



(51) International Patent Classification:

E21B 43/11 (2006.01) *E21B 43/117* (2006.01)
E21B 43/116 (2006.01)

(21) International Application Number:

PCT/US2015/041128

(22) International Filing Date:

20 July 2015 (20.07.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(71) Applicant: **HALLIBURTON ENERGY SERVICES INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, Texas 77032 (US).

(72) Inventors: **ROBEY, Richard E.**; 5 Charleston Ct., Mansfield, Texas 76063 (US). **HOELSCHER, Christopher C.**; 5800 Arbor Valley, Arlington, Texas 76016 (US).

(74) Agents: **COOKE, Brett T.** et al.; Haynes and Boone, LLP, 2323 Victory Avenue, Suite 700, Dallas, Texas 75219 (US).

AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

(54) Title: LOW-DEBRIS LOW-INTERFERENCE WELL PERFORATOR

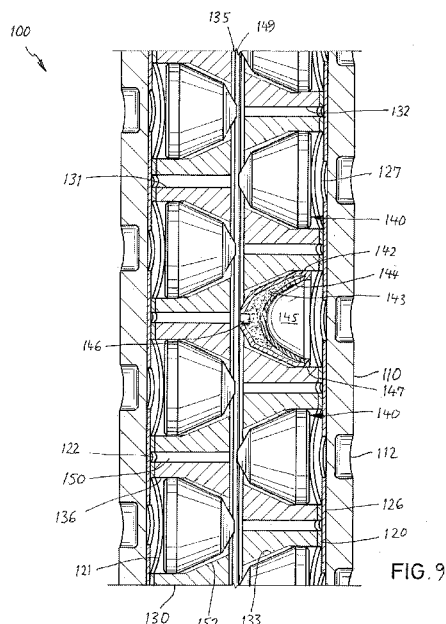


FIG. 9

(57) Abstract: A low-debris low-interference semi-solid well perforator having selectively variable free volume and method for providing such is disclosed according to one or more embodiments. The perforator may include a charge tube holding an independently floating axial stack of selectively variable divider segments, each having one or more concavities formed in upper and lower sides. The segments are arranged so that concavities of adjacent segments form sockets, into which shaped charges are located. The segments provide support to minimize deformation of shaped charge cases yet provide less than 360 degrees circumferential contact about the shaped charges to form selectively variable voids for collecting debris and spall resulting from detonation. The voids and floating segments attenuate detonation shock interference. A debris guard prevents debris from entering the wellbore. Relieving slots in the debris guard attenuates transmission of shock interference through the debris guard.

LOW-DEBRIS LOW-INTERFERENCE WELL PERFORATOR

TECHNICAL FIELD

The present disclosure relates generally to oilfield equipment, and in particular to downhole tools, drilling and related systems and techniques for drilling, completing, servicing, and evaluating wellbores in the earth. More particularly still, the present disclosure relates to an improvement in systems and methods for performing perforating operations.

BACKGROUND

After drilling the various sections of a subterranean wellbore that traverses a formation, individual lengths of relatively large diameter metal tubulars are typically secured together to form a casing string that is positioned within the wellbore. This casing string increases the integrity of the wellbore and provides a path for producing fluids from the producing intervals to the surface. Conventionally, the casing string is cemented within the wellbore. To produce fluids into the casing string, hydraulic openings or perforations must be made through the casing string, the cement sheath, and a short distance into the formation.

Typically, these perforations are created by a perforator. A series of shaped charges are held in a hollow steel carrier. The perforator is connected along a tool string that is lowered into the cased wellbore by a tubing string, wireline, slick line, coiled tubing, or other conveyance. Once the perforator is properly positioned in the wellbore adjacent to the formation to be perforated, the shaped charges may be detonated, thereby creating perforations through the hollow steel carrier and the desired hydraulic openings through the casing and cement sheath into the formation.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments are described in detail hereinafter with reference to the accompanying figures, in which:

Figure 1 is an elevation view in partial cross section of a well system with a low debris low interference well perforator according to an embodiment;

Figure 2 is an elevation view of a portion of the perforator of Figure 1 according to an embodiment, showing a longitudinal stack of divider segments forming sockets for shaped charges, a charge tube, and a debris guard received within a cylindrical carrier;

Figure 3 is an elevation view of a divider segment of Figure 2 according to an embodiment;

- 5 Figure 4 is a plan view of the divider segment of Figure 3, showing a generally planar top surface with three concavities radially formed therein;

Figure 5 is a plan view of the divider segment of Figure 3, showing a generally planar bottom surface with three concavities radially formed therein and offset from the concavities of Figure 4;

- 10 Figure 6 is an exploded perspective view of two divider segments of Figure 3 and three shaped charges partially supported within the concavities of the divider segments;

Figure 7 is a transverse cross-section taken along lines 7–7 of Figure 2;

Figure 8 is a transverse cross-section taken along lines 8–8 of Figure 2;

Figure 9 is an axial cross-section taken along lines 9–9 of Figure 7;

- 15 Figure 10 is an axial cross-section of a portion of the perforator of Figure 1 according to one or more embodiments, showing designed variability in the geometry of divider segments resulting in the ability to finely tune the amount of free volume within the perforator;

- 20 Figure 11 is an enlarged axial cross-section of a portion of the perforator of Figure 9 after one or more shaped charges have been detonated;

Figure 12 is a transverse cross-section of the perforator of Figure 11 taken along lines 12–12 of Figure 11;

- Figure 13 is an elevation view in partial cross-section of a portion of the perforator of Figure 1 according to an embodiment, showing a longitudinal stack of divider segments forming sockets for shaped charges, a charge tube, and a debris guard received within a cylindrical carrier;
- 25

Figure 14 is a transverse cross-section of the perforator of Figure 13 taken along lines 14–14 of Figure 13;

Figure 15 is a transverse cross-section of the perforator of Figure 13 taken along lines 15–15 of Figure 13;

- 5 Figure 16 is an elevation view of a portion of the perforator of Figure 1 according to an embodiment, showing a single helical shaped charge arrangement with a non-centralized detonation arrangement;

Figure 17 is a transverse cross-section of the perforator of Figure 16 taken along lines 17–17 of Figure 16; and

- 10 Figure 18 is a flow chart of a method for selectively varying the free volume of the perforator of Figure 1 according to an embodiment.

DETAILED DESCRIPTION

- In one or more perforators, a series of shaped charges are held within a hollow thin-walled charge tube. The charge tube, with shaped charges, is disposed within a hollow steel carrier, which may have thin, recessed scallops formed in the wall that align with the shaped charges. Once the perforator is properly positioned in a wellbore adjacent to the formation to be perforated, the shaped charges may be detonated, thereby creating perforations through the recessed scallops in the hollow steel carrier and the desired hydraulic openings through the casing and cement sheath into the formation.

- 20 Each shaped charge may include an outer charge case, an explosive compound, a metal liner defining a conical void at the jet end, and a detonator at the other end. At detonation, explosive energy is released normal to the surface of the explosive compound, thereby concentrating explosive energy in the void. Enormous pressure generated by detonation of explosive compound collapses the liner and fires a high-velocity jet of metal particles outward along the axis of the shaped charge, through the carrier, wellbore casing, cement sheath, and into the formation.

- Shaped charge liners may be fabricated of various materials, including ductile metals such as steel, copper, and brass. Although ductile liner materials offer deep penetration capability, they may also result in a solid slug being formed, which may plug the casing hole just perforated. Accordingly, liners may also be fabricated of unsintered cold-pressed

powdered metal alloys or pseudo-alloys to yield jets that are mainly composed of dispersed fine metal particles, without solid slugs.

Despite the use of shaped charge geometry to radially focus and concentrate detonation forces in the desired outward direction, detonation of the shaped charge may still result in undesirable spalling and fracturing of the outer charge case. Debris from the outer charge case may freely spill from the free volume defined by the hollow steel carrier, via perforations formed through the carrier, into the wellbore. Large non-dissolvable solid debris from shaped charges and other perforating system components can interfere with and damage completion tools, surface equipment and the reservoir itself, result in lowered production, and require additional cleanup operations.

For this reason, some perforating systems may employ outer charge cases made of zinc. The zinc material substantially vaporizes during jet formation or by exposure to wellbore fluids, thereby minimizing production of large charge case particulate matter during perforation. However, zinc residue can create reservoir control issues due to zinc's inherent anodic behavior with wellbore fluids, resulting in fluid loss into the reservoir and subsequent required treatments of the perforated zone with kill fluids to reduce permeability.

Other perforating systems may employ a ductile solid charge tube or thick-walled charge tube in lieu of a thin-walled hollow charge tube for holding the shaped charges. The solid or thick-walled charge tube, defining a near-zero or low free volume perforator, may plastically deform to mechanically bond and consolidate with, and thereby contain, charge case fragments resulting from detonation, thus reducing the generation of debris within the wellbore.

Unfortunately, unlike a hollow thin-walled charge tube, the solid or thick-walled charge tube provides an excellent vehicle for undesirable transmission of impulses and shockwaves resulting from detonation of shaped charges throughout the perforator. That is, coupling materials in close proximity to the charge cases results in a deficit of free volume that transfers explosively generated shocks from charge to charge. This shockwave transmission from detonation of one or more shaped charges within a perforator may cause interference with the proper detonation of subsequent shaped charges within the perforator. Shock interference may be detrimental to jet formation and performance, resulting in degrading hole size or even burst casing.

The present specification discloses a well perforator, system, and method according to one or more embodiments that maintains the performance of a traditional high-energy steel-cased shaped charges yet provides the advantageous properties of a low-debris perforator that minimizes post-perforating solids accumulation within the wellbore by containing debris within the perforator. By introducing various voids and discontinuities, the perforator according to the present specification diminishes explosive interference between shaped charges during detonation.

The disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper,” “uphole,” “downhole,” “upstream,” “downstream,” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the apparatus in use or operation in addition to the orientation depicted in the figures. Various items of equipment, such as fasteners, fittings, etc., may be omitted to simplify the description. However, routineers in the art will realize that such conventional equipment can be employed as desired.

Figure 1 is an elevation view in partial cross-section of a well system, generally designated 9, according to an embodiment. Well system 9 may include drilling, completion, servicing, or workover rig 10. Rig 10 may be deployed on land or used in association with offshore platforms, semi-submersibles, drill ships and any other system satisfactory for drilling, completing, or servicing a wellbore 12. Rig 10 may include a hoist, rotary table, slips, elevator, swivel, and/or top drive (not illustrated) for assembling and running a working string 22. A blow out preventer, christmas tree, and/or and other equipment associated with servicing or completing a wellbore (not illustrated) may also be provided.

Wellbore 12 may extend through various earth strata into a first hydrocarbon bearing subterranean formation 20. A portion of wellbore 12 may be lined with a casing string 16, which may be joined to the formation with casing cement 17. In some embodiments, working string 22, extending from the surface, may be positioned within wellbore 12. The term working string, as used herein broadly encompasses any conveyance for downhole use, including drill strings, completion strings, evaluation strings, other tubular members,

wireline systems, and the like. Working string 22 may provide an internal flow path for workover operations and the like as appropriate. An annulus 25 may be formed between the exterior of working string 22 and the inside wall of wellbore 12 or casing string 16.

According to one or more embodiments, working string 22 may carry a low-debris low-interference well perforator 100. Perforator 100 may be designed and arranged to creating openings 31 through casing 16, casing cement 17, and into surrounding formation 20 for fluid communication between formation 20 and the interior of casing 16. As described in greater detail hereinafter, perforator 100 is characterized by a semi-solid geometry that decouples charge interaction by inducing discontinuities, or voids, which may be located proximal to shaped charges, to allow for controlled expansion of material and provide a torturous path for high-pressure high-velocity shockwaves to propagate during detonation. The semi-solid geometry may be formed by a longitudinal stack of disconnected divider segments that decouple and minimize transmission of axial shock interference.

Figure 2 is an elevation view of a low debris well perforator 100 according to one or more embodiments. Perforator 100 may be assembled in a cylindrical carrier 110 made from a length of straight wall tubing, preferably high strength steel. Any style of hollow carrier 110 specified for a particular wellbore application may be used as appropriate. Carrier 110 may have gun ports, or thin-wall recessed areas, often referred to as scallops, 112 radially and axially aligned with shaped charges 140 supported within carrier 110. Each shaped charge 140 may include an outer charge case 142, an explosive compound 143 (Figure 9), a metal liner 144 defining a conical void 145 at the jet end, and an explosive booster 146 (Figure 9) at the other end. Each shaped charge 140 may define an outer circumferential flange 147 (Figure 6) at the jet end.

In one or more embodiments, shaped charges 140 and scallops 112 may be arranged in a linear configuration along the longitudinal length of carrier 110 of perforator 100, while in other embodiments, shaped charges 140 and scallops 112 may be arranged in a helical configuration about carrier 110. For example, well perforator 100 of Figure 2 includes a treble helical arrangement, with three helical rows of shaped charges spaced 120 degrees apart, rotating 60 degrees per step.

Shaped charges 140 may be selectively and individually detonatable, so that only those shaped charges 140 facing in a single select radial direction may be detonated if desired. In one or more embodiments, perforator 100 may include multiple groupings of shaped

charges 140, wherein each grouping may be selectively and individually detonatable. However, perforator 100 described herein is not limited to a particular type of arrangement, and the forgoing general comments are provided for illustrative purposes only.

According to one or more embodiments, perforator 100 may include a plurality of divider segments 130, a thin-walled charge tube 120, and an outer debris guard 126. Divider segments 130, charge tube 120, and outer debris guard 126 may be disposed within carrier 110 so as to align shaped charges 140 with scallops 112. Divider segments 130 may be arranged in a free-floating longitudinal stack within charge tube 120. Shaped charges 140 may be partially supported between pairs of divider segments 130, as described in greater detail hereinafter. In one or more embodiments, debris guard 126 may be a thin-walled tubular member, charge tube 120 may be coaxially received within debris guard 126, and debris guard 126 may be coaxially received within carrier 110.

Figure 3 is an elevation view of a single divider segment 130 according to one or more embodiments. Figures 4 and 5 are top and bottom plan views, respectively of divider segment 130 of Figure 3. Figure 6 is an exploded perspective view of two divider segments 130 supporting three shaped charges. Referring to Figures 2–6, shaped charges 140 may be carried between pairs of divider segments 130, which may in turn be axially arranged within charge tube 120 and outer debris guard 126.

Divider segments 130 may be formed of a solid material, such as steel, aluminum, or plastic, although other suitable solid materials, both metallic and nonmetallic, may be used as appropriate, including low density materials such as foam, rubber, and aerogel. Divider segments may be formed by machining, casting, welding, molding, sintering, or 3-D printing, although other suitable manufacturing techniques may be used. Divider segments may formed with internal pores or include encapsulated liquid, powder, sand, salt, concrete, micro-balloons, or microspheres, for example.

Each divider segment 130 may include one or more concavities 133. Divider segments 130 are arranged so that concavities 133 of adjacent divider segments 130 align to form sockets 136 into which shaped charges 140 are received. According to one or more embodiments, each divider segment 130 defines generally planer top and bottom sides 131, 132. Top side 131 and bottom side 132 may each include one or more concavities 133. Each concavity 133 may have an approximately semi-cylindrical, semi-conical, semi-frustoconical, or similar shape dimensioned to accommodate an upper or lower portion of a

shaped charge 140. In one or more embodiments, concavities 133 formed in bottom side 132 may be radially offset from and intervalled between concavities 133 formed in top side 131. The number of concavities 133 per divider segment may vary. In the embodiment illustrated in Figures 2–6, three concavities 133, radially spaced 120 degrees apart, are provided in each top side 131 and bottom side 132. An axial opening 135 may be formed through divider segment 134, for accommodating a detonation means 149 (Figure 7) for shaped charges 140.

Figures 7 and 8 are transverse cross-sections taken along lines 7–7 and 8–8 of Figure 2, respectively. Figure 9 is an axial cross-section taken along lines 9–9 of Figure 7.

Reference is now made to Figures 2 and 7–9.

As best seen in Figures 2 and 9, each concavity 133 may be dimensioned so as to provide an angle α less than 180 degrees of circumferential support about outer flange 147 of the adjacent shaped charge 140. Accordingly, two adjacent divider segments 130 may support outer flanges 147 of one or more shaped charges 140 with less than 360 degrees of overall circumferential outer flange contact thereby resulting in one or more transverse voids 150 being extant between top and bottom sides 131, 132 of adjacent divider segments 130. That is, divider segments 131 of perforator 100 have no direct contact with one another prior to detonation of shaped charges 140. Transverse voids 150 allow room for controlled expansion of the outer charge case 142 and collection and recombination of debris and spall material during detonation of shaped charges 140, as described in greater detail hereinafter. Accordingly, transverse voids 150 may be termed as spall compartments. Although voids 150 may be oriented transversely to the axis of perforator 100, in one or more embodiments, voids 150 may be oriented along an acute angle with respect to the axis of perforator 100.

The selection of angle α of shaped charge support provided by divider segment 130 may vary depending on various factors including perforator diameter, manufacturing tolerances, the materials used to form divider segments 130, charge tube 120, outer debris guard 126 and gun body 110, and the caliber and ballistic characteristics of shaped charges 140. In one or more embodiments, divider segments 130 may be separated from one another by void 150 thickness of at least 0.020 inches, although other separation dimensions may be appropriate and are included within the scope of the disclosure.

As best seen in Figures 7–9, shaped charges 140 are supported at outer flanges 147 by divider segments 130. Concavities 133 may be dimensioned to result in small conical or similarly-shaped shaped charge voids 152 surrounding substantial portions of shaped charges 140. Shaped charge voids 152 allow room for controlled expansion of the outer charge case 142 and collection and recombination of debris and spall material during detonation of shaped charges 140, as described in greater detail hereinafter. The dimension and shape of concavities 133 of divider segments 130 may be varied to provide an appropriate volume of shaped charge voids 152 so that upon detonation, voids 152 become substantially filled with unconsolidated material. In one or more embodiments, the nominal distance between shaped charge outer case 142 and the interior surface of concavity 133 may be about 0.060 inches, although other separation dimensions may be appropriate and are included within the scope of the disclosure.

Charge tube 120 provides a frame for assembling divider segments 130 and shaped charges 140 and for ballistically connecting the explosive booster 146 of shaped charges 140 with a detonation system 149. In one or more embodiments, detonation system 149 does not rely on any means of ballistically coupling or transferring the detonation train between shaped charges 140. Charge tube 120 may include a plurality of gun port apertures 121 formed therethrough in radial and axial alignment with shaped charges 140 and scallops 112. The outer diameter of gun port apertures 121 may substantially match the outer diameter of outer flanges 147 of shaped charges 140 to allow installation and servicing of shaped charges 140.

Additionally, charge tube 120 may include a plurality of debris slots or other openings 122 formed therethrough. In one or more embodiments, debris slots 122 may be located 80 degrees opposite gun port apertures 121. Debris slots 122 axially align with transverse voids 150 and provide additional volume for reconsolidation of spall material and other debris during detonation of shaped charges 140. Moreover, debris slots 122 provide additional shock relief geometry to charge tube 120 for attenuating axial shock transmissions from detonation. The size and shape of debris slots 122 may be varied depending on the reconsolidation volume required. In one or more embodiments, the dimension of debris slots 122 may range between 1/4 and 3/4 of the ballistic caliber of shaped charge 140, although other sizes may be used as appropriate.

In one or more embodiments, as illustrated in Figures 2 and 7–9, debris guard 126 may be a thin-walled cylindrical tube. Charge tube 120 may be disposed within debris guard 126 within close radial tolerances. An inner surface of debris guard 126 may be in close proximity or in contact with the outermost portion of charge case 142, thereby functioning to retain shaped charges 140 within charge tube 120. Debris guard 126 may in turn be disposed within carrier 110 within close radial tolerances. Debris guard 126 may include gun port apertures 127 formed therethrough in radial and axial alignment with shaped charges 140, gun port apertures 121, and scallops 112. Gun port apertures 127 may have a diameter about the same as recessed scallops 112 of carrier 110, although other diameters may also be used.

Debris guard 126 may include relieving cuts or slots 128 formed therethrough, which may partially surround gun port apertures 127. Relieving slots 128 may provide disruption or redirection of shock waves that may otherwise travel through along debris guard 126 during detonation of shaped charges 140. The geometry of relieving slots 128 may vary as appropriate.

Debris guard 126 covers debris slots 122 of charge tube 120, preventing debris and spall collecting in debris slots 122 from exiting perforator 100 and collecting in wellbore 12 (Figure 1). Further, debris guard 126 provides a tortuous path for pressures generated within perforator 100 to escape into the wellbore via debris slots 122, the high-tolerance annular region defined between charge holder 120 and debris guard 126, and one or more perforated scallops 112.

In one or more embodiments, not expressly illustrated, multiple debris guard sleeves may be coaxially provided in lieu of a single debris guard 126. Such sleeves may be made from steel, aluminum, magnesium, plastic, foam, rubber, or other suitable materials. The multiple debris guard sleeves may have complementary or phased offset discontinuities to mitigate shock wave propagation. For example, the sleeves may be formed of discrete strips having a geometry with directionally non-continuous tortuous path facets, such as zigzag, saw-tooth or wave patterns. The sleeves may also be cut to promote loading along rows, in short strip lengths, sections, or a combination thereof. The sleeves may include relieving slots similar to relieving slots 128, which may be arranged perpendicular to the axis of perforator 100. Similar to debris slots 122 and debris guard relieving slots 128, relieving slots in multiple guard sleeves may be positioned so as not to overlap thereby creating a

more complex and tortuous labyrinth for fluid communication between perforator 100 and wellbore 12 (Figure 1).

Additionally, in one or more embodiments, not expressly illustrated, debris guard 126 may take the form of one or more longitudinal strips disposed between charge tube 120 and carrier 110 so as to cover debris slots 122. The strips may be seated within longitudinal grooves formed along the outer surface of charge tube 120, the inner surface of carrier 119, or both, thereby preventing debris and spall collecting in debris slots 122 from exiting perforator 100 while providing a tortuous path for pressures generated within perforator 100 to escape into the wellbore. Similar, to debris slots 122 and debris guard relieving slots 128, relieving slots in multiple guard strips may be positioned so as not to overlap thereby creating a more complex and tortuous labyrinth for fluid communication between perforator 100 and wellbore 12 (Figure 1).

Charge tube 120 provides a frame for assembling and positioning a longitudinal stack of divider segments 130. In one or more embodiments, divider segments 130 may be free floating, i.e., they are neither rigidly fastened to one another, to charge tube 120, nor to debris guard 126. Such a longitudinally independent arrangement may diminish detonation shock interference. Divider segments 130, charge tube 120, and debris guard 126 together provide a minimal support to outer charge cases 142 of shaped charges 140, while none independently fully seat, house or retain shaped charges 140. Divider segments 130, charge tube 120, and debris guard 126 may be assembled so that minimal radial clearances are held, whereupon detonation, expansion of each of these components resulting from internal detonation pressures are supported by adjacent components.

Figure 10 is an axial cross-section that illustrates various embodiments of perforator 100. The overall axial thickness t of each divider segment 130 may be varied, depending on the specific needs of wellbore 12 (Figure 1). For example, the overall axial thickness t may range between 0.25 and 3.0 inches, although other thicknesses t may also be provided.

Moreover, the geometry of each divider segment 130 may be varied, depending on the specific needs of wellbore 12 (Figure 1). By varying the geometry of divider segments 130, the volume of transverse voids 150 and shaped charge voids 152 may be controlled, thereby allowing the operator to easily select an overall desired free volume of perforator 100. In other words, perforator 100 may provide a fine resolution in varying the free volume of perforator 100 along a sliding scale from a minimum free volume to a maximum

free volume. For example, over the length of a 6.75 inch diameter 16 foot long perforator, there may be as many as eighty-seven divider segments 130 in a particular configuration, allowing nearly infinite variability of designed free volume along a perforating interval. Thick divider segments 130, thin divider segments 130, or a combination of thick and thin divider segments 130, may be used in a given perforator 100. Thick or thin transverse voids 150, or a combination thereof, may be provided in a given perforator 100. And, large or small shaped charge voids 152, or a combination thereof, may be provided in a given perforator 100.

Moreover, as shown in Figure 10, divider segments 130 need not be unitary or homogeneous. For example, a divider segment 130A may be formed of a longitudinal stack of disks or plates 139, a coaxial arrangement of sleeves (not illustrated), or other suitable arrangement, which may further promote creation of spall and attenuation of undesired fragmentation forces. Each disk 139 may define a discontinuity volume to reduce shock wave transmission.

A theory of operation of perforator 100 is now described with references to Figures 11 and 12, which illustrate perforator 100 after a number of shaped charges 140 have been detonated (indicated by reference numeral 140'). Divider segments 130 surround charge cases 142 with a solid material, thereby substantially preserving the structural integrity of outer charge cases 142 and minimizing the generation of debris that would otherwise occur with free volume detonation. Divider segments 130 are arranged provide a predetermined empty volume—voids 150, 152—for material consolidation and dampening of detonation shock propagation.

Shock attenuation or dampening occurs when a shock wave crosses a void between adjacent divider segments 130. When a compression wave meets a free surface, it will continue on and into the void. Propagation of this wave across the free surface creates a tensile wave on the boundary of a divider segment 130. Simultaneously, a compression wave is reflected backwards. Both the forward transmitted wave and the reflected wave are lower in magnitude than the shock initial wave. The tensile wave acting on the free surface may have a tendency pull material off as it moves across the void, producing spall.

Divider segments 130 may also provide a source of spall from detonation events.

Transverse voids 150 and shaped charge voids 152 may be initially evacuated or filled with a gas, such as air, nitrogen, argon, carbon dioxide, or the like. Divider segments 130 allow

for controlled expansion and support of outer charge cases 142, and transverse voids 150 and shaped charge voids 152 collect and reconsolidate debris and spall (indicated by reference numerals 150', 152'). In one or more embodiments, perforator 100 may be sized and dimensioned so that non-contact spacing between adjacent divider segments 130 and between shaped charge outer cases 142 and divider segments 130 are filled and become substantially solid after detonating shaped charges 140. All the components of perforator 100 may be assembled so that minimal radial clearances are held whereupon detonation, each components subject to expansion from the internal pressure is supported by adjacent components. Charge tube 120 and debris guard 126 retain debris and spall within perforator 100.

Perforator 100 also provides a tortuous path for high pressures and high velocity shock waves to travel. Independently floating divider segments 130 providing transverse and shaped charge voids 150, 152 break the continuity of a fully solid perforator system and thereby serve to dampen shock wave transmission. Moreover, debris slots 122 formed within charge tube 120 and relieving slots 128 may disrupt and redirect axial shock wave propagation. Detonation pressures may be relieved into wellbore 12 via a tortuous flow path through transverse void 150, debris port 122, the annular region between debris guard 126 and charge tube 120, and perforations 112', formed in carrier 110.

As noted above, perforator 100 may include shaped charges 140 in numerous arrangements. Figures 2–12 illustrate one or more embodiments in which shaped charges are positioned at intervalled 120 degree spacing. Referring now to Figures 13–15, a perforator 100 with intervalled 180 degree-spaced shaped charges 140 is disclosed according to one or more embodiments. Similarly, as disclosed in Figures 16 and 17, a perforator 100 having a single helical arrangement shaped charges 140 may allow for a non-centralized perforation system. Perforators 100 of Figures 13–17 may have essentially the same arrangement, features and theory of operation as perforator 100 of Figures 2–12 and are therefore, for the sake of brevity, not described in further detail. Reference may be made to the previous disclosure, in which like numerals designate like parts.

Figure 18 is a flow chart of a method 200 for selectively varying the free volume of the perforator of Figure 1 according to an embodiment. Referring primarily to Figures 10 and 16, at step 204, a group 250 of available divider segment 130 types is provided, each having a unique characteristic affecting the overall free volume of perforator 100. For

example, the shape and size of concavities 133 may vary, thus providing differing volumes of shaped charge voids 152 about shaped charges 140 or providing differing angles α of circumferential support about shaped charge flanges 147 and concomitant different thicknesses of transverse voids 150. The overall thickness each divider segment 130 type may vary, thus providing a different volume of solid material. The material of divider segment 130 type may be varied, including various metals, plastics, elastomers, and composite materials. Divider segment types may include divider segments 130 formed of stacked disks or plates 139. An almost limitless variety of divider segment 130 types is possible to allow the designer free reign in providing a low-debris, low interference modular perforator 100 of selectively variable free volume to match operational needs.

At step 208, from group 250 of available divider segment 130 types, a first divider segment type may be selected based on characteristics of the wellbore. At step 212, at least upper and lower divider segments 130 of the first divider segment type may be disposed within hollow charge tube 120 so that concavities in the bottom side of said upper divider segment and in the top side of the lower divider segment are radially aligned. Depending on the perforator 100, the number of divider segments may vary from as little as two to several hundred. Multiple types of divider segments 130 from group 250 may be provided within a given perforator 100.

At step 216, a shaped charge 140 may be disposed between concavity 133 in the bottom side of the upper divider segment 130 and concavity 133 in the top side of the lower divider segment 130. The outer circumference 147 of shaped charge 140 may be supported along less than 180 degrees by each divider segment 130 so as to form a transverse void 150 having a first axial thickness between the bottom side of the upper divider segment and the top side of the lower divider segment. At step 220, charge tube may be disposed within a debris tube 126, which in turn may be disposed within hollow carrier 110.

In summary, a several embodiments of a well perforator have been described. Embodiments of a well perforator may generally have: A charge tube having a wall with first opening formed therethrough centered at a first radial of the charge tube; a circular first divider segment disposed within the charge tube, the first segment having a first concavity formed in a lower side of the first segment along the first radial of the charge tube; a circular second divider segment disposed within the charge tube below the first segment, the second segment having a first concavity formed in an upper side of the second

segment along the first radial of the charge tube; the first concavities of the first and second segments together defining a first socket aligned with the first opening of the charge tube; a first shaped charge disposed within the first socket; and a first void formed between the first segment and the second segment. Embodiments of a well perforator may generally have: A hollow cylindrical carrier; a first shaped charge disposed within the carrier; a circular first segment having a first concavity formed along a first radial of the first segment, the first segment disposed within the housing above the first shaped charge so that the first concavity of the first segment partially envelops a circumference of the first shaped charge; a circular second segment having a first concavity formed along a first radial of the first segment, the first segment disposed within the housing below the first shaped charge so that the first concavity of the second segment partially envelops a circumference of the first shaped charge; and a first spall compartment formed between the first segment and the second segment operable to receive spall resulting from a detonation of the first shaped charge. Embodiments of a well perforator may generally have: A charge tube; a plurality of circular segments axially disposed within the charge tube, each segment having an upper side, a lower side, a first concavity formed in the upper side, and a first concavity formed in the lower side, the plurality of circular segments arranged so that the first concavity formed in the upper side of each segment aligns with the first concavity formed in the lower side of an adjacent segment, thereby each pair of adjacent segments forming a socket; a plurality of shaped charges disposed in the plurality of sockets; and each adjacent pair of the plurality of segments forming a spall compartment.

Any of the foregoing embodiments may include any one of the following elements or characteristics, alone or in combination with each other: The first void is formed along a radial of the charge tube opposite the first radial; the first void is a generally planar transverse void oriented perpendicular to an axis of the perforator; the first and second segments contact only a portion of an outer casing of the shaped charge thereby defining a shaped charge void formed between the socket and the first shaped charge; the first segment provides less than 180 degrees of circumferential contact with an outer casing of the shaped charge; the second segment provides less than 180 degrees of circumferential contact with the outer casing of the shaped charge; the lower side of the first segment does not contact the upper side of the second segment to form the first void; a debris opening formed through the charge tube in fluid communication with the first void; a debris guard covering the debris opening; a relieving slot formed through the debris guard at a position not adjacent to the debris opening; the debris guard is a cylindrical sleeve; the charge tube

is coaxially disposed within the debris guard; a gun port aperture formed through a wall of the debris guard centered at the first radial of the charge tube; a hollow carrier, the charge tube coaxially disposed within the hollow carrier; a second opening formed through the wall of the charge tube centered at a second radial, respectively, of the charge tube; a second concavity formed in the lower side of the first segment along the second of the charge tube; a second concavity formed in the upper side of the second segment along the second radial of the charge tube; the second concavities of the first and second segments together defining a second socket aligned with the second opening of the charge tube; a second shaped charge disposed within the second socket; a second void formed between the first segment and the second segment along a radial of the charge tube opposite the second radial; the second radial of the charge tube is 180 degrees from the first radial of the charge tube; a third opening formed through the wall of the charge tube centered at a third radial of the charge tube; a third concavity formed in the lower side of the first segment along the third radial of the charge tube; a third concavity formed in the upper side of the second segment along the third radial of the charge tube; the third concavities of the first and second segments together forming a third socket aligned with the third opening of the charge tube; a third shaped charge disposed within the second socket; a third void formed between the first segment and the second segment along a radial of the charge tube opposite the third radial; the second radial of the charge tube is 120 degrees from the first radial of the charge tube; the third radial of the charge tube is 240 degrees from the first radial of the charge tube and 120 degrees from the second radial of the charge tube; the first void is operable to receive spall resulting from detonations of the second and third shaped charges; the second void is operable to receive spall resulting from a detonation of the first shaped charge and the detonation of the third shaped charge; the third void is operable to receive spall resulting from the detonations of the first and second shaped charges; fourth, fifth, and sixth concavities formed in an upper face of the first segment offset from the first radial of the charge tube by 60, 180, and 300 degrees, respectively; fourth, fifth, and sixth concavities formed in a lower face of the second segment offset from the first radial of the charge tube by 60, 180, and 300 degrees, respectively; a fourth shaped charge disposed within the fifth concavity of the first segment; a fifth shaped charge disposed within the fifth concavity of the second segment; the first void is operable to receive spall resulting from detonations of the fourth and fifth shaped charges; a second concavity formed in a lower side of the second segment along a second radial offset from the first radial of the charge tube by an angle ranging between 5 and 180 degrees; a circular

third divider segment disposed within the charge tube below the second segment, the third segment having a first concavity formed in an upper side of the second segment along the second radial of the charge tube; the second concavities of the second segment and the first concavity of the third segment together defining a second socket aligned with the second radial the charge tube; a second opening formed through the charge tube centered at the second radial of the charge tube; a second shaped charge disposed within the second socket; a second void formed between the second segment and the third segment; the first void is operable to receive spall resulting from detonations of the fourth and fifth shaped charges; a second shaped charge disposed within the housing above the first segment; a third shaped charge disposed within the housing below the second segment; the first spall compartment operable to receive spall resulting from a detonation of the second shaped charged and spall resulting from a detonation of the third shaped charge; the first segment surrounds less than 180 degrees of the circumference of the first shaped charge; the second segment surrounds less than 180 degrees of the circumference of the first shaped charge; a charge tube disposed within the housing, the first and second segments and the first shaped charge captured within the charge tube; a first debris opening formed through the charge tube in communication with the first spall compartment; and a debris guard disposed on an outer surface of the charge tube over the first debris opening, the debris guard disposed within the housing.

The Abstract of the disclosure is solely for providing the reader a way to determine quickly from a cursory reading the nature and gist of technical disclosure, and it represents solely one or more embodiments.

While various embodiments have been illustrated in detail, the disclosure is not limited to the embodiments shown. Modifications and adaptations of the above embodiments may occur to those skilled in the art. Such modifications and adaptations are in the spirit and scope of the disclosure.

WHAT IS CLAIMED

1. A well perforator, comprising:

a charge tube having a wall with first opening formed therethrough centered at a first radial of said charge tube;

5 a circular first divider segment disposed within said charge tube, said first segment having a first concavity formed in a lower side of said first segment along said first radial of said charge tube;

a circular second divider segment disposed within said charge tube below said first segment, said second segment having a first concavity formed in an upper side of said
10 second segment along said first radial of said charge tube;

said first concavities of said first and second segments together defining a first socket aligned with said first opening of said charge tube;

a first shaped charge disposed within said first socket; and

a first void formed between said first segment and said second segment.

15

2. The perforator of claim 1 wherein:

said first void is formed along a radial of said charge tube opposite said first radial.

3. The perforator of claim 1 wherein:

20 said first void is a generally planar transverse void oriented perpendicular to an axis of said perforator.

4. The perforator of claim 1 wherein:

said first and second segments contact only a portion of an outer casing of said
25 shaped charge thereby defining a shaped charge void formed between said socket and said first shaped charge.

5. The perforator of claim 1 wherein:

said first segment provides less than 180 degrees of circumferential contact with an
30 outer casing of said shaped charge; and

said second segment provides less than 180 degrees of circumferential contact with said outer casing of said shaped charge; whereby

said lower side of said first segment does not contact said upper side of said second segment to form said first void.

6. The perforator of claim 1 further comprising:
a debris opening formed through said charge tube in fluid communication with said first void.

5

7. The perforator of claim 6 further comprising:
a debris guard covering said debris opening.

8. The perforator of claim 7 further comprising:

10 a relieving slot formed through said debris guard at a position not adjacent to said debris opening.

9. The perforator of claim 7 wherein:

said debris guard is a cylindrical sleeve; and

15 said charge tube is coaxially disposed within said debris guard.

10. The perforator of claim 9 further comprising:

a gun port aperture formed through a wall of said debris guard centered at said first radial of said charge tube.

20

11. The perforator of claim 1 further comprising:

a hollow carrier, said charge tube coaxially disposed within said hollow carrier.

12. The perforator of claim 2 further comprising:

25 a second opening formed through said wall of said charge tube centered at a second radial, respectively, of said charge tube;

a second concavity formed in said lower side of said first segment along said second of said charge tube;

30 a second concavity formed in said upper side of said second segment along said second radial of said charge tube;

said second concavities of said first and second segments together defining a second socket aligned with said second opening of said charge tube;

a second shaped charge disposed within said second socket; and

a second void formed between said first segment and said second segment along a radial of said charge tube opposite said second radial.

13. The perforator of claim 12 wherein:

5 said second radial of said charge tube is 180 degrees from said first radial of said charge tube.

14. The perforator of claim 12 further comprising:

10 a third opening formed through said wall of said charge tube centered at a third radial of said charge tube;

a third concavity formed in said lower side of said first segment along said third radial of said charge tube;

a third concavity formed in said upper side of said second segment along said third radial of said charge tube;

15 said third concavities of said first and second segments together forming a third socket aligned with said third opening of said charge tube;

a third shaped charge disposed within said second socket; and

a third void formed between said first segment and said second segment along a radial of said charge tube opposite said third radial.

20 15. The perforator of claim 14 wherein:

said second radial of said charge tube is 120 degrees from said first radial of said charge tube; and

25 said third radial of said charge tube is 240 degrees from said first radial of said charge tube and 120 degrees from said second radial of said charge tube.

16. The perforator of claim 14 wherein:

said first void is operable to receive spall resulting from detonations of said second and third shaped charges;

30 said second void is operable to receive spall resulting from a detonation of said first shaped charge and said detonation of said third shaped charge; and

said third void is operable to receive spall resulting from said detonations of said first and second shaped charges.

17. The perforator of claim 14 further comprising:

fourth, fifth, and sixth concavities formed in an upper face of said first segment offset from said first radial of said charge tube by 60, 180, and 300 degrees, respectively;

fourth, fifth, and sixth concavities formed in a lower face of said second segment offset from said first radial of said charge tube by 60, 180, and 300 degrees, respectively;

a fourth shaped charge disposed within said fifth concavity of said first segment; and

a fifth shaped charge disposed within said fifth concavity of said second segment; wherein

said first void is operable to receive spall resulting from detonations of said fourth and fifth shaped charges.

18. The perforator of claim 1 further comprising:

a second concavity formed in a lower side of said second segment along a second radial offset from said first radial of said charge tube by an angle ranging between 5 and 180 degrees;

a circular third divider segment disposed within said charge tube below said second segment, said third segment having a first concavity formed in an upper side of said second segment along said second radial of said charge tube;

said second concavities of said second segment and said first concavity of said third segment together defining a second socket aligned with said second radial said charge tube;

a second opening formed through said charge tube centered at said second radial of said charge tube;

a second shaped charge disposed within said second socket; and

a second void formed between said second segment and said third segment.

said first void is operable to receive spall resulting from detonations of said fourth and fifth shaped charges.

19. A well perforator, comprising:

a hollow cylindrical carrier;

a first shaped charge disposed within said carrier;

a circular first segment having a first concavity formed along a first radial of said first segment, said first segment disposed within said housing above said first shaped

charge so that said first concavity of said first segment partially envelops a circumference of said first shaped charge;

a circular second segment having a first concavity formed along a first radial of said first segment, said first segment disposed within said housing below said first shaped charge so that said first concavity of said second segment partially envelops a circumference of said first shaped charge; and

a first spall compartment formed between said first segment and said second segment operable to receive spall resulting from a detonation of said first shaped charge.

20. The perforator of claim 19 further comprising:

a second shaped charge disposed within said housing above said first segment;

a third shaped charge disposed within said housing below said second segment; and

said first spall compartment operable to receive spall resulting from a detonation of said second shaped charge and spall resulting from a detonation of said third shaped charge.

21. The perforator of claim 19 wherein:

said first segment surrounds less than 180 degrees of said circumference of said first shaped charge; and

said second segment surrounds less than 180 degrees of said circumference of said first shaped charge.

22. The perforator of claim 19 further comprising:

a charge tube disposed within said housing, said first and second segments and said first shaped charge captured within said charge tube.

23. The perforator of claim 22 further comprising:

a first debris opening formed through said charge tube in communication with said first spall compartment; and

a debris guard disposed on an outer surface of said charge tube over said first debris opening, said debris guard disposed within said housing.

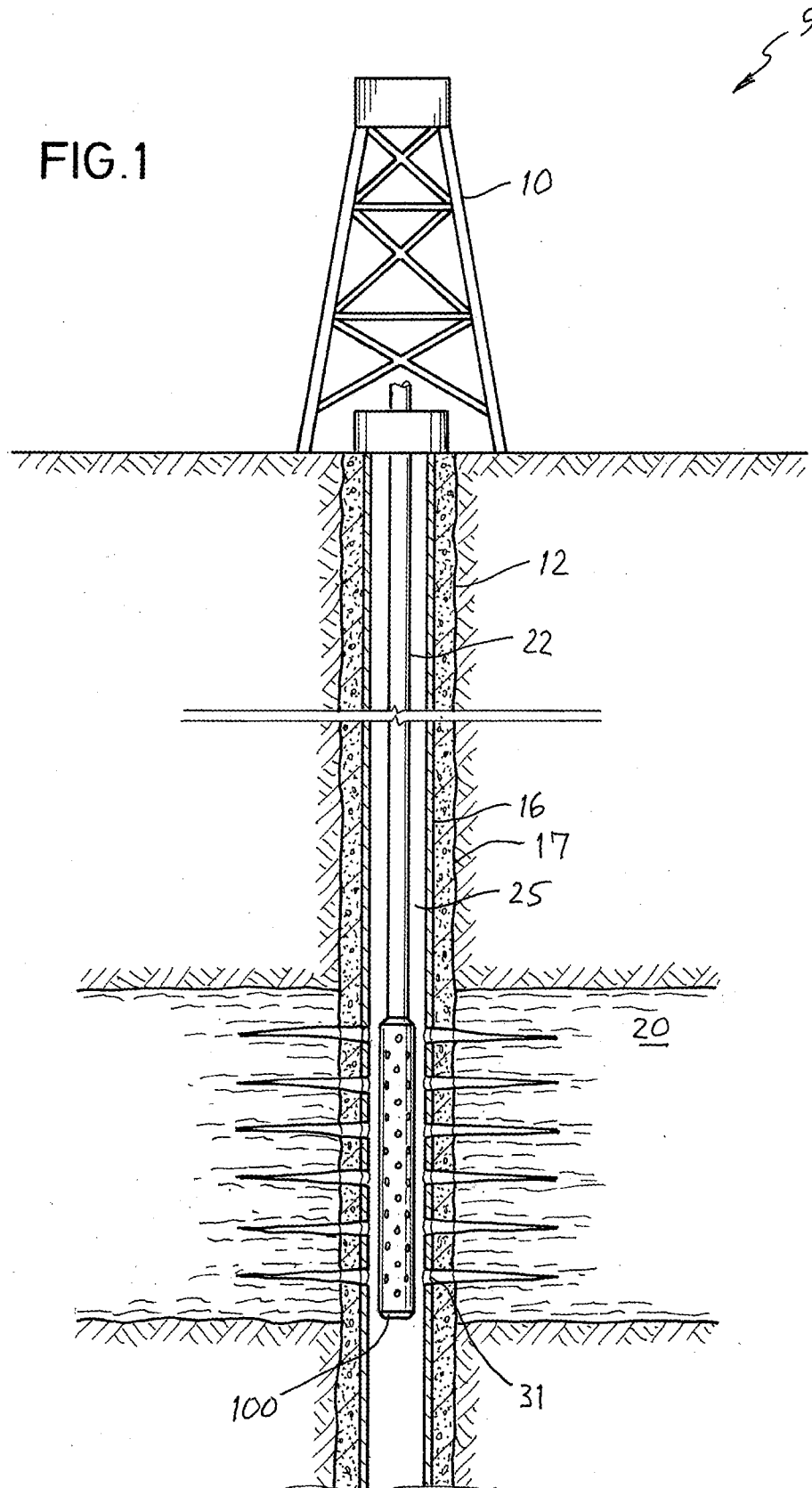
24. A well perforator, comprising:

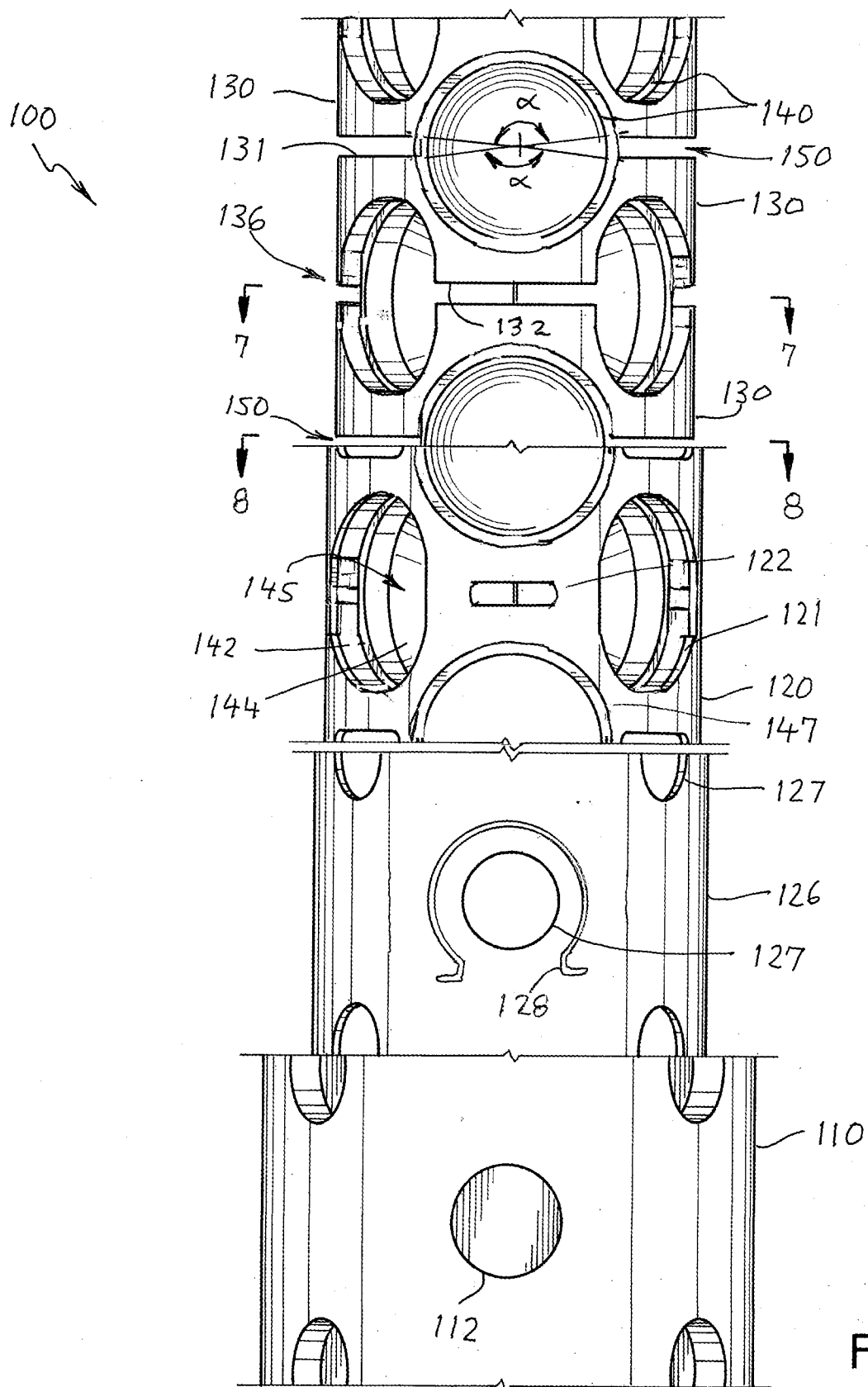
a charge tube;

a plurality of circular segments axially disposed within said charge tube, each segment having an upper side, a lower side, a first concavity formed in said upper side, and a first concavity formed in said lower side, said plurality of circular segments arranged so that said first concavity formed in said upper side of each segment aligns with said first
5 concavity formed in said lower side of an adjacent segment, thereby each pair of adjacent segments forming a socket;

a plurality of shaped charges disposed in said plurality of sockets; and
each adjacent pair of said plurality of segments forming a spall compartment.

FIG.1





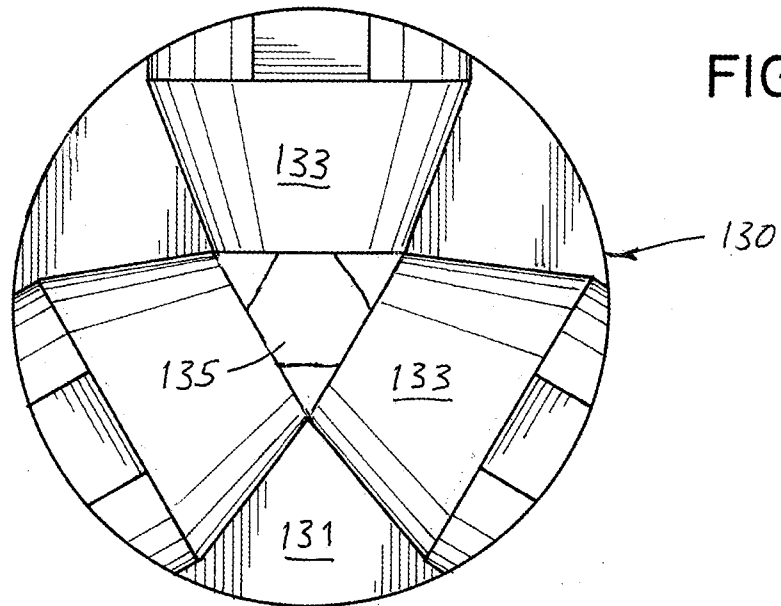


FIG. 4

FIG. 3

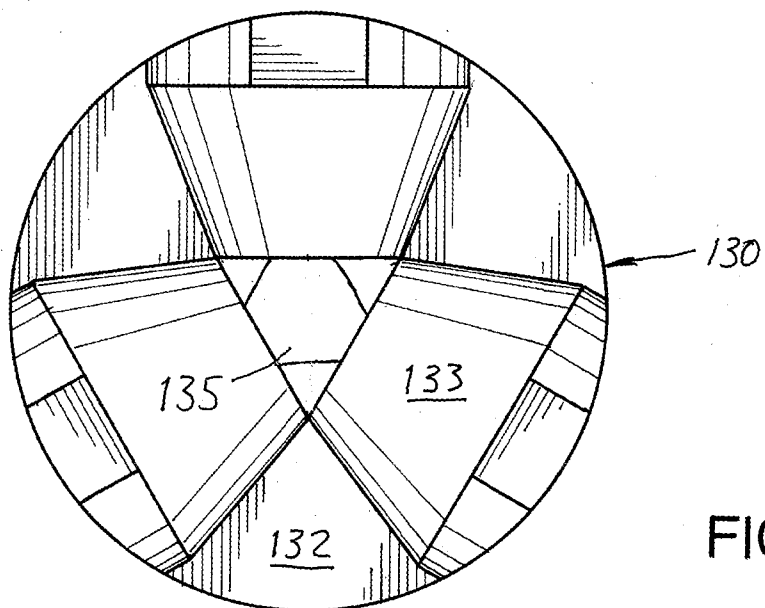
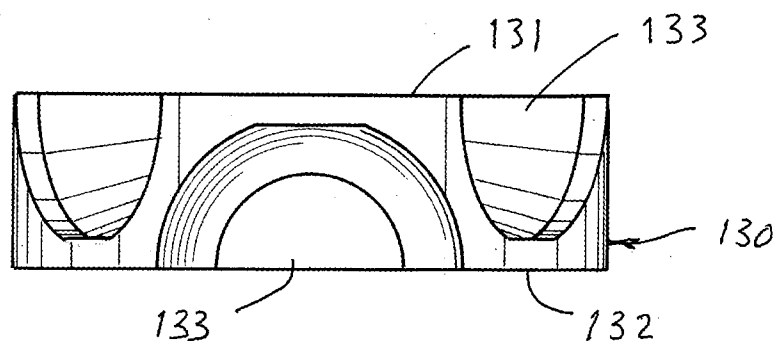


FIG. 5

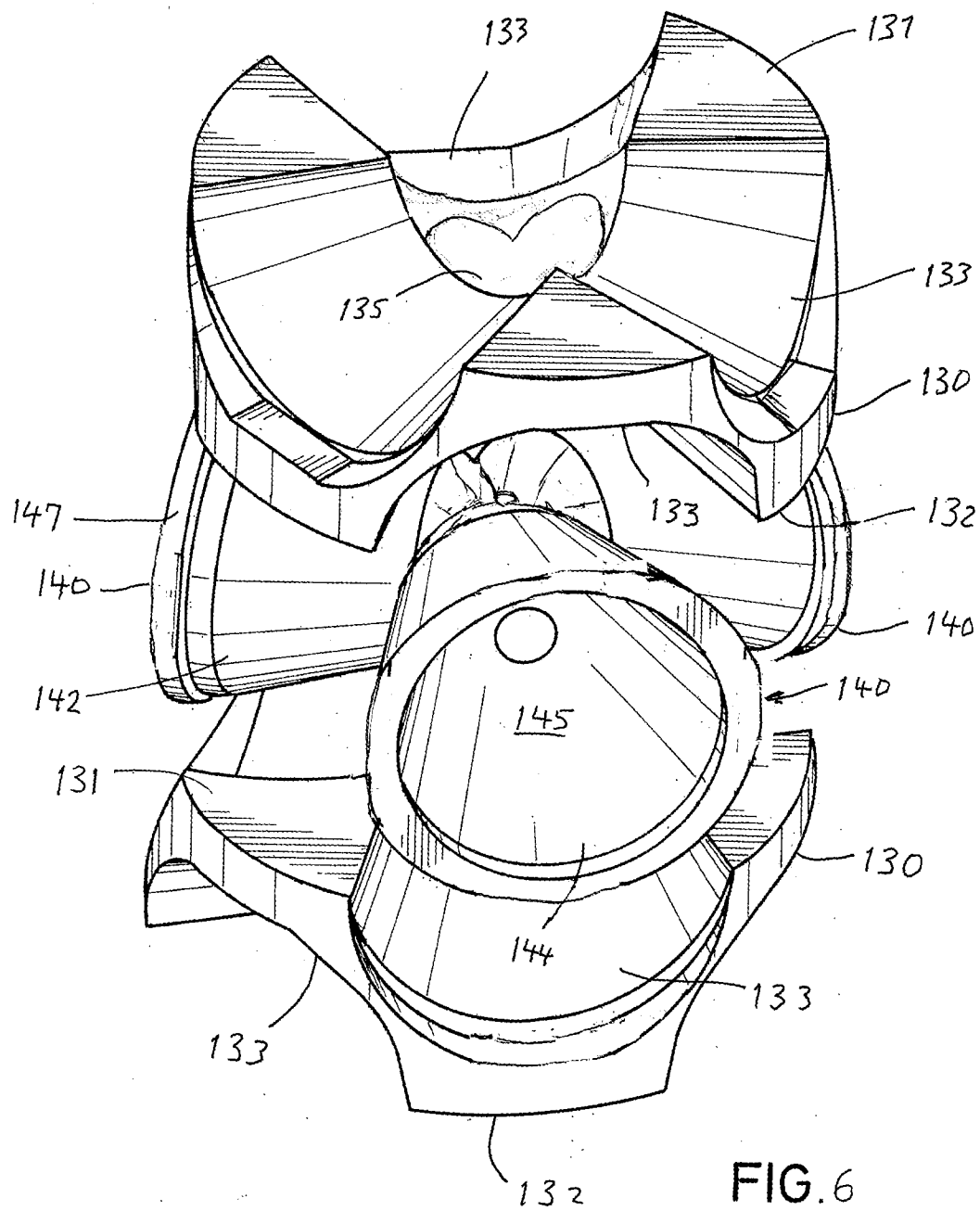


FIG. 6

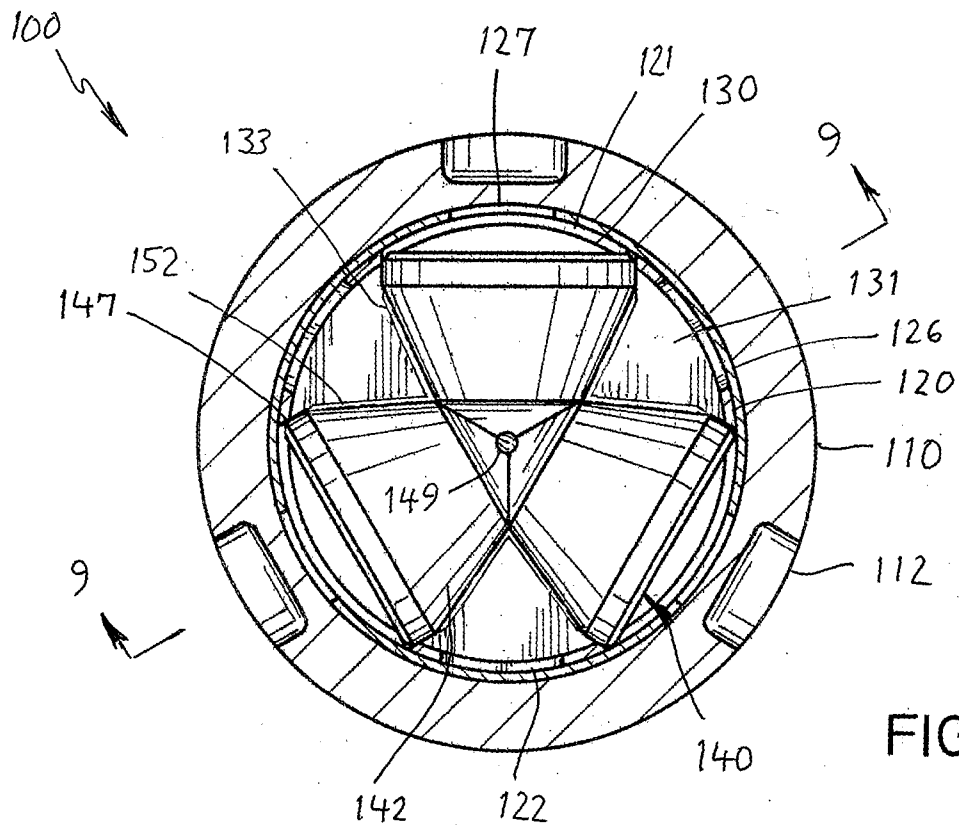


FIG. 7

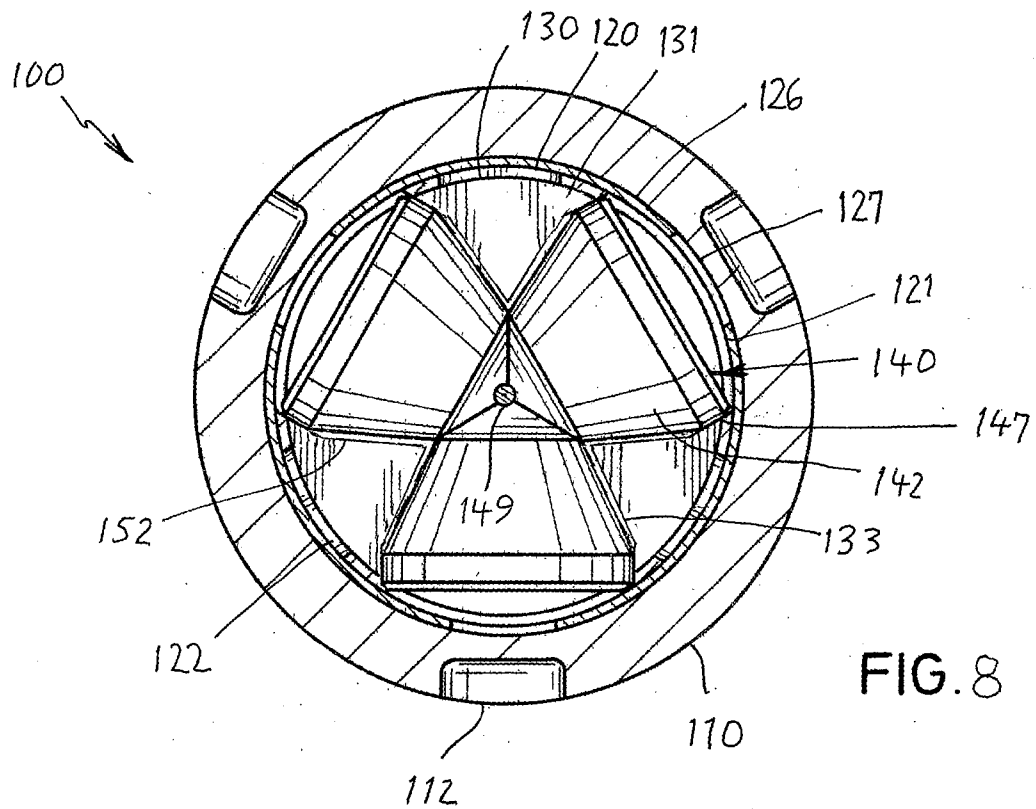


FIG. 8

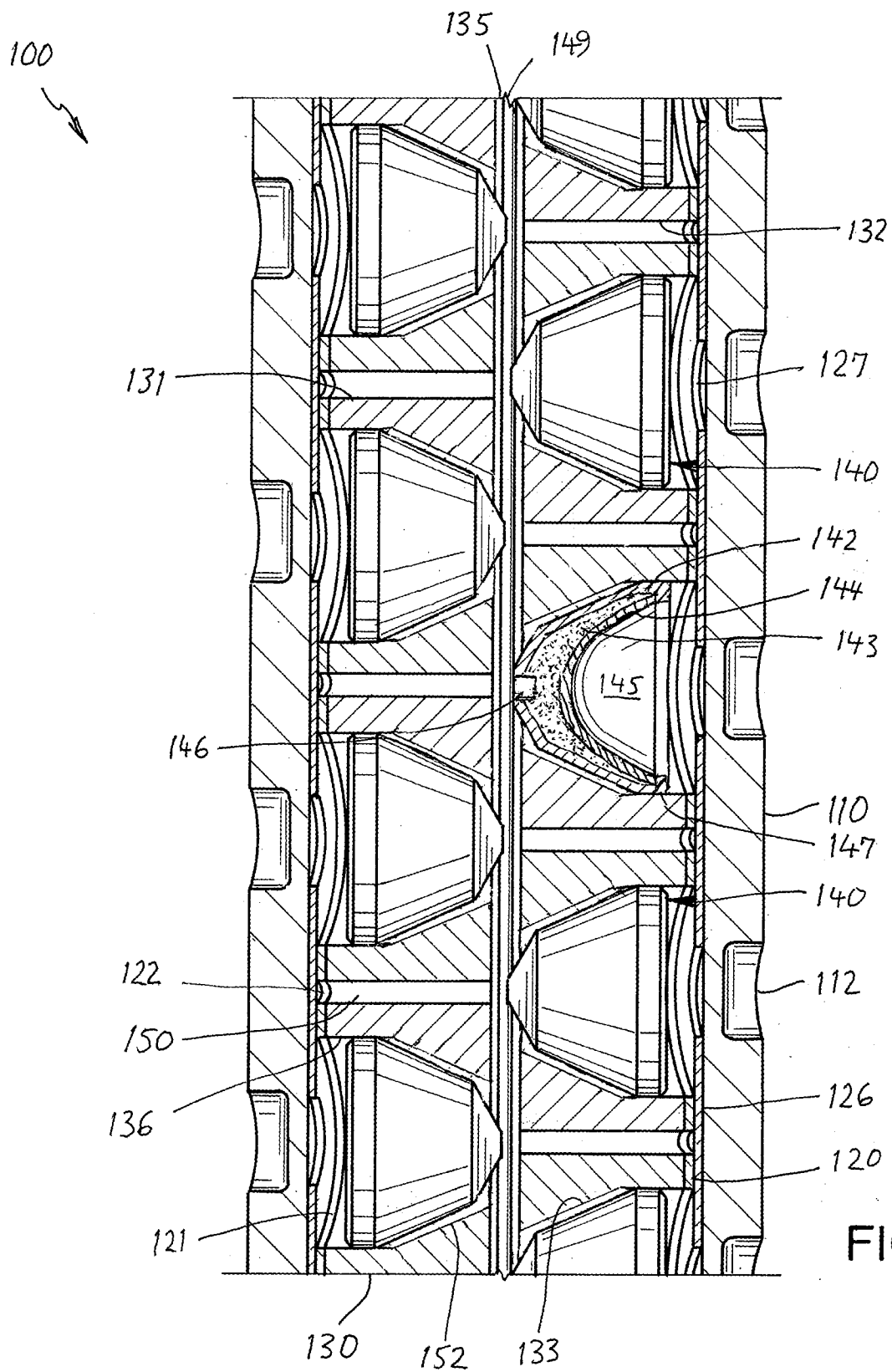


FIG. 9

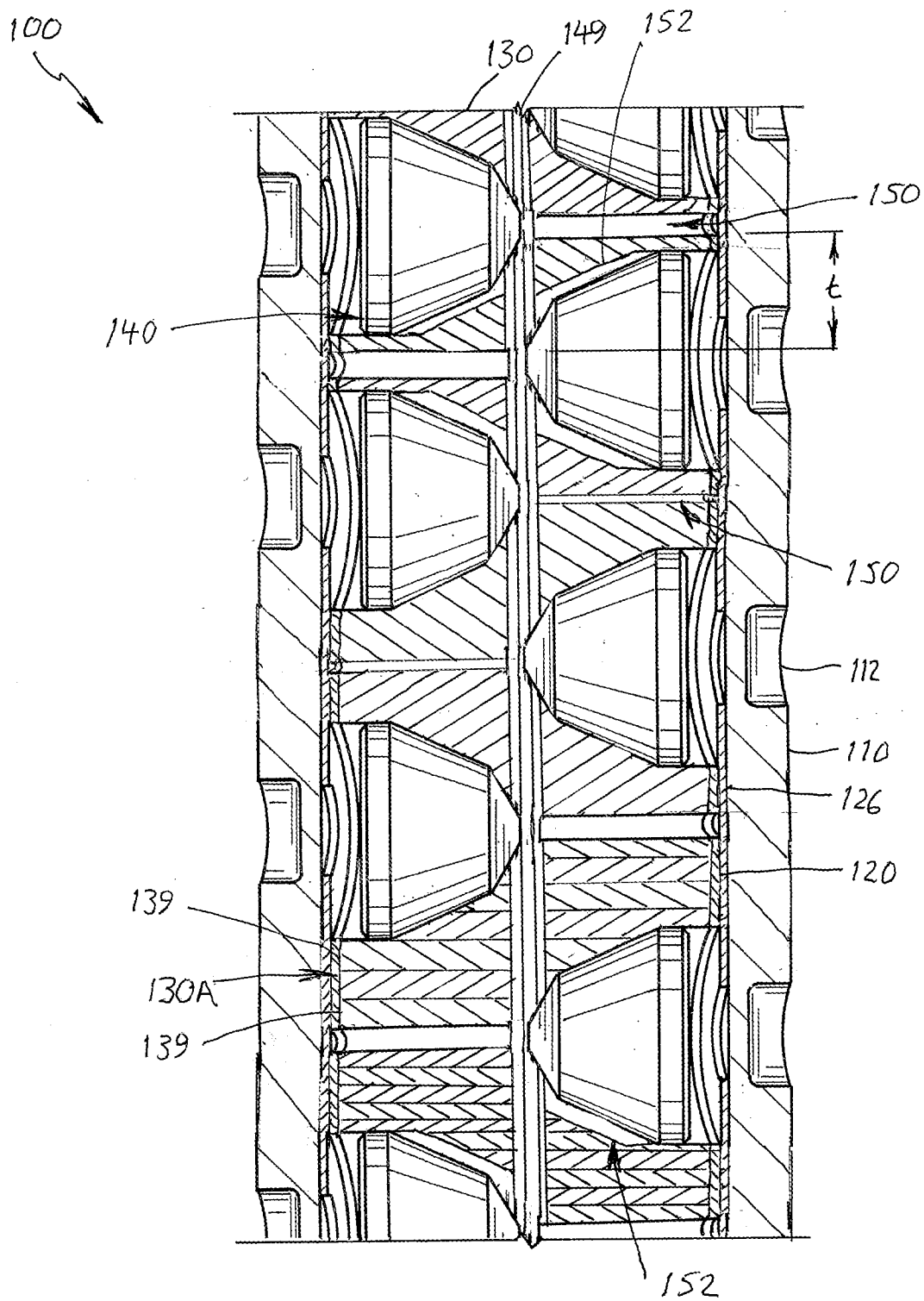


FIG. 10

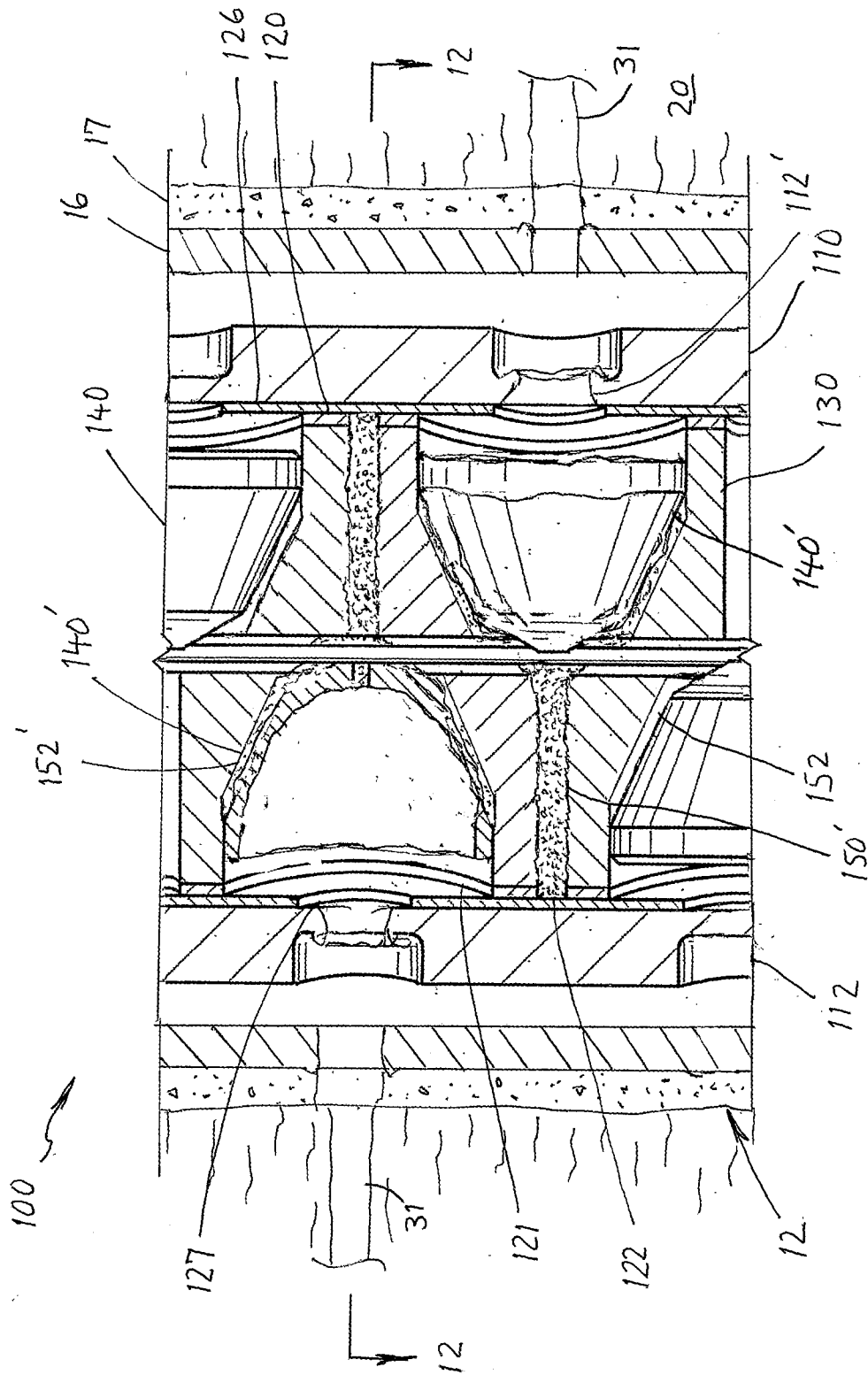


FIG. 11

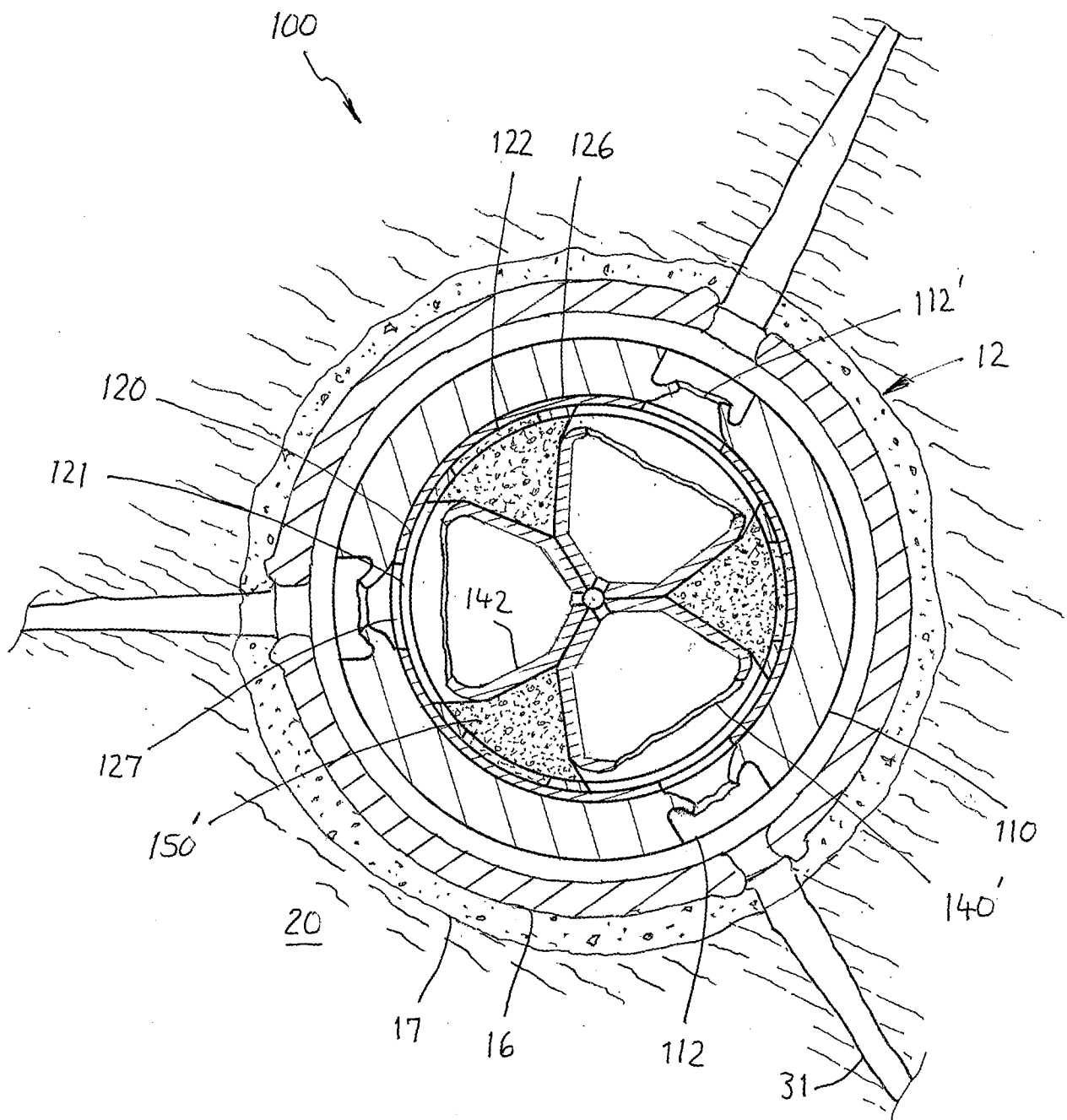


FIG. 12

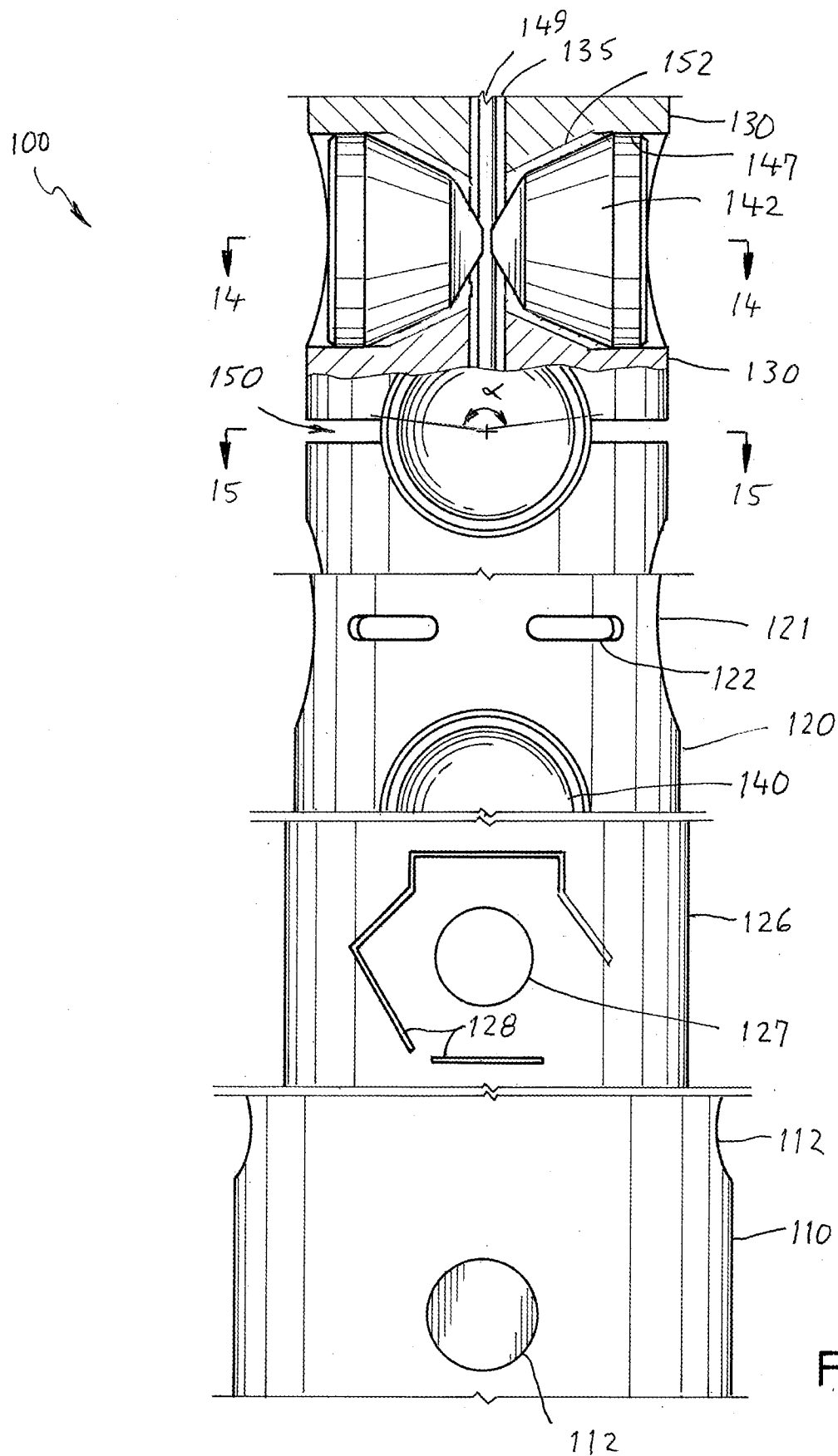


FIG. 13

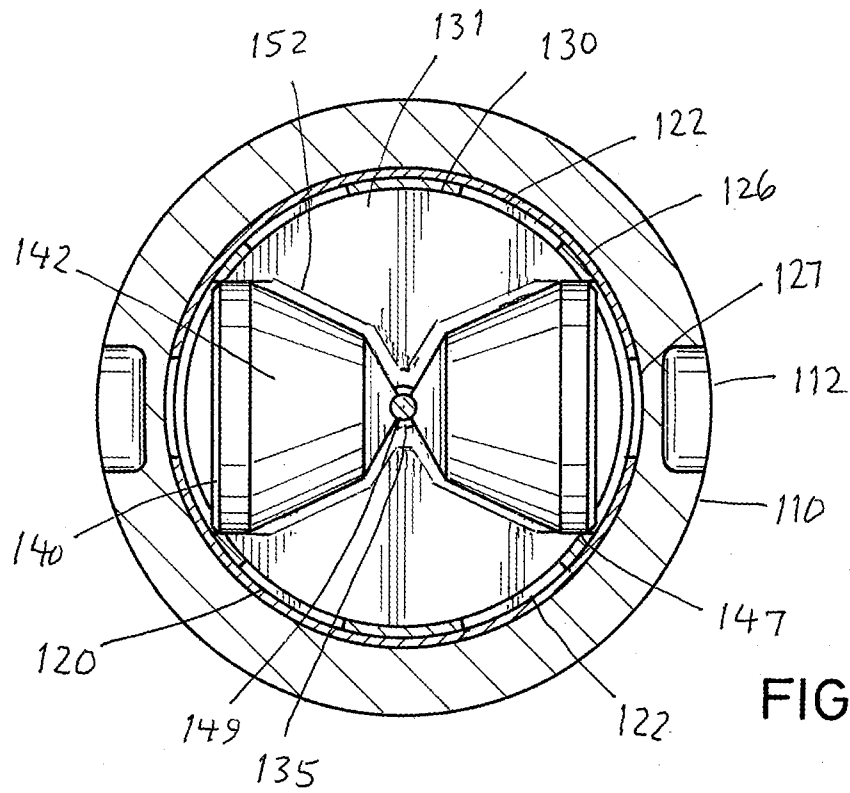


FIG. 14

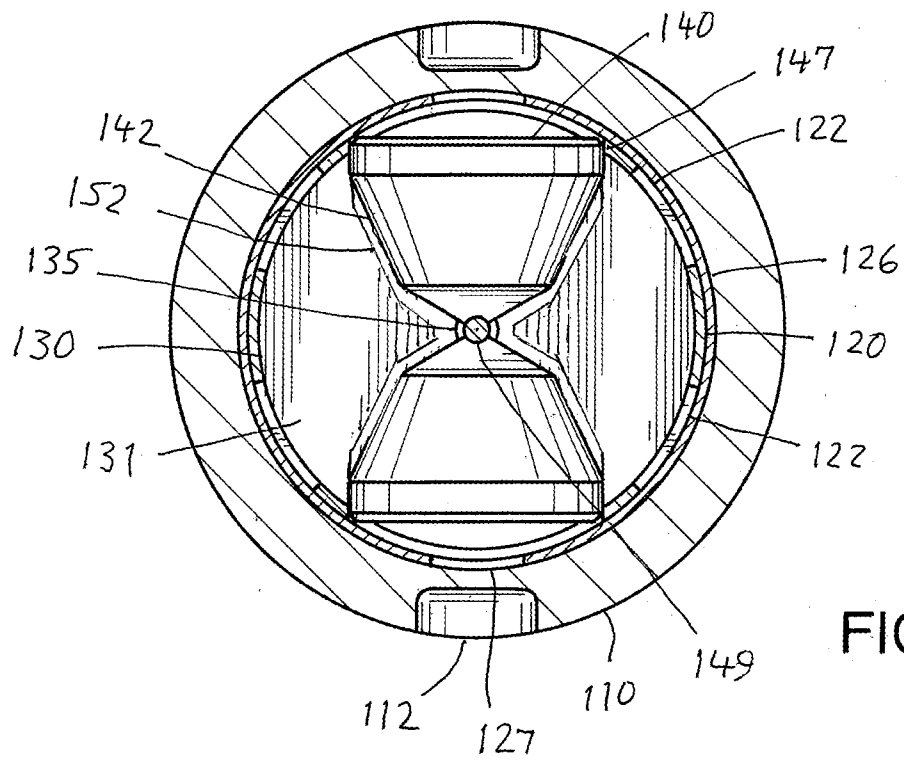


FIG. 15

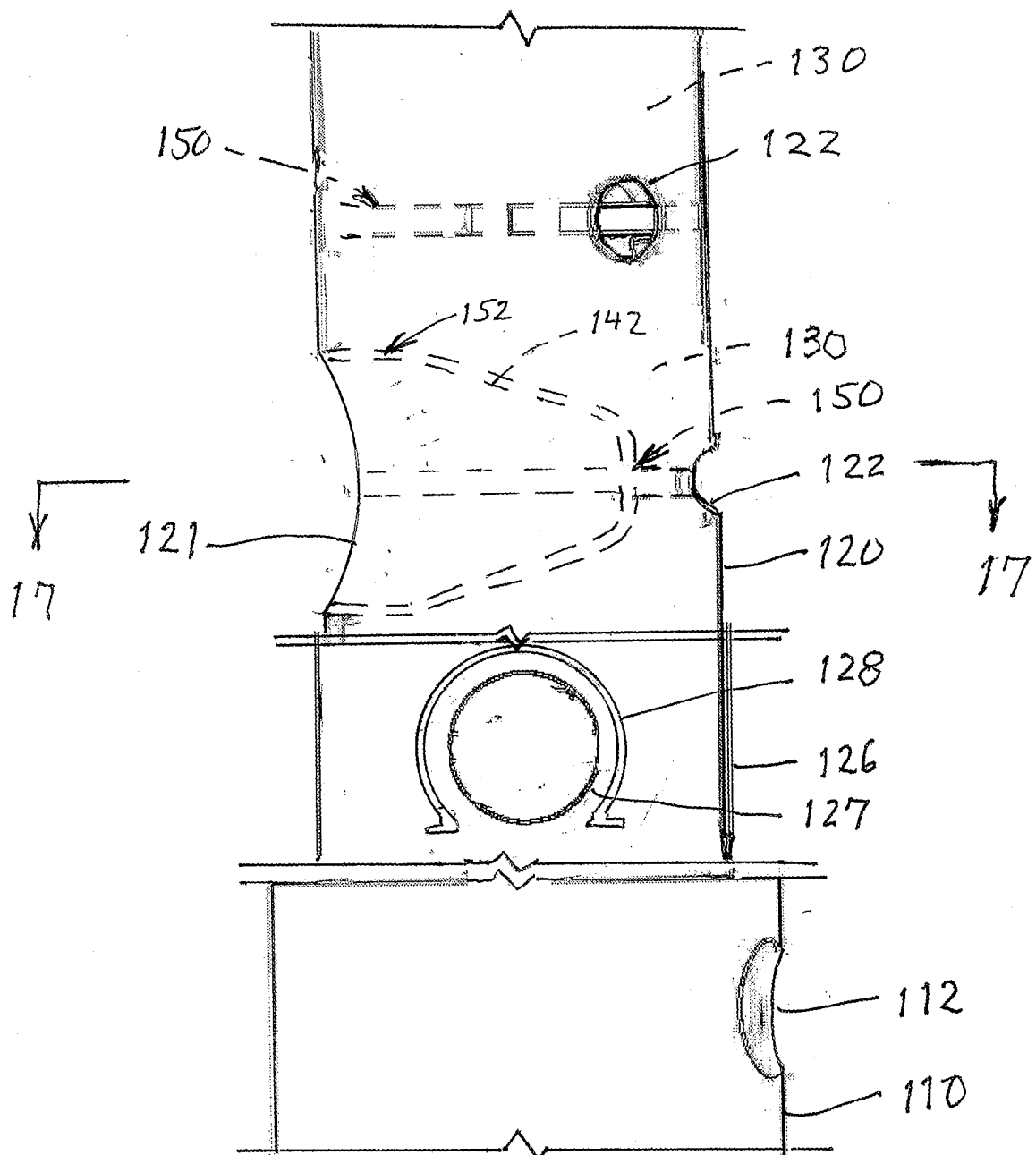


FIG. 16

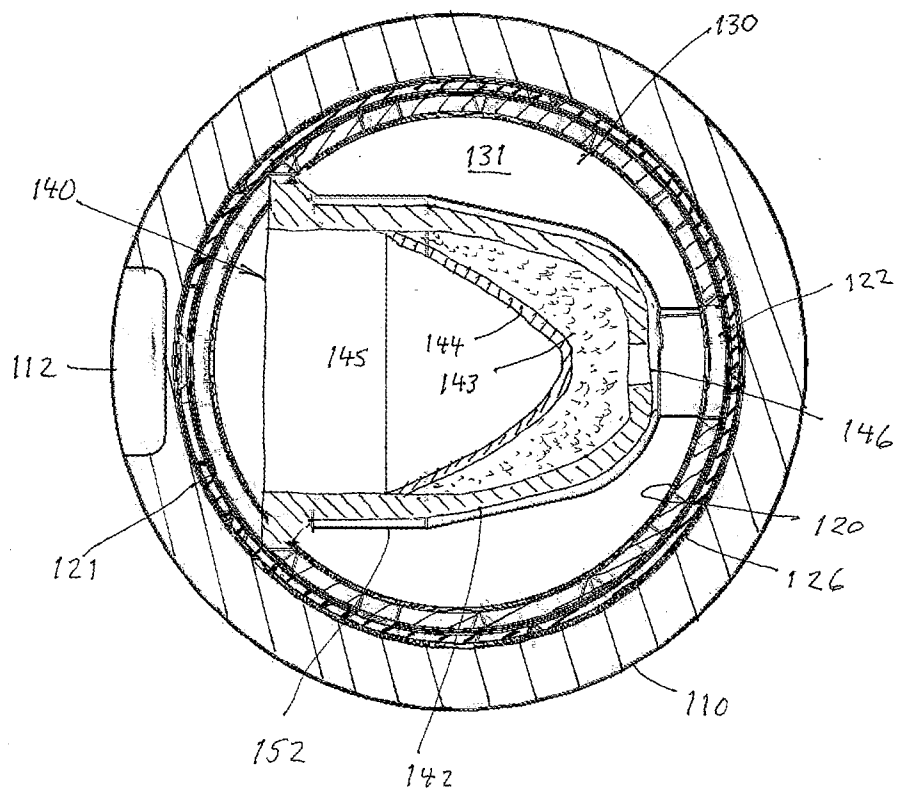


FIG 17

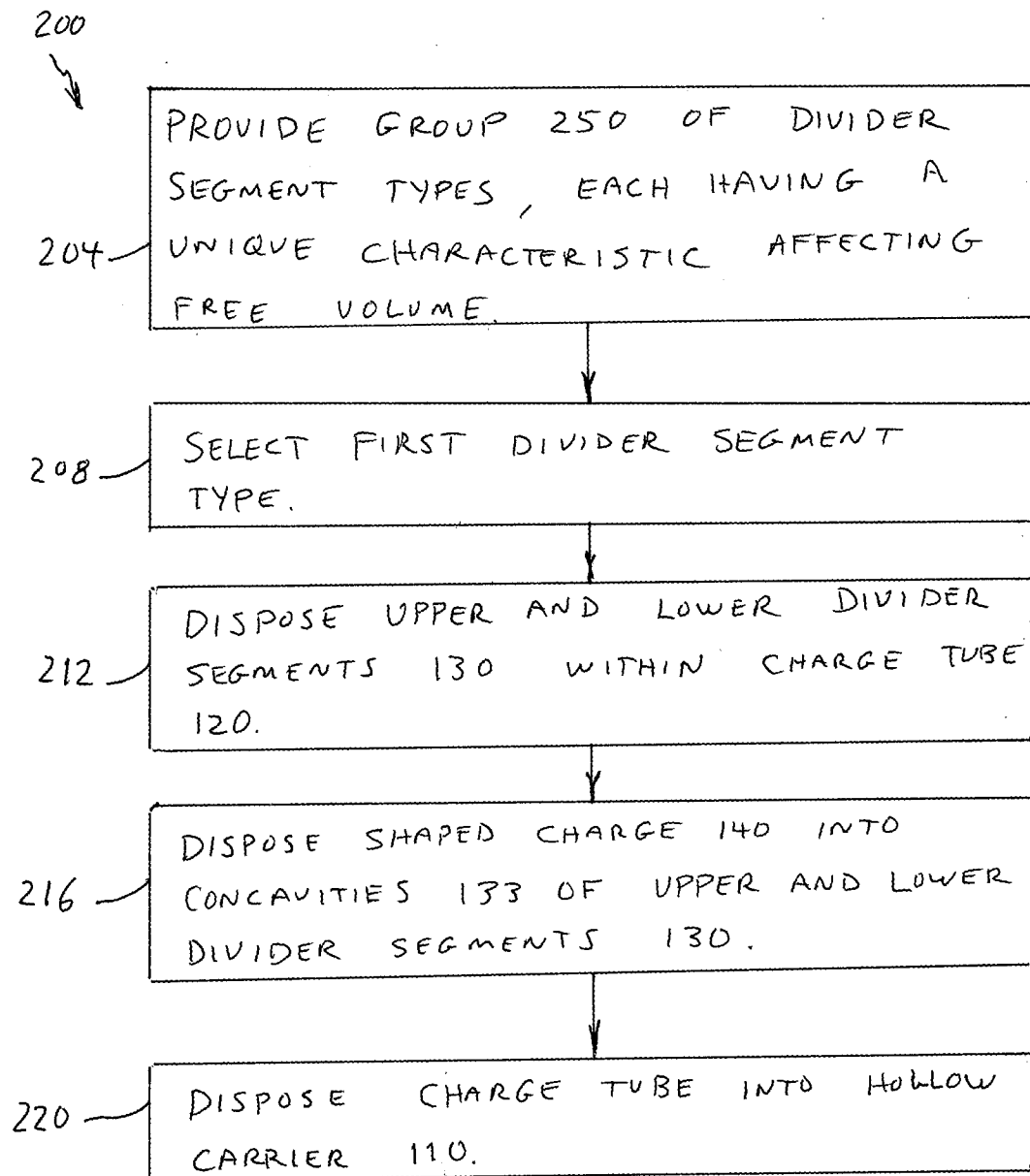


FIG. 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/041128**A. CLASSIFICATION OF SUBJECT MATTER****E21B 43/11(2006.01)I, E21B 43/116(2006.01)I, E21B 43/117(2006.01)I**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 43/11; E21B 43/117; F42B 3/00; F42C 19/12; E21B 43/116

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: charge tube, divider segment, concavity, shaped charge, void, and perforator

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4800815 A (APPLEDORN et al.) 31 January 1989 See abstract, column 3, lines 6-63, and figure 1.	1-24
A	US 5505134 A (BROOKS et al.) 09 April 1996 See abstract, column 10, line 50 - column 11, line 17, and figure 1.	1-24
A	US 4609057 A (WALKER et al.) 02 September 1986 See abstract, column 3, line 10 - column 4, line 60, and figures 1-5.	1-24
A	US 5323684 A (UMPHRIES, DONALD V.) 28 June 1994 See abstract, column 4, lines 6-23, and figure 1.	1-24
A	US 4598775 A (VANN et al.) 08 July 1986 See abstract, column 5, line 24 - column 6, line 57, and figures 2-4.	1-24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

24 August 2016 (24.08.2016)

Date of mailing of the international search report

24 August 2016 (24.08.2016)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

HAN, JOONG SUB

Telephone No. +82-42-481-3578



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/041128

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4800815 A	31/01/1989	CA 1314765 C EP 0281361 A2 EP 0281361 A3 EP 0281361 B1 US 4915029 A	23/03/1993 07/09/1988 22/03/1989 10/02/1993 10/04/1990
US 5505134 A	09/04/1996	CA 2145740 A1 CA 2145740 C CA 2599056 A1 CA 2599056 C EP 0651229 A2 EP 0651229 A3 EP 0651229 B1 EP 0675262 A1 EP 0675262 B1 GB 2288005 A US 5347929 A	30/09/1995 18/12/2007 30/09/1995 01/06/2010 03/05/1995 02/11/1995 15/10/1997 04/10/1995 17/11/1999 04/10/1995 20/09/1994
US 4609057 A	02/09/1986	None	
US 5323684 A	28/06/1994	None	
US 4598775 A	08/07/1986	None	