
Apparatus with fixed mass	47,900 @ 120 keV	4,362	11.0
Apparatus without fixed mass	34,553 @ 190 keV	13,709	2.5

Table 6 (4-inch source depth)

Device	Total Counts (C1)	Counts with Energy > 300 keV (C2)	Ratio (C1/C2)
Calibration Block	2,278,909	454,481	5.0
Apparatus with fixed mass	1,991,407	455,658	4.4
Apparatus without fixed mass	1,880,130	701,194	2.7

Table 7 (4-inch source depth)

Device	Total Counts (C1)	Counts in the 662 keV peak (C3)	Ratio (C1/C3)
Calibration Block	2,278,909	21,427	106.5
Apparatus with fixed mass	1,991,407	27,461	72.5
Apparatus without fixed mass	1,880,130	124,125	15.1

Table 8 (8-inch source depth)

Device	Peak Height @ Low Energy (H1)	Peak Height at 662 KeV (H2)	Ratio (H1/H2)
Calibration Block	35,583 @ 110 keV	2,025	17.6
Apparatus with fixed mass	29,234 @ 120 keV	2,756	10.6
Apparatus without fixed mass	22,840 @ 190 keV	9,248	2.5

Table 9 (8-inch source depth)

Device	Total Counts (C1)	Counts with Energy > 300 keV (C2)	Ratio (C1/C2)
Calibration Block	1,294,769	266,185	4.9
Apparatus with fixed mass	1,186,617	282,955	4.2
Apparatus without fixed mass	1,211,977	453,537	2.7

Table 10 (8-inch source depth)

Device	Total Counts (C1)	Counts in the 662 keV peak (C3)	Ratio (C1/C3)
Calibration Block	1,294,769	13,448	96.6
Apparatus with fixed mass	1,186,617	15,179	78.1
Apparatus without fixed mass	1,211,977	91,028	13.3

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the

5 specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

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CLAIMS:

1. An apparatus for calibrating a nuclear gauge having a radiation source and a radiation detector, comprising:

5 a support having a lateral support surface for receiving and supporting the underside of the nuclear gauge of the type having the radiation source located in a vertically moveable source rod and a radiation detector, said support having an opening therein positioned for
10 receiving the vertically moveable source rod therethrough; and

a radiation filter capable of producing an energy spectrum incident upon the radiation detector that substantially matches the energy spectrum of at least one
15 solid block of material, wherein said radiation filter has a setting that simulates a known density when exposed to a 662 keV radiation source, said setting producing a ratio of total counts detected to counts with energy over 300 keV of at least 70% of the same ratio produced by the solid block
20 of material of the known density, as measured by a 1-inch by 1-inch NaI scintillation detector, said filter comprising

a block of a radiation attenuating material of predetermined shape located beneath said support and mounted for movement relative to said support to present a variable
25 extent of radiation attenuation to the radiation detector of the nuclear gauge, and

a fixed mass operatively positioned adjacent to the radiation detector and beneath said support to further attenuate radiation emitted from the radiation source of the
30 nuclear gauge.

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2. An apparatus according to claim 1, wherein said block of said radiation attenuating material has a vertical cavity therein positioned beneath said opening of said support and adapted for receiving the source rod of the nuclear gauge, said cavity being eccentrically located within said predetermined shaped block

3. An apparatus according to claim 2, wherein said block of said radiation attenuating material is mounted for rotation relative to said support.

10 4. An apparatus according to claim 3, wherein said block of said radiation attenuating material is positioned for rotation about the central axis of said cavity.

5. An apparatus according to claim 4, further comprising a motorized drive cooperating with said block of said radiation attenuating material for rotating it about the central axis of said cavity.

6. An apparatus according to claim 1, wherein the predetermined shape of said block of said radiation attenuating material is cylindrical.

20 7. An apparatus according to claim 1, further comprising a rotatable platform positioned beneath said block of said radiation attenuating material for imparting rotational movement thereto such that said block of said radiation attenuating material presents a variable extent of radiation attenuation to the radiation detector of the nuclear gauge upon rotation of the block.

8. An apparatus according to claim 1, wherein said support additionally includes a guide operatively positioned to guide a nuclear gauge into a position wherein said source rod of said gauge is overlying said opening.

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9. An apparatus according to claim 1, wherein said fixed mass comprises at least one plate constructed of material selected from the group consisting of aluminum, magnesium, lead, polyethylene, cadmium, tungsten, graphite
5 and combinations thereof.

10. An apparatus according to claim 1, wherein said fixed mass comprises a plurality of plates, each plate constructed of material selected from the group consisting of aluminum, magnesium, lead, polyethylene, cadmium,
10 tungsten, graphite and combinations thereof.

11. An apparatus according to claim 1, wherein said radiation filter has the setting that simulates the density of magnesium when exposed to a 662 keV radiation source, said setting producing a ratio of total counts detected to
15 counts with energy over 300 keV of at least about 4.0 at a radiation source depth of 2 inches, as measured by a 1-inch by 1-inch NaI scintillation detector.

12. An apparatus according to claim 11, wherein said ratio is at least about 4.5.

20 13. An apparatus according to claim 1, wherein said radiation filter has the setting that simulates the density of magnesium when exposed to a 662 keV radiation source, said setting producing a ratio of total counts detected to counts with energy over 300 keV of at least about 3.5 at a
25 radiation source depth of 8 inches, as measured by a 1-inch by 1-inch NaI scintillation detector.

14. An apparatus according to claim 13, wherein said ratio is at least about 4.0.

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15. An apparatus according to claim 1, wherein said ratio is about 80% of the ratio produced by the solid block of material of the known density.

16. A method of calibrating a nuclear density gauge,
5 comprising the steps of:

providing the nuclear gauge having a radiation detector and a radiation source located in a vertically moveable source rod;

providing a calibration apparatus having a lateral
10 support surface for receiving and supporting the underside of the nuclear gauge and a radiation filter located beneath the support surface, the filter being capable of producing an energy spectrum incident upon the radiation detector that substantially matches the energy spectrum of at least one
15 solid block of material, wherein said radiation filter has a setting that simulates a known density when exposed to a 662 keV radiation source, said setting producing a ratio of total counts detected to counts with energy over 300 keV of at least 70% of the same ratio produced by a solid block of
20 material of the known density, as measured by a 1-inch by 1-inch NaI scintillation detector, and wherein the radiation filter comprises

a block of a radiation attenuating material of predetermined shape located beneath said support and mounted
25 for movement relative to said support to present a variable extent of radiation attenuation to the radiation detector of the nuclear gauge, and

a fixed mass operatively positioned adjacent to the radiation detector to further attenuate radiation
30 emitted from the radiation source of the nuclear gauge;

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placing the nuclear gauge on the lateral support surface;

positioning the radiation source of the nuclear gauge at a predetermined source depth position; and

5 obtaining an accumulated count of scattered radiation with the nuclear gauge while on the apparatus.

17. A method according to claim 16, further comprising the steps of adjusting the radiation filter to provide a different extent of radiation attenuation; and obtaining a
10 second accumulated count of scattered radiation with the nuclear gauge in said position on the apparatus.

18. A method according to claim 17, wherein the block of said radiation attenuating material is cylindrical and mounted for rotation, and wherein the step of adjusting the
15 radiation filter comprises rotating the cylindrical block to present a different extent of radiation attenuation to the radiation detector of the nuclear gauge.

19. A method according to claim 17, further comprising the steps of adjusting the radiation filter to provide still
20 another different extent of radiation attenuation; and obtaining a third accumulated account of scattered radiation with the nuclear gauge in said position on the apparatus.

20. A method according to claim 16, further comprising the step of repositioning the vertically moveable source rod
25 to a different source position and obtaining an additional accumulated count of scattered radiation with the nuclear gauge.

21. A method according to claim 16, further comprising the step of adjusting the radiation filter to the setting
30 that simulates the density of magnesium when exposed to a

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662 keV radiation source, said setting producing a ratio of total counts detected to counts with energy over 300 keV of at least about 4.0 at a radiation source depth of 2 inches, as measured by a 1-inch by 1-inch NaI scintillation

5 detector.

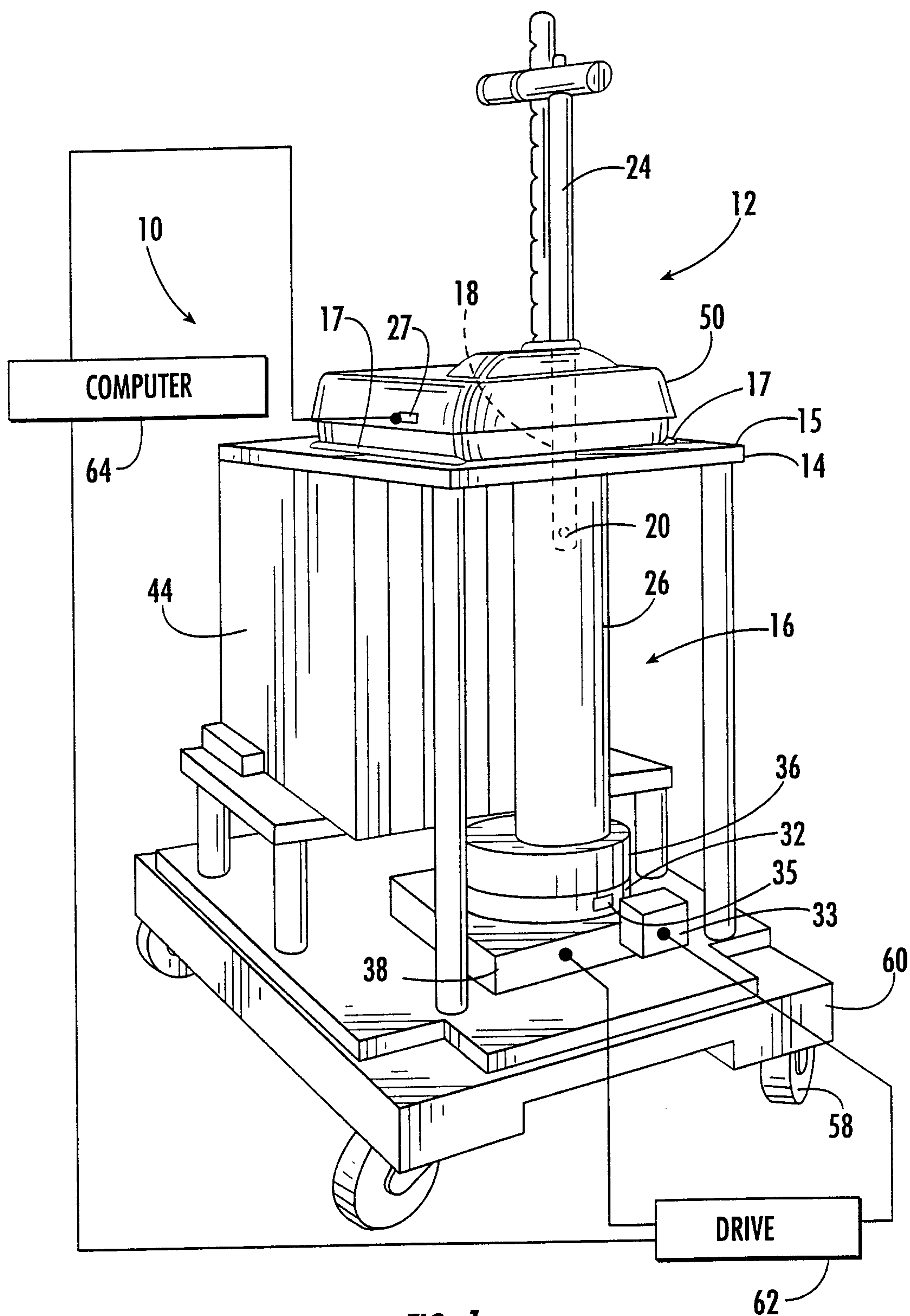
22. A method according to claim 16, further comprising the step of adjusting the radiation filter to the setting that simulates the density of magnesium when exposed to a 662 keV radiation source, said setting producing a ratio of
10 total counts detected to counts with energy over 300 keV of at least about 3.5 at a radiation source depth of 8 inches, as measured by a 1-inch by 1-inch NaI scintillation detector.

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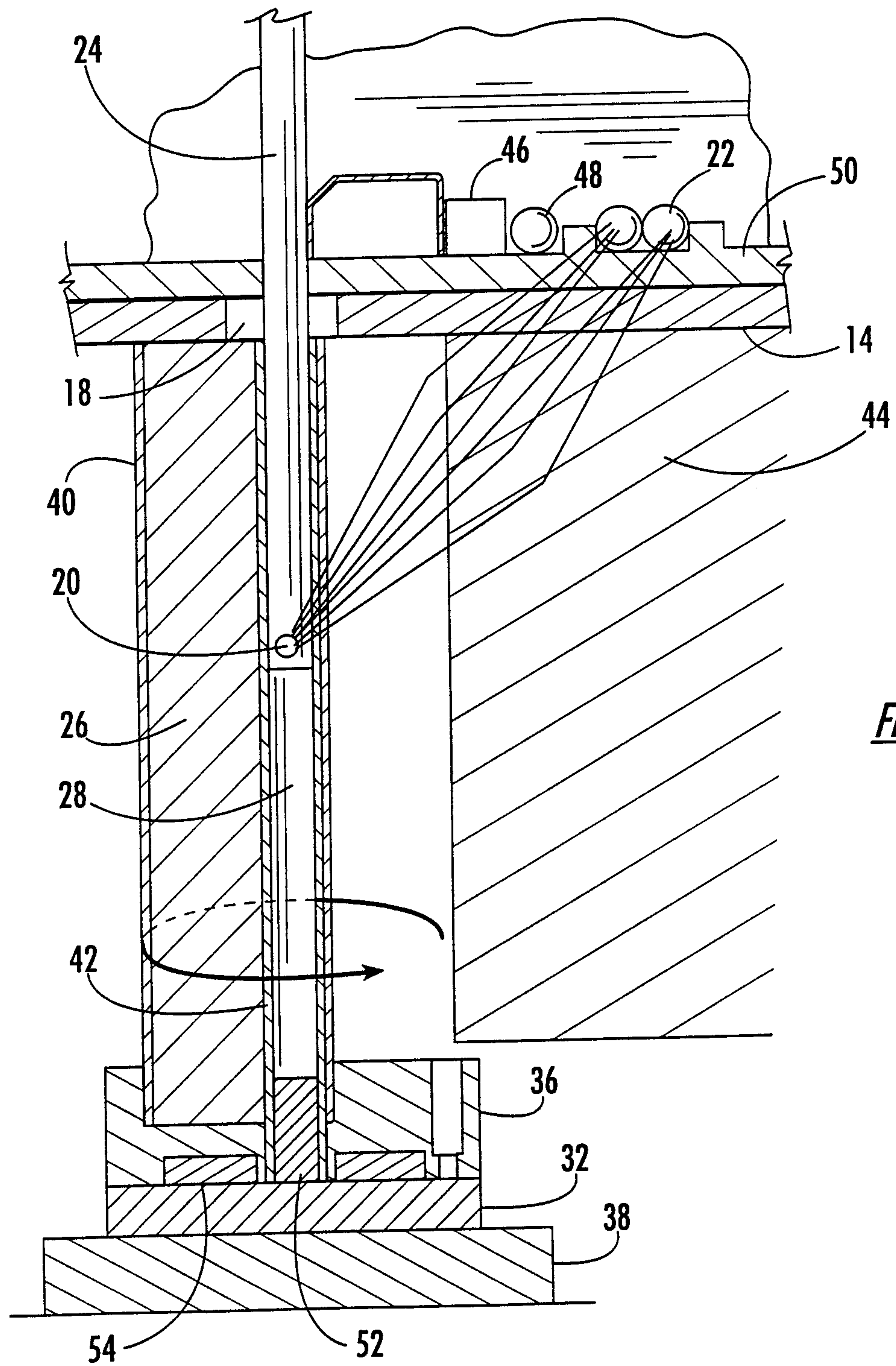
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PATENT AGENTS

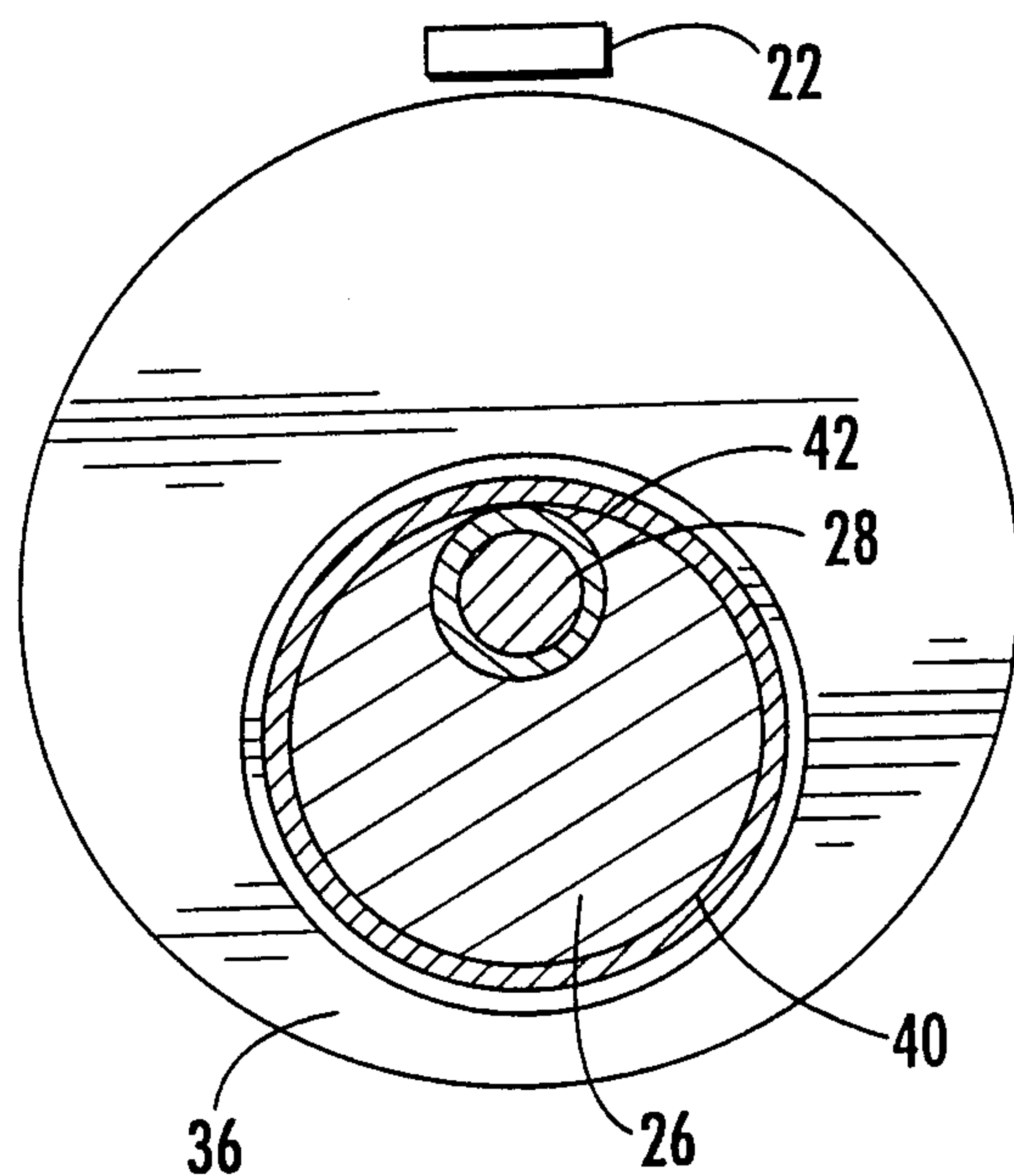
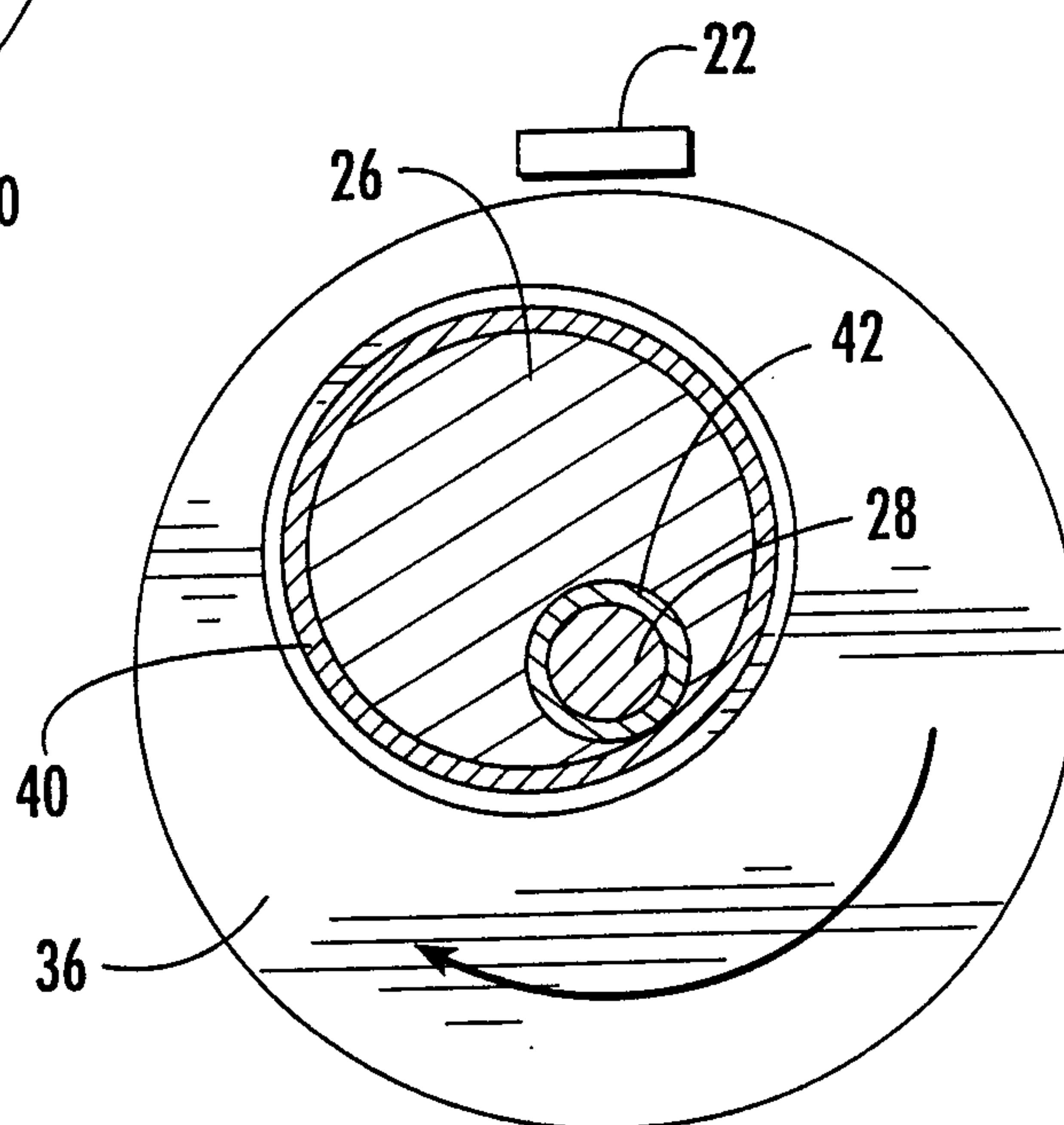
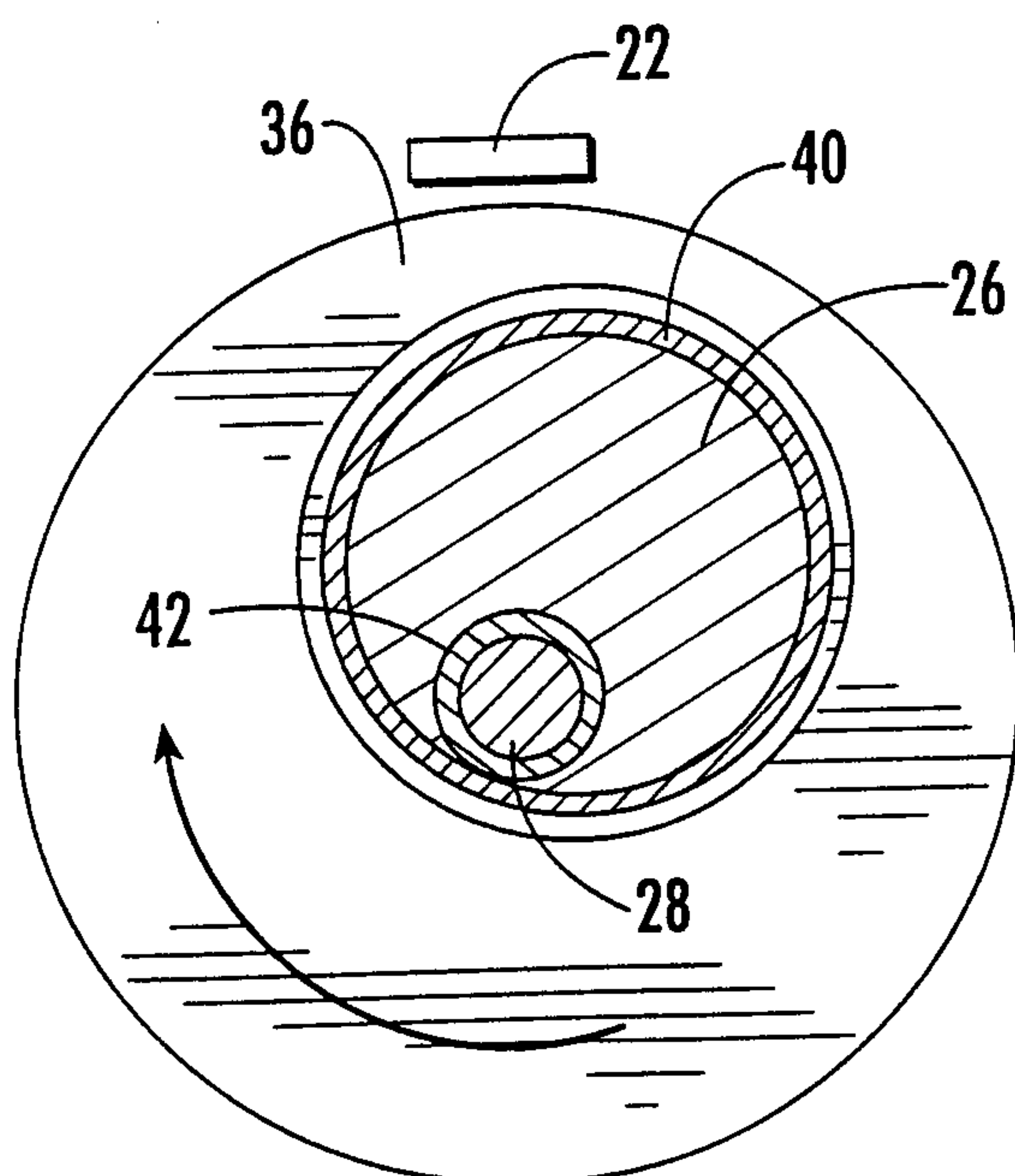
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***FIG. 1.***

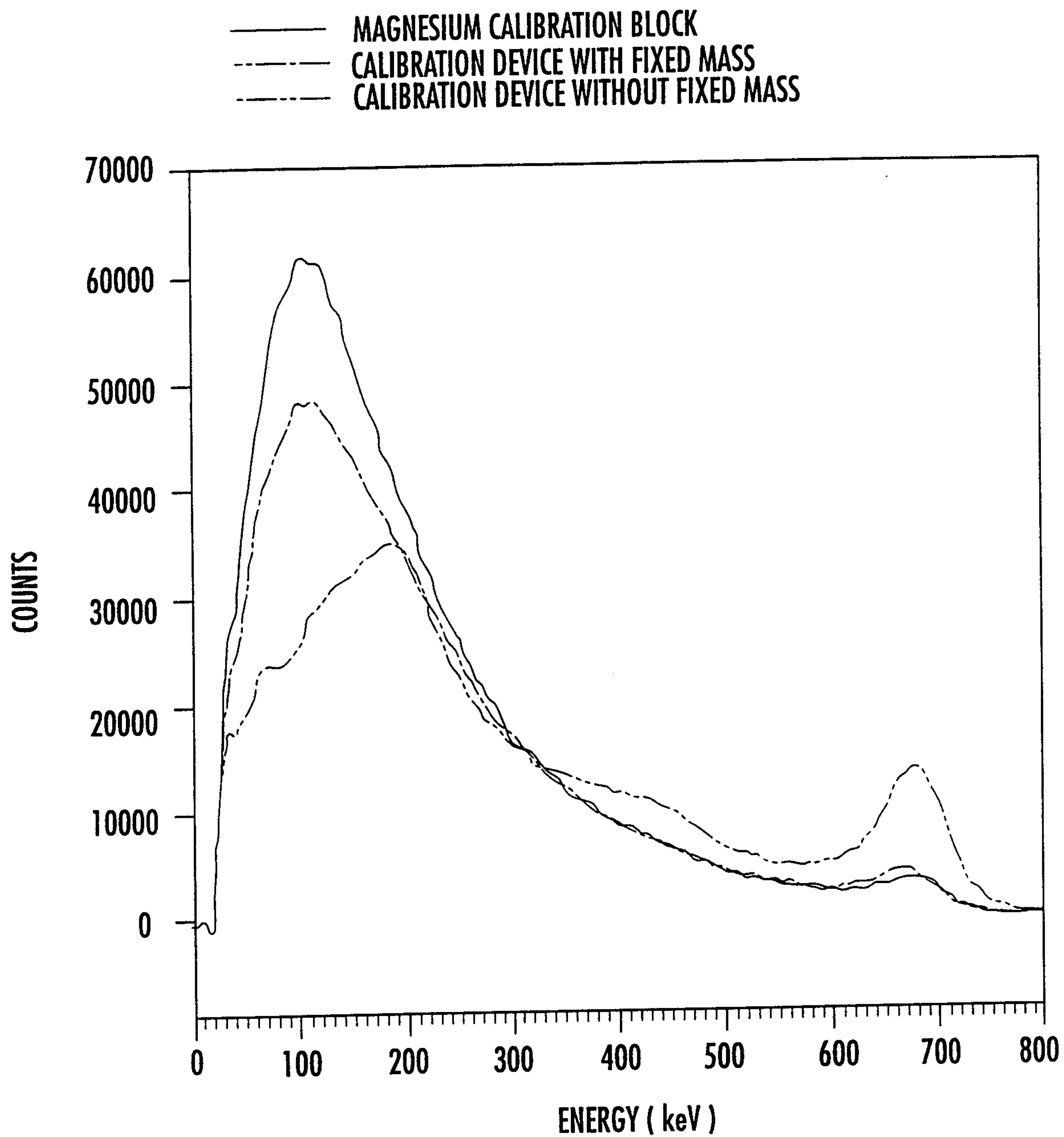
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**FIG. 2.**

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FIG. 3A.FIG. 3B.FIG. 3C.

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FIG. 4.

