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Neugebauer

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[54] **LOW FLUX LEAKAGE MAGNET CONSTRUCTION**

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[52] **U.S. Cl.** **335/304,** 335/306, 310/254, 310/261

[51] **Int. Cl.** **H01f 7/02**

[58] **Field of Search** .... 335/210, 302, 304, 335/306; 250/49.5 D; 310/254, 261

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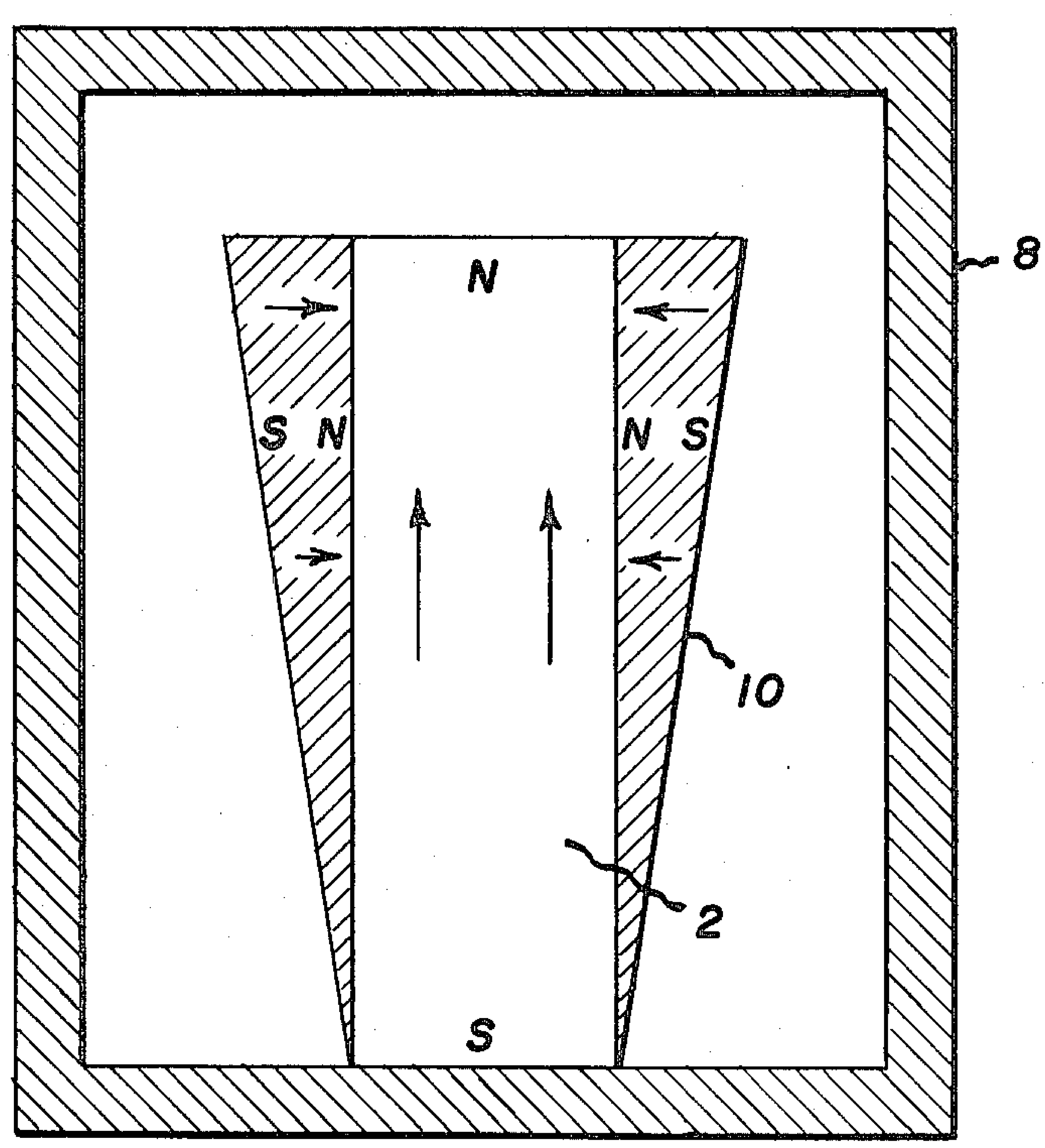
Primary Examiner—George Harris
Attorney—Nathan J. Cornfeld et al.

[57] **ABSTRACT**

A magnet construction is disclosed wherein the flux of a first, principal magnet is conserved by placing a second magnet adjacent the first magnet with the magnetic axes of the two magnets perpendicular to each other. The second magnet is constructed of a highly anisotropic material having low permeability perpendicular to its magnetic axis and preferably having a high coercive force and good magnetization retention. Preferably the second magnet surrounds the first magnet to minimize the flux leakage of the first magnet.

15 Claims, 8 Drawing Figures



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SHEET 1 OF 3

FIG.1.

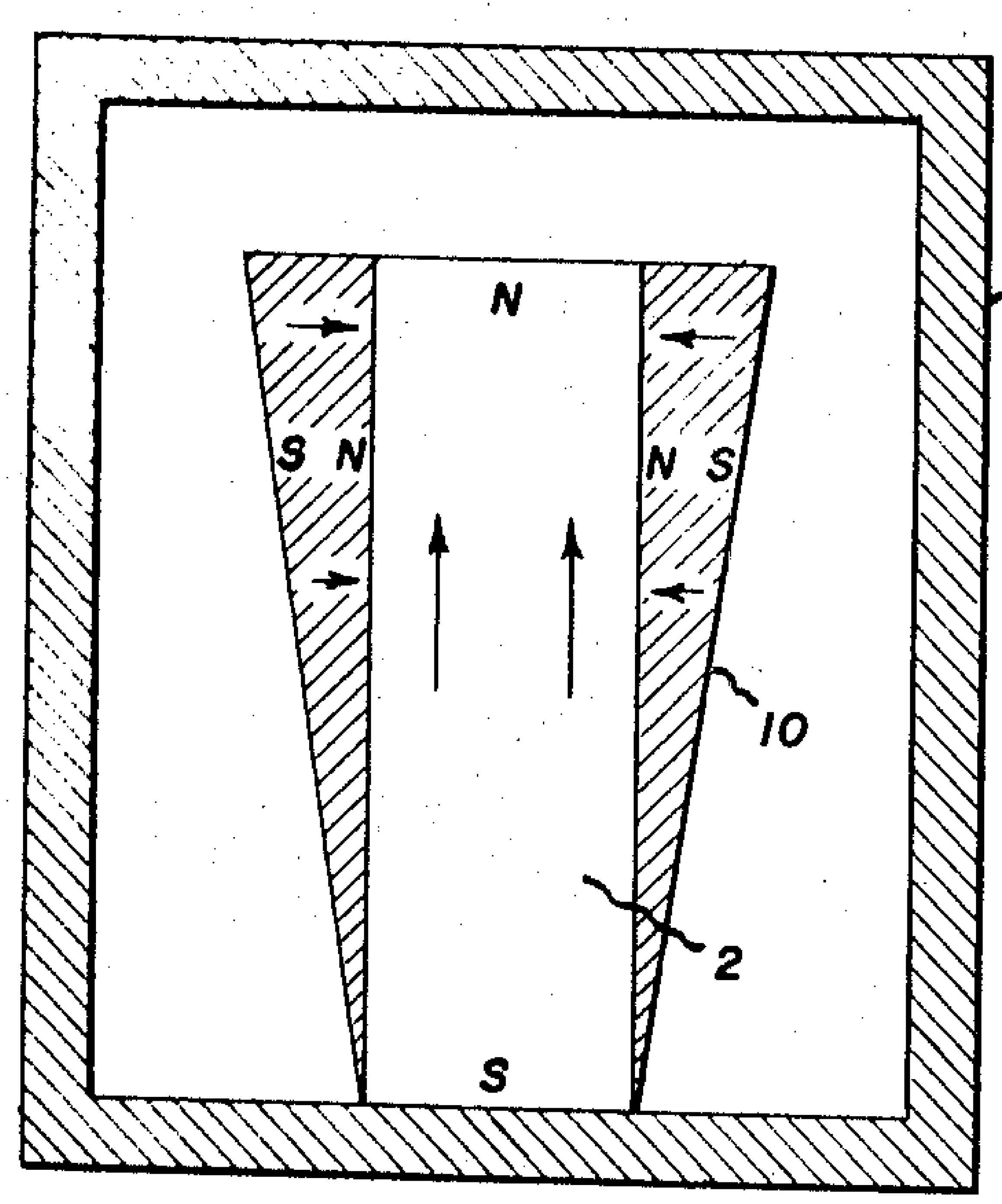


FIG.2.

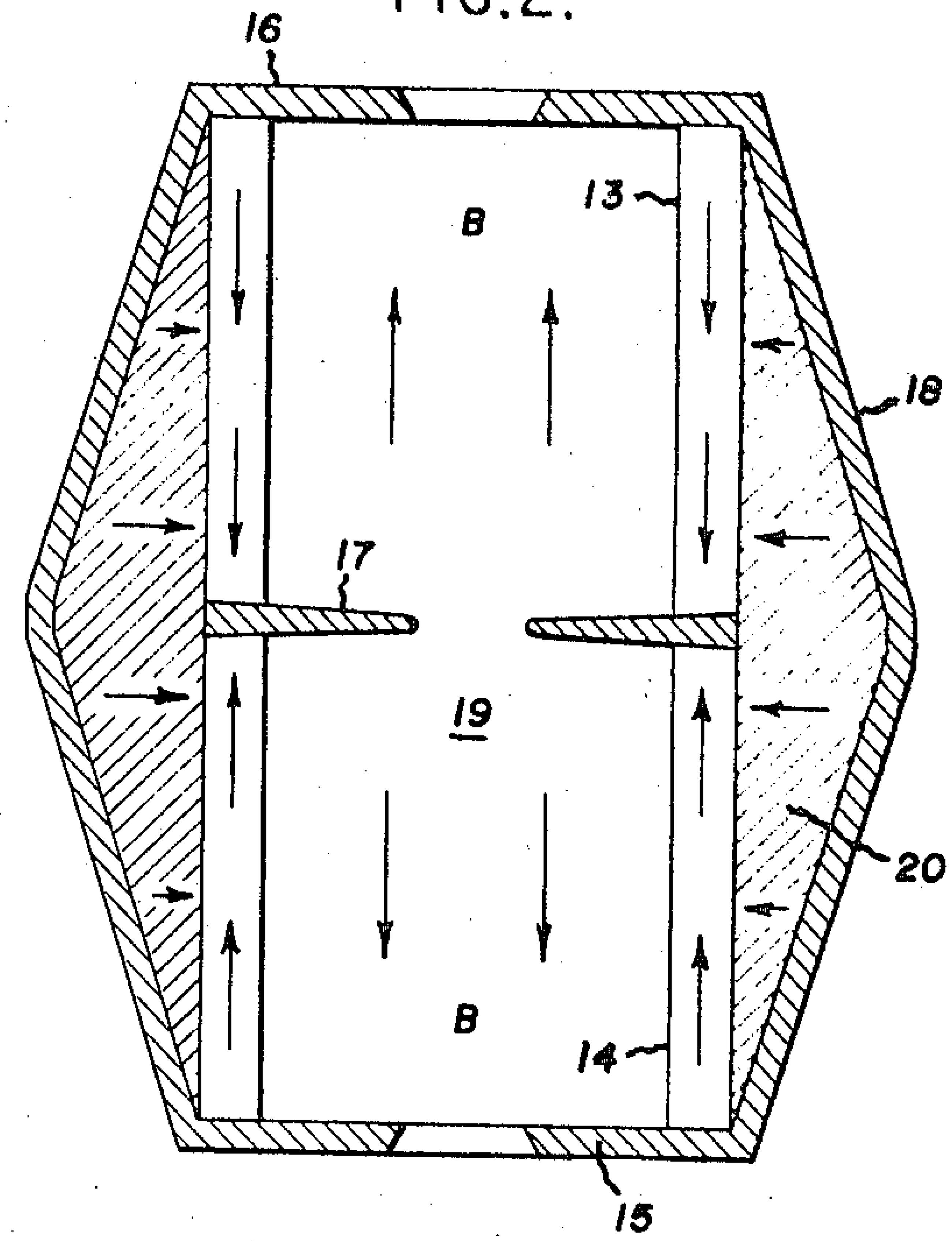


FIG.3.

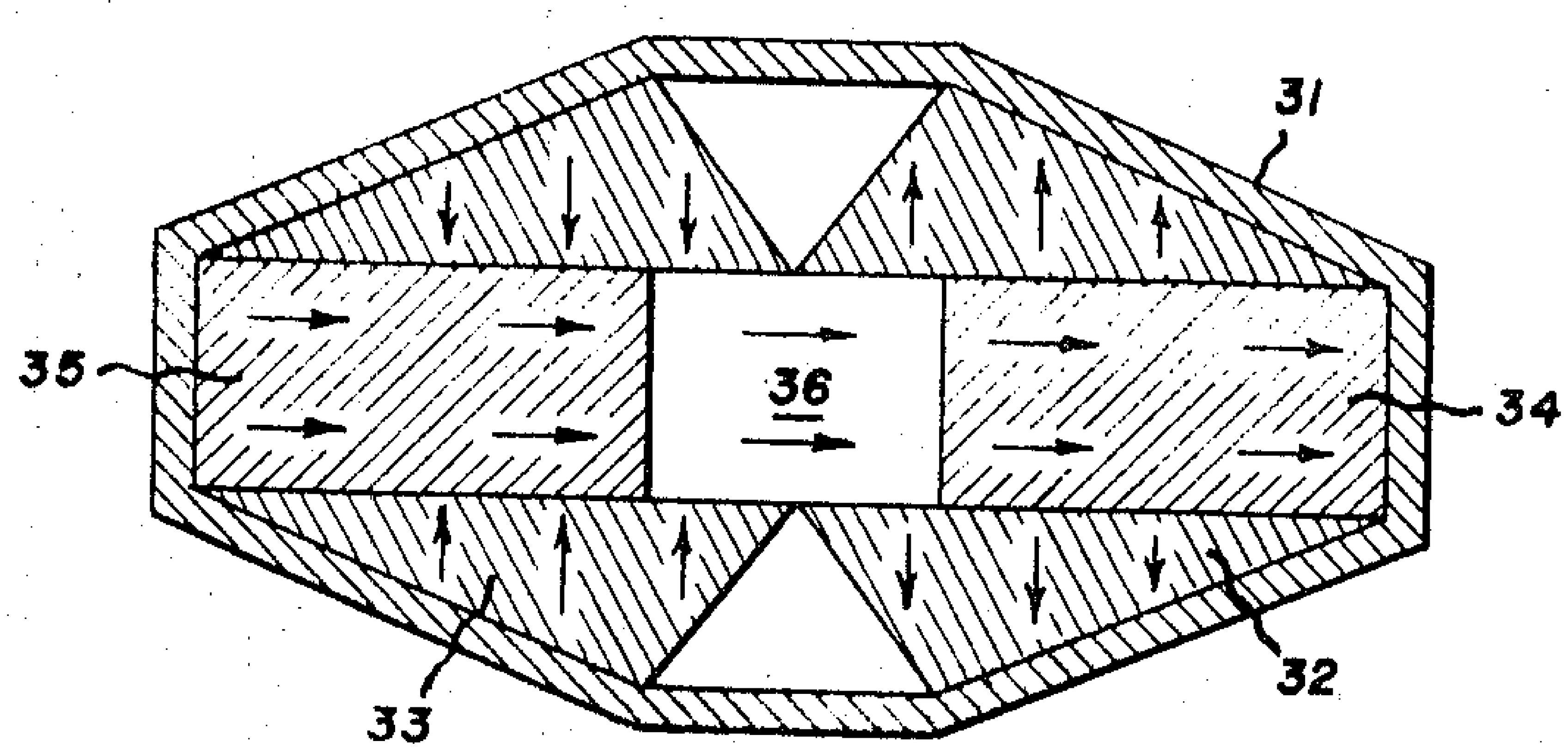


FIG.5.

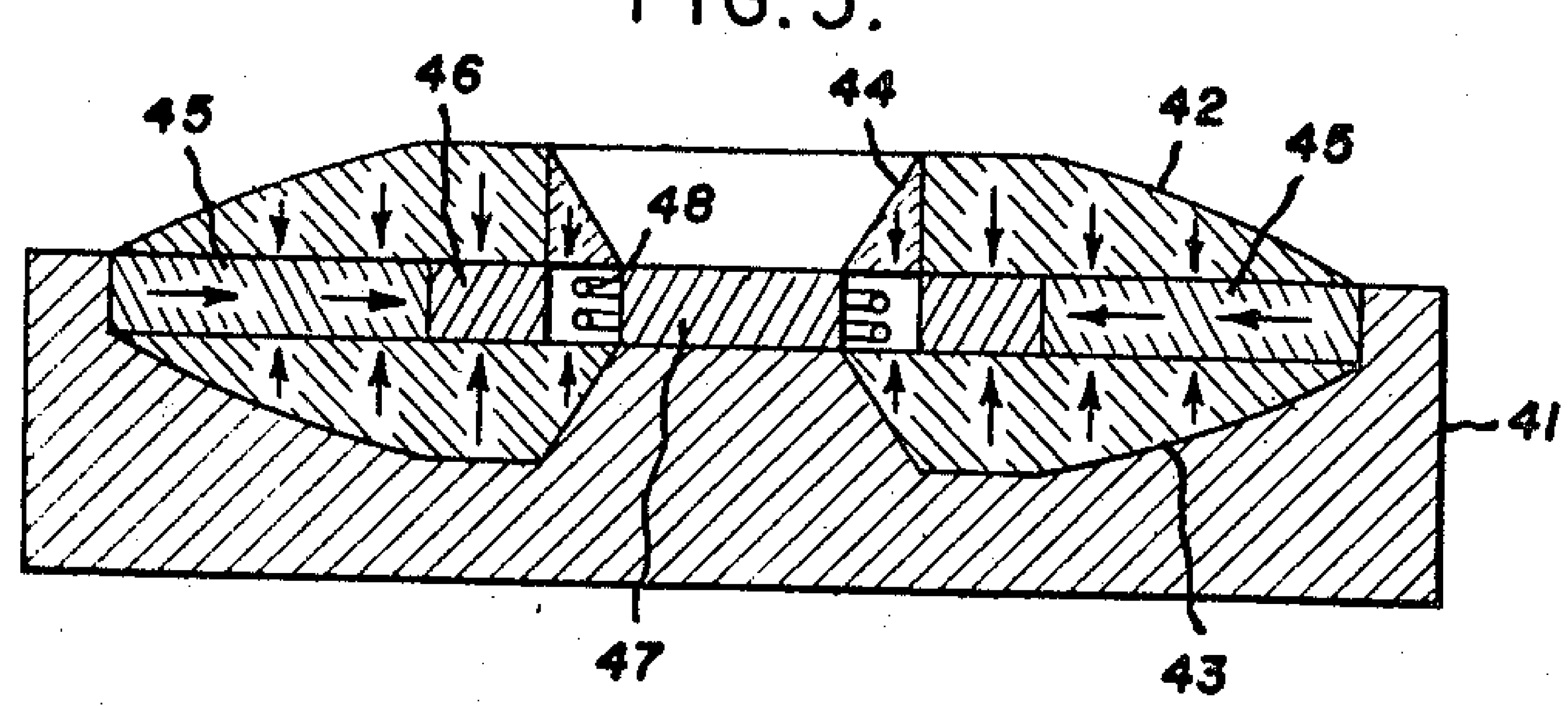


FIG. 4.

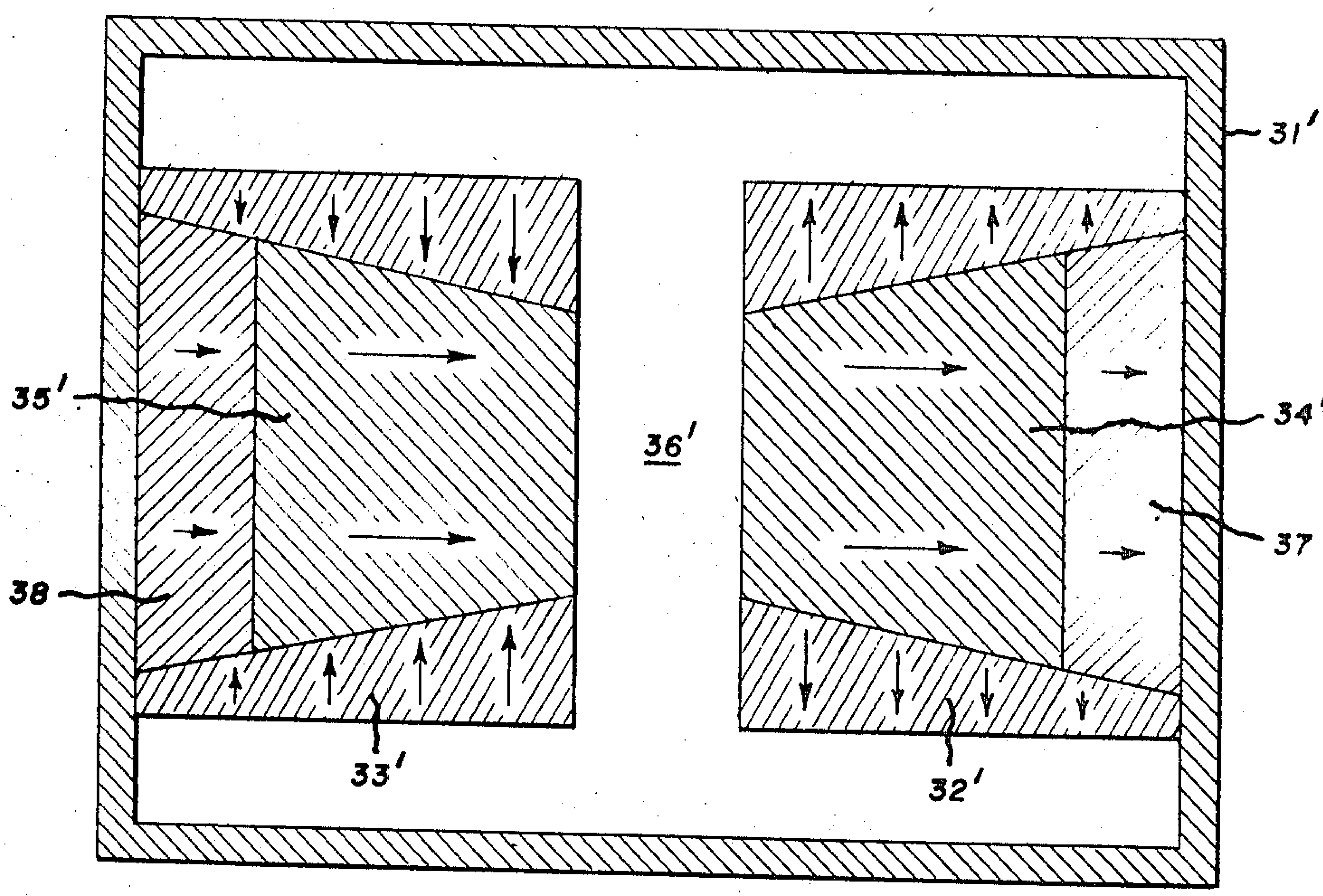
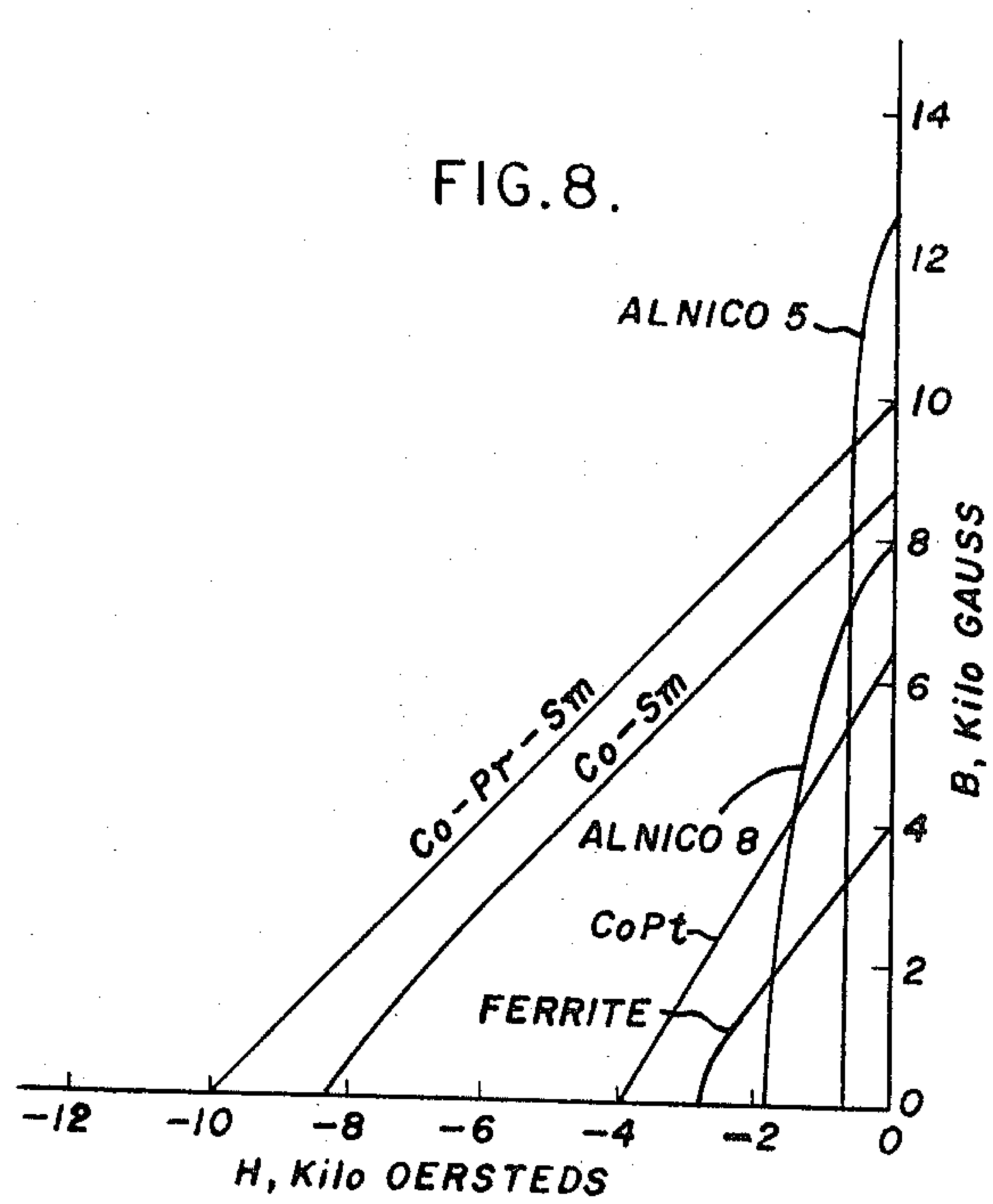

31'
35'
34'
36'
37
38
33'
32'

FIG. 8.


ALNICO 5
Co-Pr-Sm
Co-Sm
ALNICO 8
CoPt
FERRITE
14
12
10
8
6
4
2
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B, Kilo GAUSS
-12
-10
-8
-6
-4
-2
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H, Kilo OERSTEDS

FIG. 6.

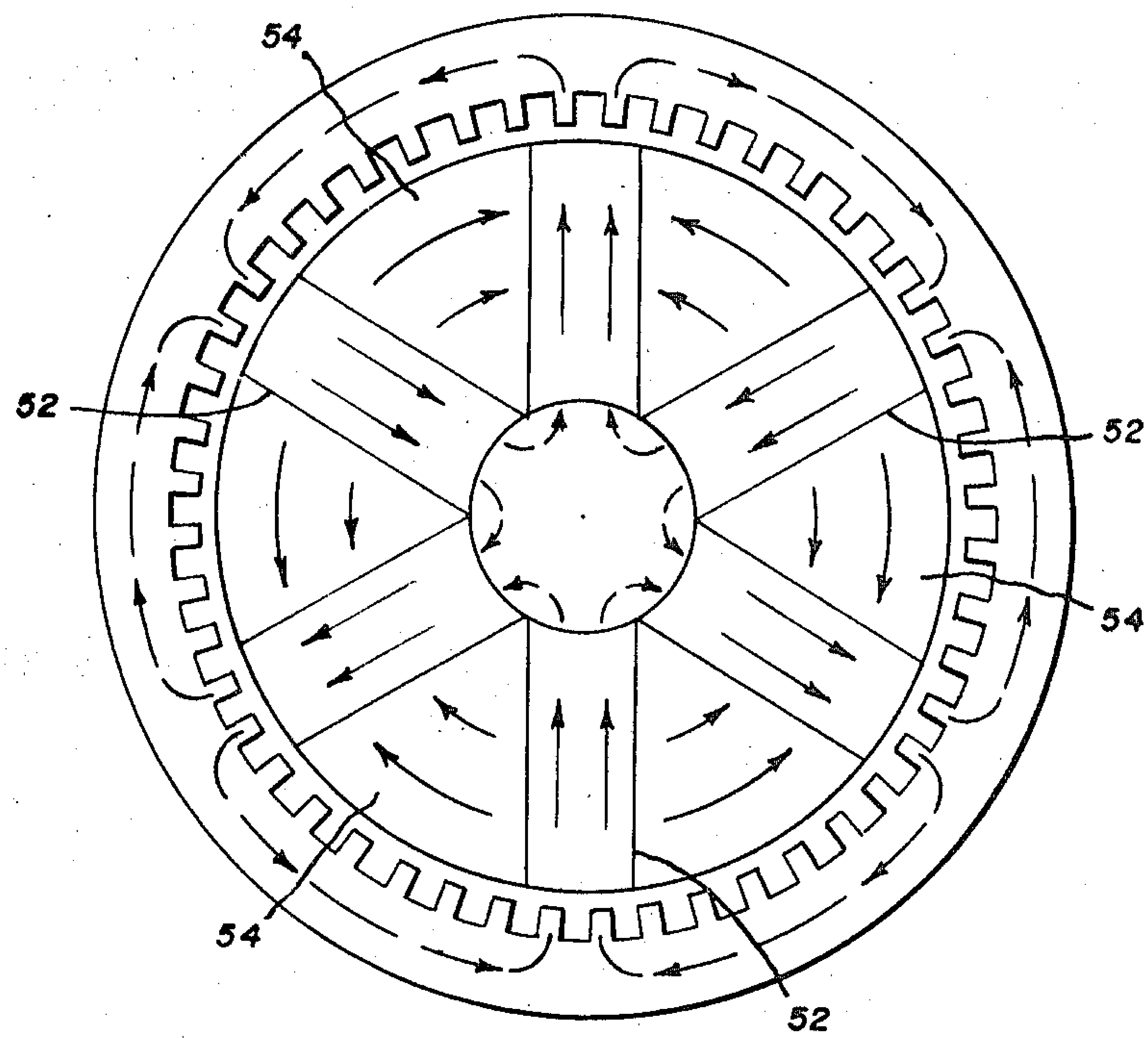
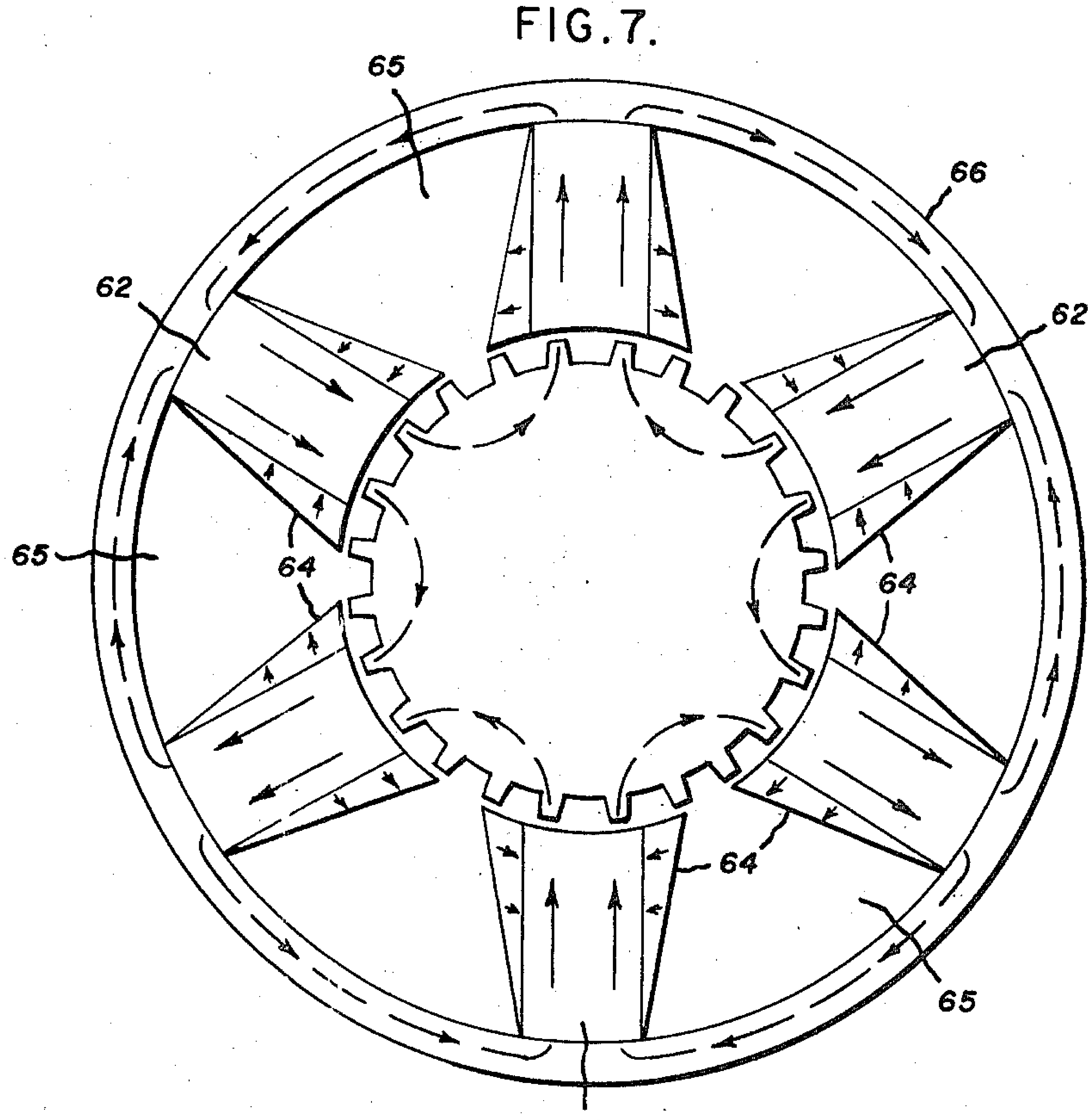


FIG. 7.



LOW FLUX LEAKAGE MAGNET CONSTRUCTION

BACKGROUND OF THE INVENTION

Permanent magnets are normally characterized as materials having magnetic flux producing properties generally along an axis. However, in actual practice, some of the flux is generated in directions skewed from the main axis. This may be regarded as leakage or lost flux since the flux so generated contributes little, if any, to the desired magnetic intensity. The extent of this loss varies with the type of material as well as the geometric design of the magnet. In any event the usual remedy is to increase the total size of the magnet to achieve the desired magnetic intensity. This, however, has the undesirable effect of adding excessive weight to the magnetic system.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide an improved magnet construction wherein the leakage flux is minimized.

It is another object of the invention to provide a magnet construction having an improved magnetic intensity per unit weight ratio.

These and other objects of the invention will be apparent from the specification and accompanying drawings.

In accordance with the invention the magnetic flux of a first magnet is conserved by placing a second permanent magnet adjacent the first magnet with the magnetic axis of the second magnet perpendicular to the axis of the first magnet to prevent leakage of flux from the first magnet. The second magnet comprises a highly anisotropic material having a low magnetic permeability in a direction perpendicular to its magnetic axis. Preferably, the second magnet comprises a high coercive force material with good magnetization retention properties.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a bar magnet constructed in accordance with the invention.

FIG. 2 is a cross-sectional view of a magnet for a klystron constructed in accordance with the invention.

FIG. 3 is a cross-sectional view of a magnet for a voltage tunable magnetron constructed according to the invention.

FIG. 4 is a cross-sectional view of a modified version of the magnet construction of FIG. 3.

FIG. 5 is a cross-sectional view of a loud speaker magnet constructed according to the invention.

FIG. 6 is a cross-sectional view of a portion of a motor having a rotor magnet construction in accordance with the invention.

FIG. 7 is a cross-sectional view of a portion of a motor having a stator magnet construction in accordance with the invention.

FIG. 8 is a graph showing B-H curves for magnetic materials.

DESCRIPTION OF THE INVENTION

Turning now to FIG. 1, the invention is illustrated as comprising a central bar magnet 2 and a second magnet 10.

Bar magnet 2, in the illustrated embodiment, comprises a solid rod with the magnetic axis generally along the mechanical axis of the rod. Magnet 2 can be made of any conventional magnet material such as, for example, steel or Alnico.

Magnet 10 is of generally conical configuration with a central bore therein conforming to the diameter of magnet 2 so that magnet 10 may be slipped over magnet 2. Magnet 10 is preferably conically shaped or tapered for a reason which will be described below. Magnet 10 can be permanently attached to magnet 2, for example, by bonding the magnets together with generally magnetically transparent means such as epoxy cement or the like. In accordance with the invention magnet 10 is constructed of a highly aniostropic material having a low permeability normal to its magnetic axis. Preferably, the material also should exhibit a high coercive force and good magnetic retention properties. The latter property is particularly desirable to prevent demagnetization or alteration of the magnetic properties of magnet 10 by magnet 2. Materials which possess these properties and which have been found to be useful in the practice of this invention include the rare earth-cobalt alloys described and claimed in U.S. Pat. Nos. 3,655,463 of Apr. 11, 1972; 3,655,464 of Apr. 11, 1972; 3,684,593 of Aug. 15, 1972; and 3,695,945 of Oct. 3, 1972; and all assigned to the assignee of this invention.

The use of the term "rare earth-cobalt alloys" is intended to include one or more of the rare earth elements alloyed with cobalt. The term "rare earth" is intended to include the 15 elements of the lanthanide series having atomic numbers 57–71 inclusive. The element yttrium (atomic number 39) is commonly included in this group of metals and is therefore to be considered, in this specification, as also included in the term "rare earth".

As shown by the arrows in FIG. 1, magnet 10 is in accordance with the invention, radially magnetized so that its direction of magnetization is generally perpendicular to the magnetic axis of magnet 2. Any skewing of the flux lines generated by magnet 2 are thus corrected or prevented from "leaking" out of the sides of magnet 2. This conservation or increase of the available flux in magnet 2 enables one to reduce the overall size, and thus the weight, of magnet 2 to a size commensurate with the desired amount of flux without the previous necessity of additionally compensating for flux losses by "leakage" of stray flux.

The magnetic material used in accordance with the invention for magnet 10 must have low permeability in a direction normal to the magnetic axis, i.e. parallel to the magnetic axis of the main magnet 2 to prevent shorting the field of the main magnet.

The term low permeability is intended to define a relative permeability of the cladding magnet material in a direction normal to its magnetic axis more like that of vacuum than that of ferromagnetic materials.

The cladding magnet material must also, in accordance with the invention, have a high anisotropy, i.e., the material should be highly magnetizable only along one axis. The degree of anisotropy of a material can be found by determining the alignment factor which is the residual induction (B_r) of the material divided by the saturation magnetization ($4\pi J_s$). If a theoretically perfect alignment factor was assigned a value of 1 and an alignment factor representing completely random alignment assigned a value of 0.5, the alignment factor representing highly anisotropic material would have a value of at least 0.80 and preferably 0.95 or higher.

As previously mentioned, the magnetic material used in constructing cladding magnet **10** preferably should have a relatively high coercive force to provide the required magnetic potential necessary for operation of the invention. Coercive force is a material property defined as the field strength (H_c) at which the magnetic induction (B) becomes zero. High coercive force material, then, is defined in this specification as referring to a strongly magnetizable material requiring a coercive force of at least 2 Kilo oersteds, and preferably 4 Kilo oersteds, to reduce the magnetic induction to zero.

Referring to FIG. **8**, B–H curves in the second quadrant of the hysteresis loops for various magnetic materials are plotted using the EMU system of units. It will be seen that the slopes of the curves vary, with the cobalt-rare earth curves approaching a 45° slope, the theoretically ideal condition. The ratio of the value of H_c to the residual induction B_r the magnetic induction B corresponding to zero magnetizing force H is an indication of the magnetization retention properties of the material. It can be seen that the value of H for the Alnico materials with respect to B_r is much lower than that of the CoPt, ferrite and cobalt-rare earth materials and, in fact, such Alnico materials are unsuitable for use as cladding magnets in accordance with the invention. The term good magnetization retention properties, then, is defined in this specification as referring to a material having a value of H_c at least 60% of B_r (when expressed in the EMU system in Oersteds and gauss respectively) and preferably 80–90% or higher.

Referring now to FIG. **2**, a specific application of the teachings of this invention is illustrated. A magnet comprising a single reversal permanent magnet circuit for a linear beam tube is shown. Cylinders **13** and **14** may be constructed of conventional magnetic material and are magnetized axially and placed in opposition as shown. Cylinders **13** and **14** produce the flux that passes through pole pieces **15** and **16** and the open space **19** to be occupied by a linear beam tube such as a klystron or traveling wave tube. Reversal pole piece **17** carries twice the flux as either of the end pole pieces.

In accordance with the invention, magnetic cylinders **13** and **14** are jacketed by a magnetic member **20** generally shaped as a double cone.

Magnetic member **20** is constructed of magnetic material having the properties described above for magnet **10**. Member **20** is radially magnetized, as indicated in the figure, substantially perpendicular to the flux lines of cylindrical magnets **13** and **14**. In this embodiment, the second, flux conserving, magnet **20** is not constructed of uniform thickness. Since the magnetic potential in cylinders **13** and **14** varies linearly with distance from the respective end pole pieces **15** and **16**, the variation in thickness of the cladding **20** must be linear along the axis of magnets **13** and **14**. Stated another way, inasmuch as the magnetic potential increases along cylinders **13** and **14**, the magnetic counter potential necessary to prevent leakage of flux from cylinders **13** and **14** must be increased by increasing the size or thickness of cladding **20**. The magnetic potential of the reversing pole **17** is constant and therefore the thickness of member **20** is constant in this region. Iron shell **18** carries no flux and is merely added to keep external fields from penetrating into the structure.

The thickness of member **20** at any point is dtermined by the magnetic potential on the principal magnet **13** or **14** as well as the coercive force of the material used in constructing member **20**. The shape and configuration of the cladding magnet or magnets can thus be determined either empirically or by calculations using the magnetic potential of the principal magnet and the magnetic properties of the cladding magnet material. These parameters can, in turn, be determined by referring to the B–H curves for the particular materials used.

Thus, while I do not wish to be bound by any mathematical theories concerning the magnetic forces, it is believed that the shape of member **20** can be calculated by first determining the magnetic potential along the main magnets **13** or **14** by applying computational methods well known to those skilled in the art and then applying the results to the following formula:

$$T = U/H_c$$

where T is the thickness of the cladding at any given point; U is the magnetic potential (in gilberts in the EMU system of units) at that point on the surface of the main magnet; and H_c is the coercive force of the cladding material.

Since the addition of the cladding material to the original magnetic circuit alters the flux pattern previously computed, it is essential that the computation be repeated with the cladding in place. The new solution thus obtained will lead to a slightly different magnetic potential distribution U on the surface of the main magnets. The cladding thickness is then slightly adjusted according to the above formulation. This process is repeated until a solution is obtained that is self-consistent within the desired degree of accuracy.

To demonstrate the method of computing the cladding thickness, the circuit of FIG. **2** will be analysed. Still referring to FIG. **2**, the flux density $\overline{B}$ is specified to be axially directed with a complete reversal of direction in the center of the structure. The magnetic field vector $\overline{H}$ is therefore also axially directed and has a magnitude equal to $\overline{B}$ in the EMU system of units in the open space **19**. Since no surface current is flowing at the boundary between the open space **19** and the cylinders **13** and **14**, the field vector H is the same in the material of cylinders **13** and **14** as in the space **19** by the law of continuity. The flux density of the material of cylinders **13** and **14** is now established by referring to the appropriate B-H characteristic of the material with H being known. Designating B_m as the magnitude of flux density in the material of the cylinders **13** and **14** and B the magnitude of flux density in the open space **19**, the rule that the divergence of the flux density vanish implies that:

$$A_m B_m = AB$$

where A_m is the transverse area of the material comprising cylinders **13** and **14** measured in a plane perpendicular to the axis of these cylinders, and A is the transverse area of the open space **19** measured in the same plane. This relation yields the value of A_m because all the other factors are known or specified. From this value of A_m the thickness of the main flux producing cylinders is determined.

The thickness of the cladding at any point X on the surface of the main flux producing cylinders is established by first determining the magnetic potential U along the outer surface of the cylinders **13** and **14** and then referring to the appropriate B–H curve of the cladding material to obtain the coercive force H_c which is the value of H when B is equal to zero. The values of U and H_c are applied to formula (1) to determine the thickness of the cladding at the point X. A similar procedure yields an equation for the cladding thickness along cylinder **14.** Since the flux patterns were known beforehand, no repetition of the calculation is necessary in this example, the given solution already being self-consistent.

Although the method of computation outlined above yields a definite value of cladding thickness as a function of geometrical location, a thickness different from the one computed may be used. In particular, changes in the thickness lead to changes in the flux density in the open space to be occupied by a specific device, and thus afford a valuable means of adjusting the flux density for optimum device performance. In general, a lesser thickness of cladding yields a lower flux density and vice versa. The use of cladding thicknesses other than computed may result in some leakage flux which, however, is still far below the leakage flux normally associated with unclad magnetic circuits. It should also be noted here that non-tapered cladding, in some instances, may be used for manufacturing efficiencies.

Referring now to FIG. **3,** another magnetic construction, in accordance with the invention, is illustrated in a structural form most useful for crossed-field devices such as magnetrons, voltage-tunable magnetrons (VTM*s*), and crossed-field amplifiers (CFA*s*).

In this construction the useful flux is produced by cylindrical bars **34** and **35** magnetized in the same direction. This flux passes through the space **36** to be occupied by the crossed-field device and completes the circuit through iron shell **31.**

In accordance with the invention, cladding magnets **32** and **33** comprising radally magnetized cylinders sruuounding principal magnets **34** and **35.** Again the thickness of magnets **32** and **33** is not uniform but is rather directly proportional to the magnetic potential along the flux producing bars **34** and **35** or in the air gap **36.** The cladding thickness, therefore, is zero at the very center of air gap **36** because the magnetic potential is zero there. This proper adjustment of the thickness of the cladding magnet **32** and **33** results in no flux being carried by these magnets. Magnets **32** and **33** are constructed of magnetic materials having the properties previously described with respect to cladding magnet **10.** FIG. **4** illustrates an alternate construction to FIG. **3** and useful in the crossed-field devices previously described. In this embodiment magnets **34'**, **35'**, **37** and **38** are each shaped as frustums of a cone. Magnets **34'** and **37** together comprise one main magnet while magnets **35'** and **38** form the other main magnet.

Cladding magnets **32'** and **33'** have an outer cylindrical shape but are each provided with a tapered center bore conforming to the frustum shapes of the respective main magnets. An iron shell **31'** surrounds the magnet construction to serve as a return path and to shield the magnets from penetration by external fields.

To further illustrate the practice of the invention, a magnet was constructed as shown in FIG. **4.** Frustums **34'** and **35'** were constructed of Alnico **9** material with a base diameter of 1.25 inches, a diameter of 0.875 inch at the smaller end, and 1.013 inches thickness. Magnets **37** and **38** were constructed of Co_5Sm alloy having a base diameter of 1.390 inches, a diameter at the smaller end of 1.25 inches, and a thickness of 0.375 inch. Magnets **34'**, **35'**, **37** and **38** were all magnetized axially with the North poles of magnets **35'** and **38** facing the South poles of magnets **34'** and **37** as indicated by the arrows in FIG. **4.**

Cladding magnet **32'** was constructed of Co_5Sm alloy segments forming a cylinder having an outer diameter of 1.65 inches and a length or thickness of 1.388 inches. Magnet **32'** was magnetized normal to its cylindrical axis.

The segments forming magnet **32'** were provided with an internal taper to provide a conical bore to snugly receive frustum main magnets **34'** and **37.** The segments of magnet **32'** were retained to magnets **34'** and **37** using Eastman **910** cement.

The segments forming magnet **33'** were similarly assembled about main magnets **35'** and **38** and the clad magnet assemblies were mounted in iron shell **31'** with the small ends of magnets **34'** and **35'** facing one another in coaxial alignment with a spacing therebetween of 0.550 inch.

Measurements of the flux density were made and found to be about 7,400 gauss as compared to a theoretical value of about 8,000 gauss. While the flux densities of main magnets **34'**, **35'**, **37** and **38** were not actually measured without cladding, standard magnets of this type, size, and gap are normally found to have flux densities below 5,000 gauss.

In FIG. **5** a loudspeaker magnet constructed in accordance with the invention is illustrated. The main flux producing member is a radially magnetized disk **45** which is clad with axially magnetized shaped disks **42, 43,** and **44.** The pole pieces **46** and **47** serve to concentrate the flux to a density that is higher than that capable of being produced by the permanent magnet material comprising disk **45.** The large, generally circular, block **41** comprises an iron return path for the flux from the main magnet **45.**

The cladding or insulating magnets **42, 43,** and **44** are, in accordance with the invention, constructed of magnetic materials having the properties previously described with respect to magnet **10.** The axial magnetization of magnets **42, 43,** and **44** produces a magnetic counter potential perpendicular to that of radially magnetized disk **45.** The thickness of the cladding magnets **42, 43,** and **44** is, again, proportional to the magnetic potential on the surface of disk **45.** Since this is not linear along the disk, the thickness of magnets **42, 43,** and **44** is not a linear function but is rather determined by the B-H characteristics of disk **45** and the remainder of the magnetic circuit geometry.

It should also be noted here that in actual practice voice coil **48** must have some means of external communication and thus magnet **44** must be either modified or eliminated. This will result in a minor amount of leakage flux. The amount of flux lost, however, with respect to the amount conserved is small and thus the object of the invention to minimize leakage flux is still carried out by magnets **42** and **43.**

In FIG. **6,** a motor is generally shown having a permanent magnet type rotor comprising radially magnetized spokes **52** having alternate directions of magnetization. In accordance with the invention flux leakage is minimized by the insertion of circumferentially magnetized sections **54** between spokes **52** comprising materials having the magnetic characteristics previously described with respect to magnet **10.** It should be pointed out again, however, that the principal magnets, in this case spoke **52,** can be constructed of any magnetic materials depending upon the flux density desired. The direction of magnetization alternates for sections **54** to provide the desired flux leakage bucking system in accordance with the invention.

Alternatively, as shown in FIG. **7,** the stator may be constructed as a permanent magnet structure comprising radially magnetized spokes **62** clad in circumferentially magnetized sections **64.** As discussed in previous embodiments each section **64** is not of uniform thickness but is rather tapered to provide a profile of strongest magnetic potential adjacent the end of each spoke **62** facing the rotor. The amount of taper and the thickness is again determined as previously described.

For the correct choice of thickness of cladding magnets **64** the space **65** between spokes **62** will be a magnetic field free region and may therefore be filled with a highly permeable material. This space may, alternatively, be used by contouring the stator return shell **66** to fill this region.

The cladding magnets used to provide magnetic potential in accordance with the invention to inhibit leakage of flux from the main magnet are dimensioned to provide the correct amount of counter potential in accordance with the potential along the main magnet as well as the coercive force of the particular material used for the cladding magnet. The materials used for the cladding magnets must have the particular magnetic properties previously described with respect to magnet **10.**

The cladding magnet may be shaped to the desired contour by pressing the magnetic material in particulate form to the desired shape followed by sintering of the shaped magnet. The magnetic alignment of the particles before sintering and the magnetization of the sintered product are carried out as described and claimed in the aforementioned pending patent applications.

The material can also be ground or machined to the desired shape. While this would normally be done before magnetization because of the practical problems experienced when processing magnetized materials, the desired high anisotropy of the material may make it desirable to magnetize the material before fabrication. When, as in the preferred embodiment, a magnetic material having high magnetization retention properties is used, processing can be done after magnetization with minimal risk of demagnetizing the cladding material.

The resultant cladding magnets are joined to the main magnet using, for example, bonding means such as epoxy cement. Other bonding or mechanical retention means can be used provided they do not interfere with the magnetization of either the main magnet or the cladding magnets. In certain circumstances it may be desirable to remagnetize the main magnet in situ, i.e. after being clad when a material havin a low intrinsic coercive force is used for the main magnet. Since, as previously described, the cladding magnet material is preferably characterized by a high magnetization retention, the choice of bonding methods or materials will have little, if any, effect on its magnetization nor will remagnetization of the main magnet effect the cladding magnet.

Thus, the invention provides an improved magnet structure wherein the flux of a principal magnet is conserved by cladding the magnet with a second magnet having its magnetic axis perpendicular to the magnetic axis of the first magnet and further characterized as preferably having a high coercive force, with low permeability perpendicular to its magnetic axis, and highly anisotropic. Preferably, the aterial is also characterized as highly resistant to alteration of its magnetic properties. The cladding magnet is preferably contoured as previously described to provide a perpendicular, bucking, magnetic force proportionate to the potential along the principal magnet.

What is claimed is:

1. A permanent magnet construction having a minimum leakage flux comprising a first permanent magnet having a predetermined lineal extent and a magnetic axis therealong and a second permanent magnet forming a cladding completely about said first magnet and coextensive therewith, said second magnet comprising a highly anisotropic material having its magnetic axis substantially perpendicular to the magnetic axis of said first magnet and having low permeability in the direction normal to its magnetic axis to inhibit leakage of magnetic flux from said first magnet.

2. The magnet construction of claim **1** wherein said second magnet comprises a rare earth-cobalt alloy.

3. The magnet construction of claim **1** wherein said second magnet comprises a material exhibiting good magnetization retention properties.

4. A magnet construction comprising a first magnet having a predetermined lineal extent and a magnetic axis therealong and a second magnet comprising highly anisotropic material having a low permeability normal to its magnetic axis, said second magnet adjoining substantially the entire extent of said first magnet and substantially completely surrounding the magnetic axis of said first magnet, the magnetic axis of said second magnet being substantially perpendicular to the magnetic axis of said first magnet.

5. The magnet construction of claim **4** wherein the magnetic potential of the second magnet is not uniform along the magnetic axis of the first magnet.

6. The magnet construction of claim **5** wherein the magnetic potential of the second magnetic is strongest adjacent at least one end of the magnetic axis of the first magnet.

7. The magnet construction of claim **5** wherein the thickness of the second magnet perpendicular to the magnetic axis of the first magnet is tapered to provide a non-uniform magnetic potential along the magnetic axis of the first magnet.

8. The magnet construction of claim **5** wherein said second magnet comprises a rare earth-cobalt alloy.

9. The magnet construction of claim **4** wherein said first magnet comprises a plurality of magnets aligned along a common magnetic axis.

10. The magnet construction of claim **4** wherein said second magnet comprises a plurality of magnets, each having its magnetic axis normal to the magnetic axis of said first magnet.

11. The magnet construction of claim **4** wherein said first magnet comprises a pair of coaxially aligned hollow cylinders disposed in mutually axially spaced relation, and said second magnet is in the form of a double cone having a wide-thickness portion surrounding the adjacent ends of said cylinders, said wide-thickness portion being of substantially uniform thickness over an axial extent thereof corresponding to the spacing of said cylinders.

12. The magnet construction of claim **11** wherein said cylinders of said first magnet are magnetized in opposite directions and said construction further comprises a pair of radially extending reversal pole pieces disposed within the space between said cylinders.

13. The magnet construction of claim **12** wherein the cylinders are adapted to surround a linear-beam electron discharge device.

14. The magnet construction of claim **4** wherein said first magnet comprises a pair of spaced aligned solid bars of uniform diameter and having a common direction of magnetization, and said second magnet comprises a pair of cylinders having a common axis and uniform internal diameters conforming with the diameters of said bars, the magnetic axes of said cylinders being in mutually opposed directions and normal to the magnetic axis of said bars, and a magnetic shell encasing said first and said second magnets to form a complete magnetic circuit.

15. The magnet construction of claim **14** wherein the space between said bar magnets is adapted to be occupied by a crossed-field electron discharge device.

* * * * *