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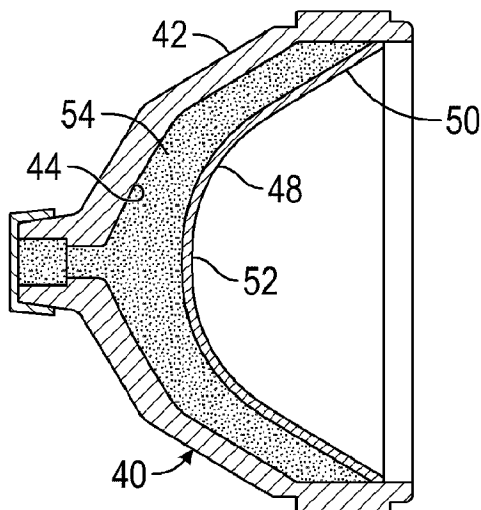
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A method for completing an unconventional subterranean formation include the steps of positioning a perforating tool in a section of the deviated wellbore that intersects the unconventional formation, forming at least one opening in a production structure without substantially penetrating into a surrounding formation by firing the perforating tool, and fracturing the formation by pumping a fracturing fluid through the at least one opening. The perforating tool may include shaped charges that have a charge case, a liner disposed in the charge case, and an explosive material filling an interior of the charge case.

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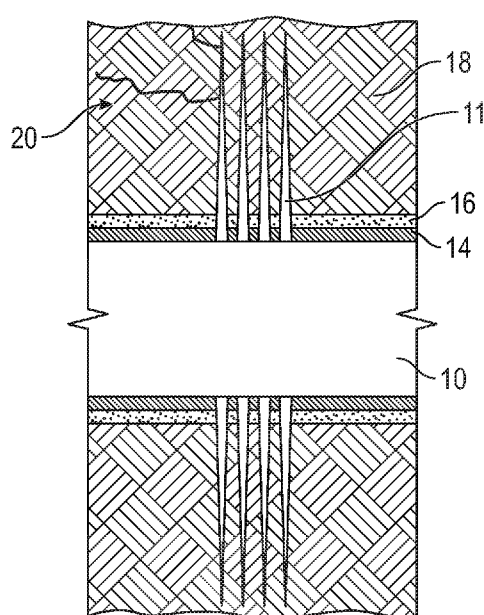


FIG. 1

(57) Abstract: A method for completing an unconventional subterranean formation include the steps of positioning a perforating tool in a section of the deviated wellbore that intersects the unconventional formation, forming at least one opening in a production structure without substantially penetrating into a surrounding formation by firing the perforating tool, and fracturing the formation by pumping a fracturing fluid through the at least one opening. The perforating tool may include shaped charges that have a charge case, a liner disposed in the charge case, and an explosive material filling an interior of the charge case.

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**TITLE: LIMITED PENETRATION PERFORATING METHODS
FOR OILFIELD APPLICATIONS**

BACKGROUND OF THE DISCLOSURE

1. Field of Disclosure

[0001] The present disclosure relates to an apparatus and method for completing a well.

2. Description of the Related Art

[0002] Hydrocarbon producing wells typically include a casing string positioned within a wellbore that intersects a subterranean oil or gas deposit. The casing string increases the integrity of the wellbore and provides a path for producing fluids to the surface. Conventionally, completing a well involves cementing the casing to the wellbore face and subsequently perforating the formation by detonating shaped explosive charges. When detonated, the shaped charges generate a jet that penetrates through the casing and cement and forms a tunnel of a short distance into the adjacent formation. A perforating tunnel may be a principal source of tortuosity in the unconventional, hydraulically fractured reservoir. Perforating may also create micro fracturing in the near well bore, which can create thief zones that take away from the desired areas for fracking, where natural fractures occur. Tortuosity and thief zones can significantly impair flow of production fluids out of the formation.

[0003] Referring to **FIG. 1**, there is shown a section of a wellbore **10** that has been completed in a conventional manner. Tunnels **11** formed by a perforating tool penetrate through a wellbore tubular **14**, such as casing, and a surrounding cement sheath **16**, and extended a certain distance, up to eight inches or more, into a formation **18**. For simplicity, the wellbore tubular **14** and the cement sheath **16** may

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be referred to as a "production structure." The production structure may also include other production equipment installed in the well. The formation **18** may be an unconventional formation, such as shale. With this prior art technique, the location and orientation of the cracks / fractures caused during the hydraulic fracturing activity may be induced to occur proximate to the tunnels **11**. Fractures **20** illustrate how such fractures may be located and oriented. However, the location and orientation of such fractures may not be best suited for efficient fluid flow due to tortuosity and the creation of thief zones.

[0004] The present disclosure departs from conventional perforating techniques by minimizing or eliminating the creation of tunnels in a formation.

SUMMARY OF THE DISCLOSURE

[0005] In aspects, the present disclosure provides a method for completing an unconventional subterranean formation. The method may include the steps of positioning a completion tool in a deviated section of the wellbore that intersects the unconventional formation, forming at least one opening in a production structure without substantially penetrating into a surrounding formation by activating the completion tool; and fracturing the formation by pumping a fracturing fluid through the at least one opening.

[0006] In aspects, the present disclosure further provides a perforating tool for performing the disclosed completion operations. The perforating tool may include shaped charges that have a charge case, a liner disposed in the charge case, and an explosive material filling an interior of the charge case. In one arrangement, the liner has an inner concave surface and an outer concave surface. An angle defining the inner concave surface may be less than an angle defining the outer concave surface.

[0007] The above-recited examples of features of the disclosure have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional features of the disclosure that will be described hereinafter and which will form the subject of the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For detailed understanding of the present disclosure, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

FIG. 1 is a schematic sectional view of a portion of a horizontal well that is perforated and fractured in a conventional manner;

FIG. 2A is a schematic sectional view of a portion of a horizontal well that is perforated according to one embodiment of the present disclosure;

FIG. 2B is a schematic sectional view of the **FIG. 2A** well portion that is being fractured;

FIG. 3 is a sectional view of a shaped charge made in accordance with one embodiment of the present disclosure; and

FIGS. 4A-C are sectional views of shaped charge liners made in accordance with embodiments of the present disclosure; and

FIG. 5 is a schematic sectional view of one embodiment of an apparatus of the present disclosure as positioned within a well penetrating a subterranean formation.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0009] Aspects of the present disclosure provide methods and related perforating tools for completing unconventional formations, such as hydrocarbon-bearing shale formations. For the present disclosure, an "unconventional" formation is generally a formation that has a permeability that is less than ten millidarcy (mD). Many "unconventional" formations have a permeability between one nano-darcy (nD) and one millidarcy (mD). Contrary to traditional perforating techniques, perforating tools according to the present disclosure are designed to only open holes in the well tubulars and surrounding cement sheathing. The rock and earth surrounding the wellbore is only minimally, at most, impacted by the perforating jets generated by the perforating tool. Thus, there may be a significant reduction, if not elimination, of tortuosity and instances of micro fractures. Thus, by leaving the formation face largely intact, the effectiveness of subsequent hydraulic fracturing operations may be improved.

[0010] The perforating and fracturing methodologies of the present disclosure are illustrated with reference to **Figs. 2A** and **2B**. In **FIG. 2A**, there is shown a section of a wellbore **10** that has been perforated according to embodiments of the present disclosure. A perforating gun **140**, the details of which are described below, has formed openings **22** that penetrate through the production structure (*i.e.*, wellbore tubular **14** and the cement sheath **16**) but do not extend into the formation **18**. Practically speaking, in some instances, a tunnel **11** (**Fig. 1**) may extend from one or more openings **22** an insubstantial distance into the formation **18**. For the purposes of the present disclosure, a penetration distance in the formation **18** that no greater than three inches is defined a "non-substantial" penetration length. In some applications, a "non-substantial" penetration length is no greater than two inches.

[0011] **Fig. 2B** illustrates a subsequent fracturing activity wherein a pressurized fracturing fluid **30** is directed into the openings **22**. It should be noted that the fracturing fluid **30** acts on a face **32** of the formation **18** that is immediately next to the cement sheath **16**. The face **32** of the formation **18** is the circumferential surface that defines the wellbore **10**. The pressure associated with hydraulic fracturing may now cause the formation to separate at naturally weaker locations in the vicinity of the

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openings **22**. This may lead to fractures that better align with the opening **22**. That is, the fractures have fluid connections with the opening **22** that promotes fluid flow with reduced resistance to flow. Fractures **34** illustrate how such fractures may be located and oriented.

[00012] The perforating openings **22** of **Figs. 2A** and **B** may be formed by using perforating tool having shaped charges specially configured for limited perforation. In embodiments, at least three aspects of a shaped charge may be configured to limit the distance a perforating jet travels: the materials making up a shaped charge liner, the shape of the shaped charge liner, and the explosive mix of the shaped charge.

[00013] Referring to **FIG. 3**, there is shown a cross section of an explosive shaped charge **40**. The shaped charge **40** has a charge case **42**. The charge case **42** has an interior surface or wall **44** that defines a hollow interior of the charge case **42**. The charge case **42** is open at the outer end and tapers inward. Disposed within the interior of the case **42** is a liner **48**. The liner **48** tapers inward from a base **50**, located at the outer end, to a nose portion **52**. The liner **48** is open at the base **50** and has a hollow interior. Disposed between the liner **48** and interior wall **44** of the casing **42** is an explosive material **54**. The explosive material **54** extends from the interior of the case **42** through channel formed in the innermost end of the case **42**. The case **42** receives a detonating cord (not shown) for detonating the explosive material **54**.

[00014] One factor affecting depth of penetration is the material making up the liner **48**. Conventionally, materials that tend to form a dense and compacted perforating jet are favored because of the traditional emphasis on depth of penetration. Embodiments of the present disclosure use materials that form a perforating jet that is less dense and relatively diffuse. Such a perforating jet exhausts energy while perforating the production structure and has insufficient mass to displace the formation. The liner **48** may be formed of materials such as aluminum, zinc, molybdenum, copper, magnesium, or other low density materials. In embodiments, the liner may also include low density materials such as thermoplastic polymers (PTFE, UHMW, etc).

[00015] Another factor effecting depth of penetration is liner shape or geometry. Liner shape can influence how and when the energy released by the explosive material interacts with the liner **48**. For example, the liner **48** formed as a shallow

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bowl may form a perforating jet that is wider and flatter than a liner having an acute conical shape. Also, the liner may use shapes such as a truncated, parabolic, plugged apex, near EFP angled liner.

[00016] Referring now to **Figs. 4A-C**, there are shown non-limiting embodiments of liners **48** that may limit penetration to only the production structure. In **Fig. 4A**, the liner **48** has an inner concave surface **51** and an outer concave surface **53**. The inner concave surface **51** is defined by an angle **56** that is less than an angle **55** defining the outer concave surface **53**. For example, the angle **55** may be one to ten degrees greater than angle **56**. Illustrative non-limiting angle pairs may be: 80 degrees for angle **56** and 82 degrees for angle **55**, 82 degrees for angle **56** and 83 degrees for angle **55**, 85 degrees for angle **56** and 88 degrees for angle **55**, 90 degrees for angle **56** and 91 degrees for angle **55**, etc. In certain embodiments, the angle **56** defining the inner concave surface may be between one and two degrees less than an angle **55** defining the outer concave surface. Additionally, an apex **60** of the liner **48** may have a thickness that is greater than any other thickness of the liner **48**.

[00017] A variant of the **Fig. 4A** embodiment is that the angle **56** is greater than the angle **55**. For example, the angle **55** may be one to ten degrees less than angle **56**. Illustrative non-limiting angle pairs may be: 80 degrees for angle **55** and 82 degrees for angle **56**, 82 degrees for angle **55** and 83 degrees for angle **56**, 85 degrees for angle **55** and 88 degrees for angle **56**, 90 degrees for angle **55** and 91 degrees for angle **56**, etc. In certain embodiments, the angle **55** defining the inner concave surface may be between one and two degrees less than an angle **56** defining the outer concave surface.

[00018] Thus, generally, the angle **55** defining the inner concave surface may be between one and two degrees different from the angle **56** defining the outer concave surface.

[00019] In **Fig. 4B**, the liner **48** has an inner surface **70** and an outer surface **72**, both of which are defined by composite geometries. The inner surface **70** has an outer convex section **74** and an inner concave section **76**. Likewise, the outer surface **72** has an outer convex section **78** and an inner concave section **80**. Inflexion point **82**, **84** for the inner and outer surfaces **70**, **72** can be positioned at a midpoint or closer to the apex **60**.

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[00020] In Fig. 4C, the liner 48 has an inner concave surface 90 and an outer concave surface 92. The inner concave surface 90 is defined by an angle 94 that is greater than an angle 96 defining the outer concave surface 92. For example, the angle 94 may be one to ten degrees greater than angle 96. Illustrative non-limiting angle pairs may be: 81 degrees for angle 96 and 84 degrees for angle 94, 83 degrees for angle 96 and 85 degrees for angle 94, 88 degrees for angle 96 and 91 degrees for angle 94, 90 degrees for angle 96 and 93 degrees for angle 94, etc. In embodiments, the angle defining the inner concave surface is between one and two degrees less than an angle defining the outer concave surface. Additionally, an apex 60 of the liner 48 may have a thickness that is greater than any other thickness of the liner 48, the thickness being the distance separating the surfaces 90, 92. The thickness may be a multiple of the thickness of the immediately adjacent liner sections. The multiple may be between two to fifteen times.

[00021] In addition to liner configuration and materials, the explosive material 54 may be formulated to generate a perforating jet that has limited perforation capabilities. Traditional explosive compositions seek to shape and propel the perforating jet to have maximum penetration ability. In accordance with the present disclosure, the explosive material 54 may include compositions that release an amount of energy, in the form of shock waves and heat that lower the detonation velocity, which then lowers jet speed. For example, the explosive material 54 can include inert or energetic additives that lower the overall energy density or include energy reducing additives at selected locations in the charge case 42. Illustrative explosive materials include RDX (Hexogen, Cyclotrimethylenetrinitramine), HMX (Octagon, Cyclotetramethylenetetranitramine), CLCP, HNS, and PYX.

[00022] Further, the charge case 42 may have a shape or geometry selected to limit effective "backup," which can then reduce the amount of energy imparted on the liner 48. The reduction in energy can lead to slower jet velocities and less penetration. The charge case 42 may be formed of steel, aluminum, zinc, metal alloys, non-metal composites, glass, etc. The material may be solid or powdered metal. The charge case 42 may also include features designed to limit penetration by interrupting the formation of a portion of the jet.

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[00023] The above perforating tools may be used to complete a hydrocarbon producing well. Referring to **FIG. 5**, there is shown a well construction and/or hydrocarbon recovery facility **100** positioned over a subterranean formation of interest **102**. The formation **102** is an unconventional formation. The facility **100** can include known equipment and structures such as a rig **106** and a production structure **108**. The production structure **108** can include casing, liners, cement, and other wellbore equipment. A work string **110** is suspended within a wellbore **10** from the rig **106**. The work string **110** can include drill pipe, coiled tubing, wire line, slick line, or any other known conveyance means. The work string **110** can include telemetry lines or other signal/power transmission mediums that establish one-way or two-way telemetric communication. A telemetry system may have a surface controller (e.g., a power source) **112** adapted to transmit electrical signals via a suitable cable or signal transmission line.

[00024] A perforating gun **140** is shown in a deviated section **142** of the wellbore **10**. By deviated, it is meant a section of the wellbore **10** is not vertical. The deviation from a vertical datum can be between one to ninety degrees (horizontal) or greater in some instances. In embodiments, the deviation may be greater than thirty degree, greater than forty five degree, or greater than sixty degrees. By way of reference, a deviation less than ninety degrees would have the section **142** pointed downward and a deviation greater than ninety degrees would have the section **142** pointed upward. By "pointed," it is meant the direction along which the wellbore **10** was drilled.

[00025] When fired, the perforating gun **140** creates one or more openings **22** as shown in **Fig. 2A**. The nature of the unconventional formation **102** is that the rock and earth, which is usually a type of shale, is highly non-permeable. Therefore, fluids residing in the formation **102** will not flow to the openings **22** at any meaningful flow rate. To promote fluid flow, a fracturing operation is performed in a conventional manner; *i.e.*, by pumping a fracturing fluid at a specified pressure via the work string **110** to the openings **22**. Because the openings **22** do not extend into the formation, the permeability of the formation has not be adversely affected during the perforating activity. Thus, the pressure applied by the fracturing fluid has a greater likelihood of causing fractures at naturally weaker locations along the face of the formation **102**.

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[00026] By way of a non-limiting example, an illustrative working example of a shaped charge configured to form the opening **22** of **Figs. 2A** and **2B** is described below. As noted above, at least three aspects of a shaped charge may be varied to obtain the openings **22**: (i) the materials making up a shaped charge liner, (ii) the shape of the shaped charge liner, and (iii) the explosive mix of the shaped charge.

[00027] The exemplary shaped charge was configured to open an hole of a production structure formed of a steel tubular and having a thickness of 0.361 inches. The cement has a thickness of 1.5 inches. A liner generally as shown in **FIG. 4A** included the following materials; aluminum, zinc, molybdenum, copper, and magnesium. The angle of the liner inner surface **56** was 90° and the liner outer surface **55** was 91°. The explosive mix included RDX.

[00028] The size of the opening **22** was 0.38 inches in diameter, with 1.13 inches penetration into the stressed shale formation. In embodiments, this technology is designed so that the depth of penetration into the formation is no more than three times the hole size diameter. Conventional perforating charges in the same working example above have penetration values 7 inches or greater into the formation.

[00029] In different aspects, the methods of completing an unconventional formation intersected by a deviated wellbore may use completion equipment other than a perforating gun. Any completion tool configured to form an opening **22** while forming a tunnel **11** having an insubstantial length may be used. For example, a milling tool or a sidewall drilling assembly may be used to form the openings **22** in the production structure. An illustrative completion assembly may utilize an electric or hydraulic motor to provide rotary power to a drill bit. Another hole opening completion tool may utilize an abrasive fluid stream. For example, a high pressure fluid source may supply the abrasive fluid to a nozzle. The nozzle can form a fluid jet that erodes the material making up the wellbore tubular to form the opening **22**.

[00030] The foregoing description is directed to particular embodiments of the present disclosure for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiment set forth above are possible without departing from the scope of the disclosure. Thus, it is intended that the following claims be interpreted to embrace all such modifications and changes.

What is claimed is:

1. A method for completing an unconventional subterranean formation, comprising:
 - positioning a completion tool in a section of the wellbore that intersects the unconventional formation, wherein the formation is formed at least of shale and has a permeability that is between one nano-darcy (nD) and one millidarcy (mD), and wherein the wellbore is deviated from a vertical datum by at least sixty degrees, wherein the completion tool is a perforating tool that includes at least one shaped charge, wherein the at least one shaped charge includes a charge case, a bowl shaped liner disposed in the charge case, and an explosive material filling an interior of the charge case, wherein the liner has an inner concave surface and an outer concave surface;
 - forming at least one opening in a production structure using the at least one shaped charge, wherein the at least one shaped charge is configured to penetrate a depth through the production structure a distance that is less than or equal to three times a diameter of the at least one opening; and
 - fracturing the formation by pumping a fracturing fluid through the at least one opening.
2. The method of claim 1, wherein the production structure includes a steel tubular and a surrounding cement sheath.
3. The method of claim 1, wherein an angle defining the inner concave surface is between one to ten degrees different from an angle defining the outer concave surface.
4. The method of claim 3, wherein the angle defining the inner concave surface is between one and two degrees less than the angle defining the outer concave surface.
5. The method of claim 1, wherein the bowl shaped liner is parabolic, and the wherein: an angle defining the outer concave surface is between eighty and ninety-one degrees, an angle defining the inner concave surface is between eighty and ninety-one degrees, and the angle defining the inner concave surface is between one and two degrees less than the angle defining the outer concave surface.

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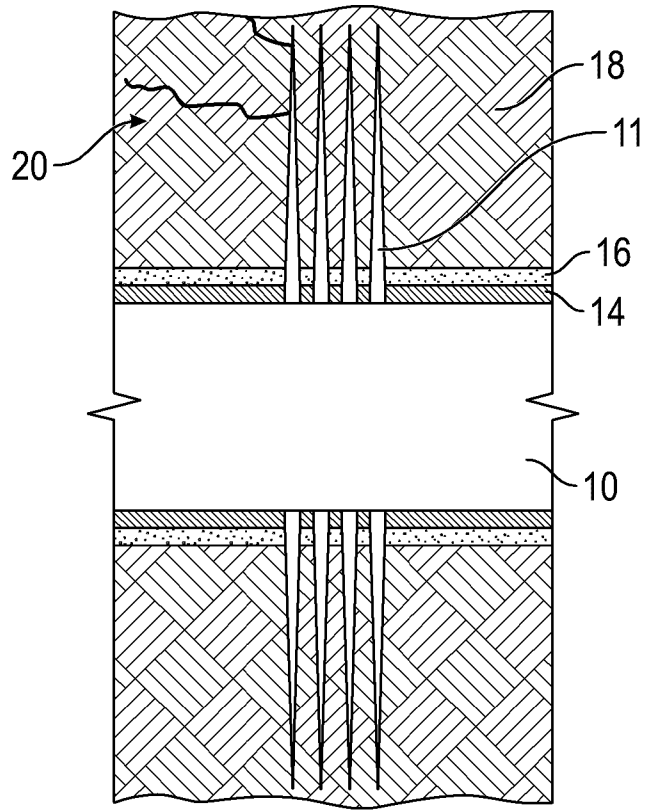


FIG. 1
(PRIOR ART)

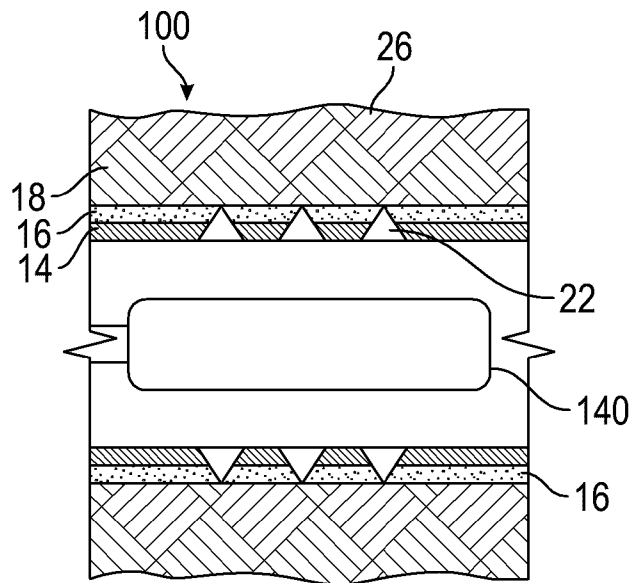


FIG. 2A

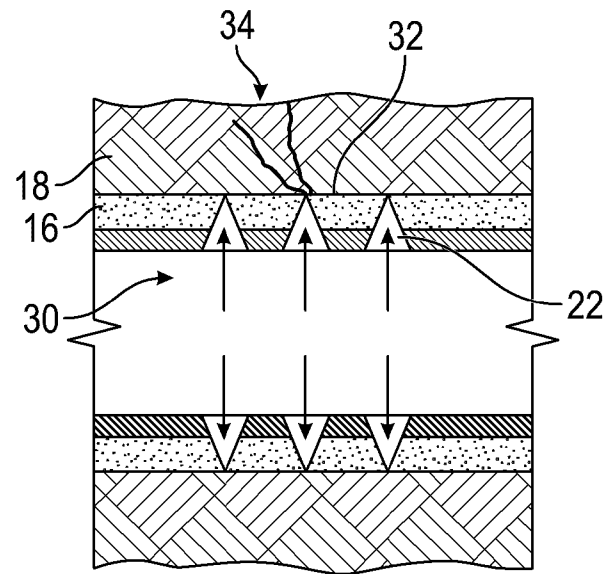


FIG. 2B

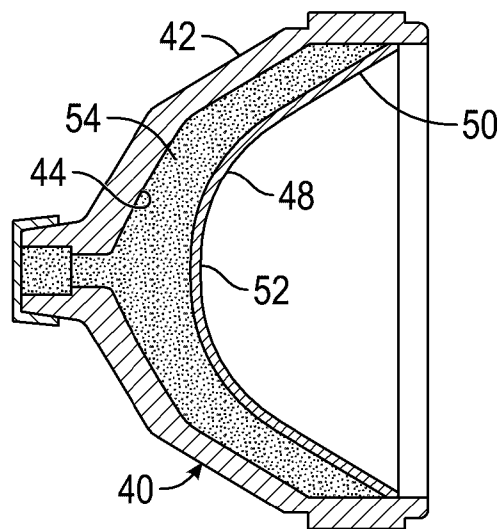


FIG. 3

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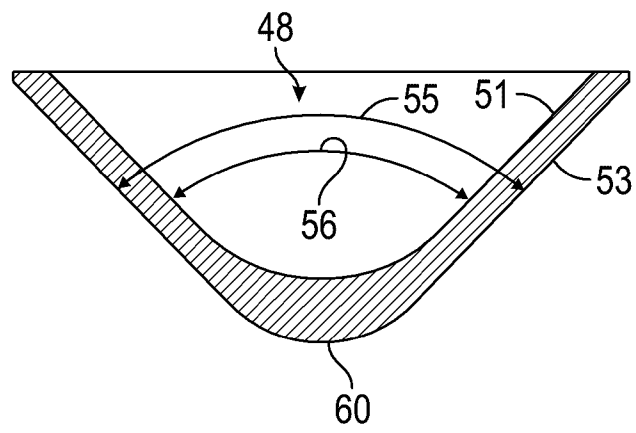


FIG. 4A

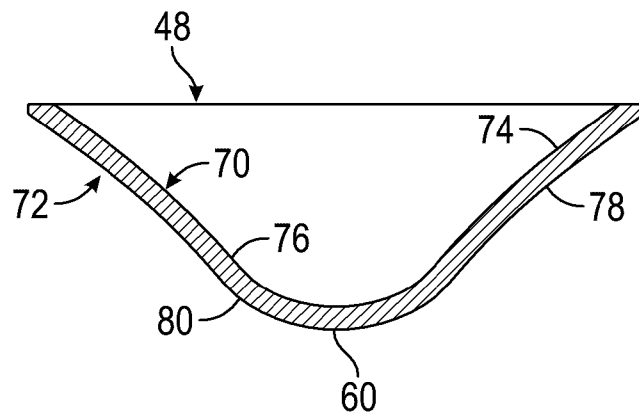


FIG. 4B

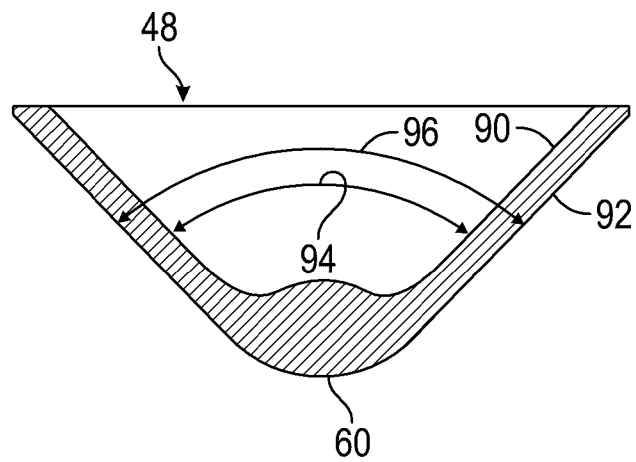


FIG. 4C

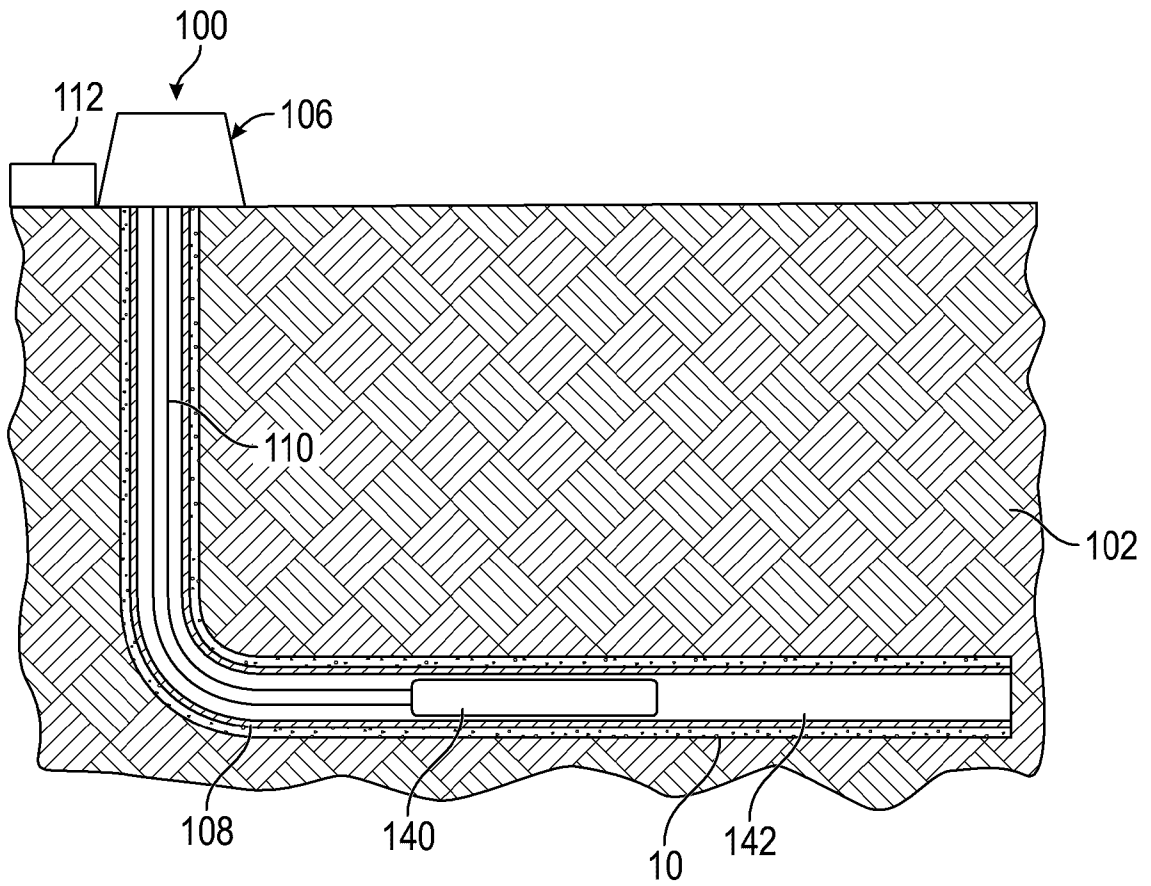


FIG. 5

