June 1, 1965

R. J. VAN DE GRAAFF

3,187,208

HIGH VOLTAGE ELECTROMAGNETIC APPARATUS HAVING AN INSULATING MAGNETIC CORE

Original Filed March 22, 1957

7 Sheets-Sheet 1

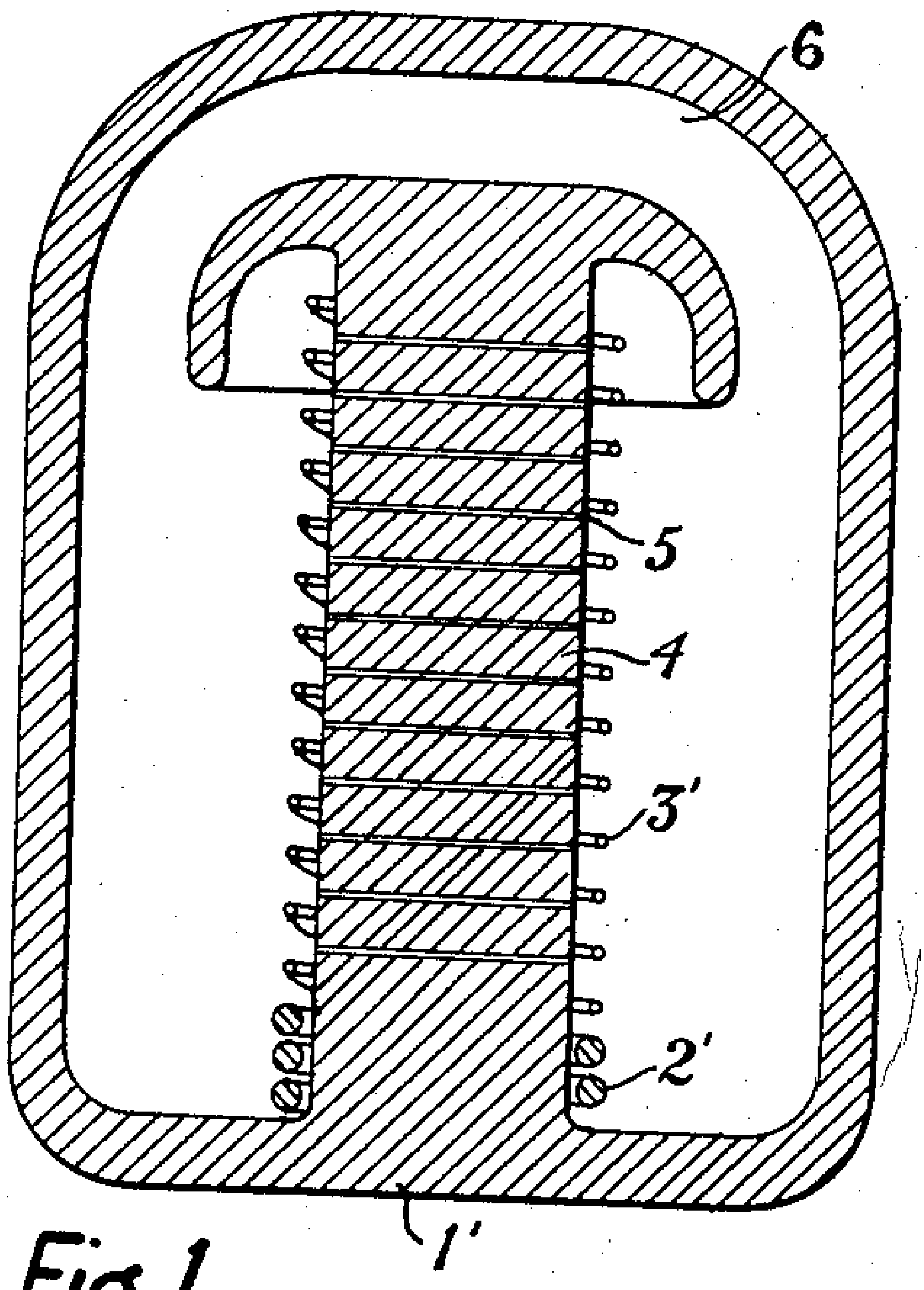

Fig 1

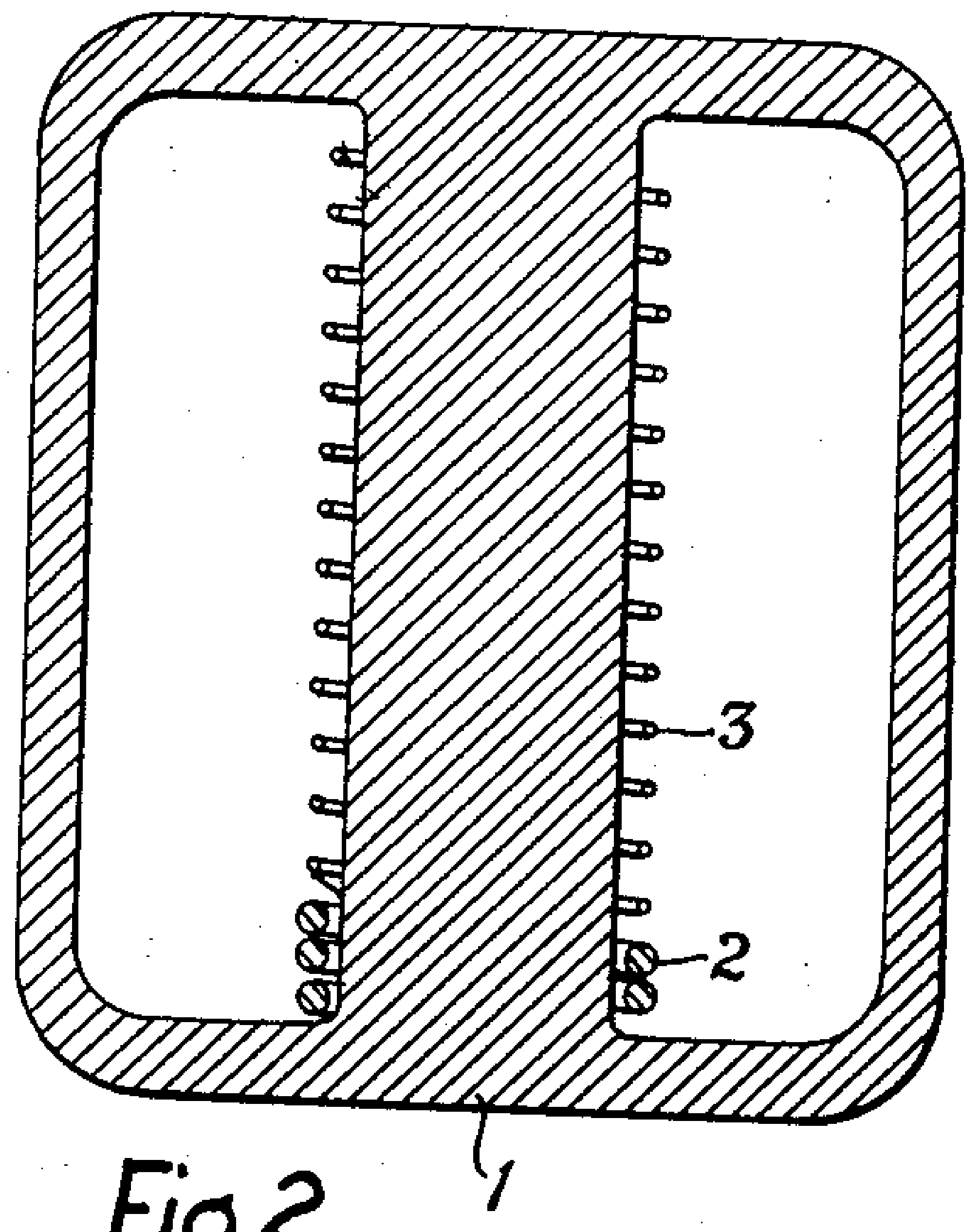

Fig.2

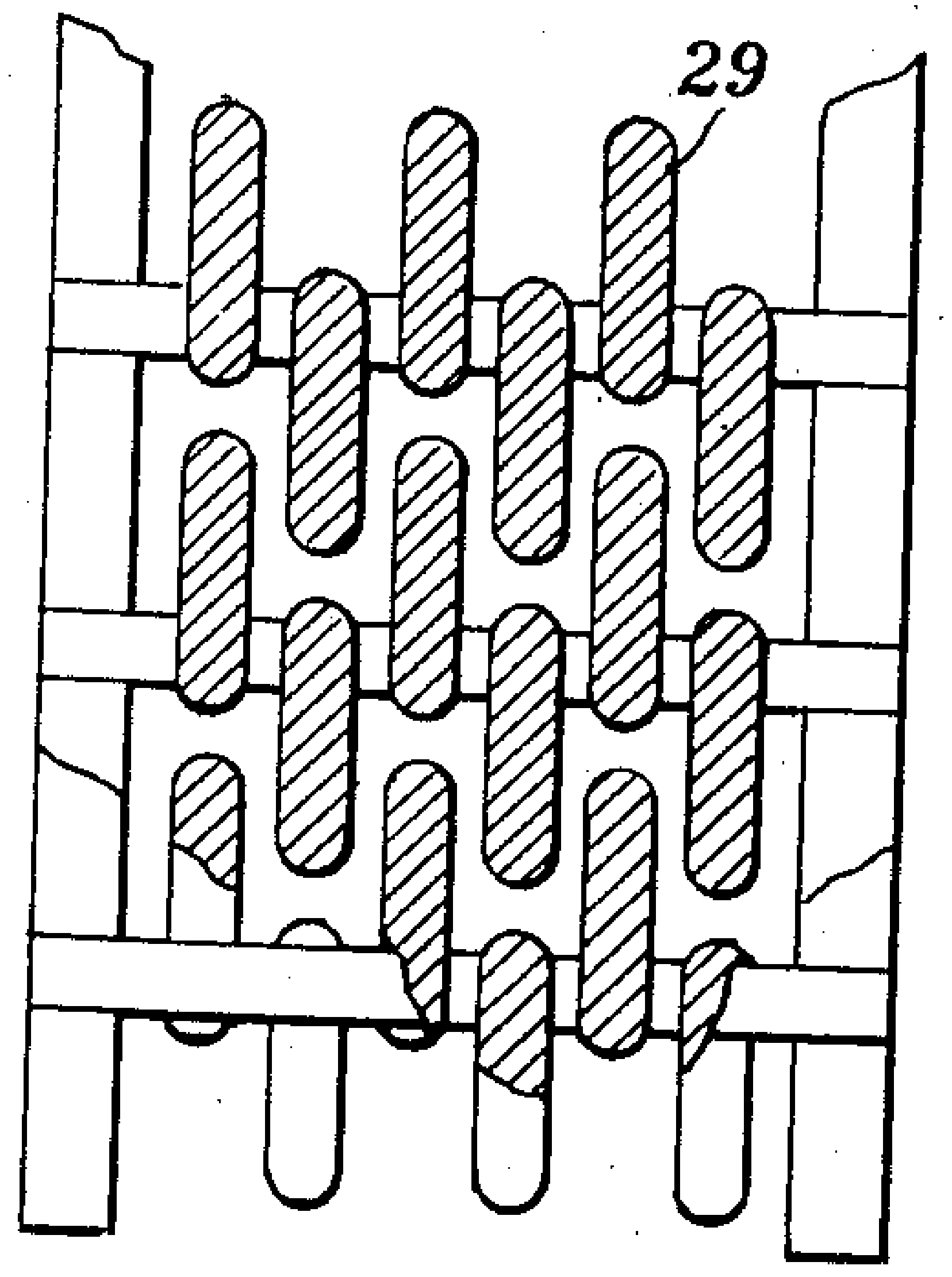

Fig.11

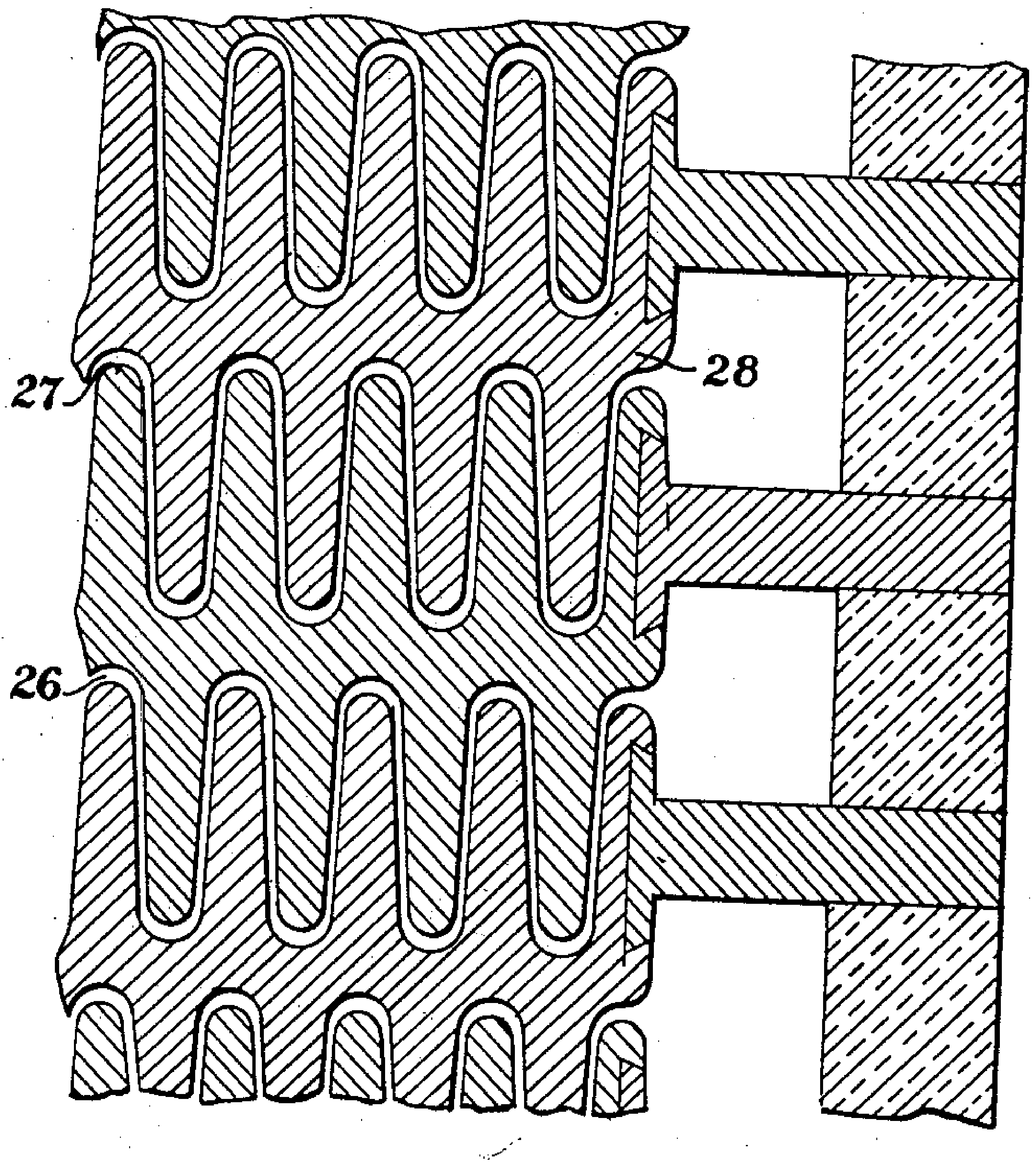

Fig.10

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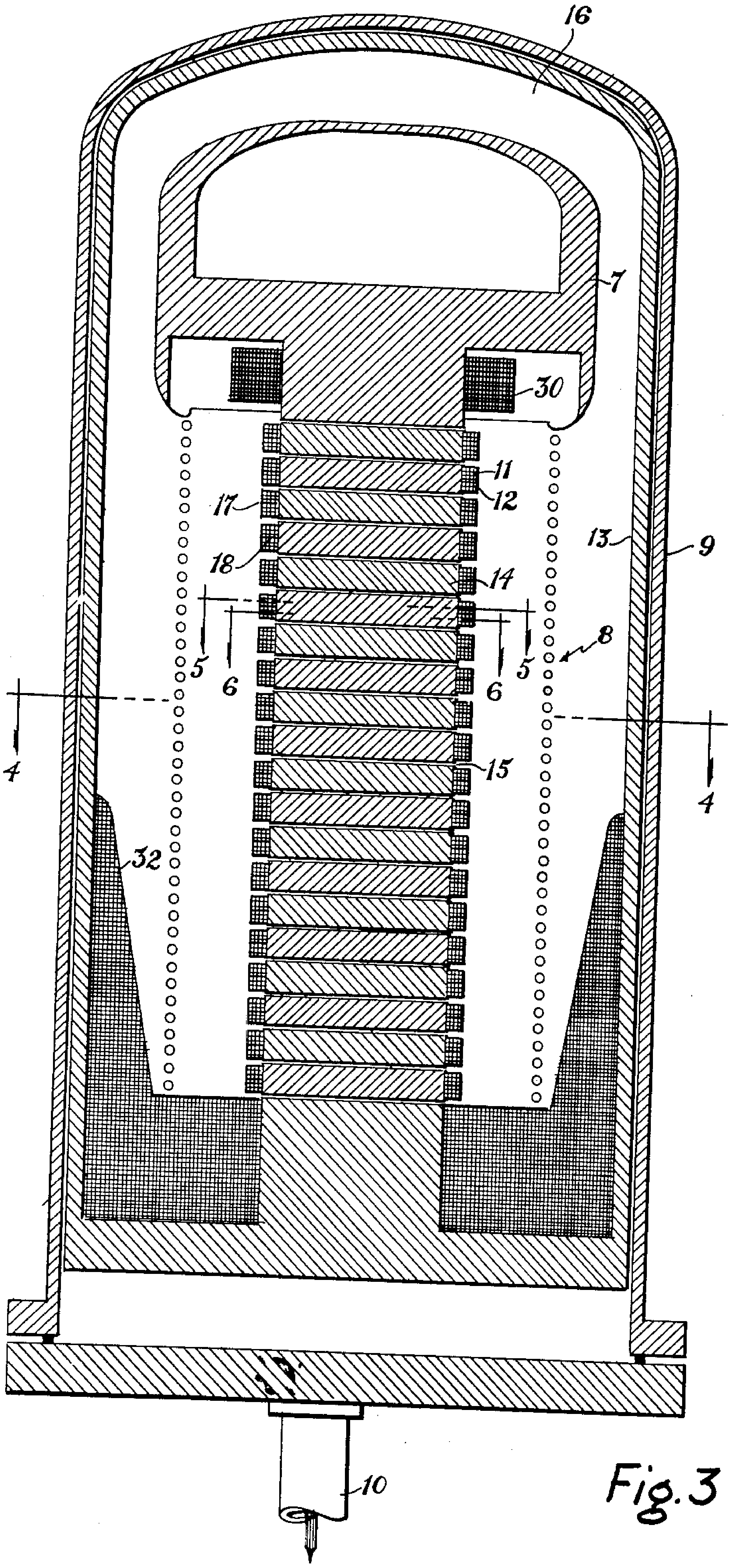


Fig. 3

Fig.4

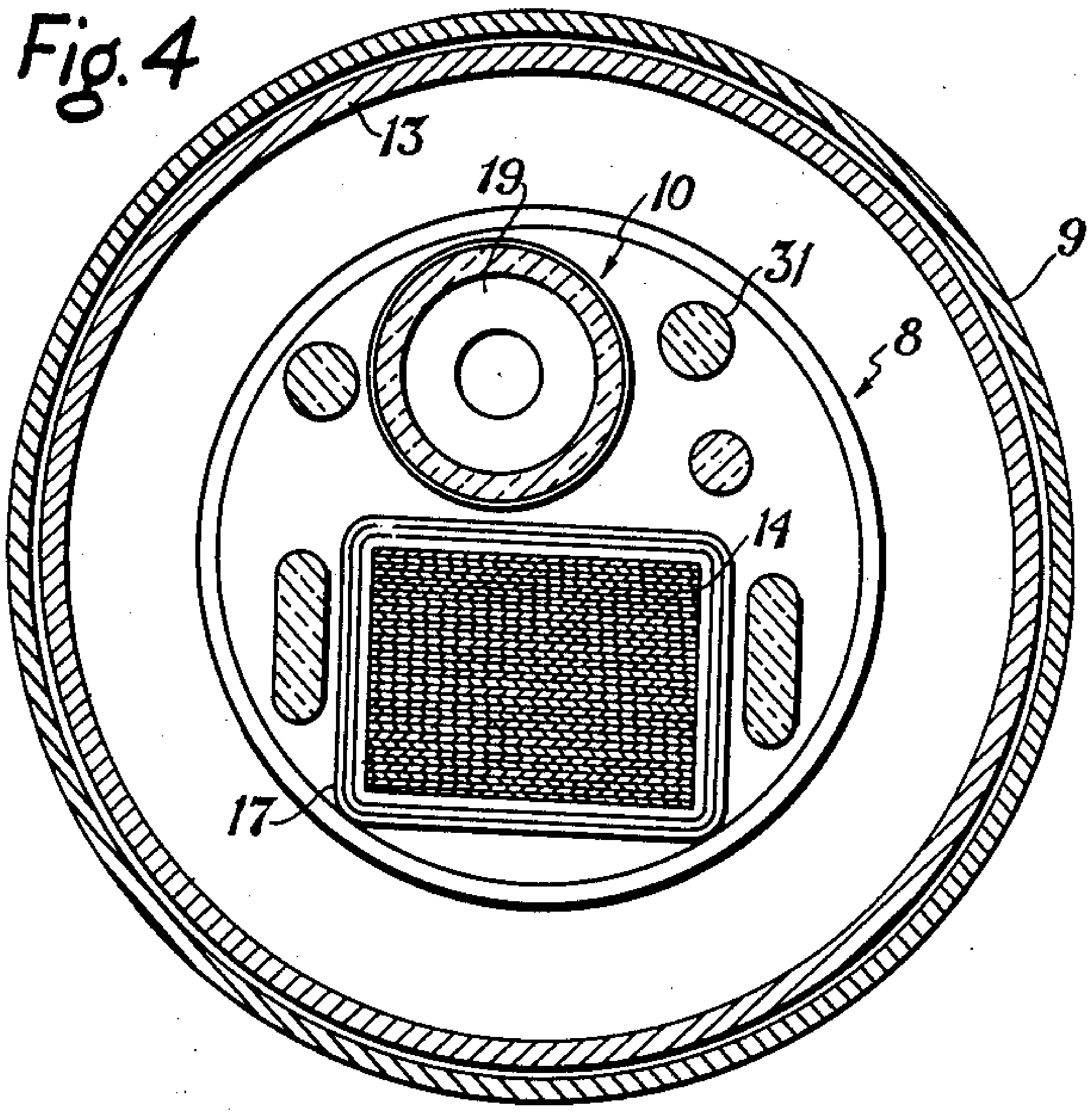
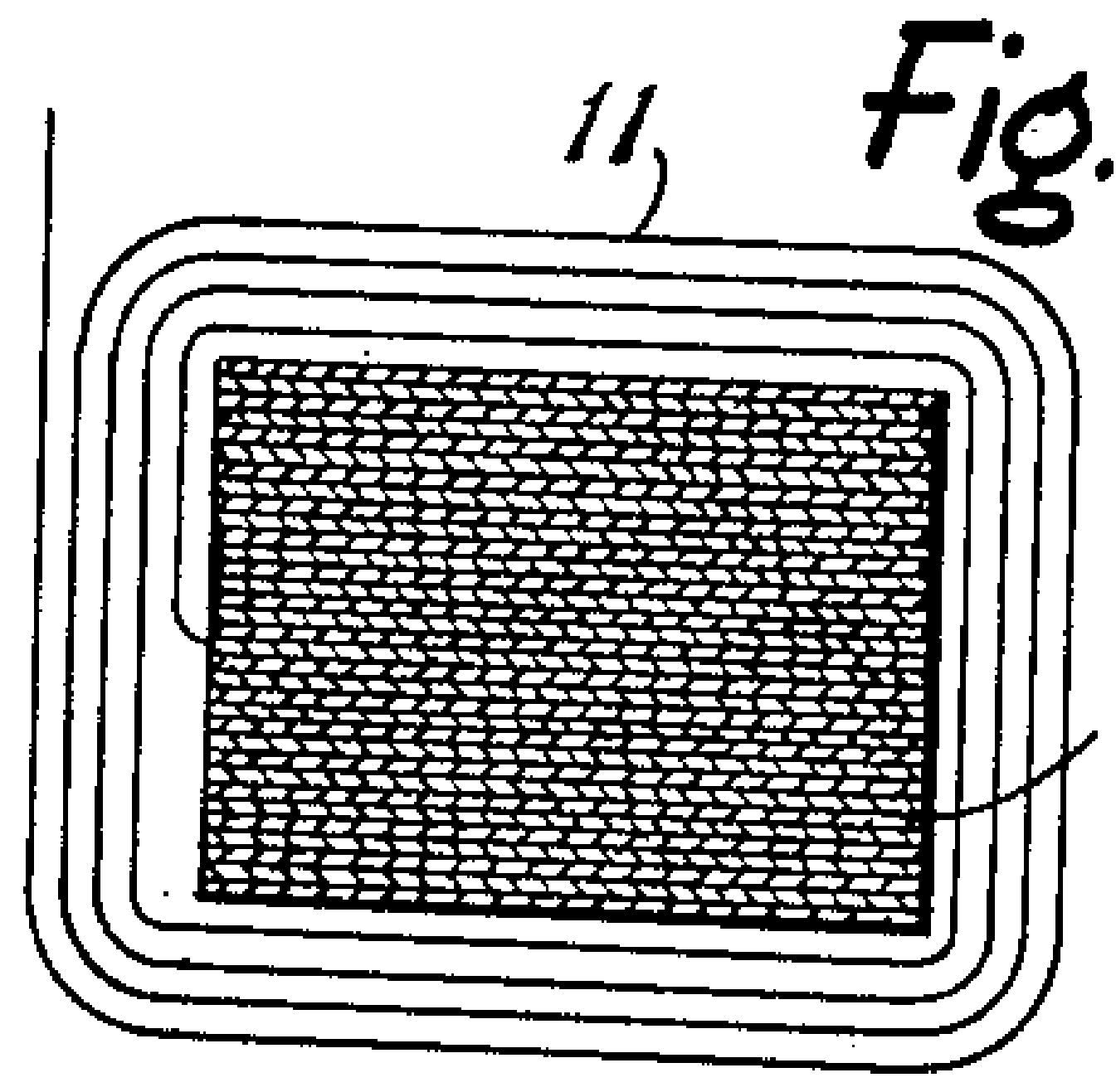


Fig.5



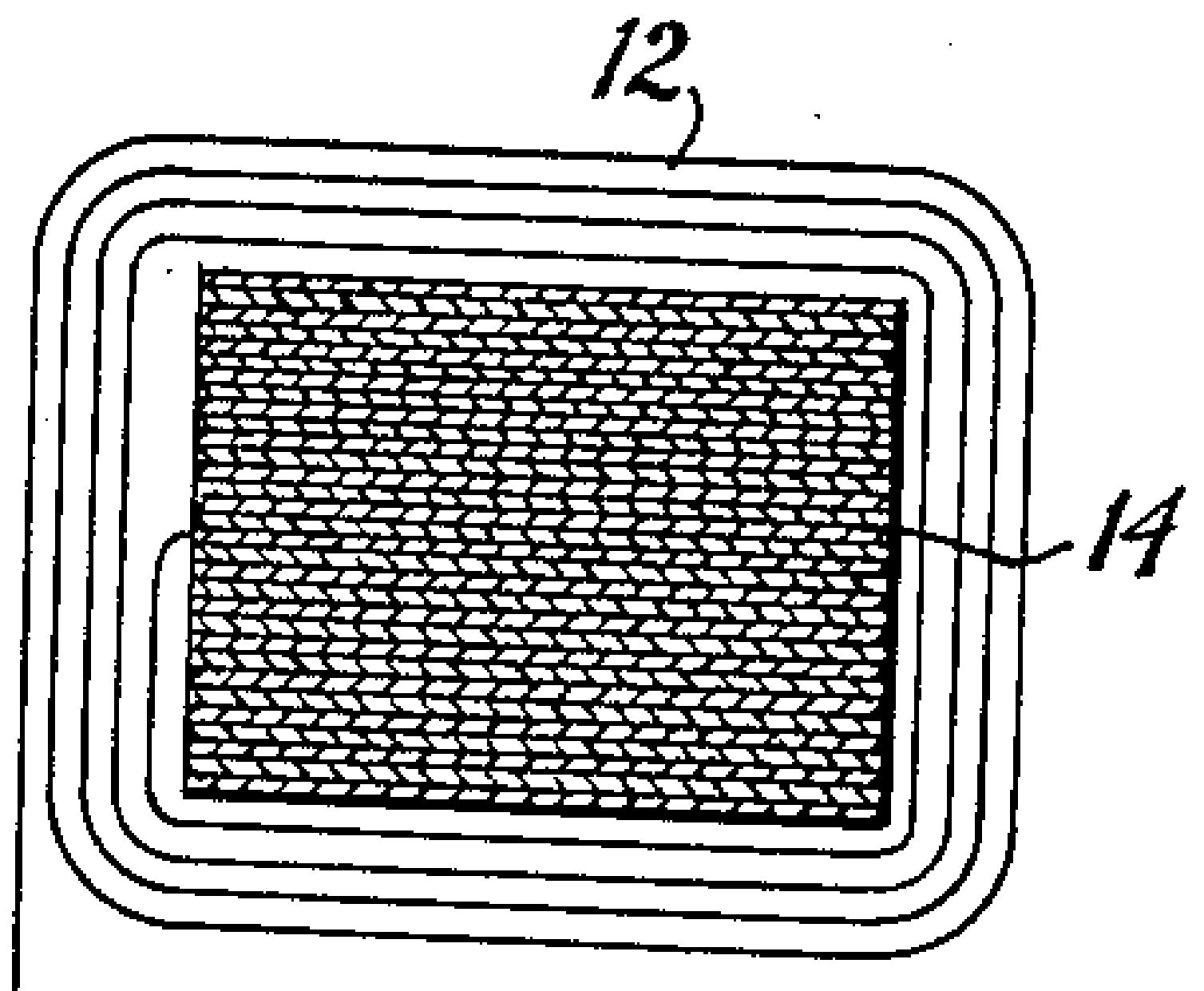


Fig.6

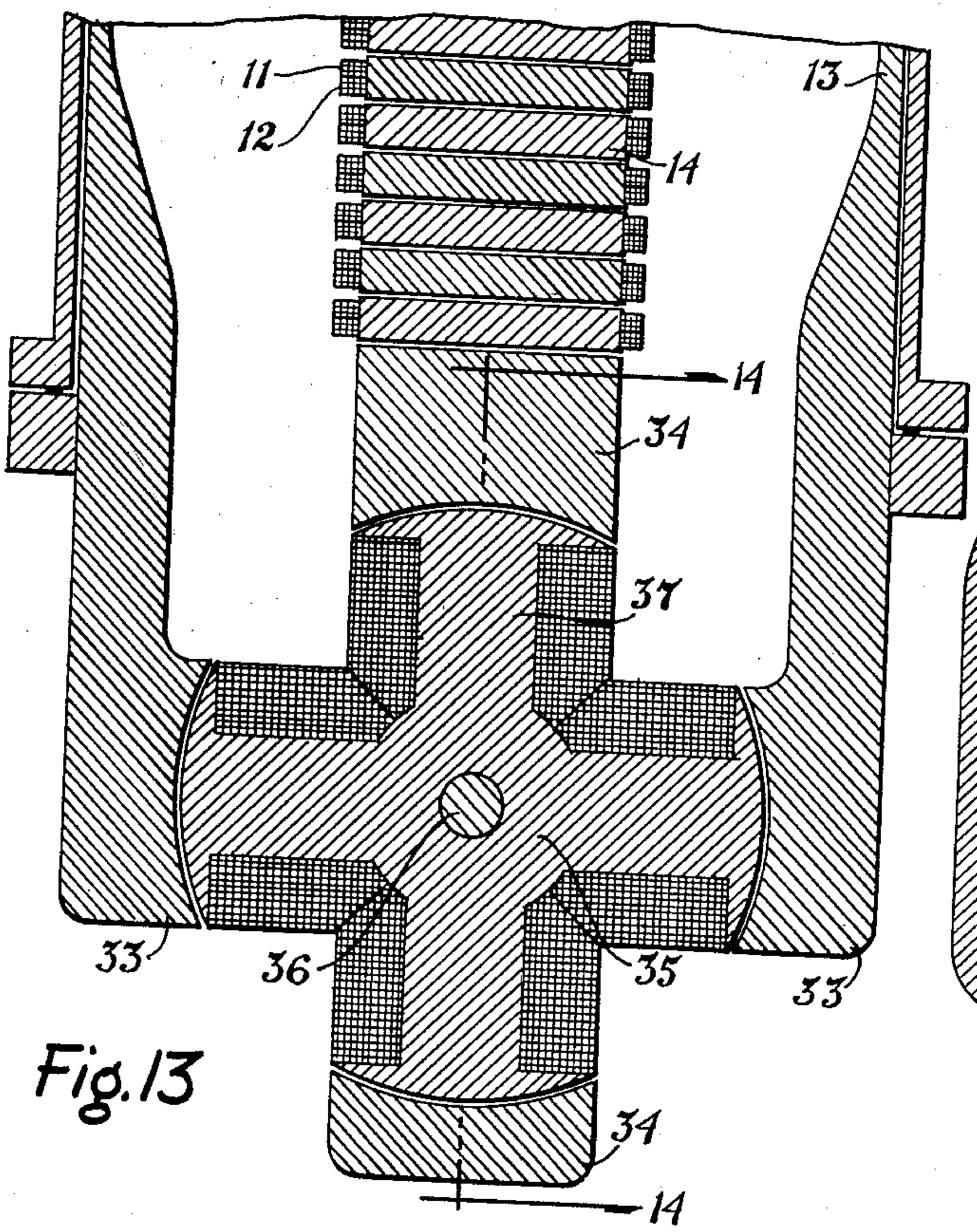
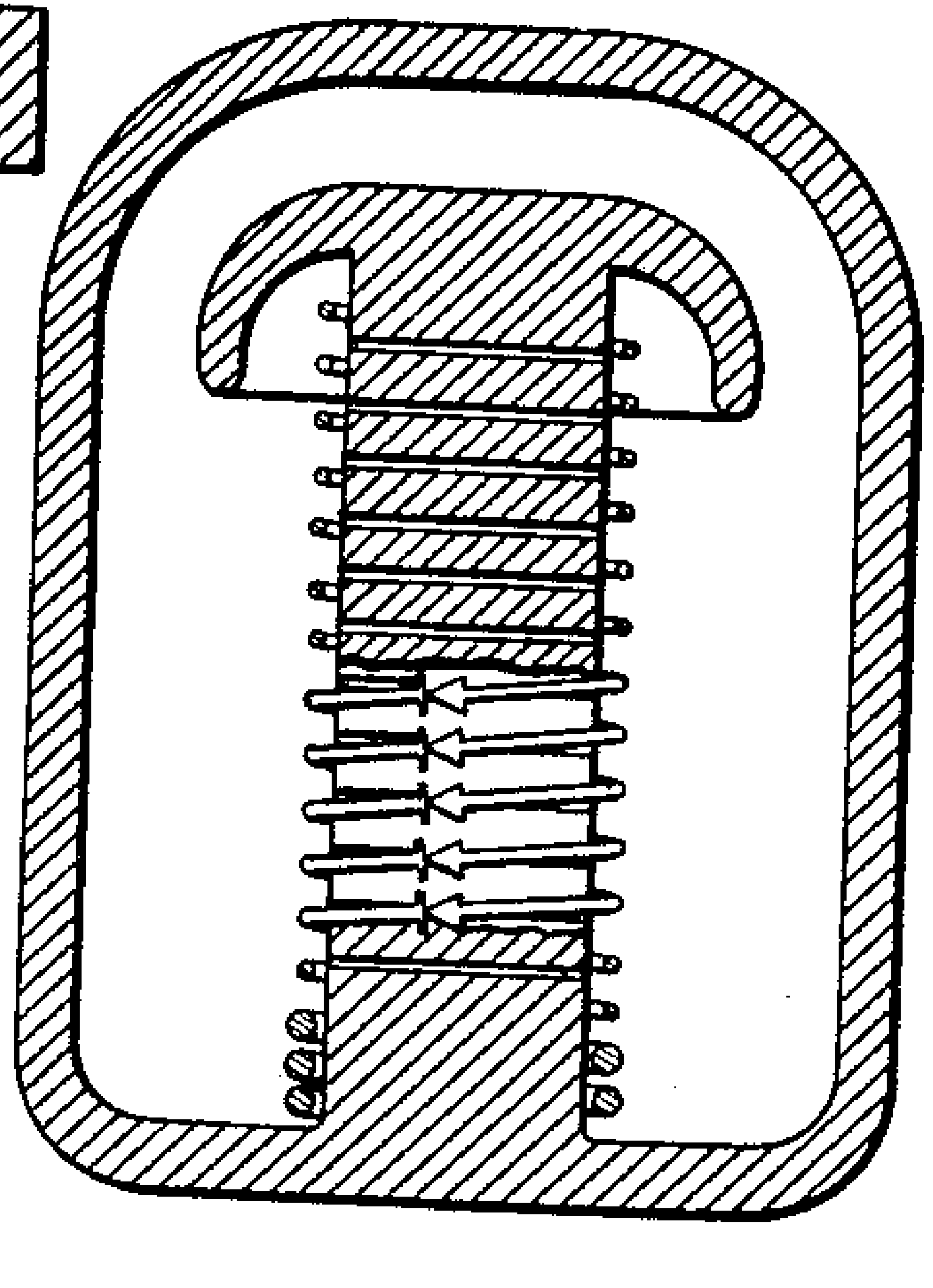


Fig.13

Fig. 1A



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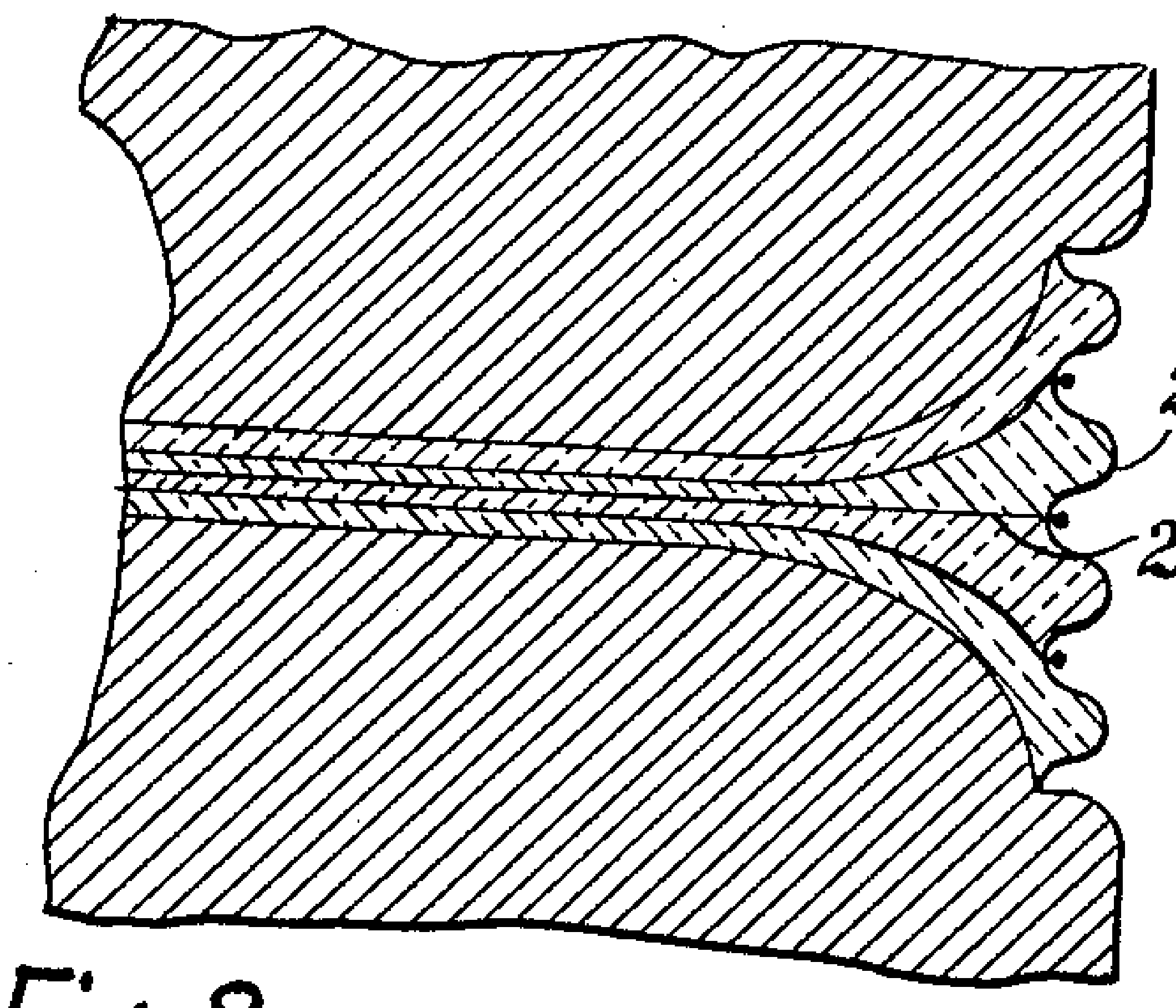

Fig. 8

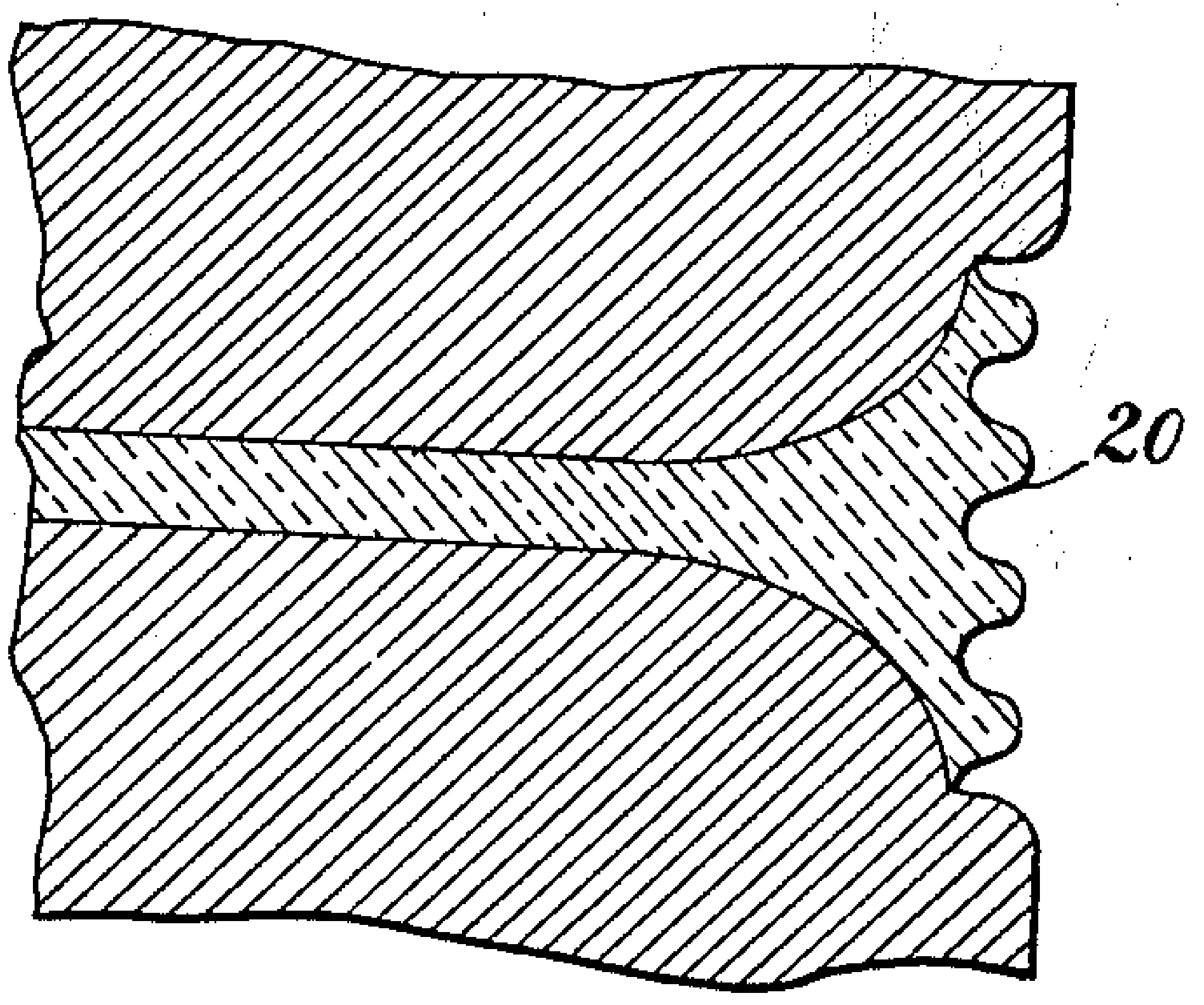

Fig. 7

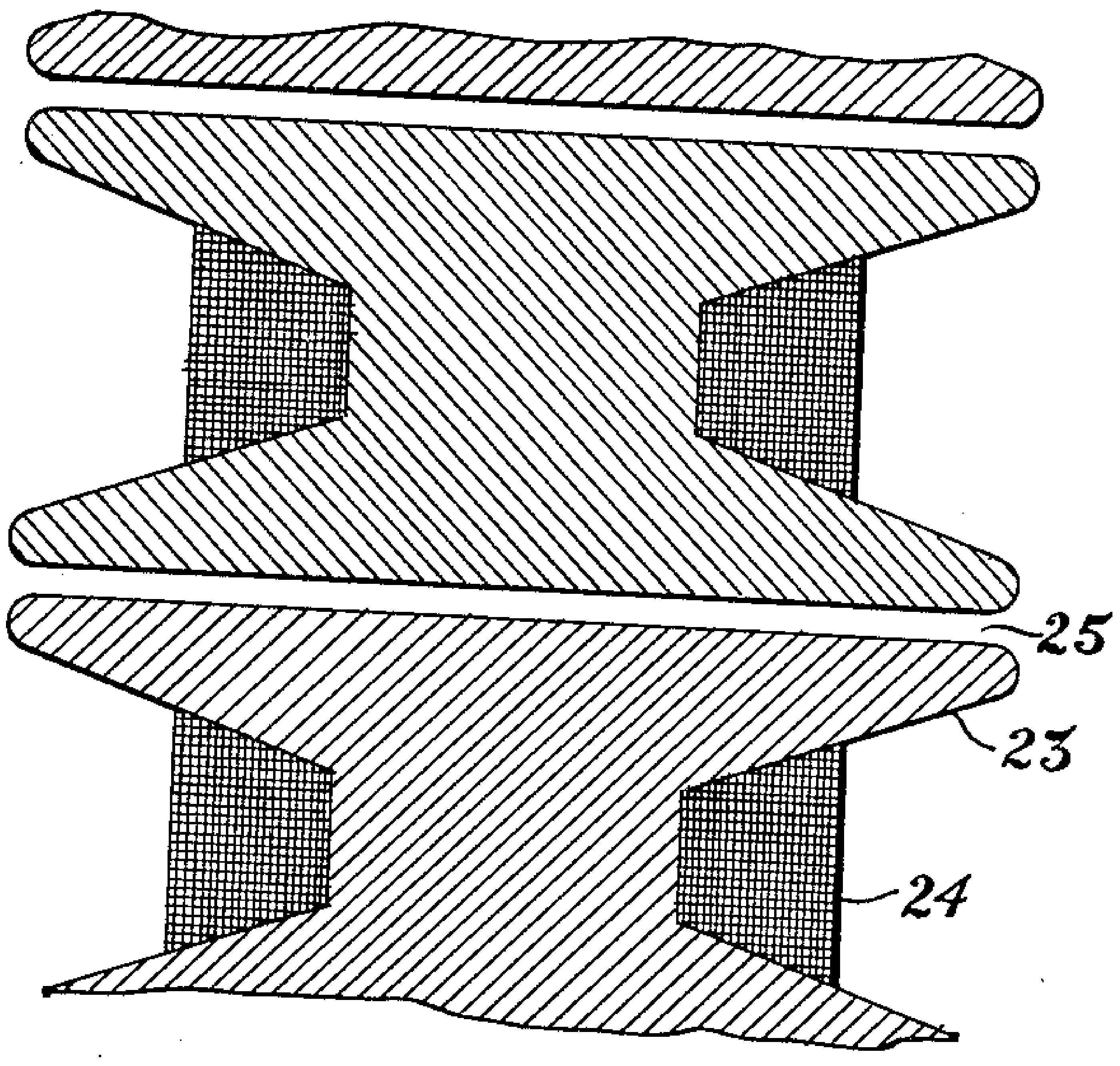

Fig. 12

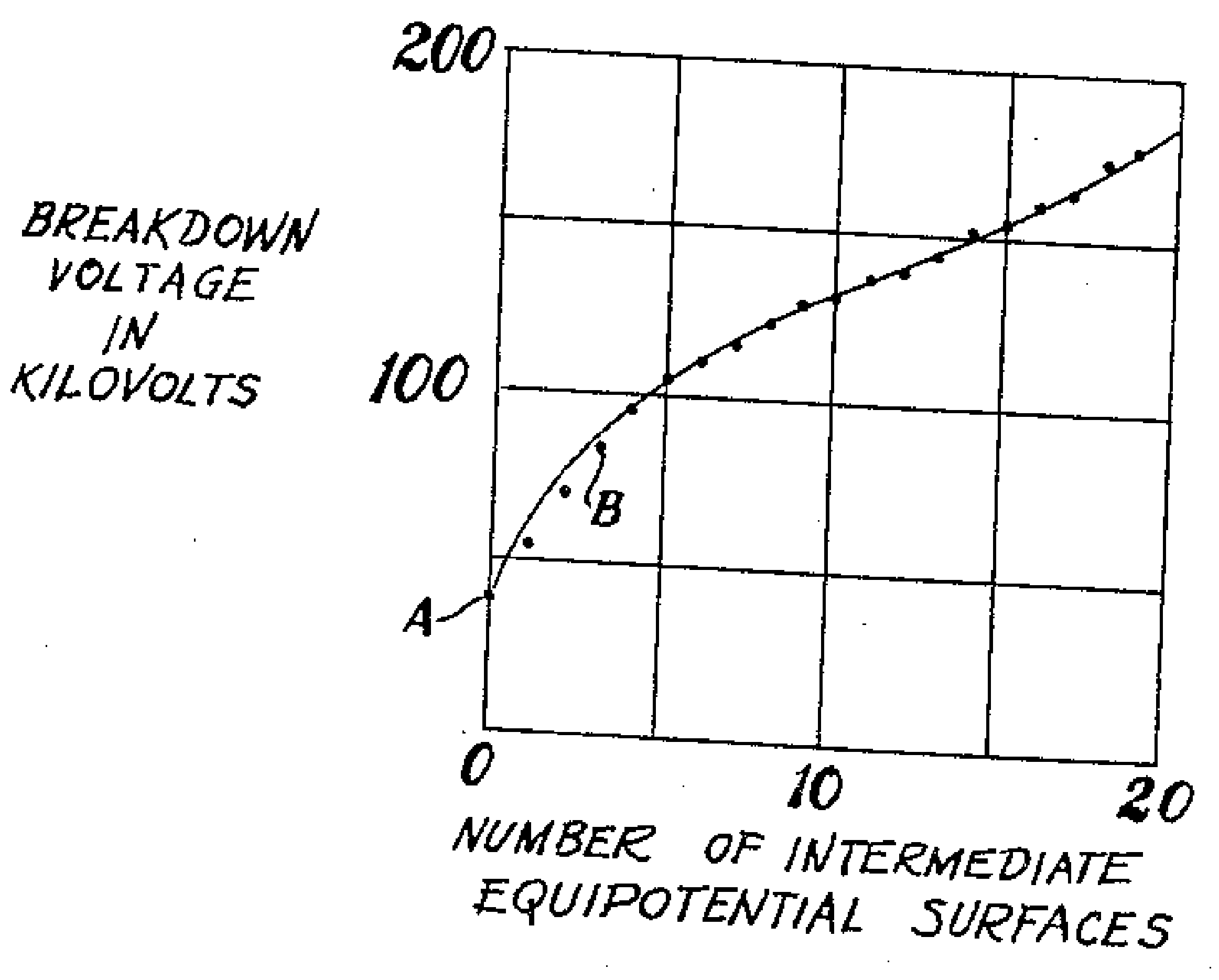

Fig. 9

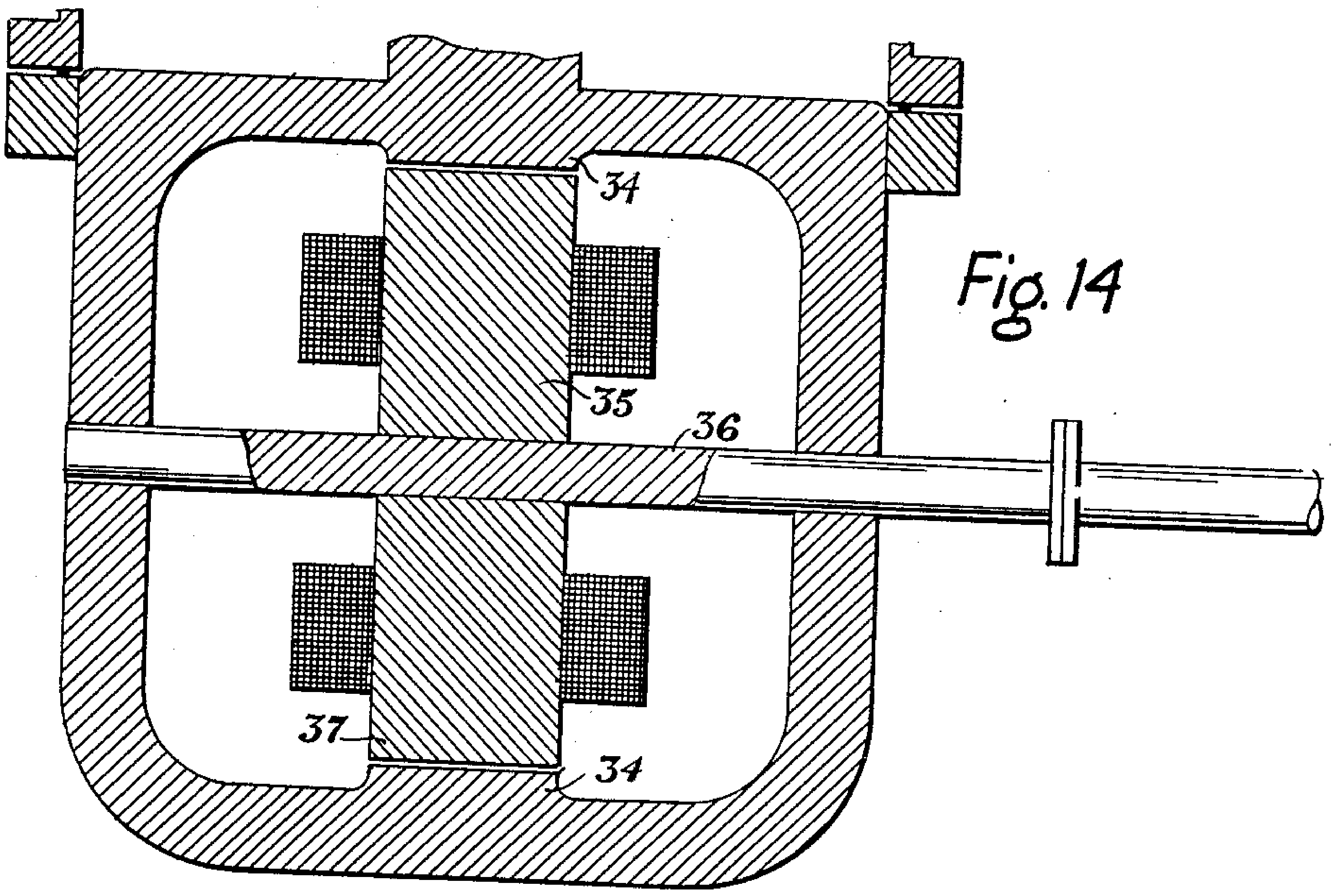

Fig. 14

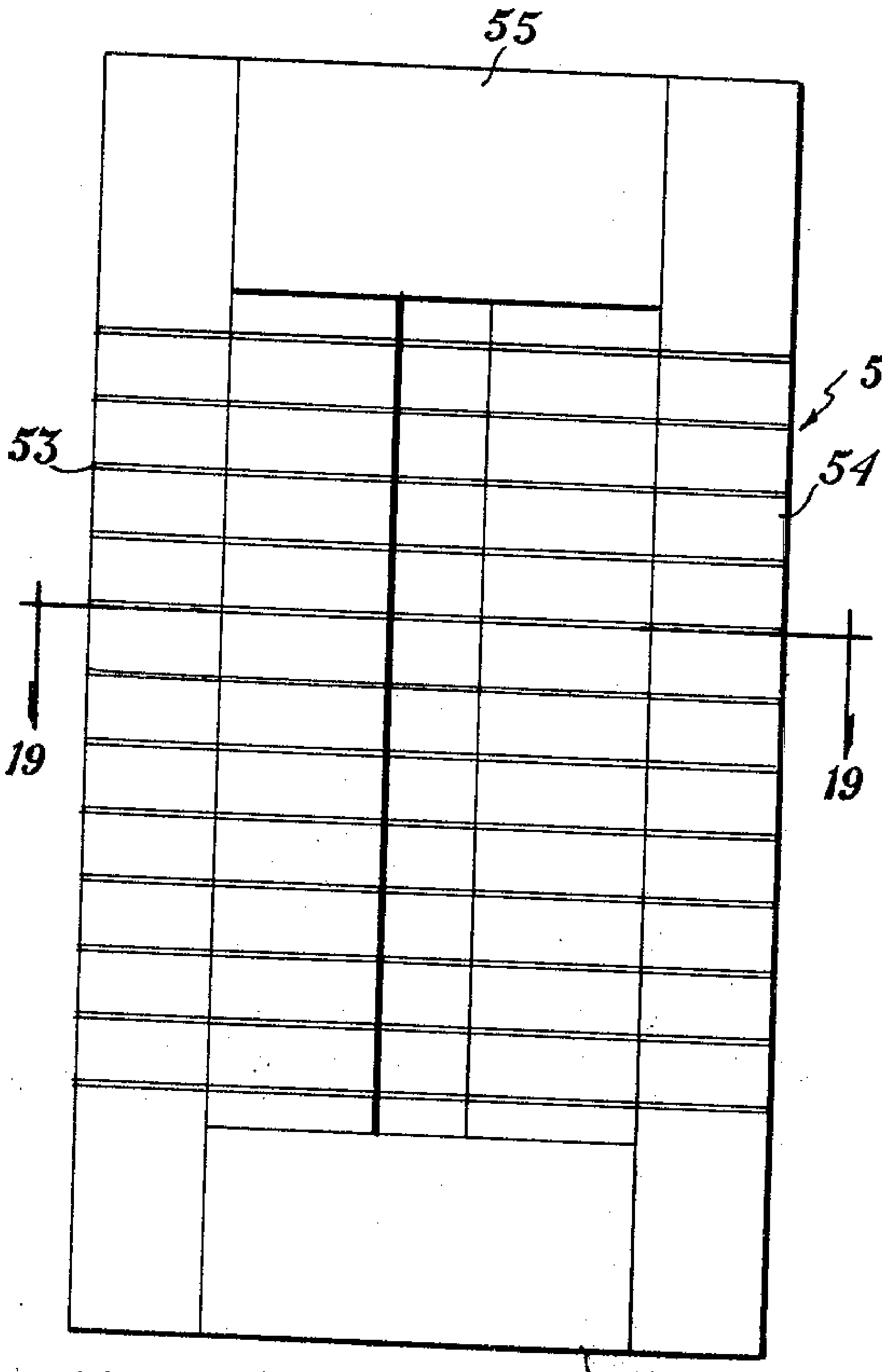

Fig. 18

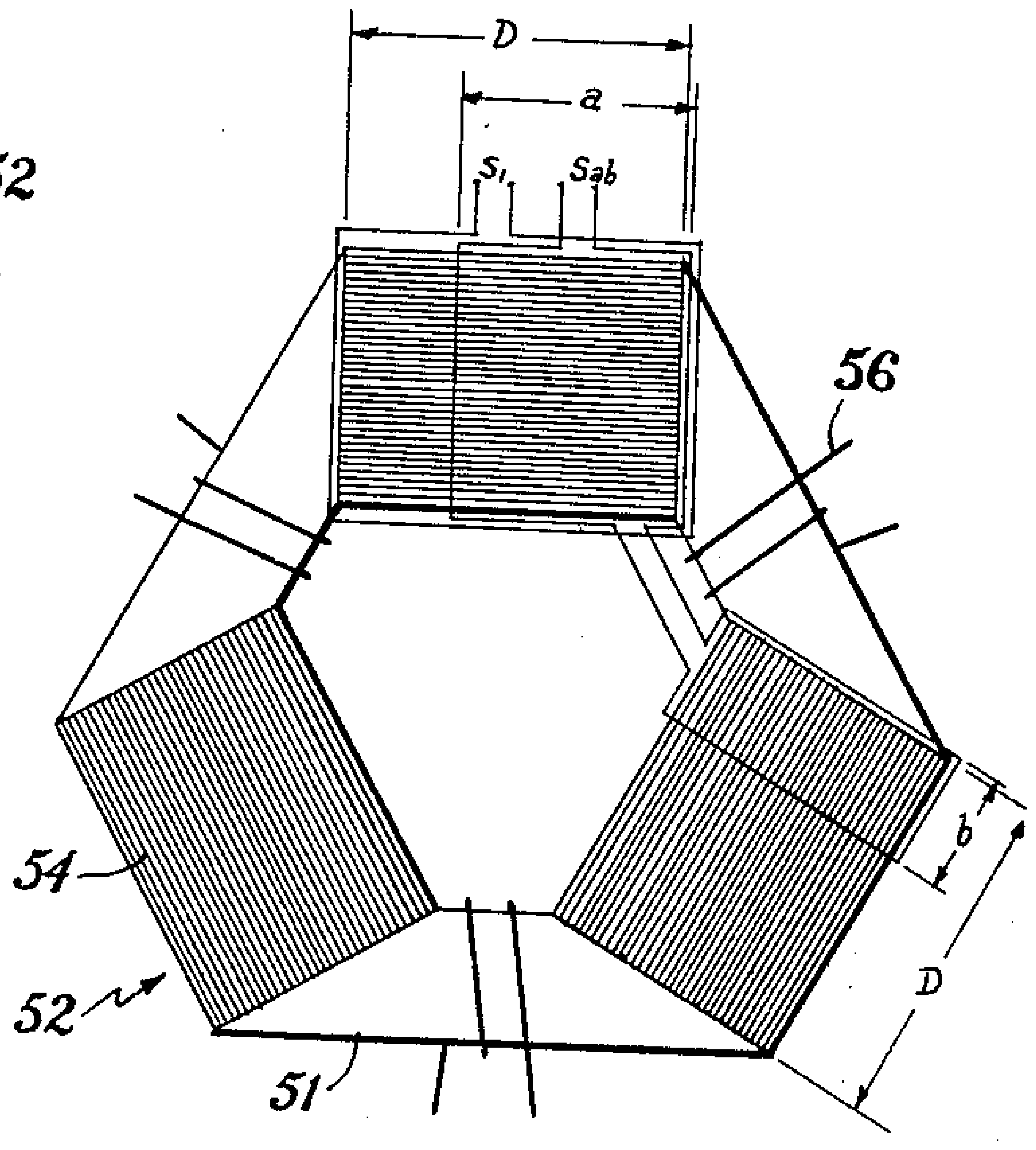

Fig. 19

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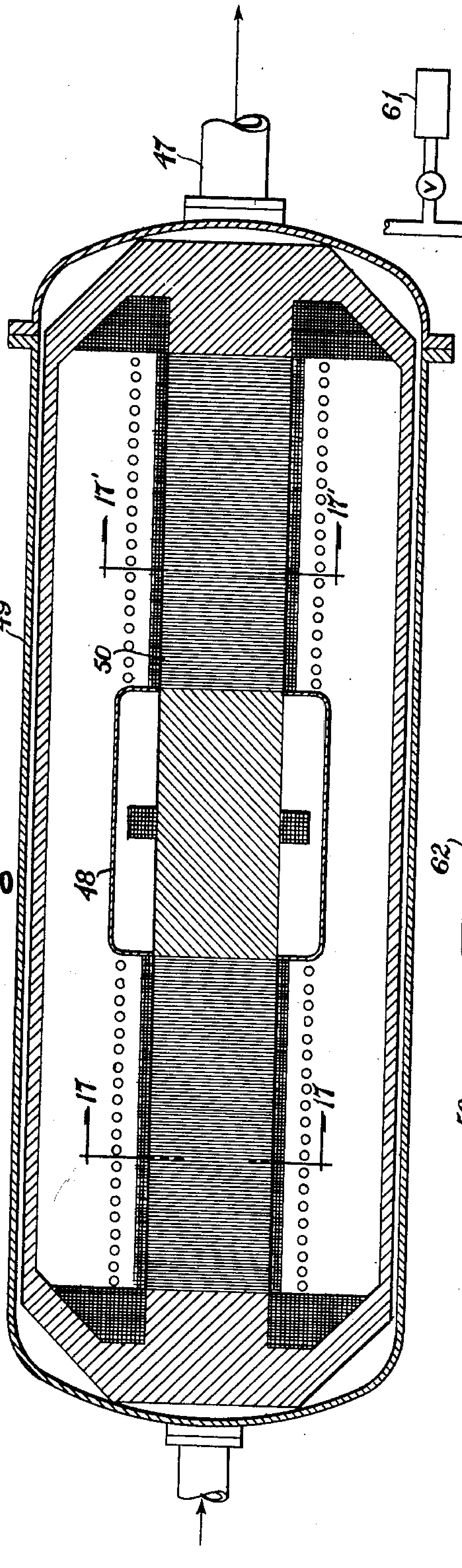

Fig.16

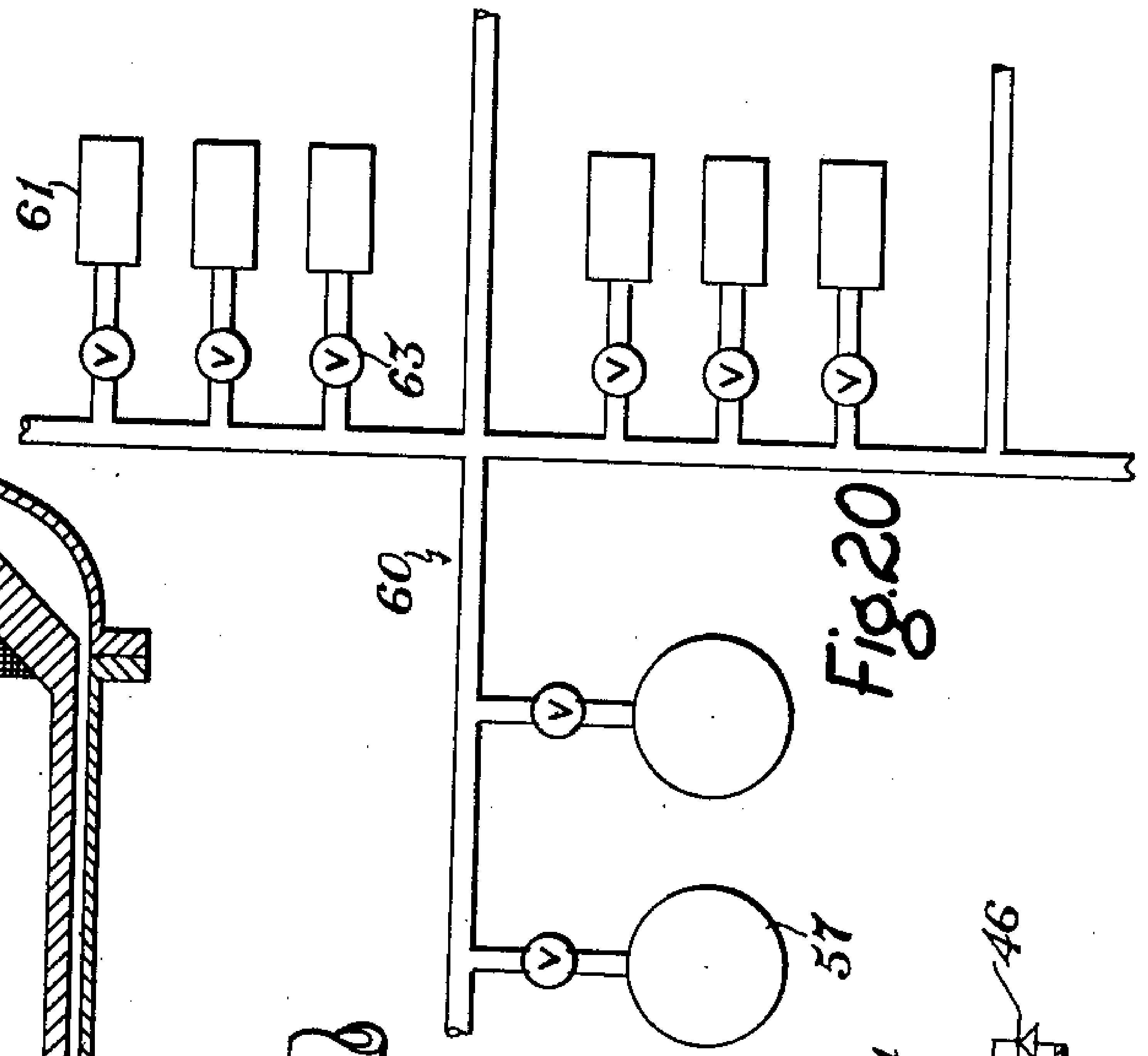

Fig.20

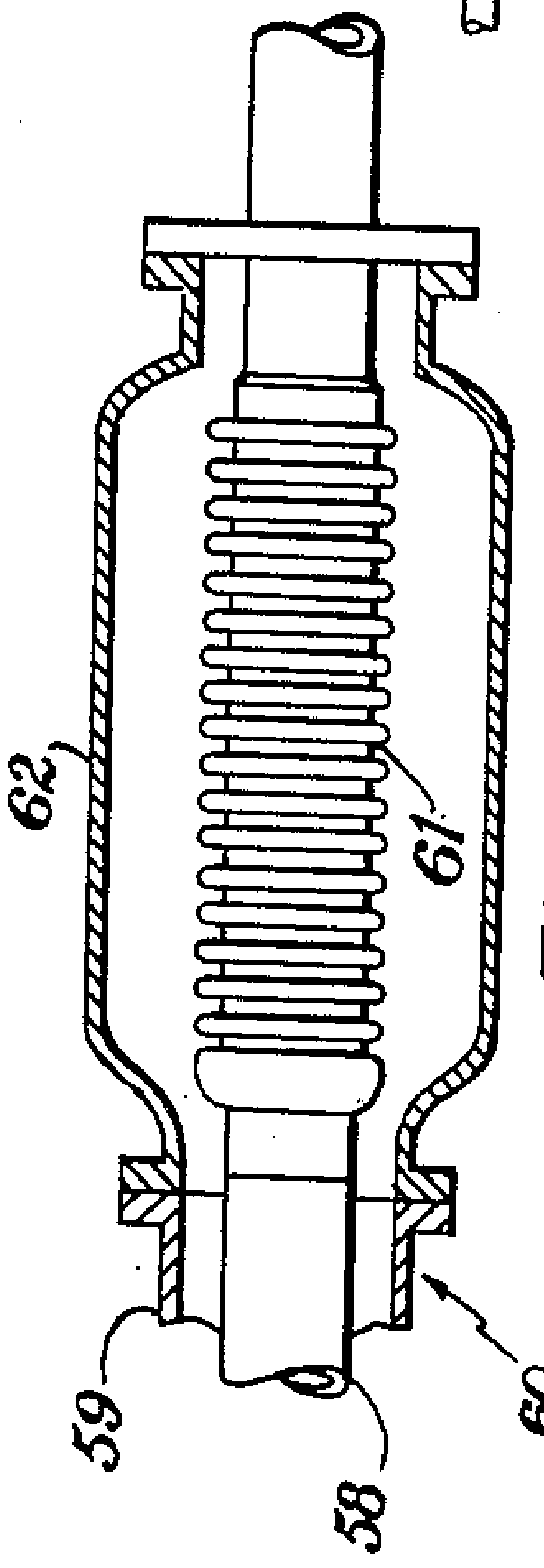

Fig.21

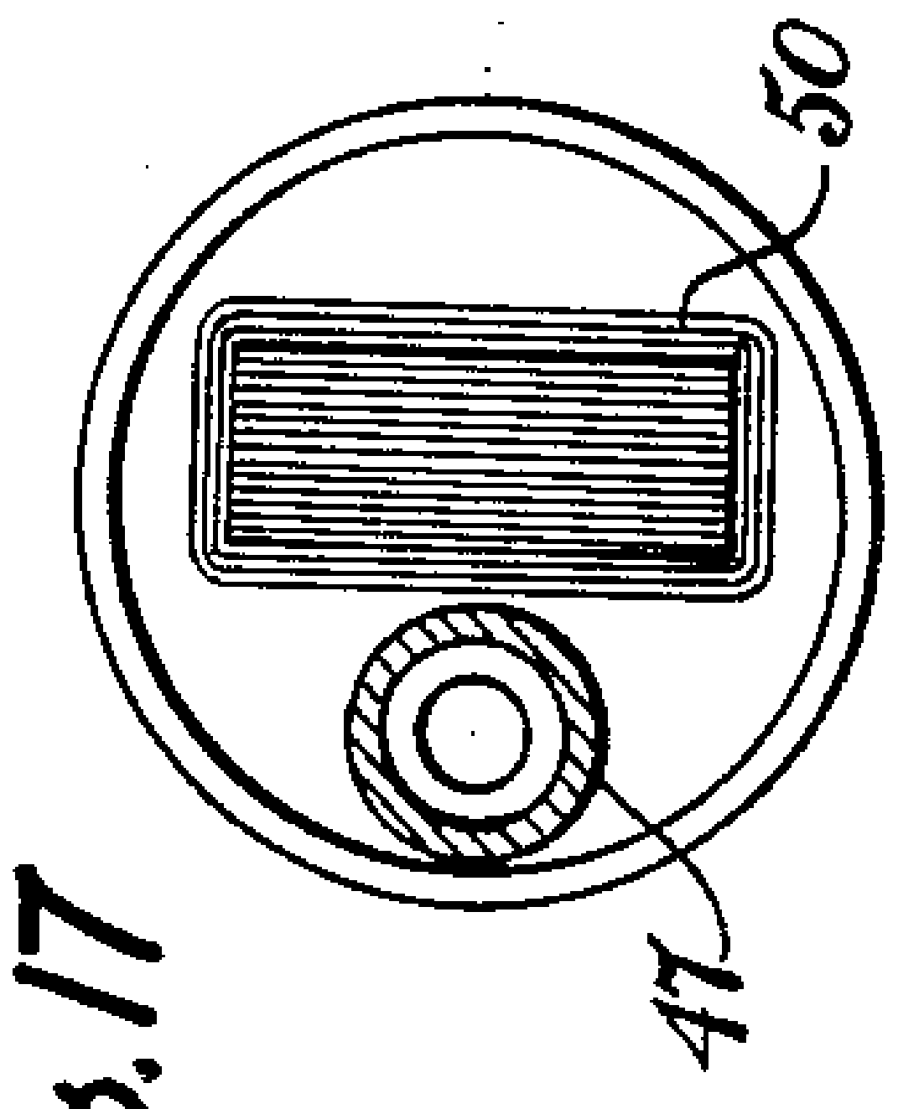

Fig.17

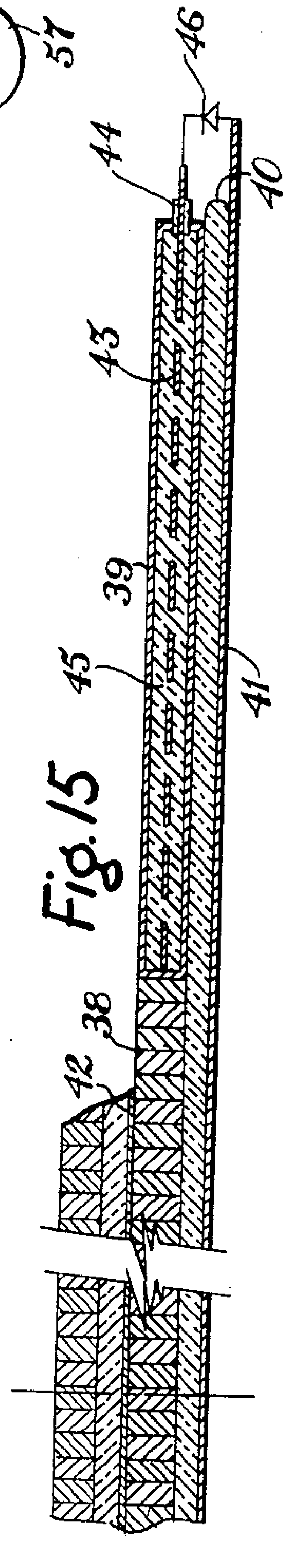

Fig.15

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HIGH VOLTAGE ELECTROMAGNETIC APPARATUS HAVING AN INSULATING MAGNETIC CORE

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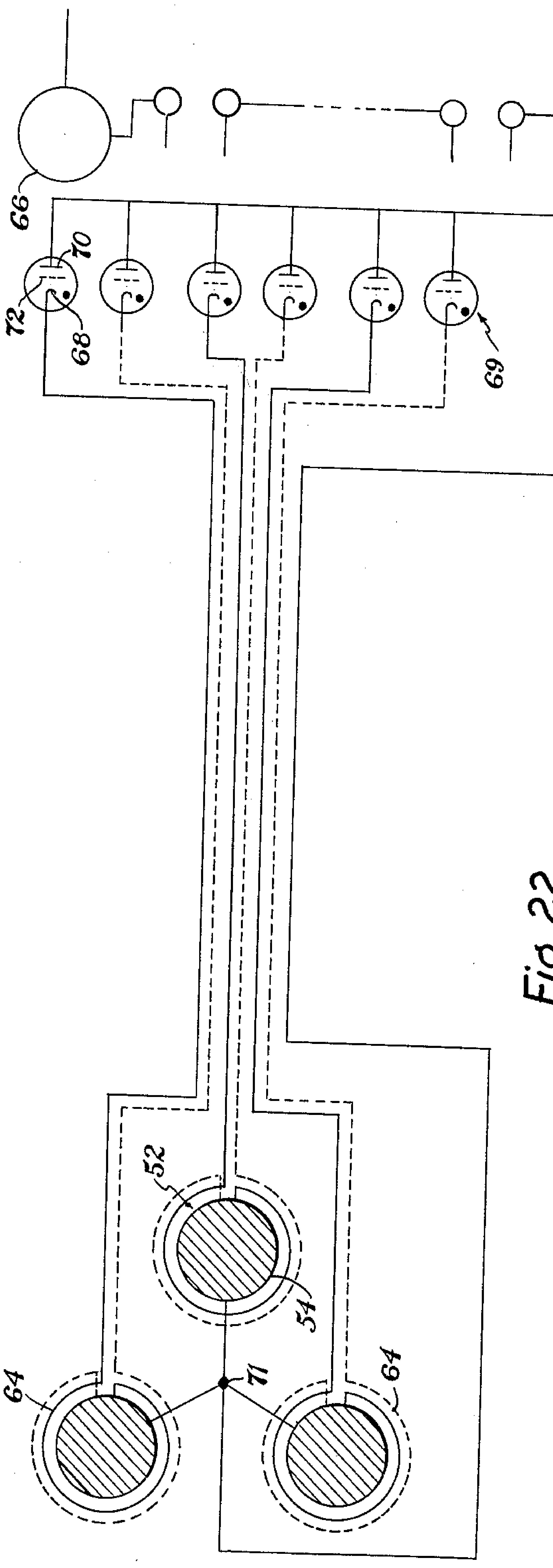

Fig. 22

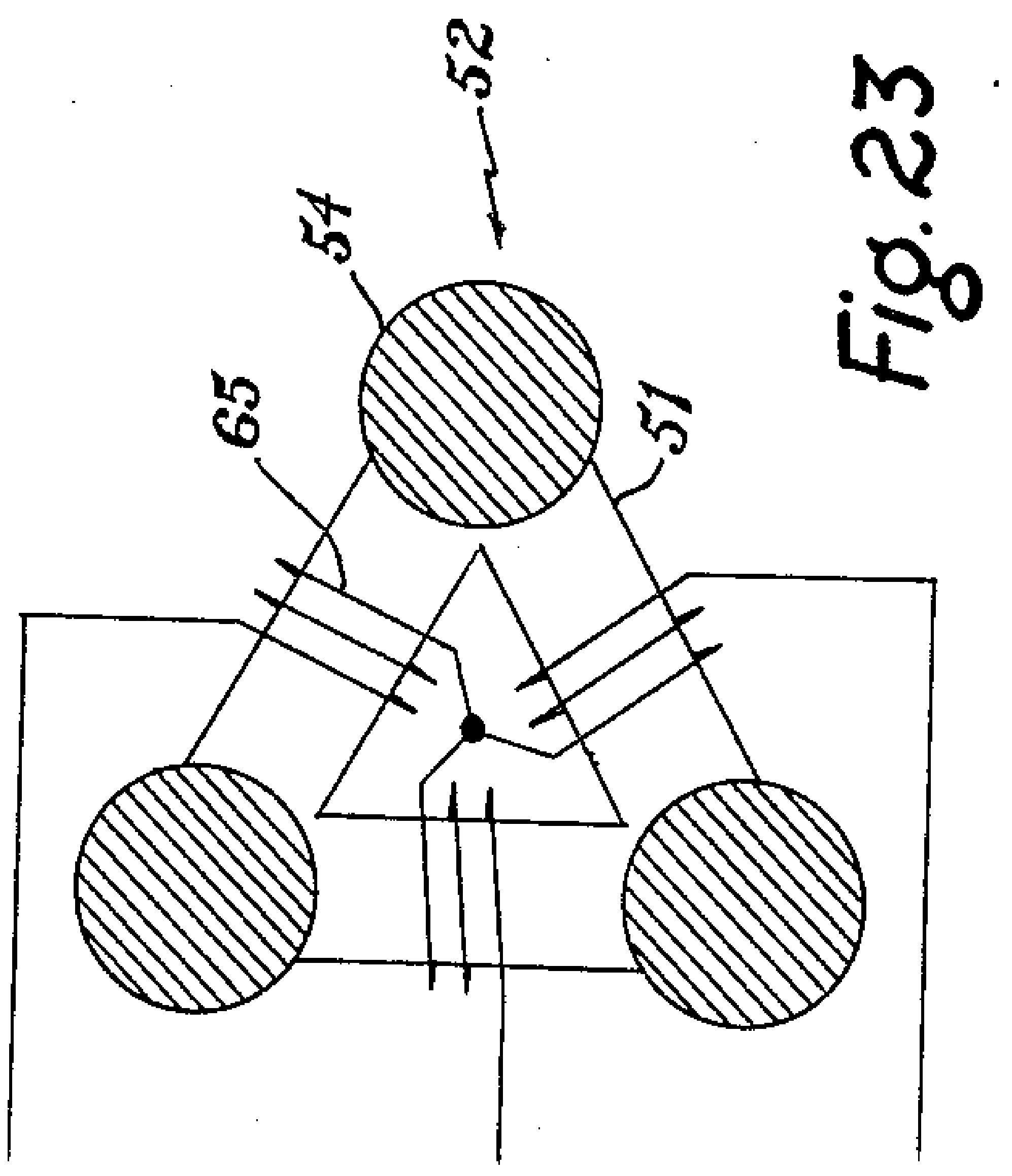

Fig. 23

United States Patent Office 3,187,208
Patented June 1, 1965

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HIGH VOLTAGE ELECTROMAGNETIC APPARATUS HAVING AN INSULATING MAGNETIC CORE

Robert J. van de Graaff, Lexington, Mass., assignor to High Voltage Engineering Corporation, Burlington, Mass., a corporation of Massachusetts

Continuation of application Ser. No. 647,915, Mar. 22, 1957. This application Nov. 21, 1961, Ser. No. 154,937
21 Claims. (Cl. 310—40)

This application is a continuation of my co-pending U.S. patent application, Serial No. 647,915, filed March 22, 1957, for High Voltage Electromagnetic Apparatus Having an Insulating Magnetic Core, and now abandoned.

This invention relates to the electromagnetic generation of electric power at high voltage by a method which comprehends the production and utilization of strong electric and magnetic fields in the same region of space, and by apparatus which comprehends an insulating magnetic circuit.

In almost every branch of its activities the electric power industry has relied on ferromagnetic materials with their attendant intense magnetic fields. D.C. generators, alternators, D.C. and A.C. motors, and transformers all make extensive use of substantially closed magnetic circuits characterized by intense magnetic fields which reside almost entirely within ferromagnetic material. In these devices the high electrical conductivity of the ferromagnetic material maintains it at or near a common electric potential, usually ground, so that there is little or no electric field in those regions in which the intense magnetic field exists. In transformers, for example, the electric fields are between the coils and the core, and since it is desirable that the coils be as close as possible to the core, electric insulation problems become more and more acute as higher voltages are sought. As a result, electrical power equipment in which ferromagnetic materials and strong magnetic fields are used has been in general limited to voltages of the order of a few hundred kilovolts.

Higher voltages have been increasingly needed for the acceleration of charged particles in nuclear physics and in the production of radiation, and high-voltage accelerators, initially produced on a research basis by various laboratory groups, are now being manufactured on an industrial scale. Such higher voltages have been produced with limited power outputs without the use of the intense magnetic fields which are generally used in the electric power industry. For example, the high-voltage resonance transformer employs magnetic fields having an intensity only a small fraction of that used in ordinary transformers, while the electrostatic belt generator produces high voltage entirely electrically with negligible magnetic fields. However, the power output of both of these devices is relatively very small compared with the output of conventional transformers and generators using the intense magnetic fields characteristic of most equipment in the electric power industry.

The invention permits the production of an intense magnetic field at any desired electric potential, so that the power production methods of the electric power industry may be employed within the structures developed by the high-voltage industry. In accordance with the invention this objective is achieved by producing the intense magnetic field in the same region of space as that in which the intense electric field is produced. Various embodiments of apparatus, to be described in detail hereinafter, may be used in carrying out the invention, and their common characteristic is an insulating core magnetic circuit. The reluctance of the total insulating gap in the magnetic circuit of the invention is of the order of the reluctance of the total air gap permissible in magnetic circuits now used in the electric power industry.

The invention may best be understood from the following detailed description thereof, having reference to the accompanying drawings, in which:

FIG. 1 is a diagrammatic sectional view of an insulating core transformer constructed in accordance with the invention;

FIG. 1A is a diagrammatic sectional view, partly in side elevation, showing an insulating core transformer constructed in accordance with the invention and including rectifiers for the production of D.C.;

FIG. 2 is a view similar to that of FIG. 1 but showing a conventional transformer;

FIG. 3 is a vertical central section of one embodiment of a charged-particle accelerator adapted to accelerate charged particles to an energy of about 1 mev. by means of a high voltage generator constructed in accordance with the invention;

FIG. 4 is a horizontal section along the line **4—4** of FIG. 3;

FIG. 5 is a section along the line **5—5** of FIG. 3, but showing the coil diagrammatically in order to indicate the direction in which it is wound;

FIG. 6 is a section along the line **6—6** of FIG. 3, but showing the coil diagrammatically in order to indicate the direction in which it is wound;

FIG. 7 is a detail showing a modification of the voltage-generating apparatus shown in FIG. 3;

FIG. 8 is a detail showing a modification of FIG. 7;

FIG. 9 is a graph to be used in conjunction with FIGS. 7 and 8;

FIG. 10 is a detail similar to that of FIG. 7, but showing another modification of the voltage-generating apparatus shown in FIG. 3;

FIG. 11 is a detail similar to that of FIG. 7, but showing still another modification of the voltage-generating apparatus shown in FIG. 3;

FIG. 12 is a detail similar to that of FIG. 7, but showing still another modification of the voltage-generating apparatus shown in FIG. 3;

FIG. 13 is a vertical central section of the lower portion of another embodiment of a charged-particle accelerator adapted to accelerate charged particles to an energy of about 1 mev., similar to that of FIG. 3, but showing an alternative means for producing a changing magnetic field in the magnetic circuit of the high voltage generator;

FIG. 14 is a vertical section along the line **14—14** of FIG. 13;

FIG. 15 is a detail similar to that of FIG. 7, but showing still another modification of the voltage-generating apparatus shown in FIG. 3;

FIG. 16 is a sectional view similar to that of FIG. 3 showing a charged particle accelerator constructed in accordance with the invention and adapted to accelerate charged particles to tens of mev. by using charge reversal;

FIG. 17 is a section along either the line **17—17** or the line **17′—17′** of FIG. 16;

FIG. 18 is a side view of a three-phase generator constructed in accordance with the invention and having a D.C. voltage output of the order of 1 mv.;

FIG. 19 is a horizontal section along the line **19—19** of FIG. 18;

FIG. 20 is a diagram showing a transmission system in which high-voltage D.C. power is transmitted from a power plant to a multiplicity of power-consuming devices, shown in FIG. 20 as acceleration tubes;

FIG. 21 is a side view, partly in section, showing one of the acceleration tubes of FIG. 20;

FIG. 22 is a diagrammatic view of a high-voltage inverter which may be used, in accordance with the invention, instead of any of the acceleration tubes in the apparatus of FIG. 20 to convert high-voltage D.C. into 3-phase power at lower voltages; and

FIG. 23 is another diagrammatic view of the high-voltage inverter of FIG. 22.

Referring to the drawings, a conventional transformer is shown in diagrammatic fashion in FIG. 2. Such a transformer comprises a magnetic circuit 1 which is linked by two coils 2, 3. If the transformer is to augment voltage, as is the case for purposes of the present comparison, then the primary 2 will have few turns and the secondary 3 will have many turns. In the conventional transformer art the magnetic circuit is not only not insulating, but in general even the slightest gap therein is sought to be minimized. In certain low-voltage transformers the introduction of gaps has certain advantages, but such gaps are not introduced for the purpose of electric insulation nor do they serve to provide such insulation. A changing current in the primary produces a changing magnetic flux which is confined, except for leakage flux, within the magnetic circuit. The changing magnetic flux in turn induces an electromotive force in the secondary, which links the magnetic circuit. In order to minimize resistance losses, the secondary is wound as close as possible to the magnetic circuit so as to minimize the length of the secondary. While a high voltage is developed across the secondary coil, the conductivity of currently available ferromagnetic materials requires that the magnetic circuit be at approximately one potential, usually ground. Therefore, the secondary must be insulated from the magnetic core at all points, and such insulation must be able to support voltages up to more than the peak voltage generated.

Compare with the conventional transformer of FIG. 2 the insulating core transformer of FIG. 1. In the latter case the magnetic circuit 1′ is broken up into magnetic elements 4 which are separated by insulating gaps 5, 6, so that each magnetic element may have an electric potential which differs from that of its neighbors. In this way not only is heavy insulation not required between the coil 3′ and the core 1′, but each magnetic element can be actually connected to some point on the coil 3′, so that an increase in electric potential is produced along the magnetic circuit which increase corresponds to the increase in electric potential along the coil 3′. The introduction of the insulating gaps increases the reluctance of the magnetic circuit, but this increase is minimized in accordance with the invention in several ways. For example, in the insulating core transformer of FIG. 1, the gaps 5 within the turns of the secondary coil 3′ are very short; whereas the relatively long gap 6 at the high-voltage end of the secondary has a very large area. Since the reluctance introduced by the gap is proportional to the length of the gap and inversely proportional to its area, increasing the latter decreases the reluctance as effectively as decreasing the former.

Referring now to FIGS. 3, 4, 5 and 6 of the drawings, the charged-particle accelerator therein shown is constructed in accordance with the optimum practical electrostatic principles developed by the high-voltage industry. That is to say, the accelerator includes a high-voltage terminal 7 of approximately hemispherical shape which is supported upon a cylindrical column 8 comprising a series of equipotential planes. The terminal and the column are enclosed within a grounded tank 9 which is filled with sulfur hexafluoride or other suitable insulating gas under pressure. Charged particles are accelerated from the high-voltage terminal to ground within an evacuated acceleration tube 10 which is supported within the column.

The precise shape of the apparatus is not critical, but in general the outer surfaces of the terminal and the column should have low curvature in order to reduce the voltage gradients. In the ideal case a high-voltage terminal, existing alone, should be spherical; but the ideal electric field configuration for accelerating a well-collimated beam of charged particles is a uniform field. A uniform field requires uniformly spaced planar equipotential surfaces, whereas an isolated charged sphere gives rise to non-uniformly spaced spherical equipotential surfaces. In the optimum accelerator configuration, an electric field is produced within an evacuated acceleration tube by electrically connecting one end of the tube to the rounded terminal, the other end being grounded. Within the acceleration tube the normally spherical equipotential surfaces are rendered planar by constructing it of a multiplicity of planar electrode apertured disks separated by annular insulators, and the electric field within the acceleration tube is rendered uniform by connecting adjacent electrode disks with suitable fixed resistors or corona gaps or otherwise controlling their potentials.

In order to reduce transverse voltage gradients at the outer lateral surface of the acceleration tube, the equipotential planes of the electrode disks are extended by connecting them to well-rounded rings which form a cylindrical column between the terminal and ground. The configuration just outlined was derived solely from electrostatic and acceleration considerations; and, in view of this configuration, the optimum location of the voltage-generating apparatus is within the column. Accordingly, the belt of the belt electrostatic generator operates longitudinally within the column. However, conventional electromagnetic voltage generators are in general not well-suited to this configuration; and a major advantage of the invention is the fact that it comprehends a powerful electromagnetic voltage generator which makes very efficient use of the available space within the column.

In accordance with the invention the terminal is raised to high voltage by inducing an electromotive force in a plurality of coils 11, 12 which are connected in series between the high-voltage terminal and ground and which link a magnetic circuit wherein a changing intense magnetic field is produced in any of several ways. Said magnetic circuit includes the high-voltage terminal, which is therefore constructed of magnetic material, and a grounded lining 13 of magnetic material on the inner surface of the tank. The terminal is magnetically connected to the lining by two insulating magnetic paths. The first insulating magnetic path links the coils and comprises a series of magnetic elements 14 which are separated by a corresponding series of thin insulating films 15. The second insulating magnetic path comprises the hemispherical insulating gap 16 between the terminal and the lining. In accordance with the invention, the terminal is so constructed as to have a large outer surface area, so that the reluctance of the second insulating magnetic path is much less than the reluctance of the first insulating magnetic path, despite the length of the gap between the terminal and the lining; in the device shown in FIGS. 3, 4, 5 and 6, the reluctance of the single large gap 16 in the second insulating magnetic path is approximately equal to that of two of the short gaps 15 in the first insulating magnetic path.

Upon each magnetic element 14 and electrically connected thereto either directly or through a resistor (not shown) there is supported a toroidal conductive case 17 which is divided axially into two compartments by a conductive diaphragm 18 which is electrically connected to the case 17. Each compartment contains one coil of which one end is electrically connected to the case and the other end extends radially out through an insulating bushing (not shown) in the case within a shielded lead and is connected to the corresponding end of the adjacent coil of the adjacent magnetic element. Starting from the end connected to the case, the coils 11 in the upper compartment of each case 17 are wound in one direction, and the coils 12 in the lower compartment of each case are wound in the opposite direction, as shown clearly in FIGS. 5 and 6, so that the electromotive forces produced in the coils by the changing intense magnetic field which they link are added in series.

It will be observed that the voltage-generating apparatus of FIGS. 3, 4, 5 and 6 makes very efficient use of the space within the column 8. In particular, it should be noted that whereas in the acceleration tube 10 the equipotential planes are defined by very thin electrode disks 19, and so are readily identified as planar, the magnetic requirements may make it desirable that the magnetic elements 14 have substantial axial thickness. As a result, the equipotential "planes" become rather thick as they pass through the magnetic circuit, and are less readily recognized a planar. It should therefore be emphasized that throughout the specification and claims the term "equipotential plane" is used as a term of art and includes "planes" having substantial thickness.

In the apparatus of FIGS. 3, 4, 5 and 6 electric insulation is provided in the first insulating magnetic path either by compressed gas or by thin insulating films 15. The thinner the film the greater its dielectric strength in volts per unit thickness, and the increase in dielectric strength is rapid with increasing thinness. It is therefore desirable to use thin films of plastics such as polyethylene or Mylar, either by using very short gaps between the magnetic elements 14 or else by subdividing each gap into a plurality of films separated by metallized surfaces. In the latter event the electric potential of the metallized surfaces should be controlled by inserting stable resistances between adjacent metallized surfaces. The use of very short gaps is desirable from the magnetic point of view, since the reluctance of the magnetic circuit is reduced by using short gaps. Owing to its ability to support a higher voltage gradient, the total voltage supportable across the short gaps 15 is comparable to that supportable across the acceleration tube 10.

In the case of solid insulation, the effect of subdividing each insulating gap of the magnetic circuit into several smaller gaps is shown in FIGS. 7 through 9. Referring first to FIG. 7, therein is shown an insulating gap containing a single solid insulator 20. In order to avoid edge effects, there is thickening of the insulation at the outer edges of the gap and the outer peripheral surface of the insulator is corrugated. In FIG. 8 is shown the subdivision of the same insulating gap by forming the insulator from several metallized plastic layers 21. The metallization is performed by evaporization techniques and thus the metal layers 22 are extremely thin, less than 1% of the total length of the gap, so that their thicknesses may be neglected. For example, the insulator may comprise a stack of layers of metallized polyethylene or Mylar. As in the gap of FIG. 7, the insulation in FIG. 8 is thickened at the outer edges and each layer of insulating material is rounded so as to give an overall corrugation effect.

The device shown in FIG. 8 could be assembled with the utilization of vacuum impregnation in order to achieve maximum dielectric strength of the assembly.

The advantage of subdividing the gap is shown graphically in FIG. 9. The breakdown voltage of the total gap is plotted as a function of the number of equipotential surfaces within the gap. Thus, if N metal layers are inserted within a gap of length D, there would be $N+1$ gaps each having a length $D/(N+1)$. The breakdown voltage of the device shown in FIG. 7 is indicated at the point A in the graph of FIG. 9 and that of the device shown in FIG. 8 is shown at the point B in the graph of FIG. 9. The dielectric strength data needed for the graph of FIG. 9 is obtained from a graph designated as FIG. 1 on page 44 of section 2 of Electrical Engineer's Handbook (Electric Power), by Pender and Del Mar, 4th edition (Wiley, 1949), it being assumed that the total insulating gap for FIGS. 7, 8 and 9 is 60 mils.

In some cases the use of gaseous insulation instead of solid insulation has certain advantages, and in FIGS. 10 and 11 there are shown modifications of the first insulating magnetic path which may be used in embodiments of the invention having gaseous insulation in the first as well as the second insulating magnetic path. An important advantage of gaseous insulation is its self-healing property; that is, the gas returns to its original state after a local electric breakdown, whereas a solid insulator usually is permanently damaged.

In the case of either solid or gaseous insulation the reluctance of the magnetic circuit can be reduced if necessary, in accordance with the invention, by increasing the area of each such gap. Referring to FIG. 12, the cross section of the magnetic core 23 is increased in the region between adjacent coils 24, so that each magnetic element 23 has somewhat the shape of an hour-glass with the coil 24 being placed in the groove. The area of each insulating gap 25 is therefore increased and its reluctance decreased as compared with a structure in which the cross section of the central core is limited to the internal cross section of the coils.

In the apparatus of FIG. 10, such increase in area is provided by corrugating each gap 26 in the manner shown. The length of the gap is almost constant throughout its area, except that the gap length must be increased in the regions of higher gradients at the relatively high-curvature portions 27 of the surfaces of the magnetic elements 28.

Other structures in which the area of the gap is increased, so that the reluctance of the gap is decreased without decreasing its dielectric strength, may be devised without departing from the spirit and scope of the invention. For example, a series of staggered rows of magnetic bars 29 may be employed, as shown in FIG. 11.

As can be seen from a careful inspection of FIG. 10, the dimension of the insulating gap 26 along the corrugation in the plane of the drawing is about 5 times the corresponding dimension of an uncorrugated gap. It is therefore clear that the introduction of the corrugations shown in FIG. 10 reduces the reluctance by a factor of approximately 5. It is equally clear from a comparison of the point B with the point A in the graph of FIG. 9 that the introduction of the 3 equipotential surfaces 22 in FIG. 8 increases the dielectric strength as compared with the device shown in FIG. 7 by a factor of approximately 2. Furthermore, the hour-glass configuration shown in FIG. 12 reduces the reluctance by a factor of approximately 3 as compared with the corresponding constant-cross-section magnetic core, since the area of the magnetic circuit at the insulating gap 25 is approximately 3 times its area at the coils 24. In accordance with the invention, the principles of the constructions shown in FIGS. 10, 8 and 12 may be combined in a single structure and such a combination can reduce the total reluctance by a factor approximately equal to the product of the above-mentioned three factors, which is 30.

Referring again to FIGS. 3, 4, 5 and 6, power for apparatus within the high-voltage terminal 7 may be derived from an additional secondary coil 30 which lies within the high-voltage terminal and which links the magnetic circuit. This coil is designed to provide moderate power at moderate voltage.

If desired, rectification may be provided by the acceleration tube 10 itself. However, steady D.C. voltage can be obtained by providing separate rectification. In accordance with the invention, rectification is provided by a series of rectifiers (not shown), such as silicon diodes, which may be supported upon an insulating shaft 31 so that at least one rectifier corresponds to each coil 11, 12. This shaft assembly 31 together with the attached rectifiers can be made readily removable through a pressure lock arrangement, so that the silicon diodes can be readily serviced and replaced.

The changing intense magnetic field may be produced in any of a variety of ways, and in the apparatus of FIGS. 3, 4, 5 and 6 the field is produced by a primary coil 32 through which an alternating current is driven by a suitable A.C. source (not shown), so that the apparatus operates essentially as a transformer. However, the invention is not limited to apparatus employing a transformer action, but includes other devices in which a magnetic circuit is utilized in the production of electric power. As in the case of the conventional transformer, the magnetic circuit of the conventional alternating current generator, or alternator, is at one potential, usually ground; but the changing magnetic flux produced by rotation of the rotor generates an electromotive force in the coils which link the magnetic circuit, so that each coil must be insulated from the armature, and such insulation must be able to withstand at least the full voltage developed by the alternator, even though the full voltage may not be developed across any single coil.

The apparatus of FIGS. 13 and 14 shows a synchronous A.C. generator constructed in accordance with the teachings of the invention. The generator of FIGS. 13 and 14 may be identical to the transformer of FIGS. 3, 4, 5 and 6, except for the lower portion of the magnetic circuit and except for the means by which the changing magnetic flux is introduced into the magnetic circuit. Referring to FIGS. 13 and 14, the lower portion of the lining 13 is extended so as to form a first pair of teeth 33, and the lower portion of the series of magnetic elements 14 is extended so as to form a second pair of teeth 34. The magnetic circuit is completed by a rotor 35 mounted on a shaft 36 which is driven by a suitable source of mechanical power (not shown) such as a turbine. The magnetic flux produced in the magnetic circuit by the field poles 37 alternates upon rotation of the rotor 35, thus inducing an electromotive force in the coils 11, 12. The output of the generator of FIGS. 13 and 14 may be rectified in the same manner as that employed in connection with the transformer of FIGS. 3, 4, 5 and 6.

It is to be understood that throughout the specification and claims the term "magnetic materials" includes not only ferromagnetic materials, but also materials such as ferrites and powdered iron. Although these have less permeability than ferromagnetic materials, they may have in some cases certain advantages, such as low eddy-current losses.

In accordance with the invention one can produce a voltage increment at any desired potential from a grounded source of electric or mechanical power. By arranging a series of such voltage-producing units, each of which produces a certain voltage output at successively higher potentials, one can construct a high voltage transformer or generator. One can then design the size of the component voltage-producing units on the basis of production considerations. Some applications may favor relatively large units. However, for mass production a multiplicity of small, rugged units would be advantageous. One such unit is shown in FIG. 15.

Referring to said FIG. 15, each unit comprises a flat, thin magnetic element 38 surrounded peripherally by a correspondingly flat and thin hollow toroid 39 of conductive material so as to form a flat, thin equipotential plane. At least one surface of the equipotential plane is metallized to smooth out irregularities due to the lamination of the magnetic material, and to the other surface is cemented a flat, thin insulating layer 40 both of whose main surfaces are metallized, the outer rim being left insulating. The whole unit is preferably although not necessarily circular, and for example may have in some cases the approximate dimensions of a 12-inch long-playing phonograph record. Electrically, the unit comprises two equipotential planes separated by the insulating layer 40; one plane is a metallization layer 41 and the other plane is the combination of the magnetic core 38, the conductive toroid 39, and another metallization layer 42. A coil 43 is wound within the toroid 39, starting at and being connected to the radially inner surface and extending spirally outward and through an insulating bushing 44 in the radially outer surface. The coil 43 is insulated from the toroid 39 everywhere except at the inner connection, and the insulation may be simply the insulation on the wire 43 or, alternatively, the toroid 39 may also include additional insulating material 45. The toroid 39 is preferably of copper sufficiently thick not only to shield the coil 43 but also to conduct heat away from the axial regions of the unit to the periphery, where appropriate fins (not shown) may serve to dissipate the heat.

A multiplicity of such units may be connected in series merely by stacking them in compression, with the outer lead of each unit connected to the metallized surface 41 on the opposite side of the insulator 40 either directly or through a rectifying circuit 46. A unit having a thickness of 1 or 2 mm. might have a D.C. output of about 1 kilovolt, so that a stack several feet in length would provide an output of one million volts.

In all embodiments of the invention the magnetic material should be laminated along the lines of the magnetic field, as is well known in the electromagnetic art. Cores of rectangular cross-section, as shown in FIGS. 3 and 4, may be composed of layers of flat pieces; while cores of circular cross-section may be composed of a spirally wound ribbon radially severed in an appropriate manner.

In some cases it may be desirable to have the high voltage terminal centrally located within the tank as shown in FIGS. 16 and 17, rather than near one extremity thereof. For example, in so-called "tandem" particle accelerators making use of the phenomenon of charge reversal the evacuated acceleration tube 47 would generally extend all the way through the high-voltage terminal 48 to the opposite end of the tank 49. Owing to the presence of the acceleration tube 47, the insulating path length must be longer than that required across a gaseous insulator. It therefore becomes appropriate to construct both of the aforementioned insulating magnetic paths in a similar manner; that is, both insulating magnetic paths will comprise a series of magnetic elements 50 separated by short gaps. Such a construction may be preferred even in accelerators not using charge reversal, e.g. in order to avoid cantilever construction where the column is horizontally disposed.

In the apparatus of FIGS. 16 and 17 the lines of magnetic force may travel continuously through the central column, thereby forming a single magnetic circuit; or, in the alternative, they may travel in opposite directions in each branch of the central column and radially outward from the terminal 48 to the tank 49, thereby forming two magnetic circuits. In the latter case it would probably be desirable to enlarge the central terminal 48 so as to reduce the reluctance between it and the tank 49 across the single gap between them. Increasing either the diameter or the length of the terminal 48 would reduce the aforesaid reluctance.

Referring now to FIGS. 18 and 19, the magnetic circuit of the three-phase transformer therein shown comprises a triangular base 51 of magnetic material, at each apex of which is mounted a column 52 which is electrically subdivided by insulating gaps 53 into a plurality of magnetic elements 54 in any of the manners hereinbefore described in detail. The three-phase magnetic circuit is completed by a triangular crown 55 of magnetic material. A changing magnetic flux is introduced into the magnetic circuit by three primary coils 56 in which currents having appropriate phase relationship are driven by any suitable three-phase generator system (not shown). The primary coils 56 may surround any convenient portion of the magnetic circuit, such as the grounded end of the columns 52, but for the sake of clarity they are shown in FIG. 19 as each linking one leg of the triangular base 51. Again for clarity's sake all coils have been omitted in FIG. 18.

If desired, there might be three secondary coils, each linking one column 52, so as to provide a three-phase output, which, upon rectification, would provide a fairly smooth D.C. output. However, the output may be rendered very much smoother by providing many more phases. Such a result would be achieved if, for example, the secondary windings consisted of a series of n circuits each of which comprised x turns around one column plus y times around another column. The phase of each circuit would depend upon

$$\frac{x}{y}$$

while the voltage output of each circuit would be adjusted by varying $x+y$. In general, x and y would differ from one circuit to another.

More flexibility is achieved if the turns of some of the circuits enlink only a part of the column. Such an arrangement is made feasible by the insulating-core construction of the invention, since the potential gradient between the secondary and the adjacent magnetic core need never exceed the capabilities of the insulator surrounding the secondary wires. Referring to FIG. 19, the circuit S_{ab} enlinks

$$\frac{a}{D}$$

times the total flux of one column plus

$$\frac{b}{D}$$

times to total flux of another column. The circuit S_{ab} is shown as having one turn, but of course it would in general link one column x times and the other column y times, so that the voltage output and phase of each circuit may be adjusted by varying x and y as well as a and b.

In general, the series of n circuits will consist of m series-connected groups each containing

$$\frac{n}{m}$$

circuits connected in parallel, and m will be one-third of the total number of magnetic elements. By proper selection of the variables x, y, a and b for each circuit, each circuit may be made to have approximately the same voltage output, and the phase relationships may be adjusted to form n different phases. The number of phases (n) may be of the order of many hundred, so as to provide a very smooth D.C. voltage output. Of course, the A.C. output of each circuit must be rectified by the inclusion of a rectifier (not shown), such as a silicon diode, in series with each circuit.

While the arrangement of the secondary coils is clear from the above description thereof, it will be appreciated that disclosure of the secondary circuits and their associated rectifiers in the drawings would render FIGS. 18 and 19 completely unintelligible, in view of the passage of some of the wires through the magnetic core and in view of the enlinkment of more than one column by many of the circuits. Accordingly, only two circuit, S_1 and S_{ab}, are shown in FIG. 19 and none in FIG. 18.

As hereinbefore pointed out, the invention is not limited to transformers, but includes other electromagnetic apparatus such as generators. For example, a three-phase generator constructed according to the invention could be similiar to the transformer of FIGS. 18 and 19, except that the primaries 56 would be eliminated and various portions of the magnetic circuit, such as such as each leg of the triangular base 51, would be severed so as to receive in the gap thus formed a rotor of the general type shown at 35 in FIGS. 13 and 14. The three rotors would be adapted to produce a changing magnetic flux having three-phase characteristics.

The D.C. output of the three-phase high-voltage generator may be used to accelerate charged particles, and for this purpose an evacuated acceleration tube may be mounted centrally between the three columns 52 shown in FIGS. 18 and 19. However, the three-phase generator is particularly adapted to the generation of D.C. power for transmission to remote utilization apparatus. Thus, for example, in a chemical plant where radiation processing is being practised on a large scale, it would be desirable to have a multiplicity of radiation vaults, each with its own electron-acceleration tube, at a variety of places in the plant. The high voltage D.C. for the acceleration tubes would be generated at a single power station, which might include several generators of the type shown in FIGS. 18 and 19, and would be transmitted over a special transmission line to the acceleration tubes. In this way, the high-voltage generator is remote from the radiation areas and so does not require radiation shielding.

Referring now to FIGS. 20 and 21, each generator 57 of the central power plant may be in the open atmosphere or, for greater compactness, may be enclosed in a tank containing gaseous insulation, such as sulfur hexafluoride under a pressure of 200 p.s.i.g. For example, a 1-megavolt generator might be enclosed in a 100-inch-diameter tank. The high voltage terminal of the generator 57 is connected to a hollow conductor 58 having an outside diameter of 10 inches which is supported axially within a 20-inch-diameter grounded casing 59 filled with an insulator such as sulfur hexafluoride at 200 p.s.i.g. The resultant transmission line 60 is then connected to a multiplicity of power-consuming apparatus, shown in FIGS. 20 and 21 as electron acceleration tubes 61, each of which is supported within a tank 62 filled with compressed gas. Preferably the same insulator, such as sulfur hexafluoride under pressure, is used in the generator 57, the transmission line 60 and the acceleration-tube tank 62. When repairs are required, the unit affected can be isolated from the rest of the system by closing the approapriate gate valve 63. Each gate valve 63 preferably also includes some mechanism for disconnecting that unit from the high-voltage conductor 58, as by providing a telescoping section which is withdrawn into the transmission line 60 upon closing the gate valve 63.

If the acceleration tube 61 is of the sealed-off type, the apparatus in each radiation vault is further simplified. Moreover, the operation of the acceleration tube 61, such as filament current and cathode-cup voltage, may be centrally controlled by means of leads (not shown) within the hollow high-voltage conductor 58. The fact that radiation shielding is required neither for the voltage generators 57 nor for the transmission lines 60 is advantageous in many ways.

As hereinbefore stated, the three-phase generator shown in FIGS. 18 and 19 is particularly adapted to the generation of D.C. power for transmission to remote utilization apparatus. Moreover, such utilization apparatus need not be particle-accelerating apparatus. Under certain circumstances, high-voltage D.C. power transmission may be preferable to more conventional power-transmission techniques, as is indicated in a recent article in Journal of the Institution of Electrical Engineers, volume 2 (new series), Number 24 (December 1956), at page 711, entitled "High-Voltage D.C. Power Transmission." In accordance with the invention, the advantages of high-voltage D.C. power transmission may be used in combination with conventional apparatus operating at lower voltage A.C. power. The means by which the invention converts either mechanical power or conventional A.C. power into high-voltage D.C. power has already been described herein. An inverter for converting high-voltage D.C. power into conventional A.C. power is also necessary if the advantages of high-voltage D.C. power transmission are to be combined with conventional lower-voltage A.C. apparatus, and an inverter for this purpose, constructed in accordance with the invention, is shown in FIGS. 22 and 23.

Referring to FIGS. 22 and 23, the inverter of the invention includes an insulating magnetic circuit which may be identical to that used in the three-phase transformer shown in FIGS. 18 and 19. As hereinbefore described, such a magnetic circuit comprises three insulating-core columns 52 supported by a triangular base 51 and a triangular crown 55. The primary coils 64 of the inverter, which correspond to the secondary coils of the transformer, are of relatively simple construction, and the three insulating core columns 52 may have a circular cross-section as shown in FIGS. 22 and 23. FIG. 22 shows a horizontal section through the inverter at any of the several levels while FIG. 23 is a horizontal section taken just above the triangular base 51 and below the primary coils 64 of the inverter, and shows the triangular base 51 and the secondary coils 65 of the inverter, which correspond to the primary coils 56 of the generator.

High-voltage D.C. from the power transmission line is sub-divided into many series D.C. increments in an appropriate structure as shown in FIGURE 22. For example one million volts at the high-voltage electrode 66 may be subdivided into 10-kilovolt increments across each electrode pair 67, and in that case each insulating core column 52 might include 100 mutually insulating magnetic elements 54. Each D.C. increment is converted into six pulsating currents in six coils 64 by means of a circuit shown in FIG. 22. These pulsating currents in turn induce an alternating magnetic field in the three columns 52. It is to be noted that the effect upon the magnetic flux in the magnetic circuit which is produced by the various D.C. increments is additive in a simple manner despite the voltage difference between the several D.C. increments.

Referring to the circuit diagram in FIG. 22, each magnetic element 54 has two coils 64 associated therewith each of which has one end connected to the magnetic element 54 and the other end connected to one electrode 68 of an ignitron 69. The two coils 64 are wound in opposite directions and in FIG. 22 one coil is marked by a broken line in order to distinguish it from the other coil. There are thus six coils 64 each of which is connected to an ignitron 69. The opposite electrodes 70 of the ignitrons 69 are connected together and their common connection is connected to one electrode of an electrode pair 67. The opposite electrode of the electrode pair 67 is connected to the local ground 71 shown at the center of the three magnetic elements 54 shown in FIG. 22. The firing time of each ignitron 69 is controlled by applying suitable control potentials to the control electrode or grid 72 by techniques known in the inverter art.

The foregoing description has shown inventive means by which electrical insulation can be introduced transversely into a magnetic circuit consisting mainly of ferromagnetic or other magnetic materials, thus rendering the magnetic circuit a high-voltage insulator. In this manner strong electric and magnetic fields can be used together, in the same extended region and in full teamwork, for the production of large amounts of electric power at high voltage, preferably D.C. By the use of the new methods described, the reluctance of such a high voltage magnetic circuit can be kept to a value less than that of the reluctance of the magnetic circuits commonly used in large hydroelectric generators. As these generators have long been used for the production of extremely cheap electric power at low voltages, it is believed that the insulating magnetic circuit can be used to make possible the production of relatively cheap electric power at high voltage for the acceleration of charged particles and for other purposes.

Having thus described the method of the invention together with several embodiments of apparatus for carrying out the method, it is to be understood that although specific terms are employed, they are used in a generic and descriptive sense and not for purposes of limitation, the scope of the invention being set forth in the following claims.

I claim:

1. Apparatus for producing direct-current electric power comprising a first electrode and a second electrode, a core magnetically connecting but electrically separating said electrodes, a winding on said core and comprising a plurality of coils and a plurality of rectifiers connecting the coils to one another so as to provide at least one conductive path electrically connecting said first electrode to said second electrode, means for producing and maintaining a changing magnetic flux in said magnetic material, whereby an e.m.f. is produced in said coils the effect of which is to cause electrons to move through said winding from said first electrode to said second electrode, thereby producing electric power, and a return path for the magnetic flux produced in said core, said return path having a magnetic reluctance at most of the order of that of said core.

2. Apparatus for producing direct-current electric power comprising a core, a winding on said core and comprising a plurality of coils and a plurality of rectifiers connecting the coils to one another so as to provide at least one conductive path extending the length of the winding, said core comprising a plurality of core members of magnetic material separated by electrical insulating material, each core member being electrically connected to a coil, means for producing and maintaining a changing magnetic flux in said magnetic material, whereby electrons are caused to move through said winding in the direction permitted by said rectifiers, thereby providing electric power, and a return path for the magnetic flux produced in said core, said return path having a magnetic reluctance at most of the order of that of said core.

3. Apparatus for producing direct-current electric power comprising a plurality of direct-current power units each including a core member of magnetic material, a coil linking said core member, at least one rectifier in series with said coil, and a layer of electrical insulation on one surface of said core member; means for supporting said units upon one another so as to form a column in which adjacent units are mutually insulated by one of said layers of electrical insulation, means for connecting said coils in series, so that said rectifiers are similarly oriented, means for producing and maintaining a changing magnetic flux in said magnetic material, whereby electrons are caused to move through said coils in series in the direction permitted by said rectifiers, thereby producing electric power, and a return path for the magnetic flux produced in the magnetic material in said column, said return path having a reluctance at most of the order of that of the magnetic path formed by said core members.

4. Apparatus in accordance with claim 3 wherein each power unit comprises a flat conductive member having a central portion of magnetic material and a circumferential, toroidal conductive shell enclosing a conductive path which links said central portion and which is insulated from said shell except at one extremity of said conductive path, the other extremity thereof extending out through said shell for electrical connection to the shell of an adjacent unit.

5. Apparatus for producing direct-current electric power comprising a plurality of direct-current power units each including a core member of magnetic material, a coil linking said core member, at least one rectifier in series with said coil, and a layer of electrical insulation on one surface of said core member; means for supporting said units upon one another so as to form at least one column in which adjacent units are mutually insulated by one of said layers of electric insulation, means for connecting said coils in independent-phase relationship in a network including both series and parallel connections of said coils, said rectifiers being similarly oriented, means for producing and maintaining a changing magnetic flux in said magnetic material, whereby electrons are caused to move through said coils in the direction permitted by said rectifiers, thereby producing electric power, and a return path for the magnetic flux produced in the magnetic material in said column, said return path having a reluctance at most of the order of that of the magnetic path formed by said core members.

6. Apparatus for producing direct-current electric

power comprising a first electrode and a second electrode, a core magnetically connecting but electrically separating said electrodes, a secondary winding on said core and comprising a plurality of coils and a plurality of rectifiers connecting the coils to one another so as to provide at least one conductive path electrically connecting said first electrode to said second electrode, a primary winding linking said core, and a return path for the magnetic flux produced in said core, said return path having a magnetic reluctance at most of the order of that of said core.

7. Apparatus for producing direct-current electric power comprising a first electrode and a second electrode, a plurality of cores each magnetically connecting but electrically separating said electrodes, a plurality of windings each comprising a plurality of coils and a plurality of rectifiers connecting the coils to one another so as to provide at least one conductive path electrically connecting said first electrode to said second electrode, each of said windings, throughout its length, linking at least a portion of at least one of said cores, and means for producing and maintaining a changing magnetic flux in each core which differs in phase from that in at least one other core.

8. Apparatus for producing high voltage D.C. power comprising a first electrode, a second electrode spaced therefrom but magnetically connected thereto by several insulating magnetic cores, a winding electrically connecting said electrodes and linking said cores in helical succession, rectification means adapted to restrict current flow in said winding from one of said electrodes towards the other, and means for producing and changing the magnetic flux in said magnetic cores, the phase of such change differing among said magnetic cores, said magnetic cores providing return paths for one another.

9. A polyphase electromagnetic generator comprising in combination an insulating magnetic circuit having a high-voltage crown and a grounded base connected by a series of insulating magnetic paths, means to introduce a changing magnetic field of independent phase in each insulating magnetic path, a multiplicity of coil elements linking different parts of said insulating magnetic paths so that the electromotive force induced therein is of different phase, means for rectifying the voltage output of said coil elements, said coil elements being mutually interconnected in such a way as to form a plurality of conductive paths between said crown and said base.

10. A high-voltage generator comprising a first electrode and a second electrode, a magnetic circuit including at least one core magnetically connecting but electrically separating said electrodes, at least one winding encircling various portions of said core and electrically connecting said electrodes, said magnetic circuit including a member of magnetic material movable with respect to said winding, and means for moving said movable member, whereby a changing magnetic flux is produced and maintained within said winding, so that a high voltage is generated between said electrodes.

11. A high-voltage generator comprising a first electrode and a second electrode, a magnetic circuit including at least one core magnetically connecting but electrically separating said electrodes, at least one winding encircling various portions of said core and electrically connecting said electrodes, said magnetic circuit including a magnetized member movable with respect to said winding, and means for moving said movable member, whereby a changing magnetic flux is produced and maintained within said winding, so that a high voltage is generated between said electrodes.

12. Apparatus for producing high voltage power, comprising at least two electrodes, a magnetic circuit including a plurality of insulating magnetic cores magnetically connecting but electrically separating said electrodes, at least one winding electrically connecting said electrodes and linking various portions of said cores, said magnetic circuit including a plurality of spaced magnetic elements movable with respect to said winding and operating, by virtue of such motion, on different portions of said magnetic circuit, and means for moving said movable magnetic elements, whereby high voltage power is generated in said winding or windings by means of the mechanical motion of the magnetic elements.

13. A high-voltage accelerator comprising in combination a high voltage terminal and a ground magnetically connected by a substantially closed magnetic circuit and electrically connected by a conductive path comprising many turns linked by the first half of said magnetic circuit, said first half including a plurality of thin insulating gaps of low permeability but relatively low reluctance, the second half of said magnetic circuit including one or more insulating gaps the total reluctance of which is at most comparable to the total reluctance of said plurality of thin insulating gaps, means for inducing a changing magnetic flux in said magnetic circuit, and a conductive path within said high voltage terminal and linking said magnetic circuit whereby a source of power is available within said terminal.

14. The method of changing mechanical energy into high voltage electrical energy which method comprises applying mechanical energy to a magnetic member which forms part of an insulating magnetic circuit so as to move said magnetic member and thereby vary the magnetic flux in said insulating magnetic circuit, two portions of said insulating magnetic circuit having a high potential difference therebetween and being electrically connected by a winding linking said insulating magnetic circuit.

15. The method of generating high voltage between two parts of a magnetic circuit linked by a winding which electrically connects said parts, which method comprises moving a portion of said magnetic circuit so as to change the magnetic flux therein and impeding electron flow in said magnetic circuit between said parts.

16. Apparatus for producing high voltage power, comprising a first electrode, a second electrode spaced therefrom but electrically connected thereto by a coil, intermediate points on said coil being electrically connected to flat conductive members of generally circular periphery arranged so as to form a column of generally cylindrical shape, a magnetic circuit including an insulating magnetic core within said coil magnetically connecting but electrically insulating said second electrode and said first electrode, and means other than said coil for producing and changing the magnetic flux in said magnetic circuit.

17. Apparatus for producing high voltage power, comprising a first electrode, a second electrode spaced therefrom but electrically connected thereto by a coil, intermediate points on said coil being electrically connected to flat conductive members of generally circular periphery arranged so as to form a column of generally cylindrical shape, a magnetic circuit including an insulating magnetic core within and substantially filling said coil magnetically connecting but electrically insulating said second electrode and said first electrode, and means other than said coil for producing and changing the magnetic flux in said magnetic circuit.

18. A high voltage generator comprising in combination a high voltage terminal, a grounded member surrounding said terminal, a series of mutually insulated low-curvature conducting surfaces forming a column between said high voltage terminal and said grounded member, a magnetic circuit linking the lateral boundary of said column, means to subject said magnetic circuit to the action of a changing magnetic field, and means to convert the resultant changing magnetic flux into an electromotive force between said high voltage terminal and said grounded member.

19. Apparatus for producing high voltage power, comprising a first electrode, a second electrode spaced therefrom but electrically connected thereto by a coil, intermediate points on said coil being electrically connected to

flat conductive members of generally circular periphery arranged so as to form a column of generally cylindrical shape, a magnetic circuit including an insulating magnetic core within said coil magnetically connecting but electrically insulating said second electrode and said first electrode, and means other than said coil for producing and changing the magnetic flux in said magnetic circuit, the voltage-holding properties of said core being unimpaired by any conductors.

20. Apparatus for producing high voltage D.C. power comprising a first electrode, a second electrode spaced therefrom but electrically connected thereto by a winding, intermediate points on said winding being electrically connected to flat conductive members of generally circular periphery arranged so as to form a column of generally cylindrical shape, rectification means adapted to restrict current flow in said winding from one of said electrodes towards the other, a magnetic circuit network including a plurality of insulating magnetic cores within said column and magnetically connecting but electrically insulating said second electrode and said first electrode, said winding comprising a plurality of coil segments connected in series so that successive coil segments link successive insulating magnetic cores and each insulating magnetic core is linked by a plurality of coil segments, and means for producing and changing the magnetic flux in said magnetic circuit, the phase of such change differing among said insulating magnetic cores.

21. The method of producing direct current electric power comprising the following steps: connecting magnetically but separating electrically a first electrode and a second electrode by means of a core, connecting electrically said first electrode to said second electrode by a winding on said core which winding comprises a plurality of coils and a plurality of rectifiers connecting the coils to one another so as to provide at least one conductive path extending the length of the winding, and producing and maintaining a changing magnetic flux in said core, whereby an e.m.f. is produced in said coils the effect of which is to cause electrons to move through said winding from said first electrode to said second electrode, thereby producing electric power, and guiding the return magnetic flux corresponding to the magnetic flux produced in said core by means of a return path having a magnetic reluctance at most of the order of that of said core.

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MILTON O. HIRSHFIELD, *Primary Examiner.*

DAVID X. SLINEY, *Examiner.*