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(54) **TRANSFORMER CORE**

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## Description

FIELD OF INVENTION

**[0001]** The present invention relates generally to transformer cores and especially to three-phase cores comprising multi-edged legs. The invention also relates to single-phase shell cores having many rings, frame cores having two frames and two yokes, inductors, and components for the foregoing and transformers.

BACKGROUND

**[0002]** Three-phase transformer cores are usually made of transformer plates cut to E I shape for small transformers and to rectangular plates, which are laid edge to edge, in larger transformers. They have the drawback that the magnetic field has to pass via edges from plate to plate and that the magnetic field must go an unnecessarily long way and not always along a magnetic orientation.

**[0003]** Designers of transformer cores have striven to obtain legs with an essentially circular cross-section because that gives the best efficiency of the final transformer. However, there is always a trade-off between efficiency and production requirements, leading to non-optimal transformer cores with non-circular legs.

**[0004]** Strip cores for three-phase transformers have hitherto been difficult to manufacture. The efficiency of the core can be increased by cutting strips to variable width and winding rings, which are given a circular cross-section for single-phase transformers and semicircular cross-section for three-phase transformers. This method results in a great deal of waste and the winding process is time consuming.

**[0005]** US 4,557,039 (Manderson) discloses a method of manufacturing transformer cores using electrical steel strips having approximately a linear taper. By selecting a suitable taper, a hexagonal or higher order approximation of a circular cross section for the legs of the cores is produced. However, the tapered strips are difficult and time-consuming to produce and the design is not well adapted to large-scale production.

**[0006]** In figs. 1a-b there is shown a prior art three-phase transformer core according to Manderson, generally designated 10. The core has a general cage-shape, as is seen in the isometric view of fig. 1, with three legs interconnected by yoke parts. In fig. 1a, a cross-sectional view of the core is shown before final assembly. The core comprises tree identical ring-shaped parts or frames 12, 13, and 14, the general shape of which appears from fig. 1. Each frame fills up one half of two legs with hexagonal cross-sections, see fig. 1a, thus totalling the three legs of a three-phase transformer. The frames are initially wound from constant width strips to three identical rings 12a, 13a, 14a with rhombic cross-sections comprising two angles of 60° and two angles of 120°. These rings 12a-14a constitute the basic rings. The orientation of the strips also appears from figs. 1a and 1b.

**[0007]** Outside of the basic ring in each frame there is an outer ring 12b, 13b, 14b of a regular triangular cross-section. The outer rings are wound from strips with constantly decreasing width.

**[0008]** When the three frames 12-14 are put together, see fig. 1b, they form three hexagonal legs on which the transformer windings are wound.

**[0009]** A drawback with this solution is that every size of transformer requires its own cutting of the strips. Also, the outer rings 12b-14b are made of strips with decreasing width, leading to waste and it also makes the transformer according to Manderson difficult to manufacture.

**[0010]** Transformer cores are also described in the following documents: SE 163797, US-A-2 333 464, US 2,458,112, US 2,498,747, US 2,400,184 and US 2,544,871. However, the above mentioned problems are not overcome by the cores described in these documents.

SUMMARY OF THE INVENTION

**[0011]** An object is to provide a transformer core, which is easy to manufacture and avoids material waste.

**[0012]** Another object of the present invention is to provide a transformer core wherein the energy losses are minimised.

**[0013]** Another object is to provide a method of manufacturing a transformer that is well adapted for large-scale production.

**[0014]** The invention is based on the realisation that a transformer core with one or more multi-edged legs with more than four edges can be assembled from rings of strips with constant width.

**[0015]** According to the invention there is provided a transformer core as defined in claim 1. With a transformer core according to the invention, at least some of the prior art drawbacks are overcome. Thus, the invention provides a transformer core with good magnetic properties that is easy to manufacture.

**[0016]** Further preferred embodiments are defined in the dependent claims.

BRIEF DESCRIPTION OF DRAWINGS

**[0017]** The invention is now described, by way of example, with reference to the accompanying drawings, in which:

fig. 1 is an isometric view of a prior art three-phase transformer core made of rings with rhombic and triangular cross-sections;

figs. 1a and 1b are transverse cross-sections of the core shown in fig. 1 before and after assembly, respectively;

fig. 2 is an isometric view of a three-phase transformer core according to the invention with legs with hexagonal cross-sections;

figs. 2a and 2b are transverse cross-sections of the core shown in fig. 2 before and after assembly, respectively;

fig. 3 is an isometric view of an alternative embodiment of a three-phase transformer core according to the invention with legs with hexagonal cross-sections;

figs. 3a and 3b are transverse cross-sections of the core shown in fig. 3 before and after assembly, respectively;

Fig. 3c is an isometric view of one of the frames of the transformer core shown in Fig. 3;

Fig. 3d is an exploded view of the frame shown in Fig. 3c;

Fig. 3e is a cut away isometric view of the frame shown in Fig. 3c;

Fig. 3f is a cross-sectional view of the frame shown in Fig. 3c;

Fig. 4 is an isometric view of a three-phase transformer core with octagonal legs;

Fig. 4a is a transverse cross-section of the core shown in fig. 4;

Fig. 5 is a cross-section of a transformer leg with ten edges;

Fig. 6 is a cross-section of a transformer leg with twelve edges;

Figs. 7-9 show an arrangement for influencing the leakage inductance and the harmonics in a three-phase transformer;

Fig. 10 is a transverse cross-section of a three-phase transformer core with specially shaped yoke parts for improving the magnetic flux;

Fig. 11 and 11a show a three-phase transformer core with lined up legs;

Figs. 12-14 show single-phase transformer cores according to the invention;

Figs. 15-17 show further improvements of the shape of the transformer core cross-section;

Figs. 18-21 show alternative embodiments of a three-phase core with alternatively shaped legs and yokes;

Fig. 22 is a top view of an alternative embodiment of the invention showing a three-phase transformer core with rings added to increase the flux in the legs and help in cooling the core;

Fig. 23 is a plan view of another transformer core according to the invention;

Fig. 23a is cross-sectional view of the core shown in

Fig. 23, also including in exploded form the respective frames, and in a second exploded view showing each of the combined legs;

Fig. 24 is a single-phase transformer core with ten sides in cross-section according to the invention;

Fig. 25 is a single-phase transformer core derived from the core in Fig. 24 with ten sides in cross-section according to the invention constructed for improved cooling;

Fig. 26 is an inductor core according to another embodiment of the invention, shown in isometric form;

Fig. 27 is an alternative leg for the inductor core shown in Fig. 26;

Figs. 28a-28w are cross-sectional views of various transformer or inductor legs according to the invention; and

Fig. 29 is a schematic view of a transformer or inductor according to the invention.

## DETAILED DESCRIPTION OF THE INVENTION

**[0018]** Preferred embodiments of a three-phase transformer core according to the invention will now be described.

**[0019]** Fig. 1 has already been discussed in connection with prior art and will not be explained further.

**[0020]** In fig. 2 there is shown a three-phase transformer core according to the invention, generally designated 20. In its general shape it is similar to the prior art transformer core shown in fig. 1 with a general cage-shape but that is designed in an entirely different way.

**[0021]** The core is made up of three ring-shaped parts or frames 22, 23, 24 comprising several rings. These come in two widths, broad or narrow wherein the narrow rings are made up of strips of half the width of the broad rings. Also, they come in two thicknesses, thin or thick wherein the thin rings have half the thickness of the thick rings. Unless otherwise stated, these definitions will be used throughout this description. The strips are preferably made of transformer plate.

**[0022]** Each of the frames 22-24 comprises a broad thick basic ring 22a-24a, respectively, similar to those described with reference to fig. 1. Thus, these rings form in pairs four of the sides in the hexagonal legs. The remaining rhombs in the legs are built in different ways, see figs. 2a and 2b.

**[0023]** In the first leg 25 in the background, the additional rhombic cross-section is composed of two rhomboids. The first one, designated 24b and belonging to frame 24, is a broad thin ring. The second one, designated 22b and belonging to frame 22, is a narrow thick ring.

**[0024]** In the second leg 26 to the right in fig. 2, the additional rhombic cross-section is composed of one rhomboid and two rhombs. The rhomboid is filled by the narrow thick ring 22b belonging to the frame 22. The rhombs are filled by two narrow thin rings 23b, 23c belonging to the frame 23.

**[0025]** In the third leg 27 to the left in fig. 2, the additional rhombic cross-section is also composed of one rhomboid and two rhombs. The rhomboid is filled by the broad thin ring 24b belonging to the frame 24. The rhombs are filled by two narrow thin rings 23b, 23c belonging to the frame 23. The reason that the frame 23 comprises two thin narrow rings instead of one larger ring is that this larger ring can not be both narrow and thick, as required in the left leg 27, and broad and thin, as required in the right leg 26. Thus, instead two narrow thin rings are used.

**[0026]** All upper or lower yokes connecting the legs 25-27 have different shapes but all are built from one basic ring with a large rhombic cross-section plus one ring with a rhomboidal cross-section or two rings with a small rhombic cross-section. This gives all yokes the same total cross-section area.

**[0027]** The rhombic space outside of the basic rings could of course be filled in accordance with a couple of basic principles. A second embodiment will now be described with reference to figs. 3, and 3a-f. Referring first to Fig. 3, a three-phase transformer core 30 is shown. Core 30 has frames 32, 33, 34. Each frame has vertically extending portions that run between opposite ends of a pair of opposed yokes. As explained below, the legs of each frame cooperate with legs of adjacent frames to form legs 35, 36 and 37 of transformer core 30. Since each frame is identical to the other frames, only frame 32 will be discussed.

**[0028]** Frame 32 has a broad, thick ring 32a, a narrow thin ring, 32b which goes over ring 32a, and a narrow thin ring 32c which goes partly over ring 32b and partly over 32a. Ring 32 is shown alone in Fig. 3c. Fig. 3c is a view of frame 32a from inside core 30. It can be seen in Fig. 3c that broad, thick ring 32a is lying in one plane, that ring 32b has an edge lying on the forward edge of ring 32a as viewed on the right portion of Fig. 3c, but is located so that the left edge of ring 32b is sitting near the rear edge of ring 32a. Ring 32c has its left hand surface flush against the right hand surface of ring 32b, and then is arranged so that it crosses over ring 32b and that its bottom strip is aligned with the top strip of ring 32b.

**[0029]** Frame 32 is shown in exploded form in Fig. 3d. It can again be seen that broad thick ring 32a is a wound ring, with its layers being displaced so that its innermost strip in the profile extends forwardly, out of the plane of the paper. Narrow thin ring 32c has its layers displaced inwardly, towards the plane of the paper, that is, opposite to the direction of the offset of ring 32a, as noted above. Ring 32b is narrow and thin, and the direction of the offset of its layers is the same as that of ring 32c. Fig. 3e shows a portion of frame 32 in cross-section. Ring 32a is at the innermost part of frame 32, ring 32b is close to the forward edge of ring 32a when viewed in the right hand corner of Fig. 3e, and then extends partly through ring 32c as can be seen from the direction of the windings of 32b in Fig. 3e. Narrow, thin ring 32c is rearward of ring 32b as shown in Fig. 3e, but is wound around and sits on ring 32b as can be seen in the left hand portion of frame 32.

**[0030]** A cross-section showing all three frames 32, 33, and 34 is shown before assembly in Fig. 3a and after assembly in fig. 3b.

**[0031]** Fig. 3f is a top cross sectional view of frame 32 in Fig. 3c. It shows broad thick ring 32a, narrow thin ring 32b, and narrow thin ring 32c. The offsetting or splaying of the rings 32a, b and c is clear from this view. Rings 32b and 32c are higher in the foreground and lower in the background. The dimension "w" shows the width of ring 32a, and the width of rings 32b and 32c are "w/2". The thickness of ring 32a is shown as "t" and the thickness of each of rings 32b and 32c are "t/2".

**[0032]** A further possibility is to make broad thin rings and turn the leg parts 60°, forcing a corresponding bending of the yoke parts. The yoke parts then require more space and the bending is not so easy to effect. Making narrow thick rings and turning and bending as mentioned is also possible, but difficult. Additional variants, including those with smaller divisions, are also possible.

**[0033]** A core with octagonal legs, generally designated 40, will now be described with reference to figs. 4 and 4a. In an octagonal cross-section, see e.g. the back leg 45, the sides turn 45°, which means that they have a relative angle of 135° to each other. Three rhombs, each with an angle of 45°, thus get space in the innermost edges of the legs of the core. Outside of these rhombs, two squares are filled by rings with quadratic cross-sections. Finally, a rhomb fills the rest of the octagonal cross-section of the leg.

**[0034]** From these six cross-subsections, three subsections compose the cross-section of a profiled ring going to the second leg 46. The remaining subsections compose the cross-section of a profiled ring going to the third leg 47. There is also a profiled ring connecting the second and third legs 46, 47.

**[0035]** The three profiled rings all contain two rings with equal leg parts. A first ring 42a, 43a, 44a has a rhombic cross-section and the yoke parts bent 15°. A second ring 42b, 43b, 44b outside of the first ring is quadratic and follows the form of the first ring 42a-44a.

**[0036]** Using a solution from the embodiments with hexagonal legs described with reference to figs. 2 and 3, two outer rhombs compose the cross-section of an outer ring with the yoke parts bent 15°. Alternatively, two inner rhombs compose an inner ring but bent 60°. The next ring must now give an outer rhomb in one leg and an inner rhomb in the other leg and be bent 30°. One type of profiled ring is to be preferred because it is difficult to bend a ring 60° and one can not avoid a ring with both an outer rhomb and an inner rhomb.

**[0037]** In part 42, the third ring 42c has a rhombic cross-section in the leg parts and is placed outermost in the back leg 45 but inside the right leg 46. These rhombs of the leg parts are obtained by displacing the outer strips of the ring to the right at the right leg 46 and to the left at the back leg 45. Furthermore, the legs are turned asymmetrically 30° and the yoke parts are bent accordingly. The ring is given such a circumference that it will lie outside of the other rings. The final result appears in fig. 4.

**[0038]** A 10-sided leg, generally designated 50, will now be described with reference to fig. 5. The profiled rings contain all four rings with equal leg parts. A first ring 50a, a second ring 50b and a third ring 50c with rhombic cross-sections in their leg parts are attached to the 10-sided cross-section. Thus they have the angles 36, 72, and 108° and their yoke parts bent 24°. A fourth ring 50d having a rhomboid cross-section with the angle 36° lies mainly upon the first ring 50a. Its leg parts are turned outwards 24°, causing a 48° bending of its yokes. The fourth ring also causes the yoke parts of the third ring 50c to make a larger bow to give space. A fifth ring 50e has a rhombic cross-section in its leg parts with the angle 144° when it lies outside of the third ring 50c, but the ring has a rhombic cross-section with the angle 72° when it lies outside of the fourth ring 50d. The yokes are bent only 12°. The arrows i the figure indicate that the cross-sections 50e belong to different profiled rings. There will also be a channel 51 suitable for cooling the legs. In an alternative embodiment, the channel is filled with a ring. This is an advantage when the rings co-operate by letting the magnetic field go between them. The space can e.g. be disposed of in such a way that the upper part of the rings 50c obtains new rhombic cross-sections with the angle 72°, causing the channels 52a and 52b to be formed. Further parts of ring 50c to the right can be pushed to ring 50e, which forms the spaces 53a and 53b.

**[0039]** It is possible to provide three-phase transformer cores with even more edges. Fig. 6 shows a 12-sided core, generally designated 60. The profiled rings are composed of four rings 60a-d with rhombic cross-sections with the angles 30, 60, 90, and 120°, which are attached to the 12-sided cross-section and are turned 15°. Inside of these rings there are two rings 60e, 60f with rhombic cross-sections with the angles 30 and 60°, respectively, and turned outward 15°. Attached to the fifth and sixth rings 60e, 60f there is space for a ring 60g with a rhombic cross-section with the angle 30° turned outward 45°. Its other leg part is a rectangle outside of the sixth ring 60f and turned outward 15°. Upon the ring 60d there is space for a ring 60h with a rhombic cross-section with the angle 150° and the other leg part is a rectangle attached to ring 60d and outside ring 60f. The whole cross-section is then filled. Yoke parts are separated by giving some wider bows to give space for other yoke parts.

**[0040]** The good properties of these transformer cores can be made even better for some transformer application, see fig. 7. The leakage inductance can easily be increased by an additional core 29 of strips between the primary and secondary windings of the transformer. The strips are brought together at the top and bottom. The strips can be spread around the entire primary winding or be concentrated to one place, making the secondary winding eccentric.

**[0041]** The non-linear magnetic properties of iron result in harmonics in the magnetic fields, voltages and currents.

**[0042]** An additional leg placed in the centre of the core will not get any magnetic field under perfectly symmetrical and distortion-free three-phase conditions. Common components in the phase voltages, like the third harmonics, will be influenced by a centre leg.

**[0043]** Also a combination of strips between the windings and a centre leg is possible.

**[0044]** In one embodiment, the centre leg is made of three rectangular poles 80 from strips given a thickness three times the width, laid on each other to a quadratic cross-section, see fig. 8. This is preferably triangular and a custom-made solution contains poles with a rhombic cross-section, of which three are put together to form a packet with the strip edges toward each other in a wave form, see fig. 9. Three packets are put together with small distances to form a leg with a cross-section approximating a triangle. The ends of the poles are bent outward to reach the yokes. To make the bends possible spacers between the poles are necessary. The spacers do not influence the magnetic properties because one pole from each packet 91a-c; 92a-c; 93a-c is bent to each yoke. Also the strips are, at least on one side, parallel to the spacers.

**[0045]** A rod, wound of strips in spiral form or as coils, is useful, especially if there are to be air gaps between the centre leg and the yokes. The spiral can be made wider at the ends to reduce the air gaps to the yokes.

**[0046]** The flexibility of building cores like this is good and is shown in fig. 10. The figure shows the core described in connection with fig. 4. A major part of the magnetic flux can pass from one profiled ring to another in the legs where they are touching each other. This enables the rotation of larger fluxes in the yoke triangle.

**[0047]** With the present invention, it is also possible to provide a three-phase transformer core with lined up legs. This has the advantage that the transformer is narrower than with the cage shaped core. This type of transformer is ideal for placement on e.g. train wagons.

**[0048]** Fig. 11a shows the transverse cross-section of a transformer with octagonal legs. All legs comprise four rhombs with an angle of 45° and two squares. Rings running between adjacent legs are shown in the figure while those running between the outer legs are almost entirely hidden.

**[0049]** In order to make transformer cores of this kind, the leg parts must be bendable and that the yoke parts can be bent and pass each other. There are several solutions, of which one is shown in the figure. The leg parts of the rings are bent outward and the yoke part inward or vice versa. The shape of the yoke parts is limited by the limited possibilities of plastic deformations but otherwise the yoke parts can have any shape. The principle shown in fig. 11 is to have sharp bends and straight yoke parts.

**[0050]** The rings can also be placed on each other giving rounded bends in order to save material.

**[0051]** The yokes between the left leg 115 and the centre leg 116 are built up of a ring 112a with a rhombic cross-section in the leg part, a ring 112b with a square cross-section and both bent 22.5° and a rhombic ring 112c turned 67.5° in the leg parts. The rings 112a and 112b fit into the octahedrons close to the yoke side while the ring 112c fits into the opposing side.

**[0052]** The yoke between the centre leg 116 and the right leg 117 can only be placed in the centre leg in the remaining positions: 114a-c. The cross-sections of the left and right legs 115, 117 are mirror images to the centre leg 116 so that the rings running in the centre leg are symmetric. The inner rings 114a, 114b have their closest positions in the right leg 117. However, the ring 114c with a square cross-section in the leg parts runs to the closest square-shaped position in the right leg. The reason behind that is that the ring 113a with a square cross-section between the outer legs is in an outer position on the yoke parts already present in order to reach the left leg.

**[0053]** The turning of the yokes can be impossible to achieve. In an alternative embodiment, a heavily sloping fold is used instead. This is shown for the ring 114c having the shortest yoke. The fold starts at one end of the yoke and ends at the other end, marked by 118a for the lower yoke and 118b for the upper yoke in fig. 11. Also, the yokes can be subdivided into several narrow rings.

**[0054]** Also single-phase transformers will be more efficient if they are given polygonal cross-sections. Fig. 12 shows a transformer with an octagonal cross-section composed of rings with the same cross-sections as in the three-phase transformers but with the return loops going the closest way outside of the windings. The rings can be transposed and yet given an octagonal cross-section. A small reduction of the amount of plate can e.g. be obtained by looping up to the left of the ring looping rightmost in the figure. There must its cross-section be changed to a rhombic form close to rectangular form.

**[0055]** A core with two legs can be made from the three-phase designs by bending the rings from one leg together to form only one more leg. A core is shown in fig. 13 with an octagonal cross-section in its legs. The turning of three leg-parts is 45° and the bending is 90°. A ring with a rectangular cross-section and the two rings outside of that ring are not deformed. Cores with hexagonal legs need only three rings made of strips with the same width.

**[0056]** If that octagon edge where three rhomb edges meet, is put innermost in the core, the turnings will only be 22.5° except for the rhomb in the middle, which must be turned 67.5°. Replacing this rhomb with a ring, with steps approximating the rhomb, is more realistic and is shown in fig. 14. A further improvement is made by letting the strips reach the circle, thus increasing the total cross-section.

**[0057]** It is realised that the single phase transformers described herein also can have a cross-sectional shape deviating from a perfect regular polygon, like the three-phase cores described below with reference to figures 18-21.

**[0058]** The segments outside of a polygonal leg can be filled by a thin rhombic ring of a strip with about half the width and the full thickness of the segment and wound to its total width. Folds in the strips along the middle of the rhomb as in fig. 15 make two sides to one flat side giving a triangle, the sides of which are in contact with the core. With about 2/3 width and 8/9 thickness, a fold at the edge of the innermost strip makes a trapezoid cross-section as in fig. 16. The cross-section can also be rounded.

**[0059]** By means of strips of constant width the leg parts can be given a cross-section shape closer to the shape of a circle, see fig. 17, 17a and 17b. The right leg 172 in fig. 17 will be described as an example with reference to fig. 17a, wherein a transverse cross-section of that leg is shown. Innermost, there are rings 173 of e.g. 80% of full width and to a thickness of 9% of its width. There are three rings reaching a circumscribed circle, see fig. 17a.

**[0060]** Four of the six segments have been filled with magnetic material and strips outside of the assembled core can fill the other segments.

**[0061]** A ring 174 can be placed on the outer sides of the hexagons.

**[0062]** Another embodiment is shown in fig. 17b, wherein the ring 174 has been replaced by broader strips in the other rings.

**[0063]** The transformer cores described above have all in common that the legs are perfectly regular, i.e., the corners thereof can be inscribed in a circle. However, the invention also provides cores with legs that deviate slightly from the above described regular shapes. Thus, in figures 18 and 19 there are shown three-phase transformer cores with legs having corners that can be inscribed in two circles with different radiuses. Thus, every other corner protrudes from an inner circle. The outer corners can be inscribed in an outer circle. This is shown in figure 19, wherein the left lower leg is shown with two different circles touching the corners thereof.

**[0064]** The legs can also be given a shape like the ones 185, 186, 187 shown in figure 18. In figure 18, every other angle between edges is 30° and the other 60°. This results in an irregular octagon. This can be inscribed in a 1,52° circle:

$$x^{1.52} + y^{1.52} = r^{1.52}$$

wherein x and y are two-dimensional co-ordinates and r is the radius of the circle.

**[0065]** If an increase of the transition of the magnetic fields in the legs is desired, the core can be shaped like the one 190 shown in figure 19. This core is made up of three rings 194a-c to the left in the figure, three lower rings 193a-c and five rings 192a-e to the right in the figure. The rings shown in figure 19 are described in the tables 1-3 below.

TABLE 1

| Ring | Cross-section in leg 196 | Cross-section in leg 195 | Remarks |
|---|---|---|---|
| 192a | rhombic 30° outwards | rectangular | |
| 192b | rectangular | rectangular | Displaced 0.866 of width inwards Located on 192a |
| 192c | rectangular | rhomboidal 60° outwards expanded 30° outwards | Located outside of 192a |
| 192d | rhomboidal 60° inwards plane | rhomboidal 60° outwards expanded 30° outwards | Located on 192c and outside of 192b |
| 192e | rhomboidal 60° inwards | rhombic 30° outwards | Displaced 0.616 of width inwards Located on 192b and 192d |

TABLE 2

| Ring | Cross-section | Remarks |
|---|---|---|
| 193a | quadratic | |
| 193b | rhombic 60° outwards | outside of 193a |
| 193c | rhombic 30° outwards | on 193a and 193b |

TABLE 3

| Ring | Cross-section | Remarks |
|---|---|---|
| 194a | rhombic 30° outwards | |
| 194b | quadratic | on 194a |
| 194c | rhombic 60° inwards | on 194b |

**[0066]** The magnetic field can now pass between rhomb and square and square and rhomb, respectively.
**[0067]** In an embodiment not shown in the figures, legs with twelve edges and angles of 60° and 12° are used.
**[0068]** The cross-sectional areas of polygons compared with the circumscribed circle and the hexagons are given in table 4 below:

TABLE 4

| Shape of cross-section | Relative cross-sectional area | Comparison with a circle | Comparison with a hexagon |
|---|---|---|---|
| Circle | 3.1416 | 100 | 120.9 |
| Dodecagon | 3 | 95.5 | 115.5 |
| Decagon | 2.9389 | 93.5 | 113.1 |
| Octagon | 2.8284 | 90.0 | 108.9 |
| Hexagon | 2.5981 | 82.7 | 100 |
| Duo-decagon 60 and 12° | 2.5582 | 81.4 | 98.5 |
| Duo-octagon 60 and 30° | 2.5176 | 80.1 | 96.9 |
| Square | 2 | 63.6 | 77 |

**[0069]** With angles other than 60 and 30° are chosen in a duo-octagon, the comparison value will be between 96,9% and 108,9%.
**[0070]** Yet another embodiments are shown in figures 20a and 20b. The legs shown in figures 20a and 20b are essentially elliptical octagons, i.e., the cross-section can be inscribed in an ellipse. In figure 20a, the cross-section of each leg is a polygon essentially inscribed in an ellipse with the major axis radially out from the centre line of the core. In figure 20b, the cross-section of each leg is a polygon essentially inscribed in an ellipse with the minor axis radially out from the centre line of the core.
**[0071]** The magnetic field can to a large extent pass from one yoke to another in the legs.
**[0072]** In the embodiments described with reference to figures 18-20, the positions of the corners of each leg can be described as being essentially positioned on an imaginary generalised circle defined by orthogonal co-ordinates x and y according to the following formula:

$$(x/a)^n + (y/b)^n = 1$$

wherein a and b are positive numbers and n is a positive number # 2.

**[0073]** An embodiment with improved magnetic flux will now be described with reference to figure 21a, which is a cross-sectional view and 21b, which is an end view showing a yoke part of a transformer core 210.

**[0074]** Three rings 212a, 213a and 214a are given a rhombic cross-section with an inner angle of 60°. They can then be assembled to triangular yokes and legs with five of the edges of hexagons.

**[0075]** Six thin narrow rings 212b,c, 213b,c and 214b,c are assembled outside of the rings 212a, 213a, 214a as shown in figure 21a. This gives an end view of the yoke part as shown in figure 21b. However, the bends can deviate slightly from those shown in the figure.

**[0076]** The magnetic flux now can go in all rings from one yoke to another.

**[0077]** Smoothing of the edges of the legs of the core provides for a smaller play between the core and the rotating bobbin because higher accuracy can be easily achieved during manufacturing. This in turn increases the space for the windings and decreases the load losses. The flow density in the yokes decreases slightly but is still an advantage.

**[0078]** Some of the advantages of the inventive transformer core have already been mentioned. Among the other advantages can be mentioned: lower no load losses, less weight, less volume, lower electrical leakage, a reduction of harmonics due to the symmetry of the phases of the three-phase transformer, easy maintenance etc.

**[0079]** Another embodiment of a three-phase transformer core according to the invention is shown in Fig. 22, which is a combination of the embodiments shown in Figs. 17 and 21 a, b. It shows how a three-phase transformer core which has had rings added can also help cooling the transformer. When putting rings on the legs to make its legs more rounded, one can also let strips transfer heat to the air by connecting these rings at the top and/or bottom of the transformer to a radiator/cooler of strips as shown in Fig. 22.

**[0080]** The core 220 can be provided with windings with segment strips using the principle of Fig. 17 using strips for filling the segments, but also filling the adjacent segments. The ends of a pair of segment strips 221 and 222 are when necessary bent upwards for cooling and also bent downwards at the bottom. A strip of ferromagnetic material is closely wound to a cooling ring 223 at the top of the core. The ends of the segment strips 221 and 222 are spliced and connected to the strips 224, 225 in the cooling ring 223. Now both magnetic flux and heat are transferred.

**[0081]** Often the transformer is placed within a container 227. Sometimes the transformer is so hot that the container must be protected from the heat.

**[0082]** Because the inventive cores are very silent, they can be connected by means of a heat transferring material 226 to the container 227 or part of it. This is of interest because the resistance increases with temperature and the power losses increase as well. The transfer of noise from the core will be reduced by bends on the material, e.g. aluminum plate.

**[0083]** Also the ends of a set of wires or foils 228 from the windings, especially from a low voltage coil, can with advantage be attached to a cooling device 229, e.g. a body cooled by water circulating within it via pipes 229a.

**[0084]** Another three-phase transformer core is shown in Fig. 23, and identified by the numeral 230. Transformer core 230 is shown as a top view in Fig. 23 wherein tree yokes are visible. A cross-section of core 230 is shown in Fig. 23a, which also shows the core, and the frames, in exploded form. Core 230 has three frames 232, 233 and 234. It can be seen that frames 232-234 are different from each other, but this may be better for large transformers for reducing the strain on the core. Frames 232-234 together form legs 235, 236 and 237. Considering the view shown in the centre portion of Fig. 23a and the exploded portion showing frame 232, it can be seen that the latter includes a basic broad, thick ring 232a, and a narrow thick ring 232b. Frame 233 is composed of a narrow thick ring 233a, another narrow thick ring 233b, a narrow thin ring 233c and another narrow thin ring 233d.

**[0085]** Finally, considering frame 234, it can be seen that this leg includes a broad, thick ring 234a and a narrow, thick ring 234b.

**[0086]** Transformer core 230 is composed of a set of rings, all of which are made from transformer plate of one width for each ring, combined in such a manner as to provide the desired legs with a hexagon cross-section in each leg. The construction of core 230 is different from other cores described earlier having hexagon cross-sections, but they all can be made using conventional manufacturing techniques with transformer plate of one width, namely broad or narrow.

**[0087]** One would not expect that the provision of more rings in a transformer core could give simpler and better solutions to the problems noted earlier. A three-phase core with its legs in a row is relatively easy to assemble with octagonal legs, so one would not strive to make hexagonal legs. Single-frame cores can advantageously be made with decagonal legs. There are many decagons with inscribed rhombs. One of the decagons has the advantage that all but one of the rings for filling the rhombs have their axes in the three directions deviating with a minimum angle of 36°. A shell core 240 is shown in Fig. 24. It has rings providing in the cross section of shell core 240 rhombs 241a-j.

**[0088]** By bending the yokes of core 240 shown in Fig. 24, a frame core 250 is obtained and shown in Fig. 25. Rings can be wound with the distance between the turns so that air can pass through it. The rhombs within the leg innermost is a rhomb with an angle of 72°. The rhombs are in layers with the number of rhombs from innermost 4,3,2,1. They are marked from left to right 251c, 251b, 251a, 251j. In second row they are 251d, 251f, 251i. In third row they are 251e and 251h. Last is a rhomb marked 251g. In the first layer, the rhombs have all sides with the angle 72°. In the second layer, the rhombs have all sides with the angle 108°. In the third layer the rhombs have all sides with the angle 36°. In the fourth layer the rhomb has all sides with the angle 144°. This shows the systematic shape of this decagon with inscribed rhombs. The circle is so effectively filled that ring 251c could be omitted. A ring 252 having strongly turned out legs is especially good with respect to cooling because the yokes are also turned, so that air can rise when it passes between the strips. The foregoing tells us how to find the best shape of dodecagon etc. with inscribed rhombs. First the corresponding shell core was shown in Fig. 24. The rings need not have their frames or leg parts turned or yoke parts bent and were shown in Fig. 25. The surface of the strips with the air will be very large.

**[0089]** Some of the advantages of the inventive transformer core have already been mentioned. Among the other advantages the following can be mentioned: lower no load losses, less weight, less volume, lower electrical leakage, a reduction of the harmonics due to the symmetry of the phases of the three-phase transformer, easy maintenance etc. The mechanical stability of all of the cores can be improved by modifications to the cores to provide places for rings with octagonal legs as well as hexagonal, decagonal and other legs. The inventive core is insensitive to rough handling, as would occur during transport. It embodiment with interlocking frames are self-supporting. The weight saving over corresponding cores is very significant, amounting to about 40%; this is significant for large transformers whose weight is several tons. Transportation is facilitated in that the frames can be transported independently of each other.

**[0090]** Referring next to Fig. 26, an inductor core according to the invention is shown. It can be seen that this inductor core has a construction very similar to the transformer core 20 shown in Fig. 2. However, the inductor, identified by the numeral 260, has a pair of air gaps extending through each leg. Thus, inductor 260 includes three legs 265, 266 and 267, each having as a cross-section a hexagon as that shown in transformer core 20 in Fig. 2. Each leg has a pair of air gaps identified as 265a, 265b for leg 265, air spaces 266a and 266b for leg 266, and air gaps 267a and 267b for leg 267.

**[0091]** The hexagonal legs 265-267 could be replaced with cylindrical legs 270 shown in Fig. 27. Each leg 270 is divided into two parts 271a, 271b having an air space 272 between them. Air spaces separate the opposite ends of leg 270 from the yokes of inductor 260.

**[0092]** The concept of the present invention can be used to provide legs of various cross sections, such as to fit into conductor coils having round or elliptical shapes, where the cross section approaches such shapes. These are shown in Figs. 28a-28w. Fig. 28a is a quadrate 601. Fig. 28b depicts a hexagon with three rhombs. Fig. 28c shows an octagon with six rhombs. Fig. 28d illustrates a decagon having ten rhombs. Another possibility is shown in Fig. 28q, where there is a decagon with ten rhombs, having no new rhombs created but are rather redistributed. Figs. 28r through 28u are other examples of decagons. Figs. 28h and 28i show the octagon in Fig. 28c from two different corners. Figs. 28j and 28k show the octagon of fig. 28c from different sides. Fig. 28l depicts the octagon of fig. 28c from a different direction. Figs. 28m through 28n show that it is possible to alter rhomboids to rhombs in hexagons.

**[0093]** Fig. 28v illustrates that it is possible to inscribe rhombs in an ellipse. A contour which can be divided into two curves, one with a 180° rotation with respect to the other curve, can have rhombs inscribed within it. Polygons with less number of sides will appear inside the original polygon. They can be mirrored or rotated 180° and make it possible to redistribute the rhombs. A rotated hexagon is marked with a circle in Fig. 28w. Of course, matched irregular contours can circumscribe any form of collection of rhombs.

**[0094]** A three-phase transformer or inductor 290 according to the invention is shown in Fig. 29. It includes a three-phase transformer or inductor core 292 as discussed earlier. Transformer or inductor 290 includes a winding assembly 294 and operates in the conventional manner, but having improved operating capabilities due to the core.

**[0095]** Preferred embodiments of a transformer core according the invention have been described. The person skilled in the art realises that these can be varied within the scope of the claims. Thus, the cross-section of the legs can be built up in many ways, comprising many combination of rhombs, rhomboids, squares and/or rectangles.

## Claims

1. A core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) for a transformer or an inductor comprising three legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) and at least one yoke part, wherein said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) have a cross-sectional shape that is multi-sided with more than four sides with intermediate corners, **characterised in that**

   - said core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) is made up of rings (22a-24a, 23b, 23c, 32a-c, 42a-c, 43a-c, 44a-c, 50a-e, 60a-g, 112a-c, 114a-c, 192a-e, 193a-c, 194a-c, 212a-c, 213a-c, 214a-c) rolled, from strips of constant width, and

- said corners are positioned on a generalised circle, approaching round or elliptical shape, as defined by orthogonal co-ordinates x and y according to the following formula:

$$(x/a)^n + (y/b)^n = 1$$

wherein a and b are positive numbers and n is a positive number ≠ 2.

2. The core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) according to claim 1, **characterised in that** every other angle between adjacent edges is 30° and the other angles are 60°.

3. The core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) according to claim 1 or 2, **characterised in that** n is 1.52.

4. The core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) according to any of claims 1-3, **characterised in that** the cross-section of said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) is a polygon inscribed in an ellipse with a major axis radially out from the centre line of the core.

5. The core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) according to any of claims 1-3, **characterised in that** the cross-section of said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) is a polygon inscribed in an ellipse with a minor axis radially out from the centre line of the core.

6. A transformer (290) comprising a core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) as claimed in any of claims 1-5, said core comprising three legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) and yoke parts interconnecting said legs, said transformer further comprising a winding arrangement, and wherein each of said rings make up part of two of said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) and interconnecting yokes.

7. An inductor (260, 292) comprising a core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) as claimed in any of claims 1-5, and a winding arrangement, wherein said core (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) comprises three legs and yoke parts interconnecting said legs, and each of said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) has an air gap (265a, 265b, 266a, 266b, 267a, 267b) and a cross-sectional shape that is multi-sided with more than four sides with intermediate corners,
**characterised in that**

- said core is made up of rings rolled from strips of constant width, each of said rings making up part of two of said legs (25-27, 35-37, 45-47, 235-237, 265-267, 270) and interconnecting yokes.

## Patentansprüche

1. Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) für einen Transformator oder eine Induktionsspule mit drei Schenkeln (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) und mindestens eine Jochteil, wobei die Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) eine Querschnittsform haben, die mehrseitig ist, wobei mehr als vier Seiten Zwischenecken aufweisen,
**dadurch gekennzeichnet, dass**

- der Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) aus Ringen (22a - 24a, 23b, 23c, 32a-c, 42a-c, 43a-c, 44a-c, 50a-e, 60a-g, 112a-c, 114a-c, 192a-e, 193a-c, 194a-c, 212a-c, 213a-c, 214a-c) besteht, die aus Streifen konstanter Breite aufgewickelt sind, und
- die Ecken auf einem verallgemeinerten Kreis positioniert sind und sich einer runden oder elliptischen Form nähern, wie durch orthogonale Koordinaten x und y gemäß der folgenden Formel definiert:

$$(x/a)^n + (y/b)^n = 1$$

wobei a und b positive Zahlen sind und n eine positive Zahl ≠ 2 ist.

2. Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach Anspruch 1, **dadurch gekennzeichnet, dass** jeder zweite Winkel zwischen benachbarten Rändern 30° beträgt und die anderen Winkel 60° betragen.

3. Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach Anspruch 1 oder 2, **dadurch gekennzeichnet, dass** n 1,52 ist.

4. Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach einem der Ansprüche 1 - 3, **dadurch gekennzeichnet, dass** der Querschnitt der Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) ein in einer Ellipse einbeschriebenes Polygon mit einer radial aus der Mittellinie des Kerns heraus verlaufenden Hauptachse ist.

5. Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach einem der Ansprüche 1 - 3, **dadurch gekennzeichnet, dass** der Querschnitt der Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) ein in einer Ellipse einbeschriebenes Polygon mit einer radial aus der Mittellinie des Kerns heraus verlaufenden Nebenachse ist.

6. Transformator (290), der einen Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach einem der Ansprüche 1 - 5 umfasst, wobei der Kern drei Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) und die Schenkel verbindende Jochteile umfasst, wobei der Transformator weiterhin eine Wickelanordnung umfasst und wobei jeder der Ringe einen Teil von zwei der Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) und Verbindungsjoche bildet.

7. Induktionsspule (260, 292) mit einem Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) nach einem der Ansprüche 1 - 5 und einer Wickelanordnung, wobei der Kern (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) drei Schenkel und die Schenkel verbindende Jochteile umfasst und jeder der Schenkel (25 - 27, 35 - 37, 45 - 47, 235- 237, 265 - 267, 270) einen Luftspalt (265a, 265b, 266a, 266b, 267a, 267b) und eine Querschnittsform aufweist, die mehrseitig ist, wobei mehr als vier Seiten Zwischenecken aufweisen,
**dadurch gekennzeichnet, dass**

- der Kern aus Ringen besteht, die aus Streifen konstanter Breite aufgewickelt sind, wobei jeder der Ringe einen Teil von zwei der Schenkel (25 - 27, 35 - 37, 45 - 47, 235 - 237, 265 - 267, 270) und Zwischenjoche bildet.

## Revendications

1. Noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) pour un transformateur ou un inducteur comprenant trois pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) et au moins une partie de carcasse, lesdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) ayant une forme en section transversale qui possède plusieurs côtés avec plus de quatre côtés avec des coins intermédiaires,
**caractérisé en ce que**

- ledit noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) est constitué d'anneaux (22a-24a, 23b, 23c, 32a-c, 42a-c, 43a-c, 44a-c, 50a-e, 60a-g, 112a-c, 114a-c, 192a-e, 193a-c, 194a-c, 212a-c, 213a-c, 214a-c) enroulés à partir de bandes de largeur constante, et
- lesdits coins sont positionnés sur un cercle approximatif, s'approchant de la forme ronde ou elliptique, comme défini par des coordonnées orthogonales x et y, conformément à la formule suivante

$$(x/a)^n + (y/b)^n = 1,$$

a et b étant des nombres positifs et n étant un nombre positif différent de 2.

2. Noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon la revendication 1, **caractérisé en ce qu'**un angle sur deux entre des bords adjacents vaut 30° et les autres angles valent 60°.

3. Noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon la revendication 1 ou 2, **caractérisé en ce que** n vaut 1,52.

4. Noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon l'une quelconque des revendications 1 à 3, **caractérisé en ce que** la section transversale desdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) est un polygone inscrit dans une ellipse avec un grand axe radialement décentré par rapport à l'axe central du noyau.

5. Noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon l'une quelconque des revendications 1 à 3, **caractérisé en ce que** la section transversale desdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) est un polygone inscrit dans une ellipse avec un petit axe radialement décentré par rapport à l'axe central du noyau.

6. Transformateur (290) comprenant un noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon l'une quelconque des revendications 1 à 5, ledit noyau comprenant trois pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) et des parties de carcasse reliant entre elles lesdites pattes, ledit transformateur comprenant en outre un agencement d'enroulement, et chacun desdits anneaux constituant une partie de deux desdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) et carcasses d'interconnexion.

7. Inducteur (260, 292) comprenant un noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) selon l'une quelconque des revendications 1 à 5, et un agencement d'enroulement, ledit noyau (20, 30, 40, 50, 60, 210, 220, 230, 240, 250) comprenant trois pattes et des parties de carcasse reliant entre elles lesdites pattes, et chacune desdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) ayant un entrefer (265a, 265b, 266a, 266b, 267a, 267b) et une forme en section transversale qui a plusieurs côtés avec plus de quatre côtés avec des coins intermédiaires,
**caractérisé en ce que**

- ledit noyau est constitué d'anneaux enroulés à partir de bandes de largeur constante, chacun desdits anneaux constituant une partie de deux desdites pattes (25-27, 35-37, 45-47, 235-237, 265-267, 270) et carcasses d'interconnexion.

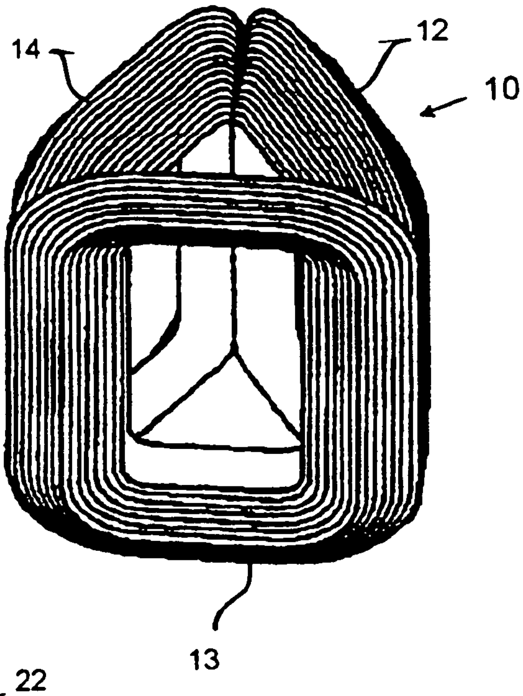



Fig. 1

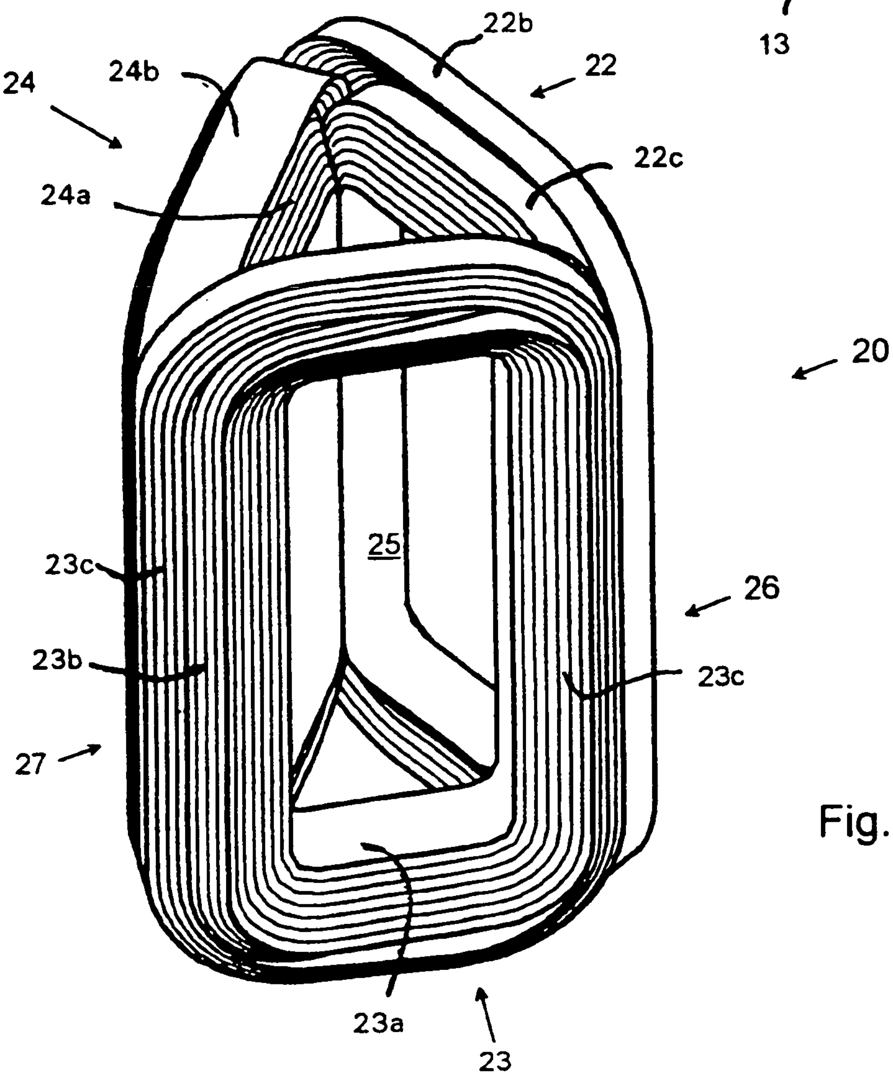



Fig. 2

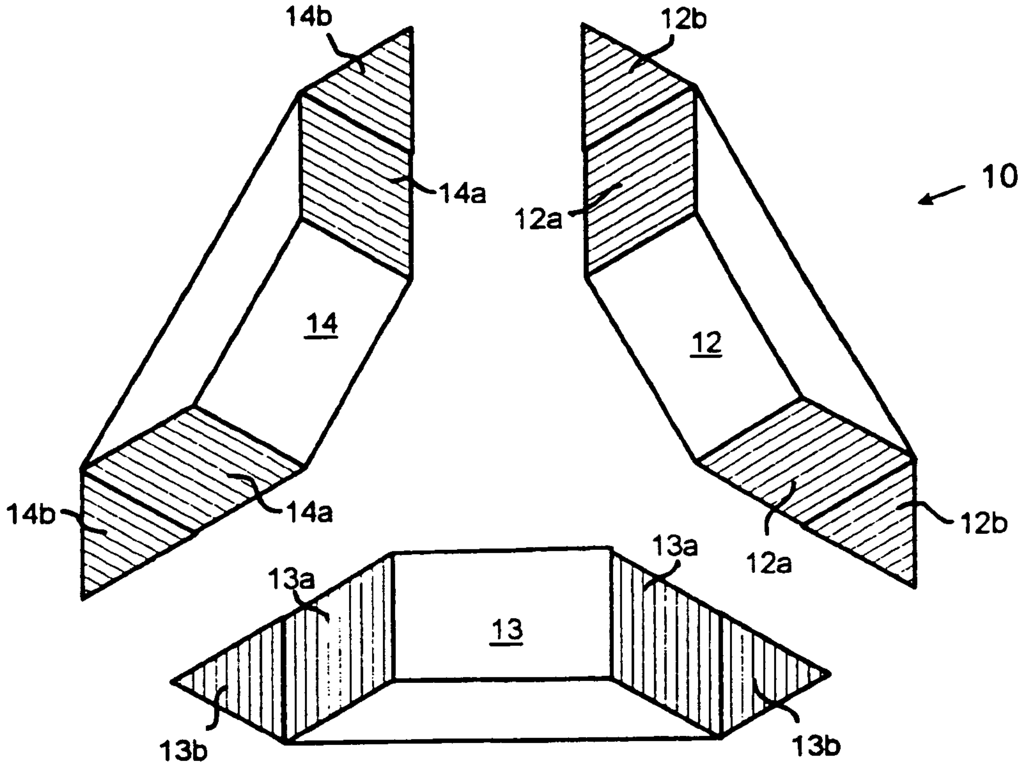

14b
14a
14
14b
14a
12b
12a
12
12b
12a
10
13a
13
13a
13b
13b

Fig. 1a

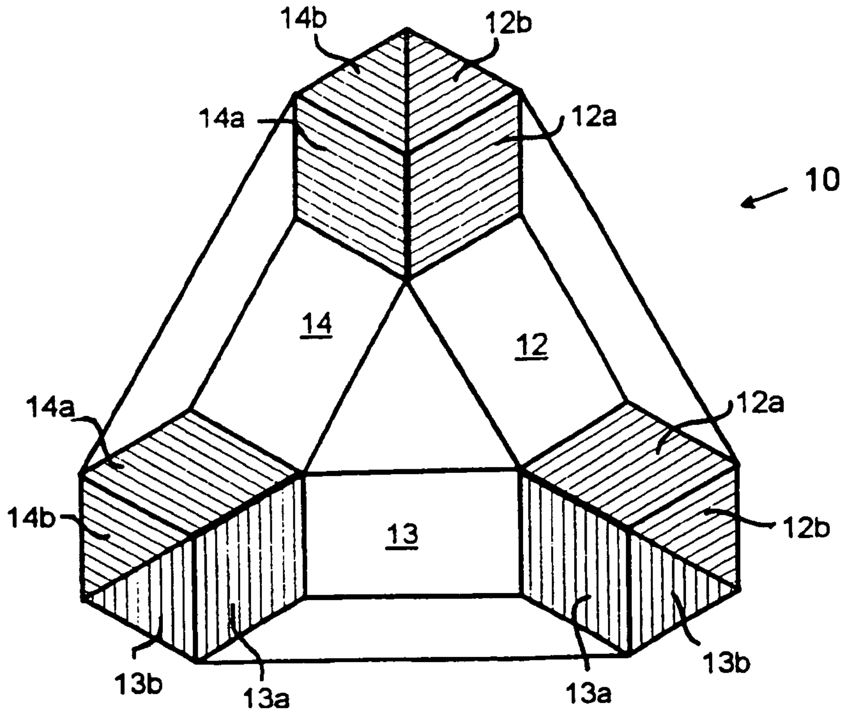
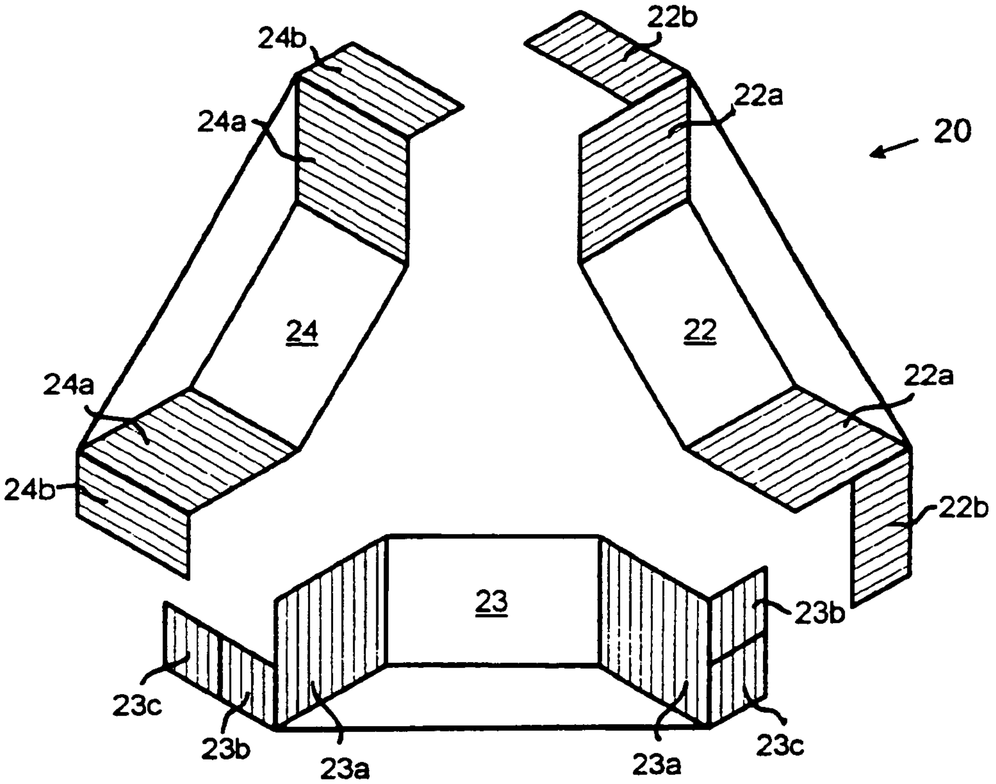
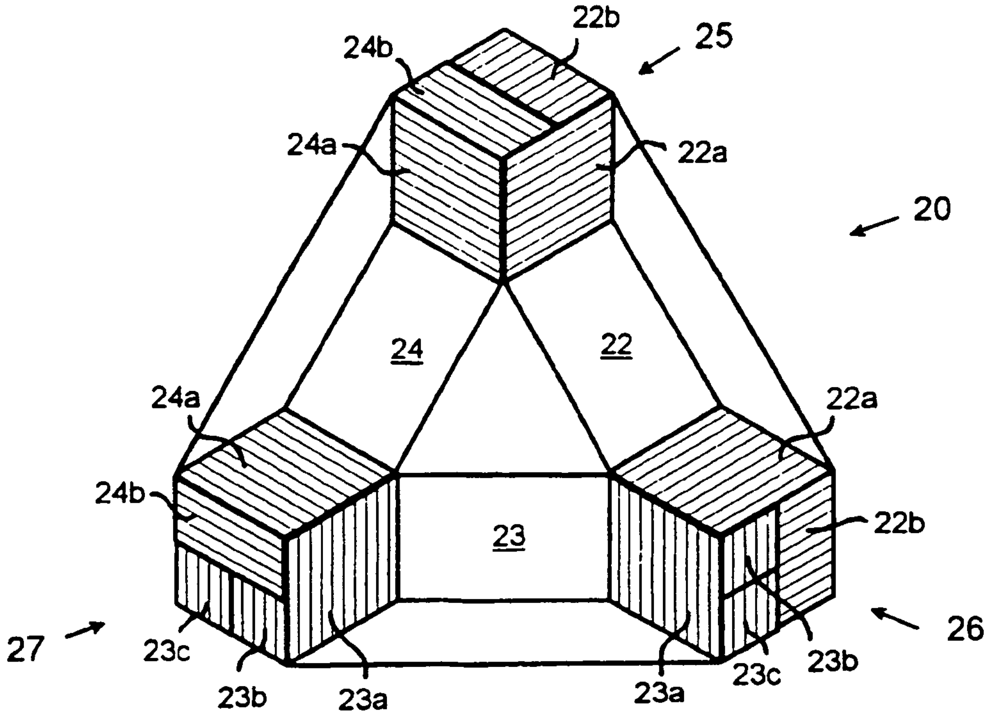

14b
12b
14a
12a
10
14
12
14a
12a
14b
13
12b
13b
13a
13a
13b

Fig. 1b



24b
24a
24
24a
24b
22b
22a
20
22
22a
22b
23
23b
23c
23b
23a
23a
23c


Fig. 2a



22b
25
24b
24a
22a
20
24
22
24a
22a
24b
23
22b
27
23c
23b
23a
23a
23c
23b
26


Fig. 2b

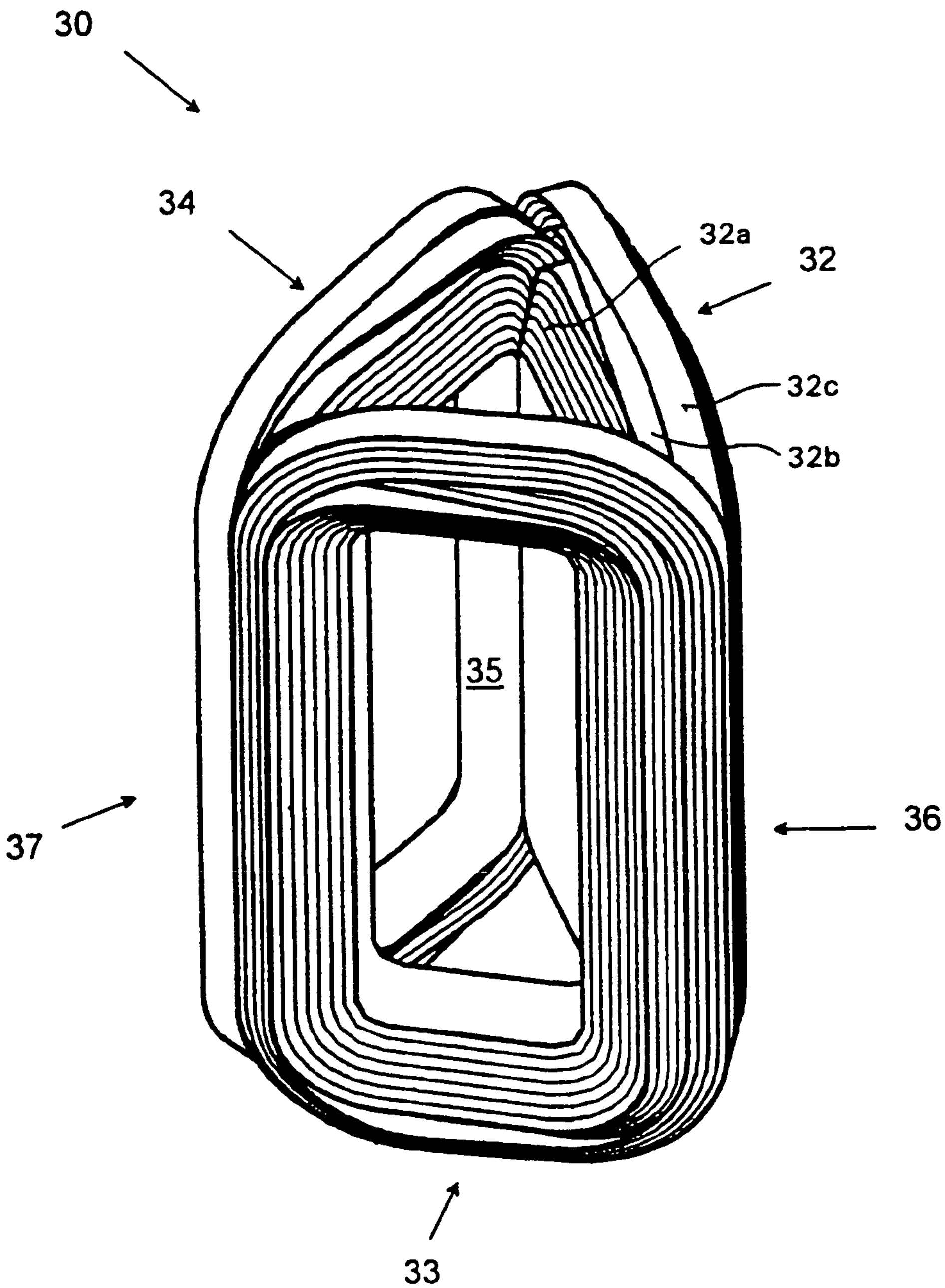
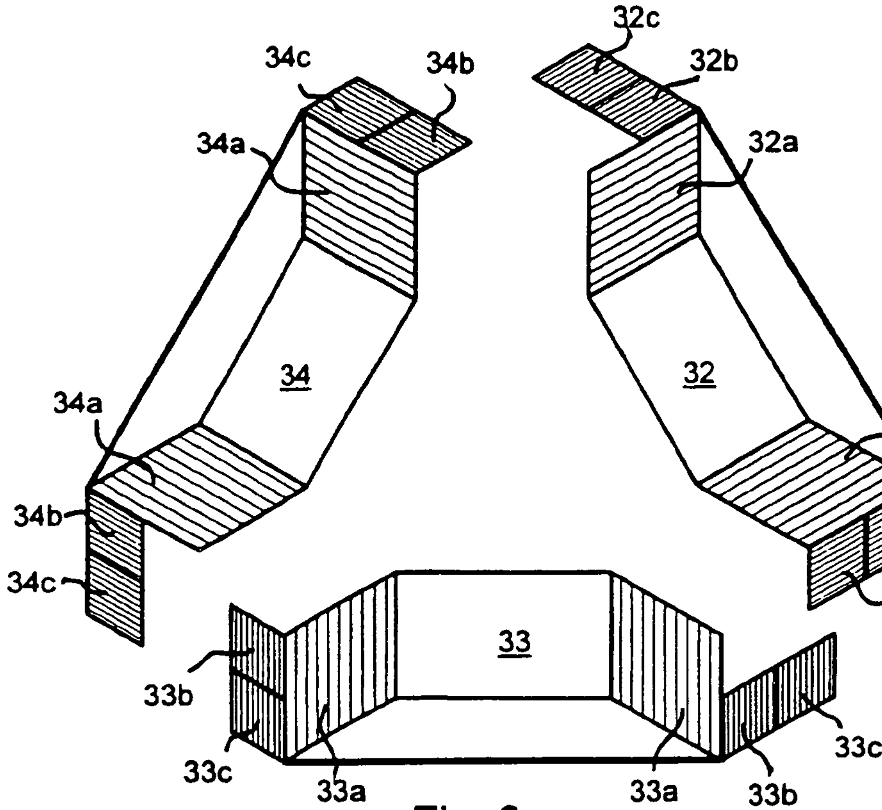



Fig. 3


32c
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34b
32b
34a
32a
34
32
34a
32a
34b
32c
34c
32b
33
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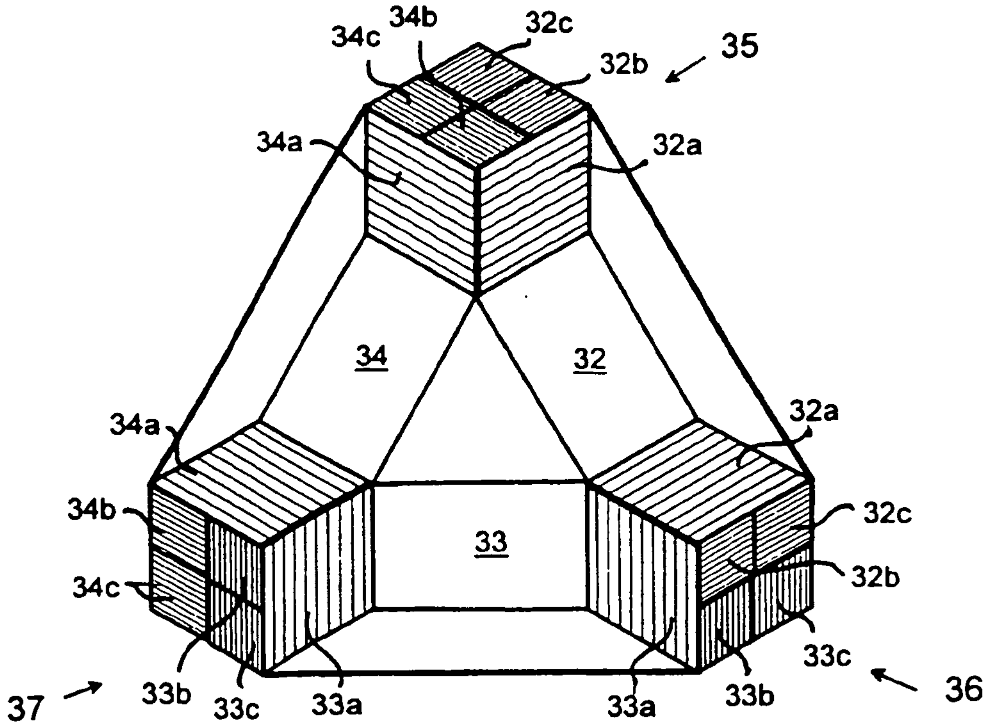
33a
33b

Fig. 3a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34c
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32b
34a
32a
34
32
34a
32a
34b
33
32c
34c
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33a
33b
36

Fig. 3b

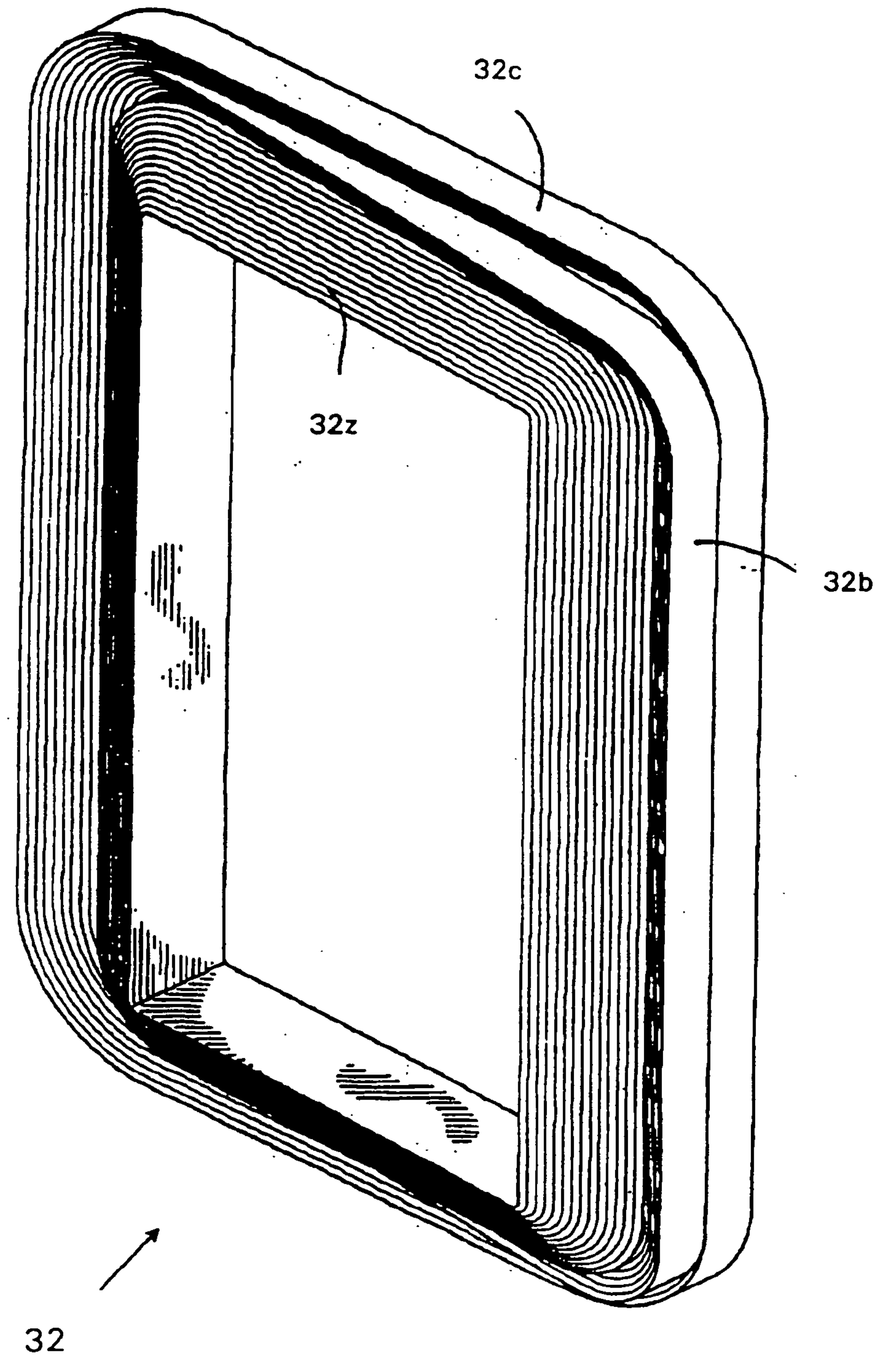



Fig. 3c

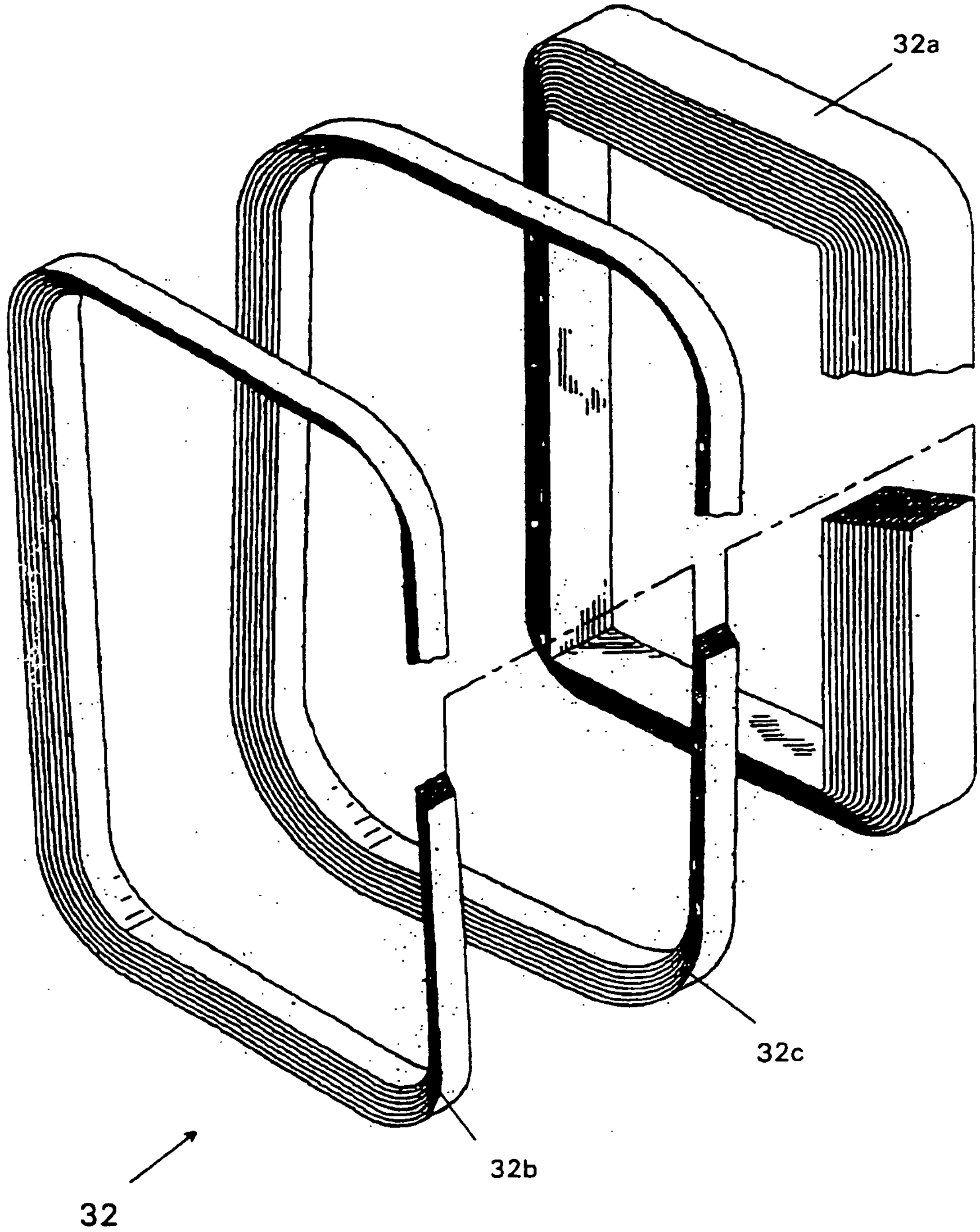



Fig. 3d

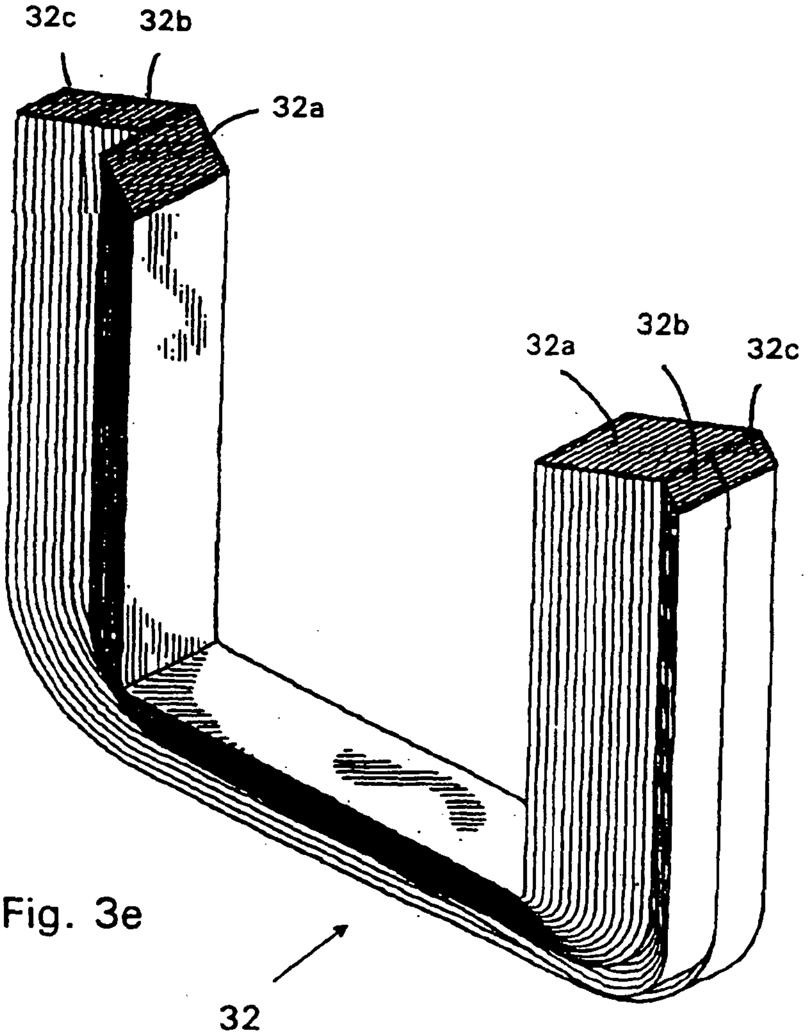



Fig. 3e

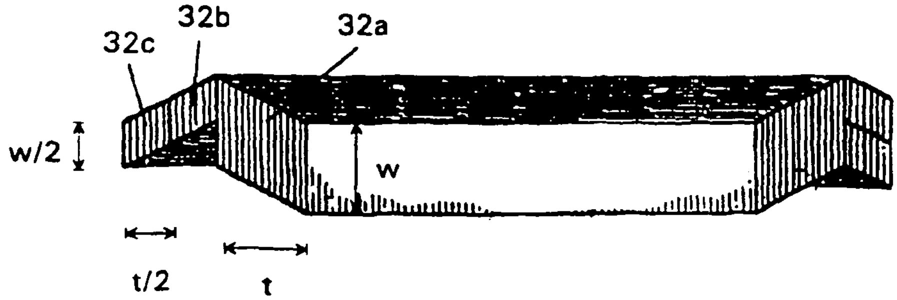



Fig. 3f

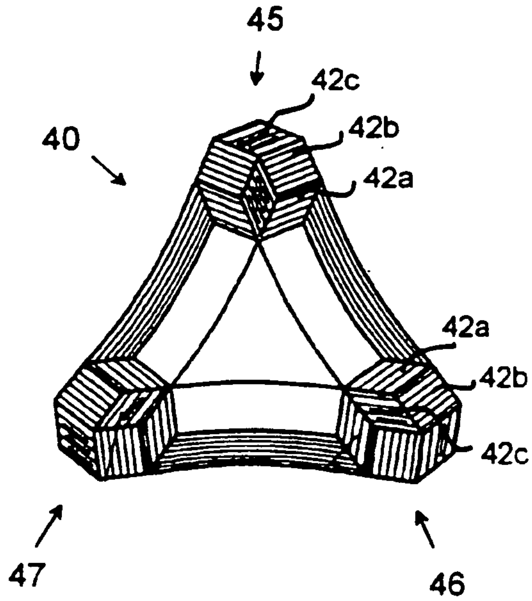



Fig. 4a

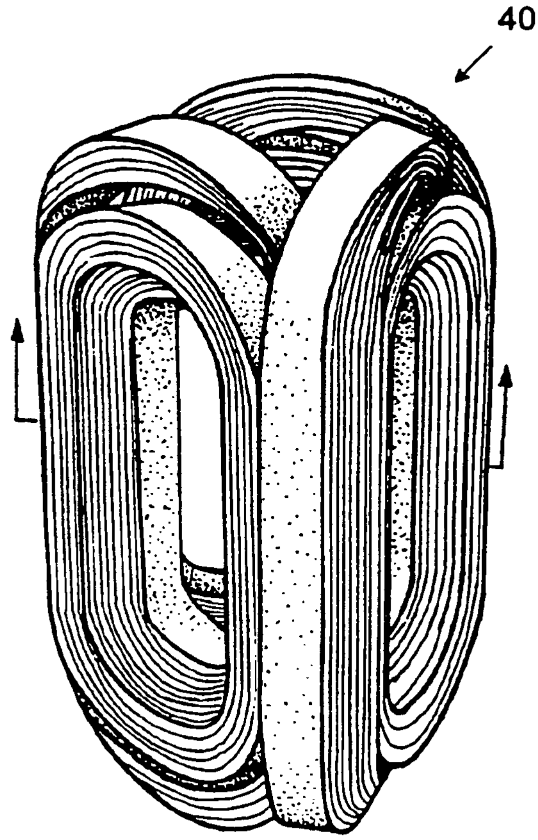



Fig. 4

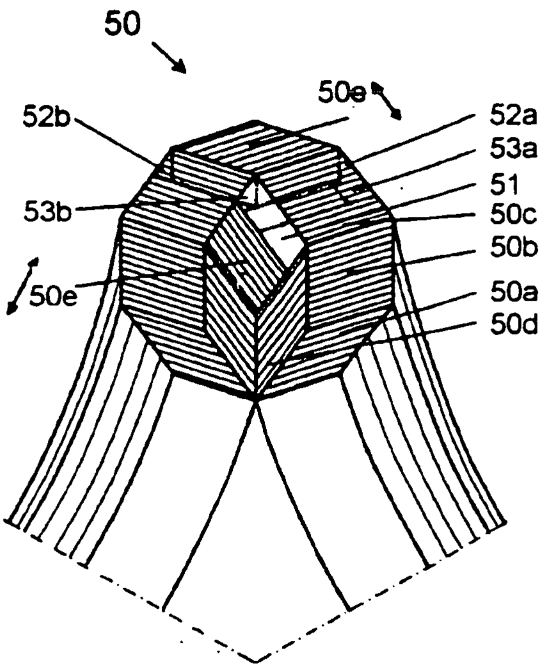



Fig. 5

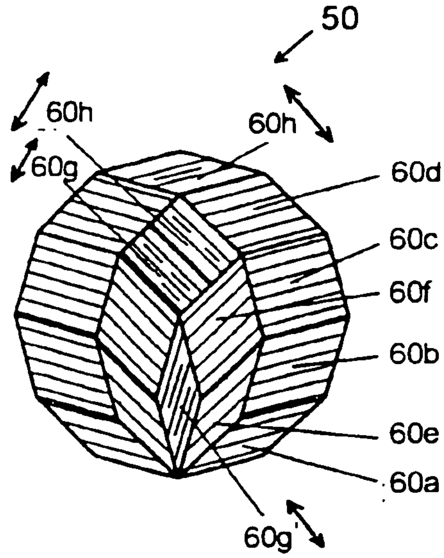



Fig. 6

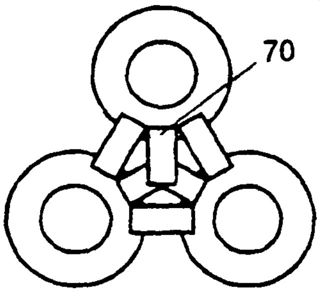



Fig. 7

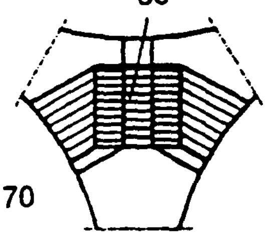
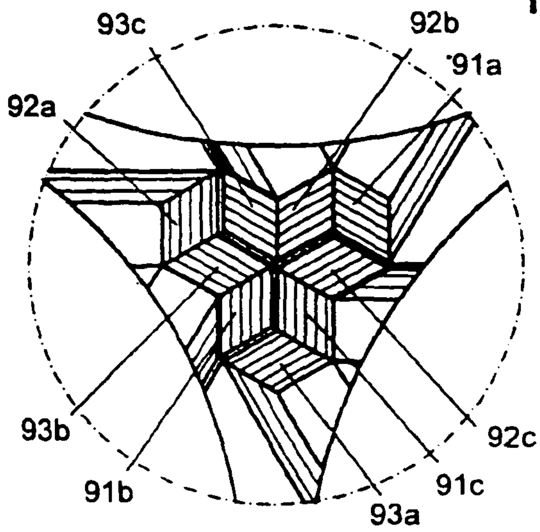



Fig. 8

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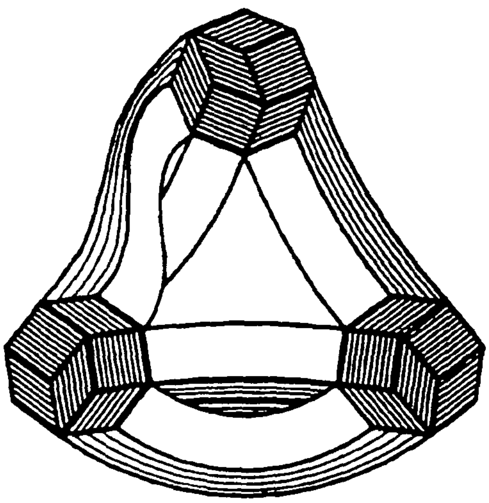
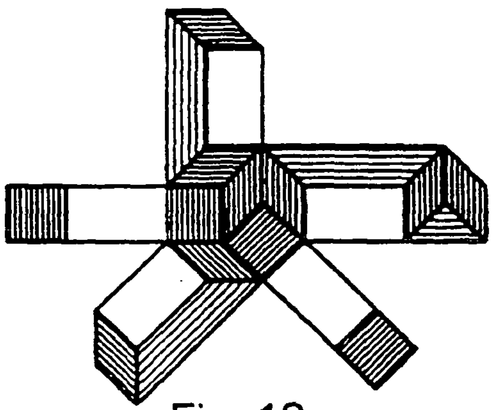


Fig. 10



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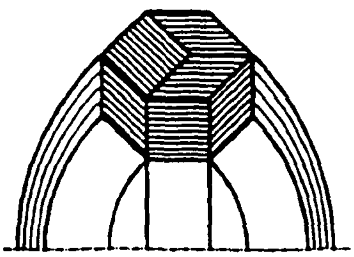


Fig. 13

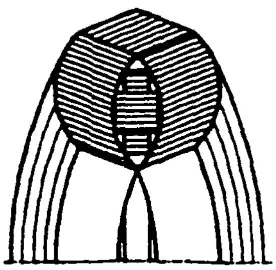


Fig. 14

Fig. 15

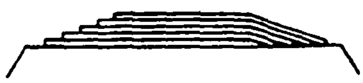


Fig. 16

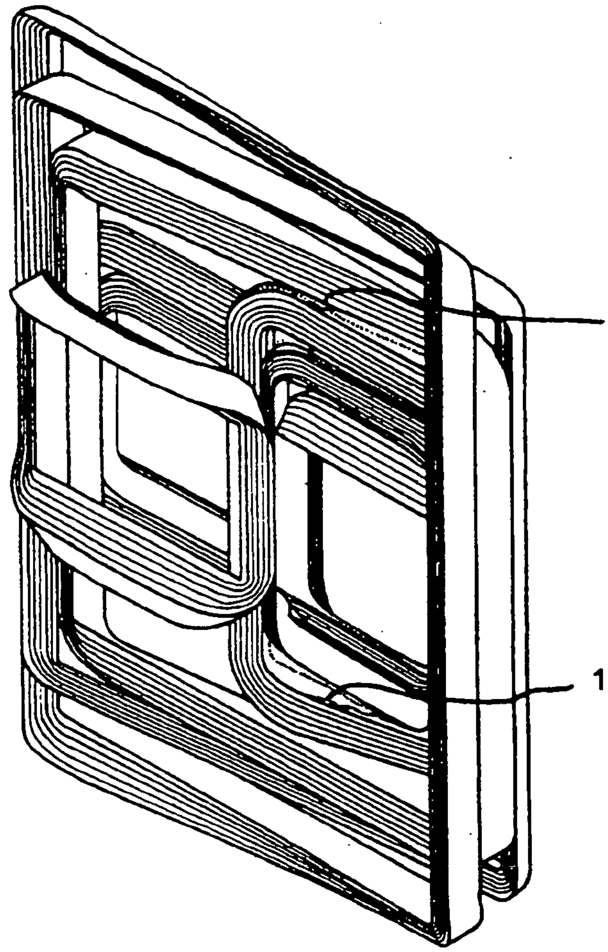



Fig. 11

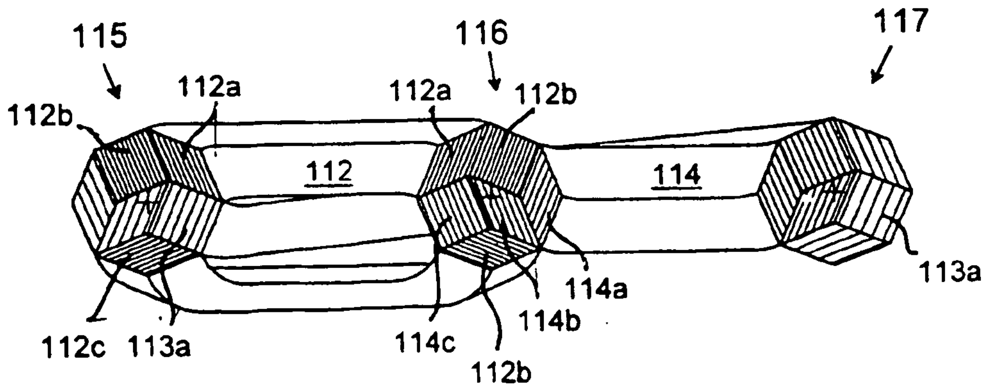



Fig. 11a

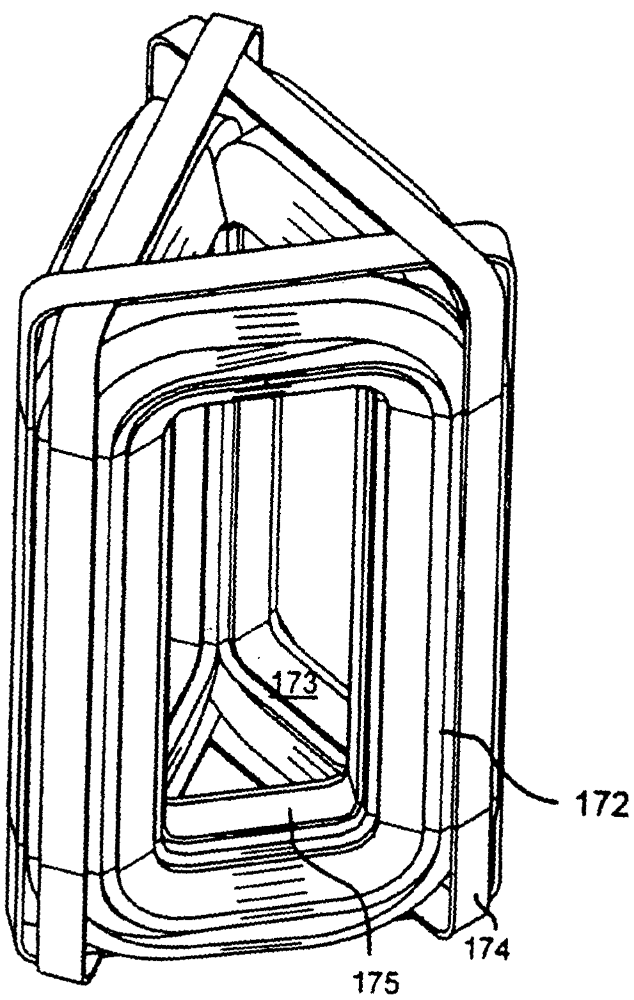



Fig. 17

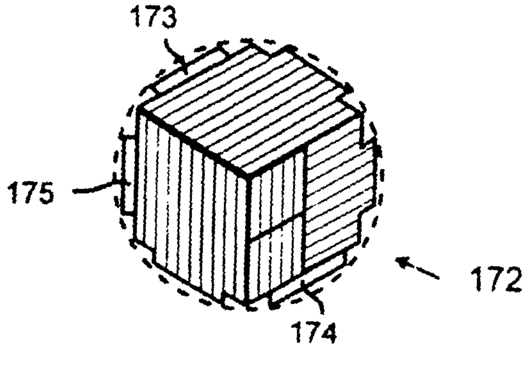



Fig. 17a

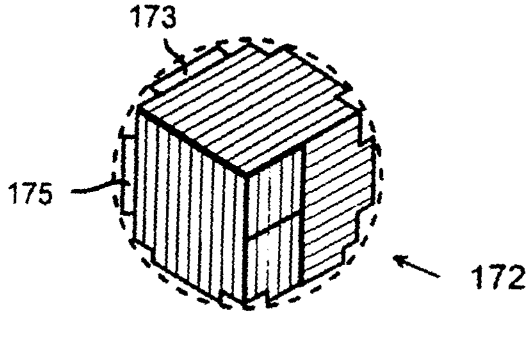
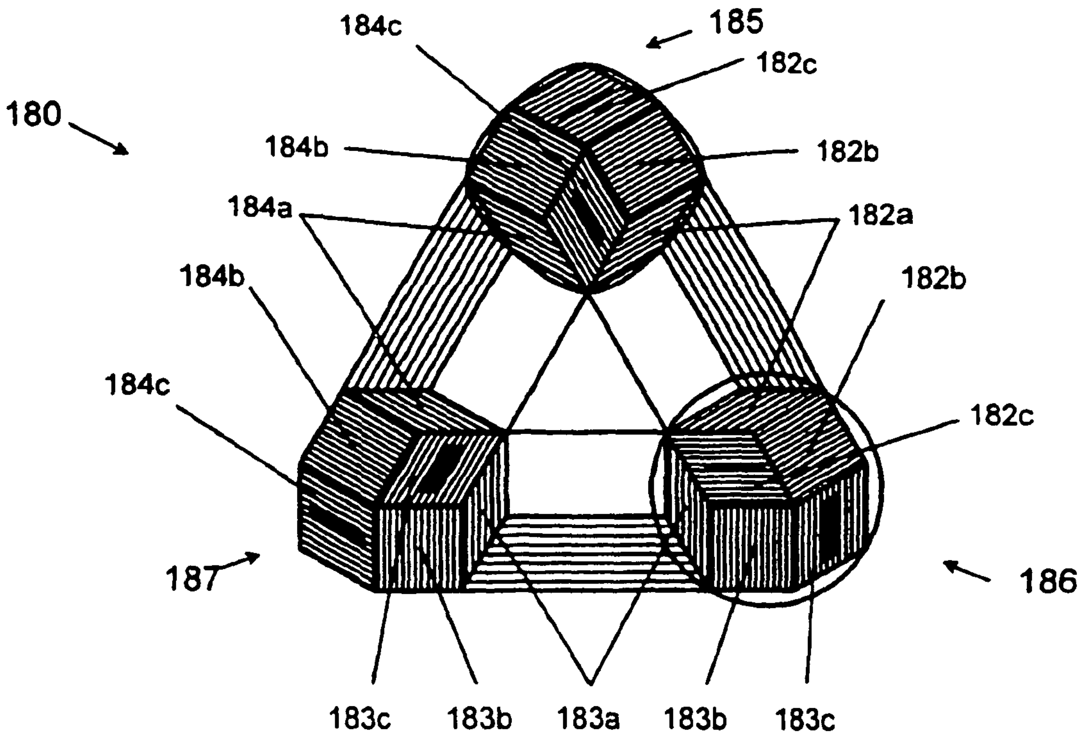



Fig. 17b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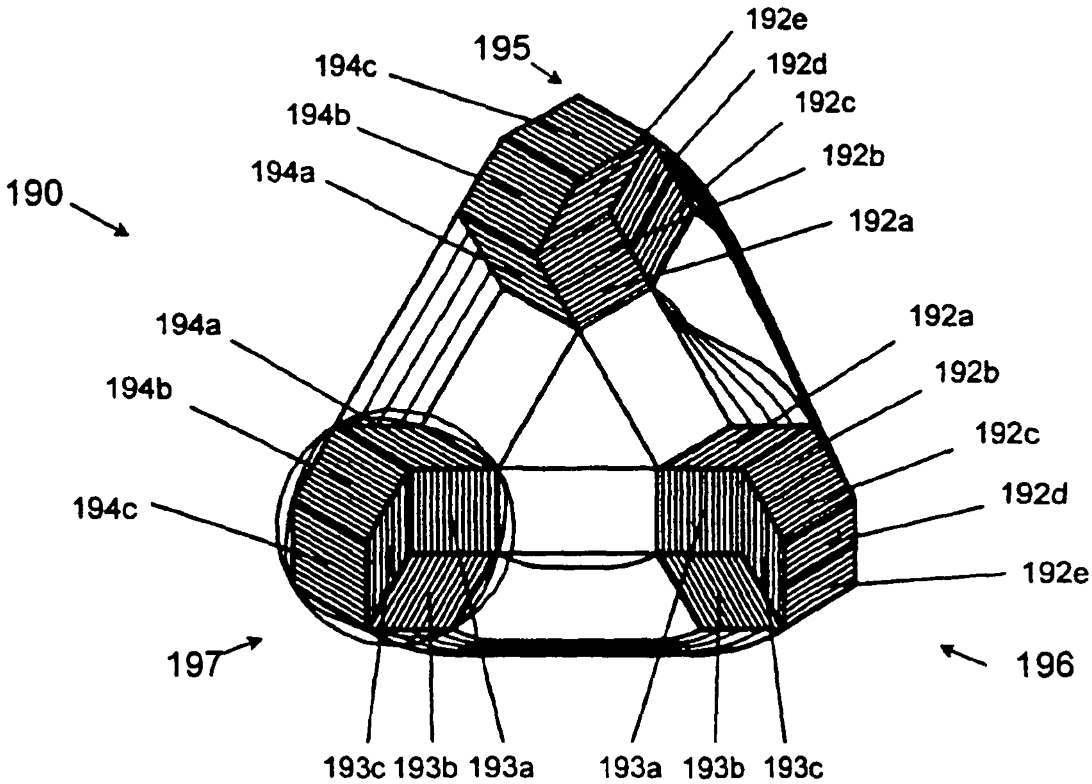
183b
183c

Fig. 18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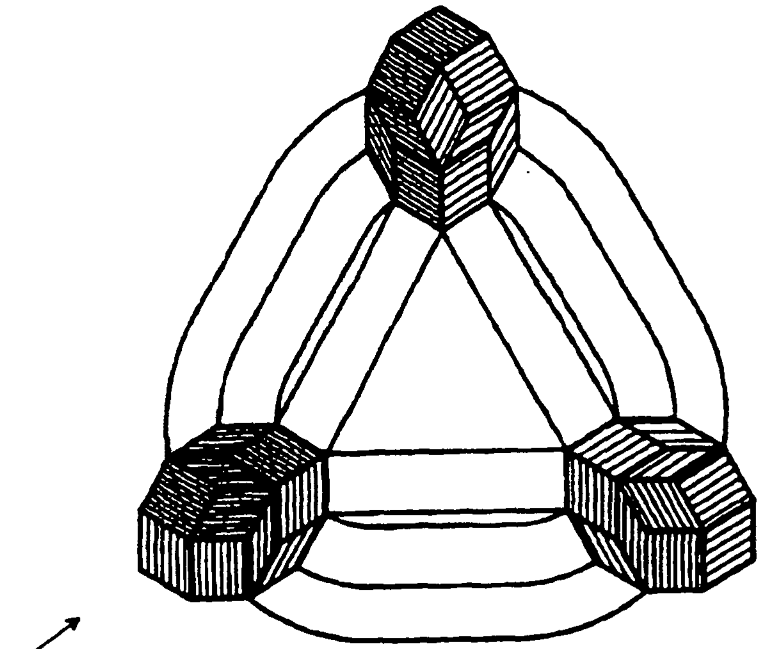
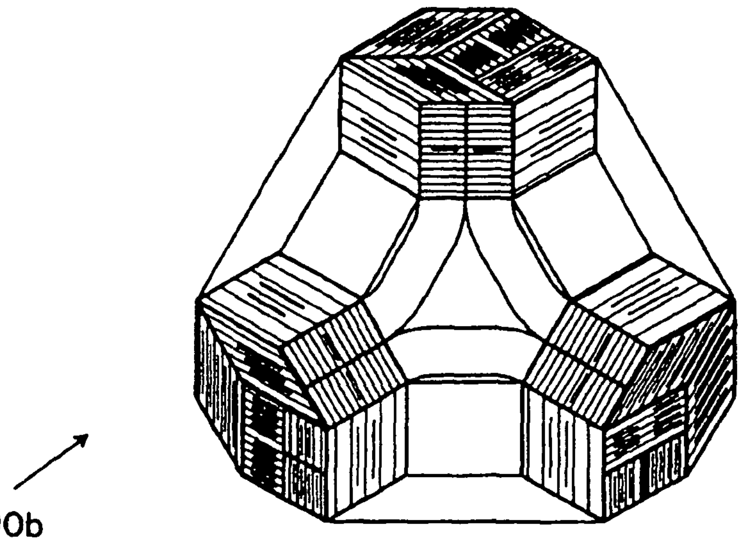
196
193c 193b 193a
193a 193b 193c

Fig. 19



200a

Fig. 20a



200b

Fig. 20b

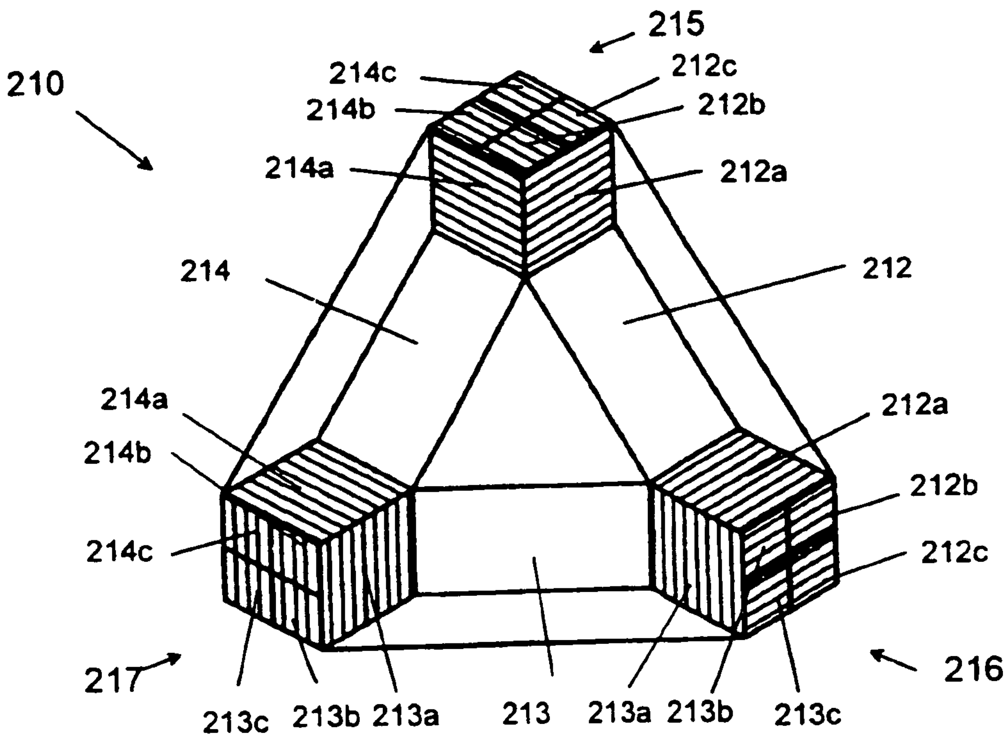


Fig. 21a

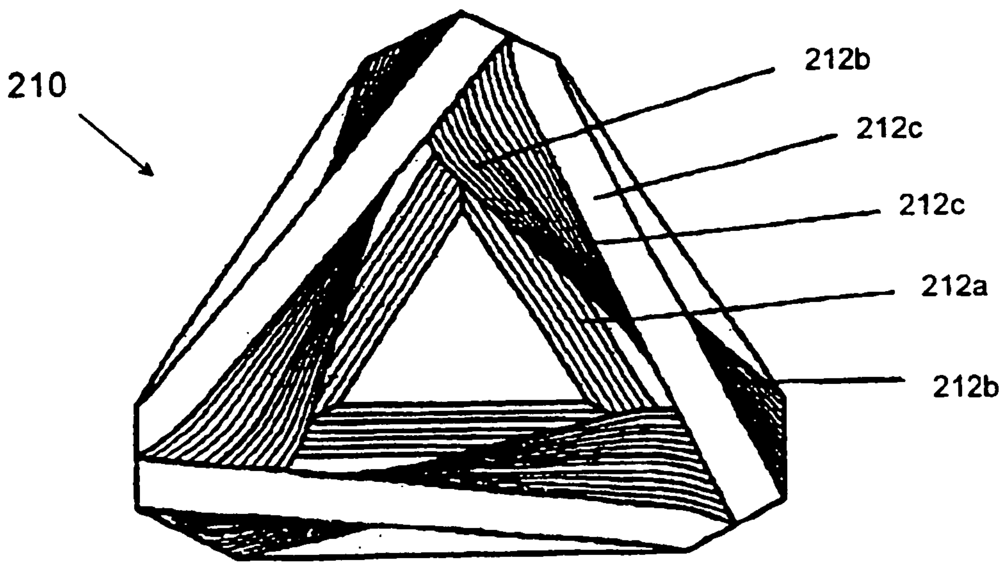


Fig. 21b

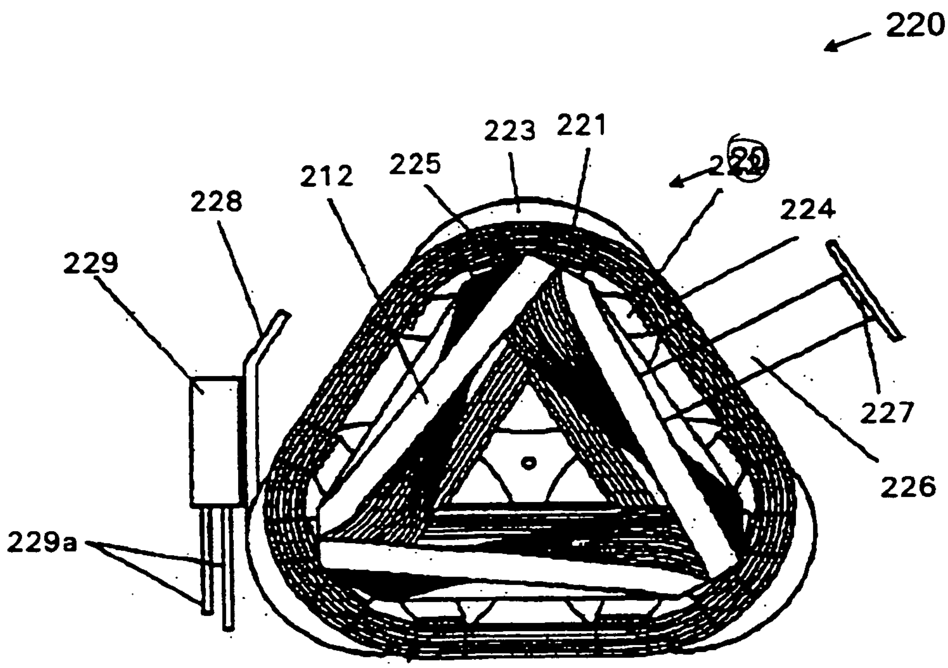



Fig. 22

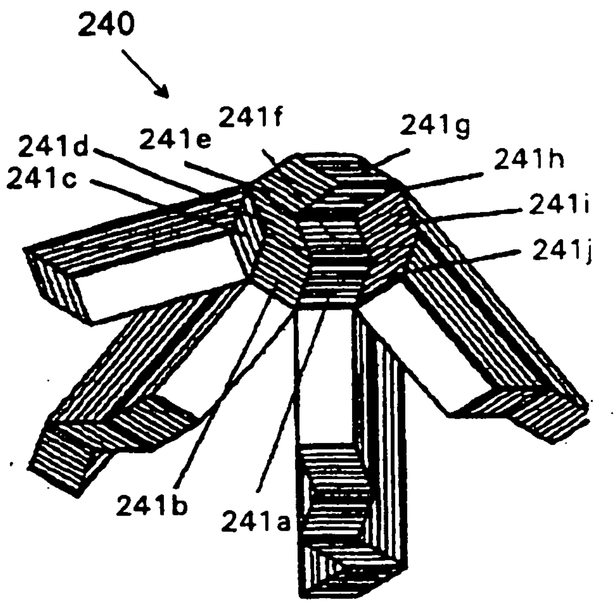



Fig. 24

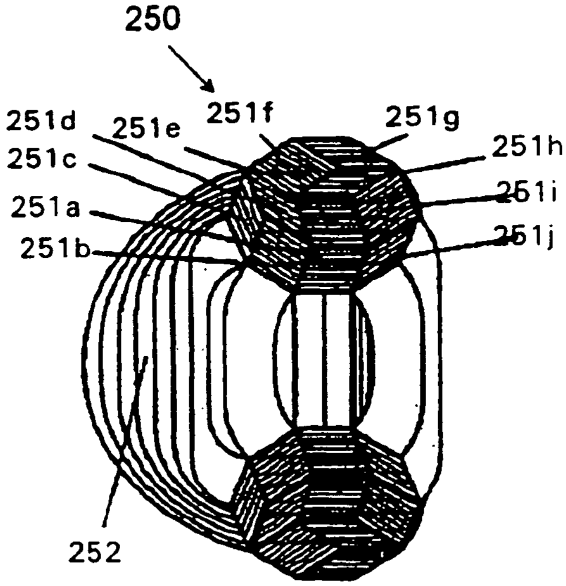



Fig. 25

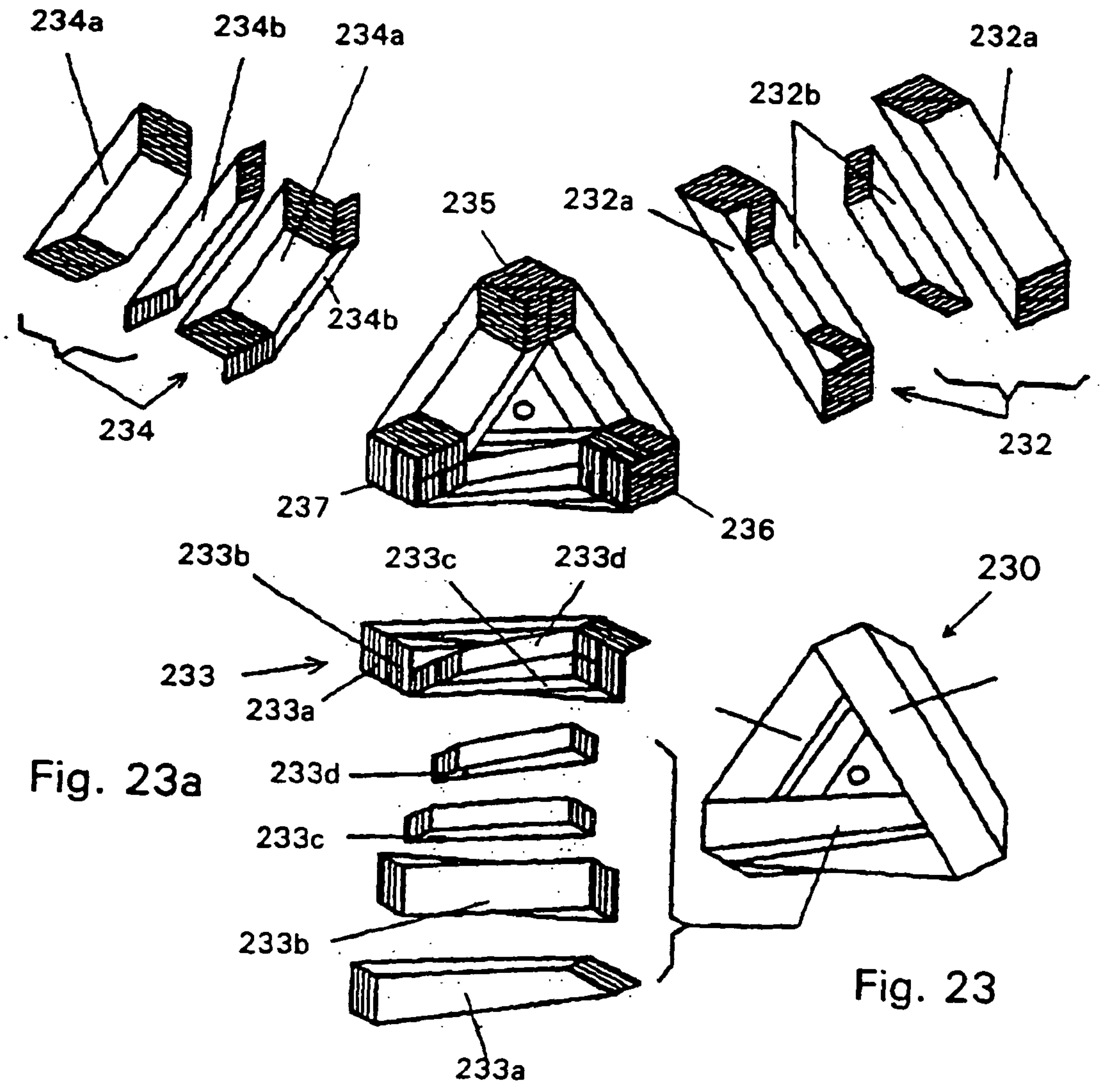
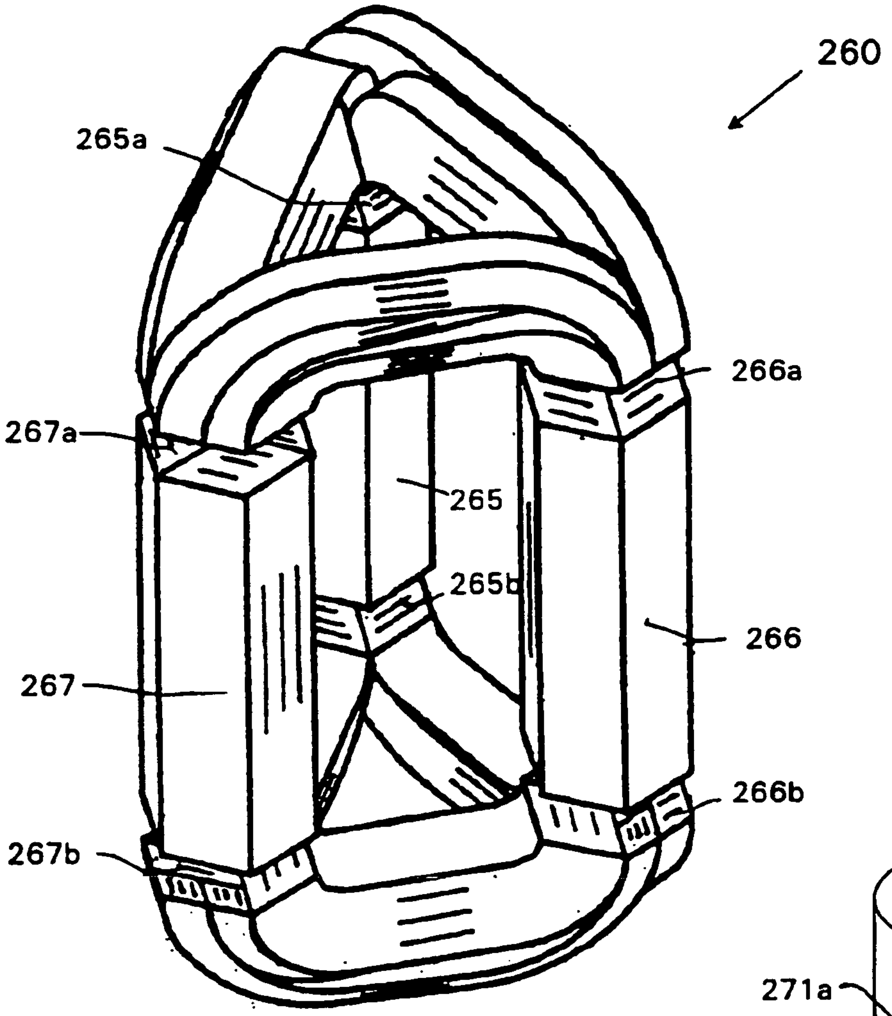



Fig. 23a

Fig. 23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265b
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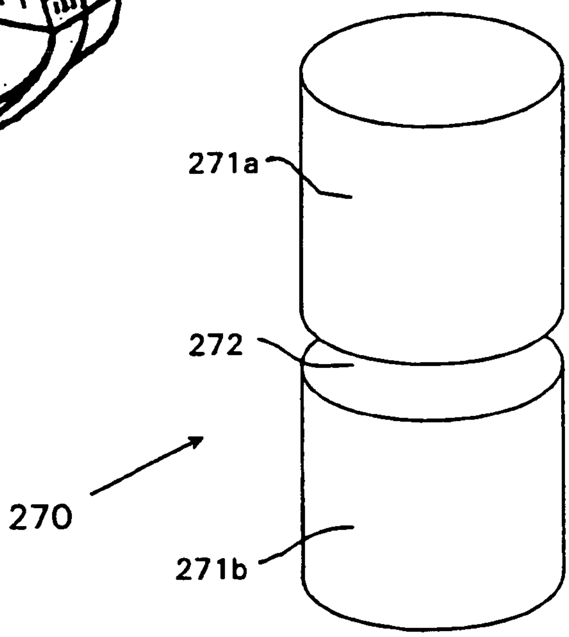
267
266b
267b

Fig. 26


271a
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271b

Fig. 27

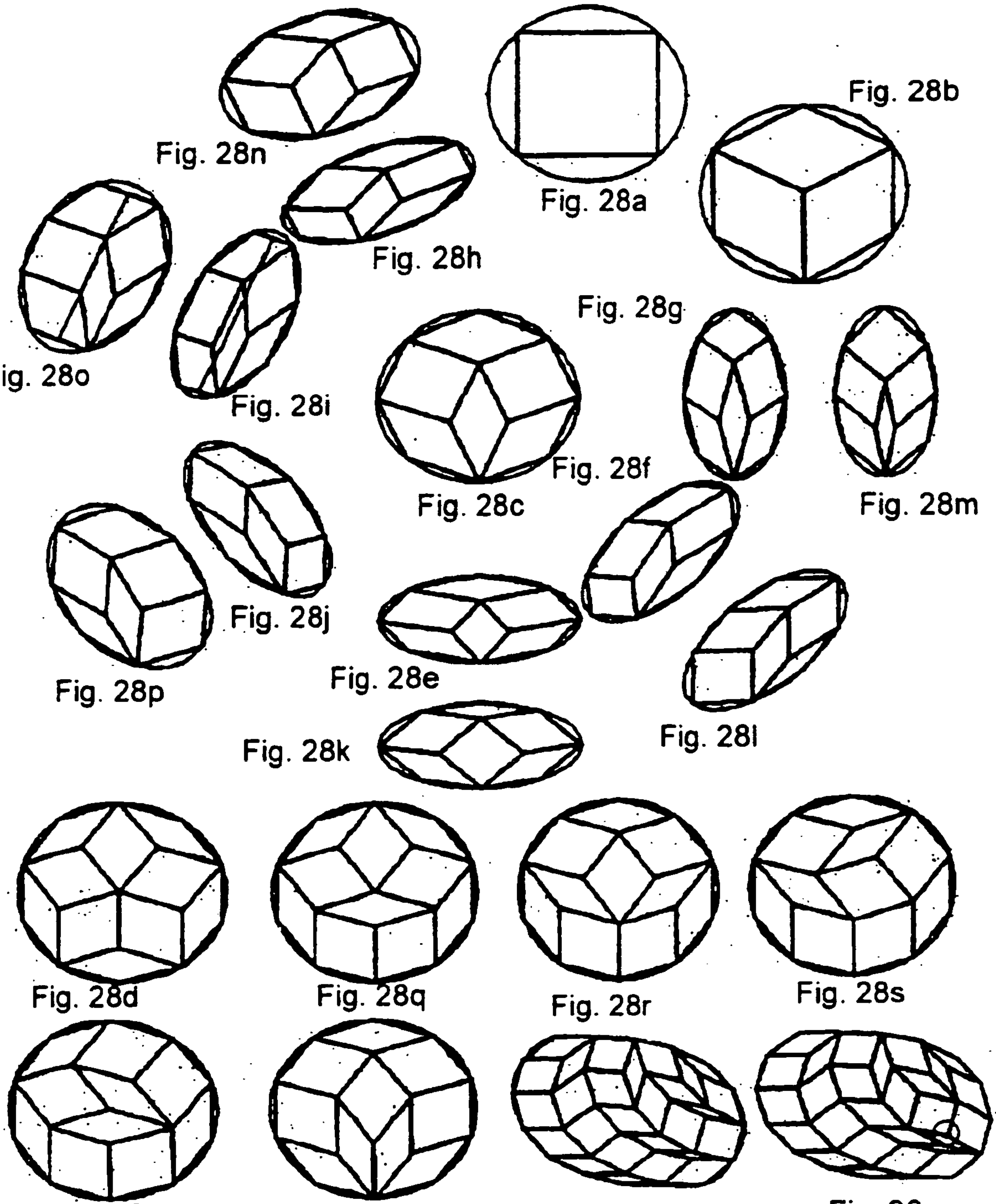

Fig. 28n

Fig. 28a

Fig. 28b

Fig. 28h

Fig. 28o

Fig. 28i

Fig. 28g

Fig. 28c

Fig. 28f

Fig. 28m

Fig. 28j

Fig. 28p

Fig. 28e

Fig. 28k

Fig. 28l

Fig. 28d

Fig. 28q

Fig. 28r

Fig. 28s

Fig. 28t

Fig. 28u

Fig. 28v

Fig. 28w

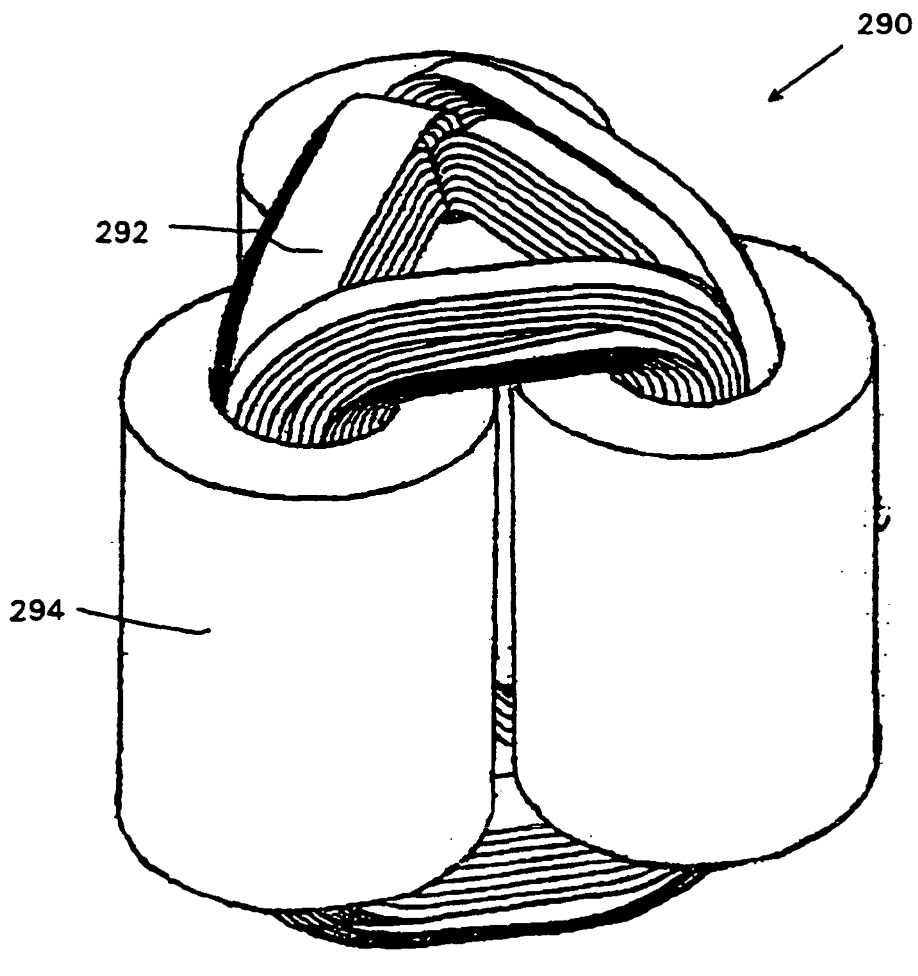


Fig. 29

## REFERENCES CITED IN THE DESCRIPTION

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