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(54) **HIGH DENSITY PERFORATING GUN SYSTEM PRODUCING REDUCED DEBRIS**

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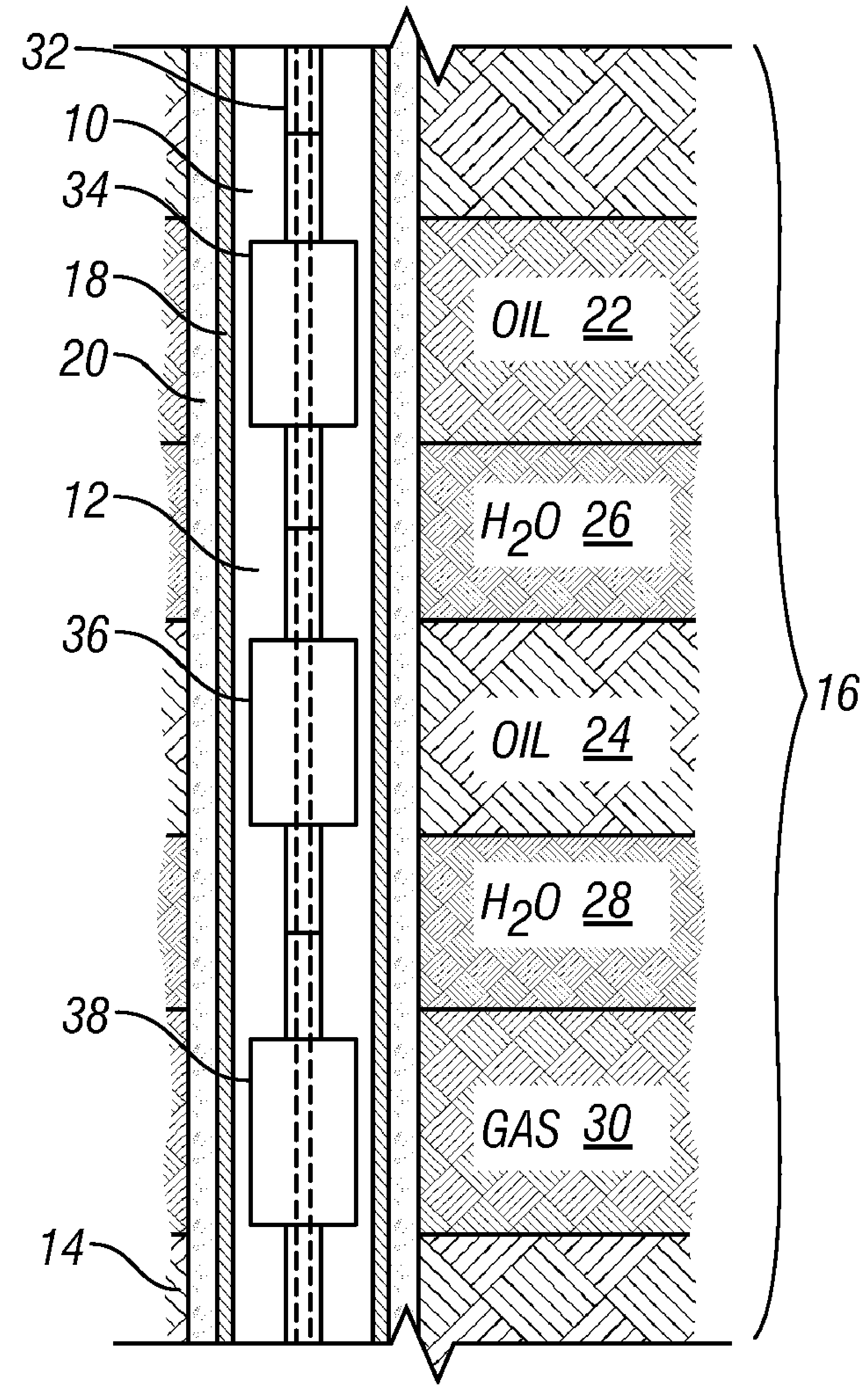
(52) **U.S. Cl.** **89/1.15**

(57) **ABSTRACT**

A perforating system has a perforating module comprising a unitary body of explosive. The explosive is contained within a non-explosive casing, or liner, having formed indentations and a cover thereover. The indentations, which will transform into explosively formed penetrators (EFP's) upon detonation, have a perimeter shape that allows for improved packing density, e.g., a hexagonal perimeter, which results in relatively little "dead space" wherein no perforating penetrators are generated. In operation, the module provides a relatively dense shot pattern and substantially reduced amount of post-detonation debris that could clog the perforations and/or require remedial clean-up or repeat perforation.



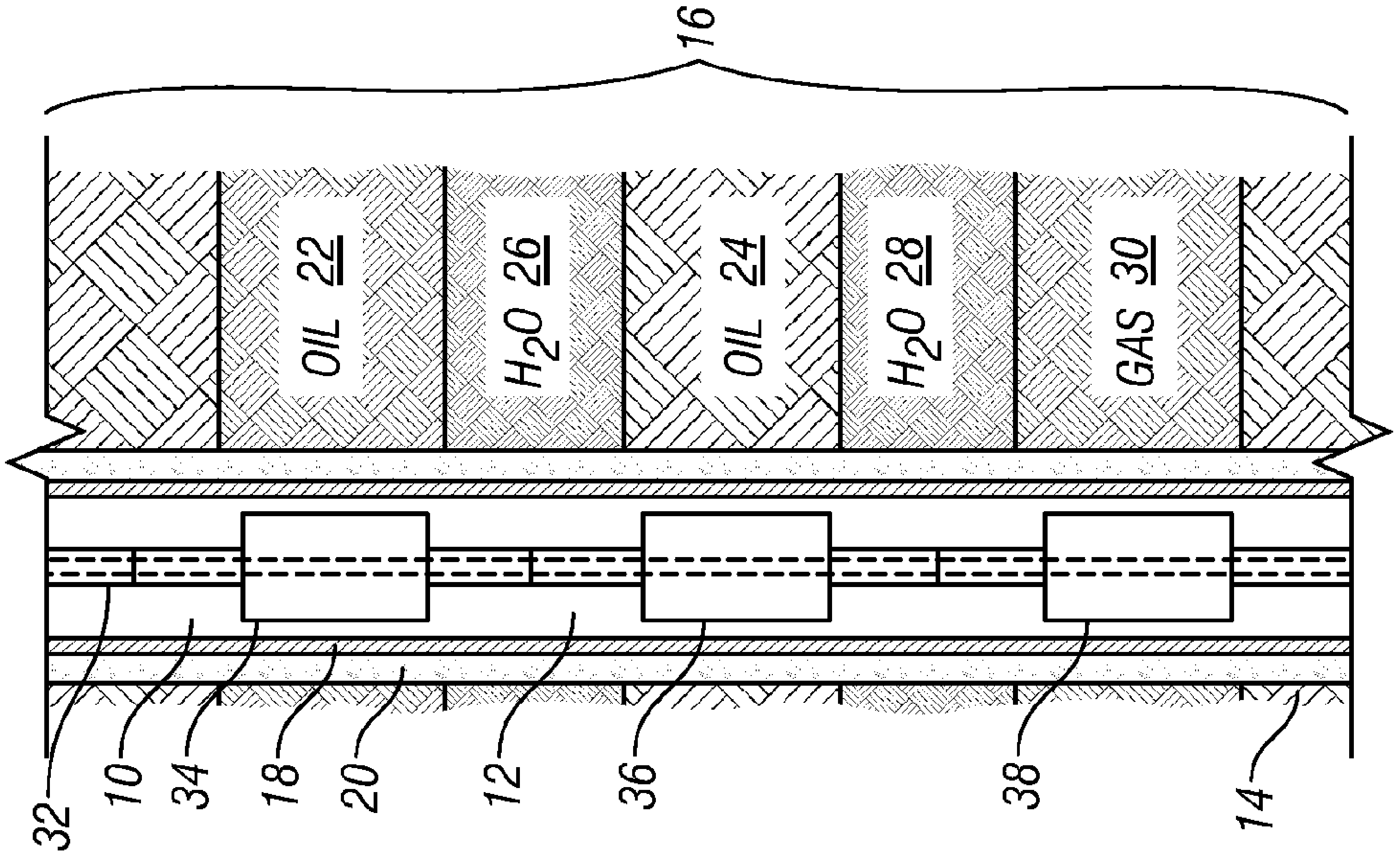
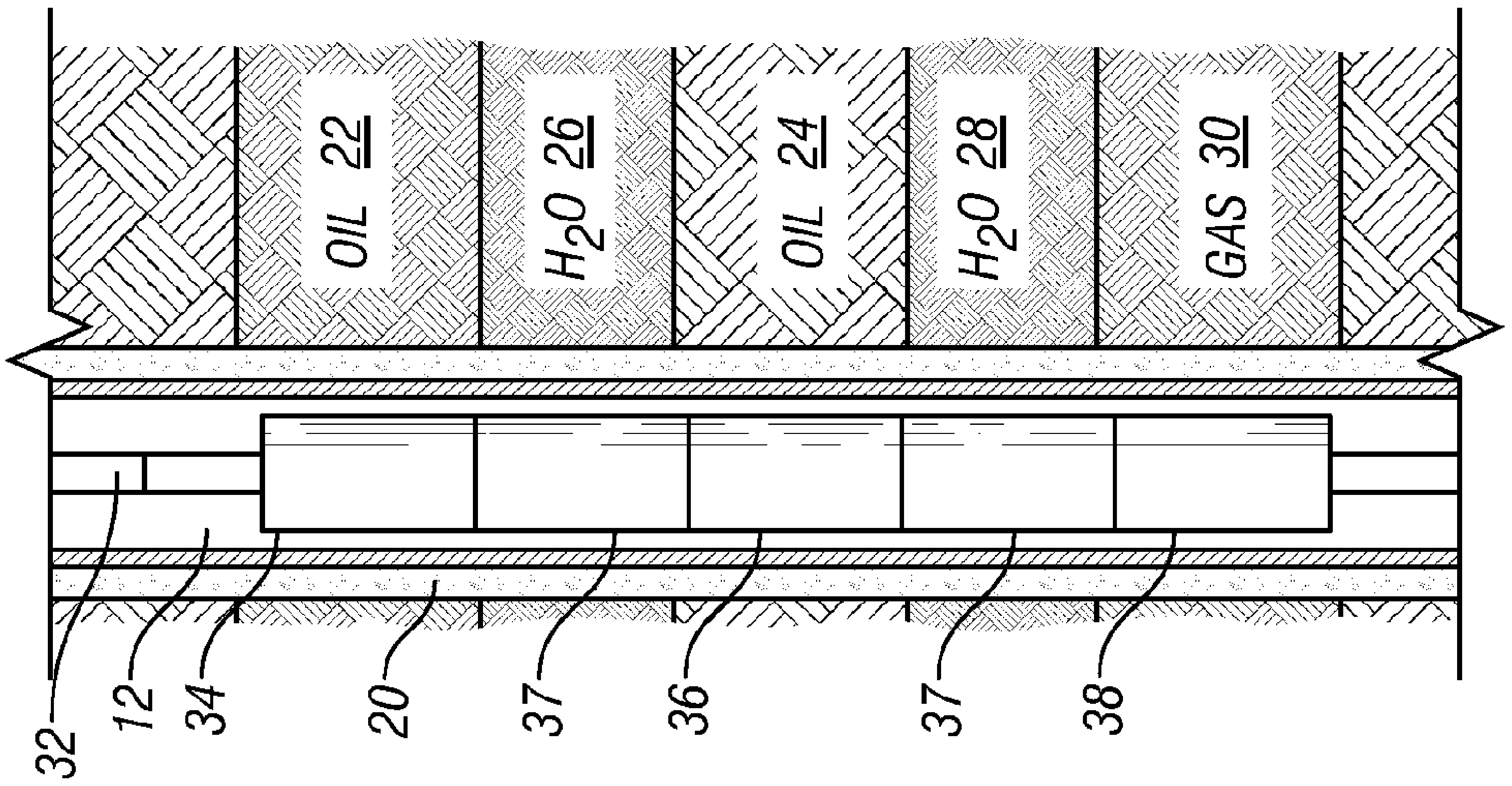

16
OIL 22
H_2O 26
OIL 24
H_2O 28
GAS 30
32
10
34
18
20
12
36
38
14

FIG. 1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OIL 24
H_2O 28
GAS 30
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37
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37
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FIG. 1A

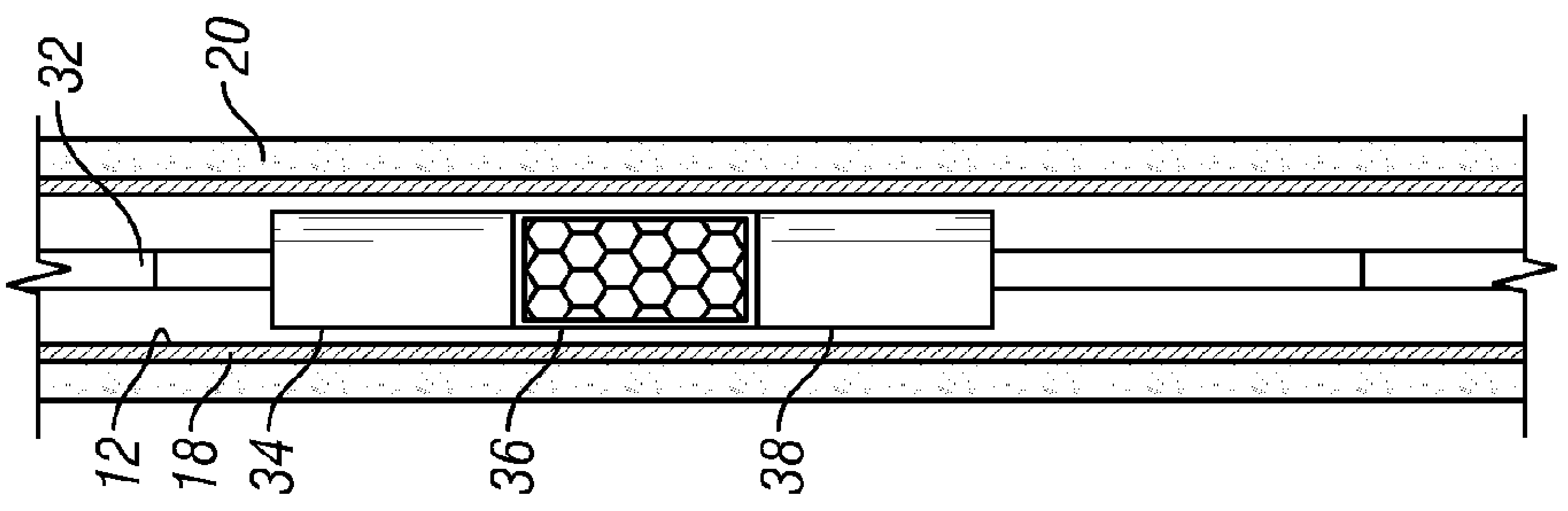

FIG. 1B

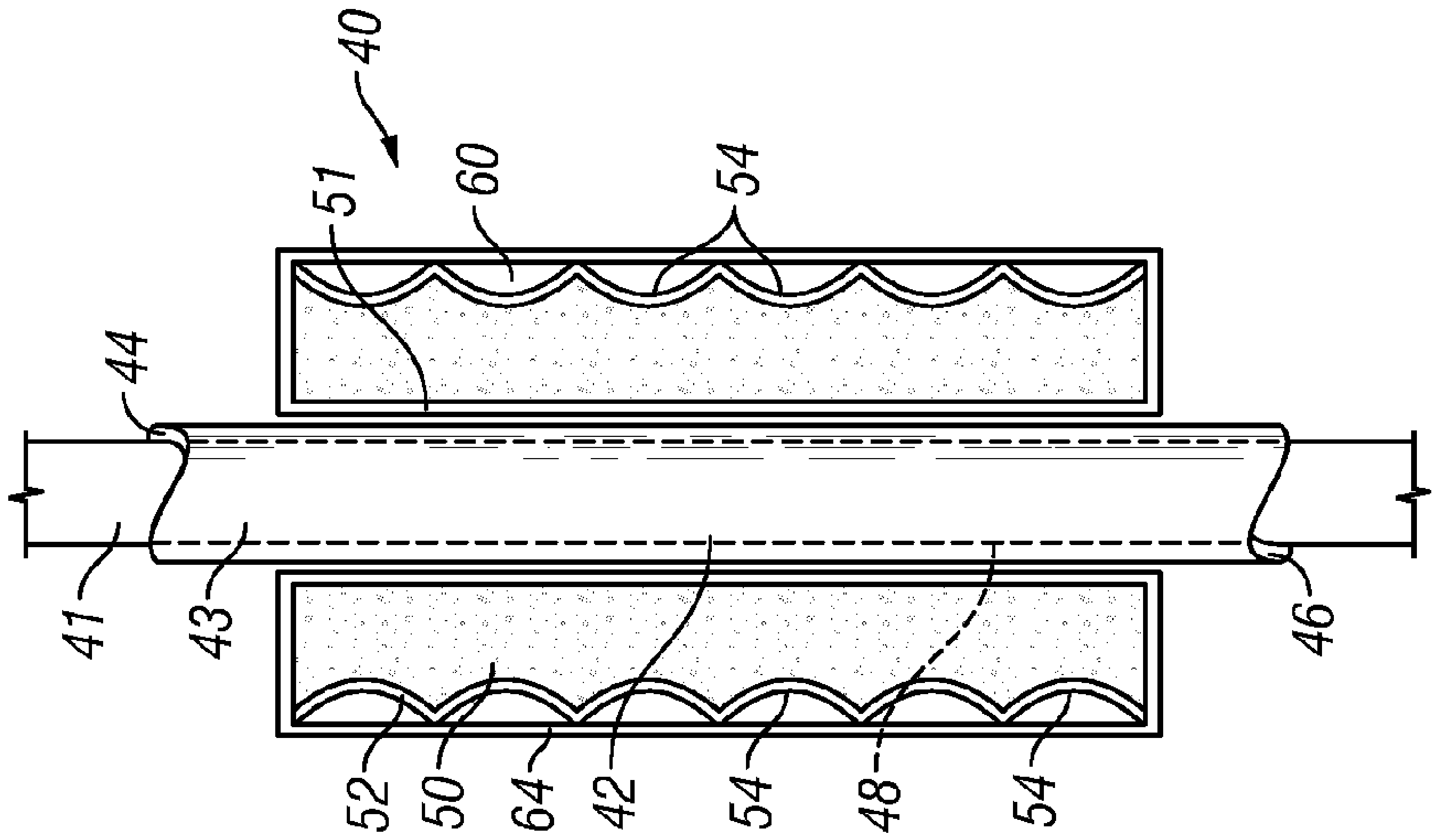

FIG. 2

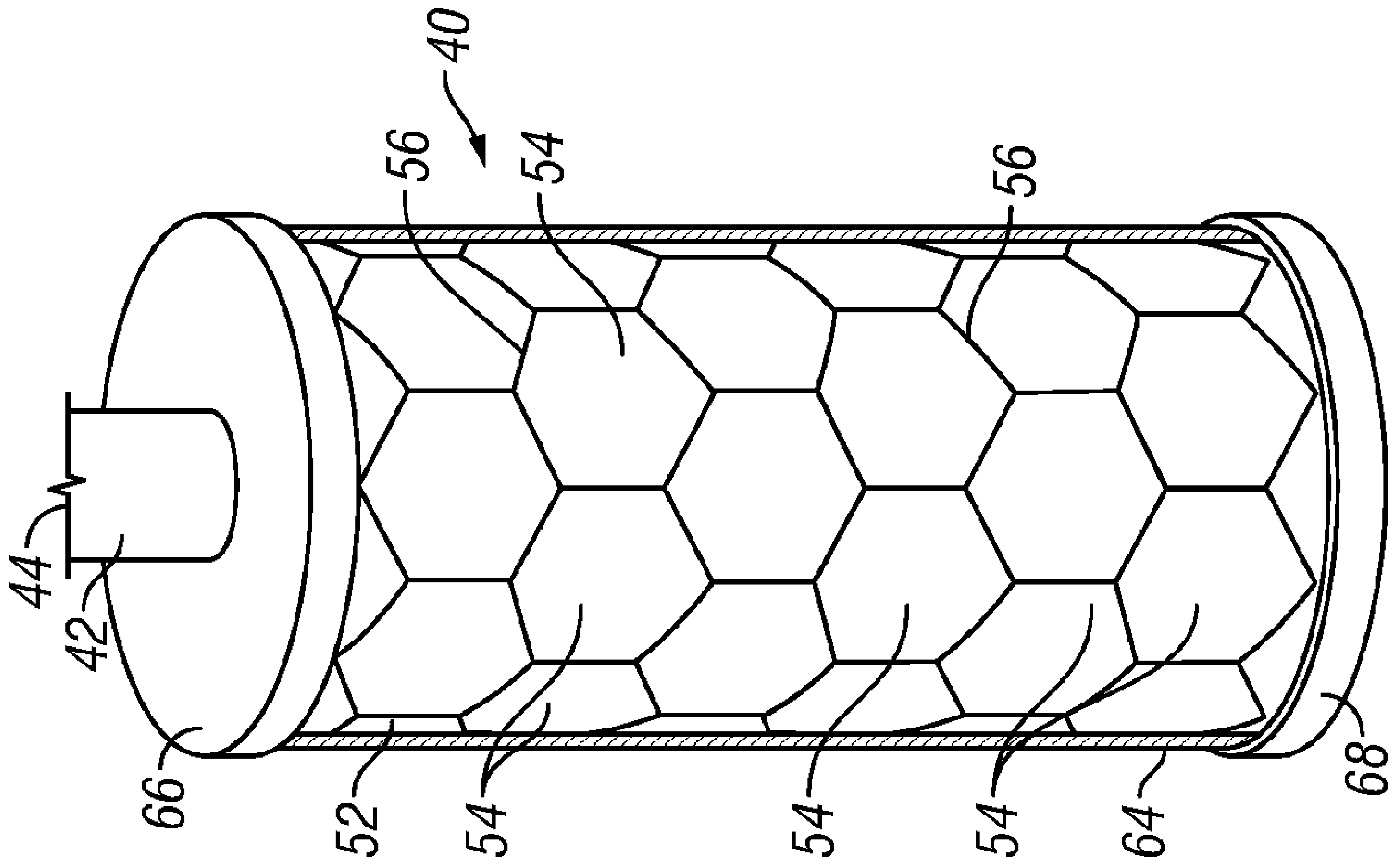

FIG. 3

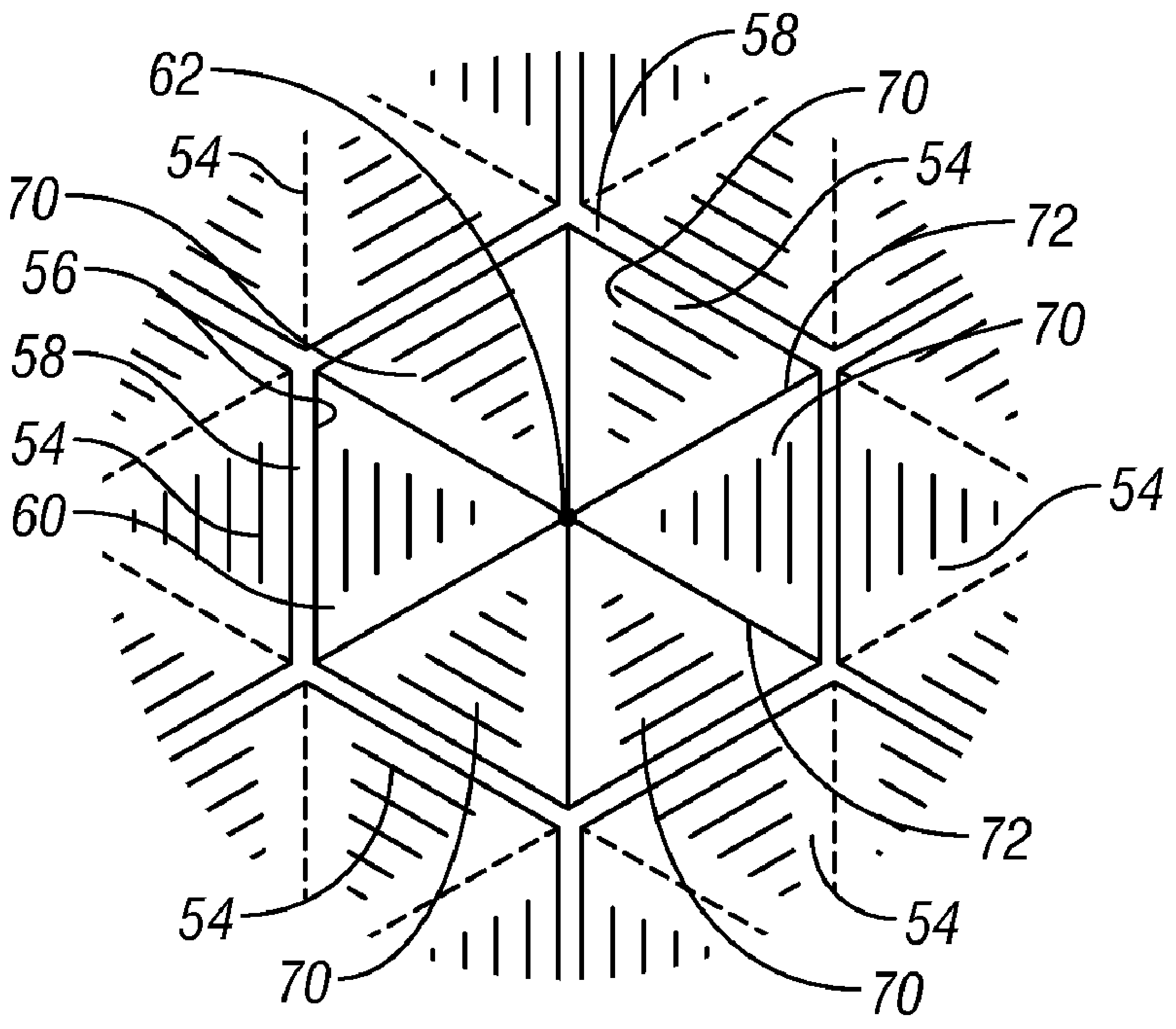
58
62
70
54
54
70
72
56
70
58
54
54
60
72
54
54
70
70

FIG. 4

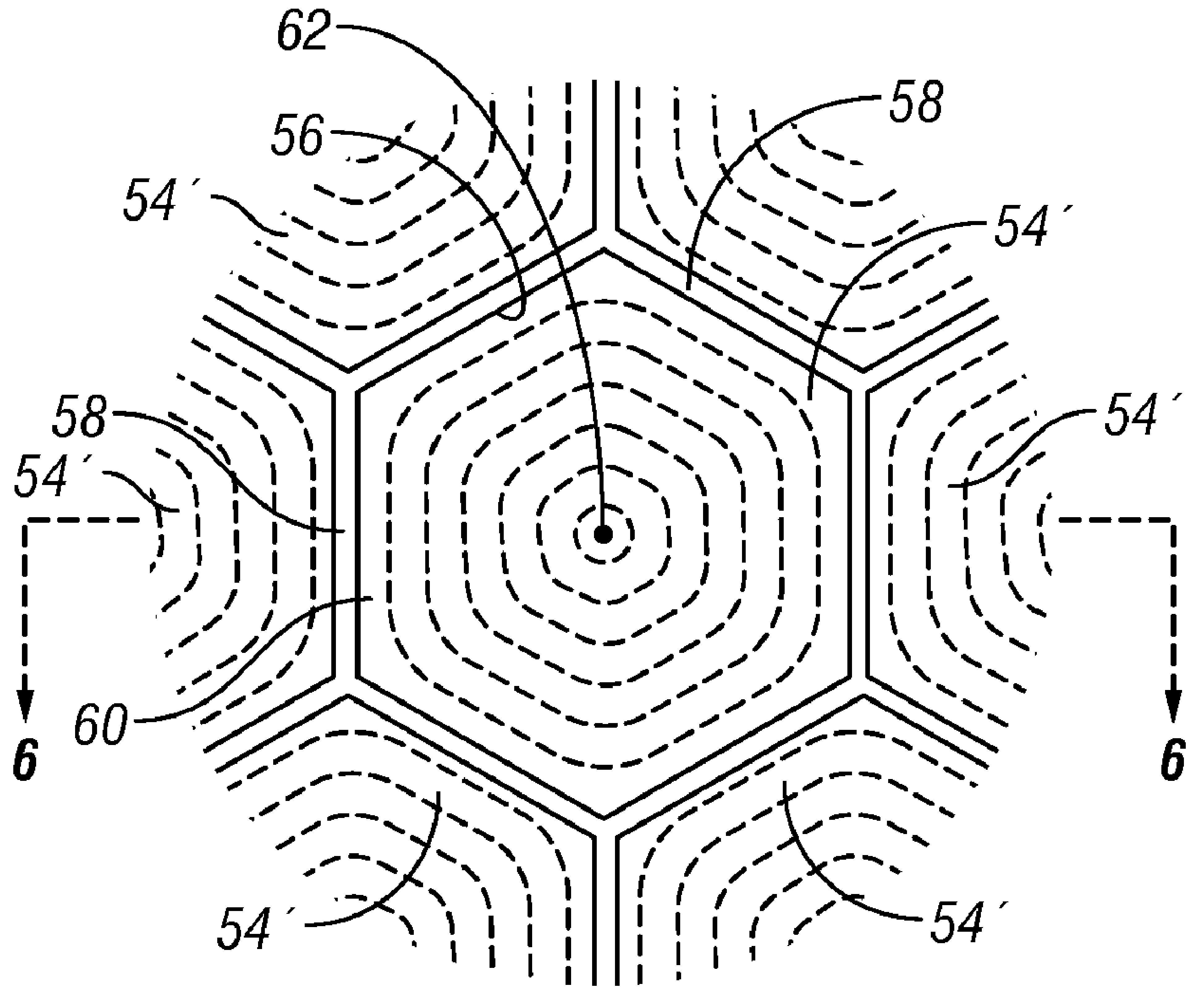
62
58
56
54´
54´
58
54´
54´
6
60
6
54´
54´

FIG. 5

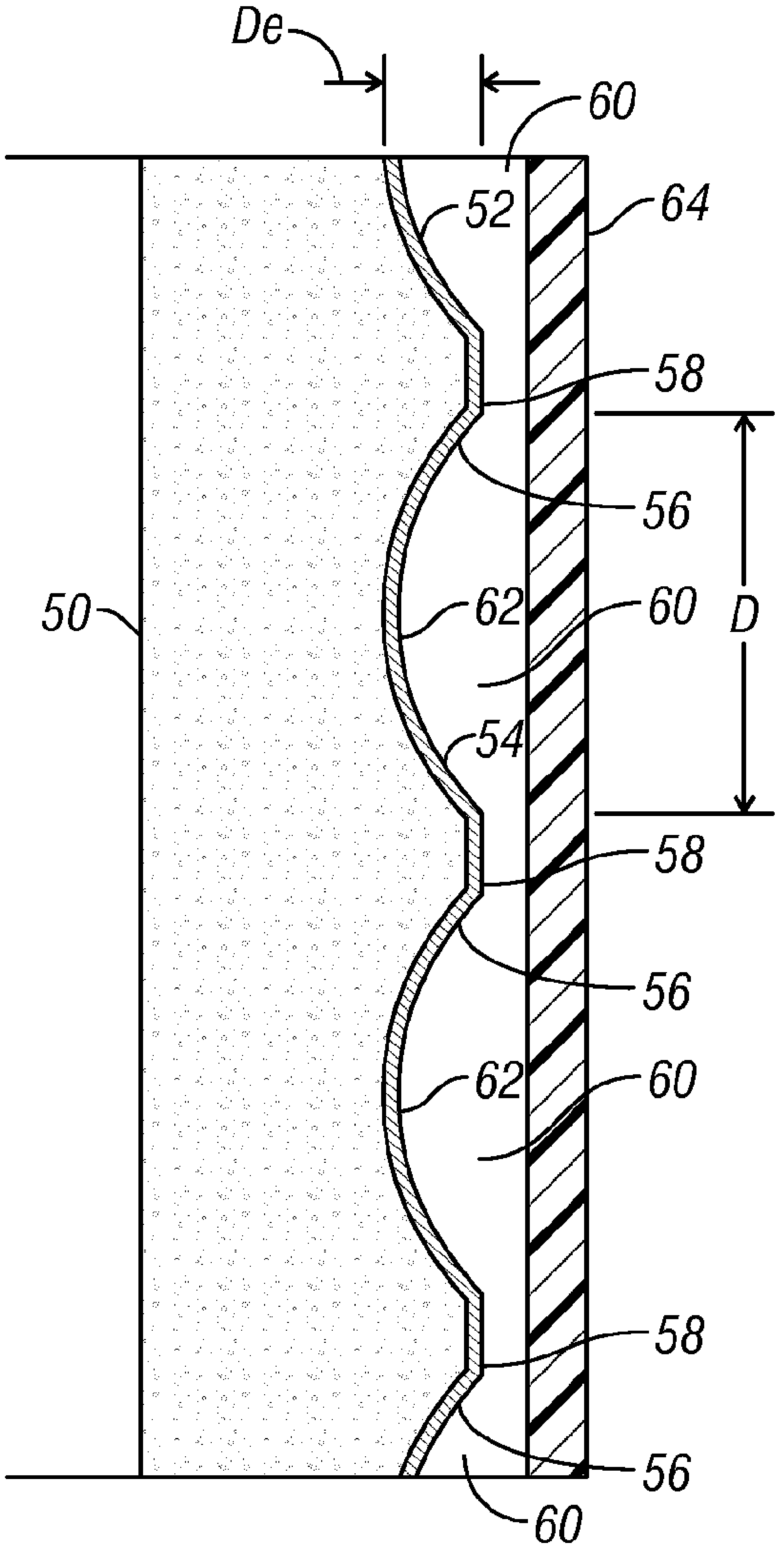
De
60
52
64
58
56
50
62
60
D
54
58
56
62
60
58
56
60

FIG. 6

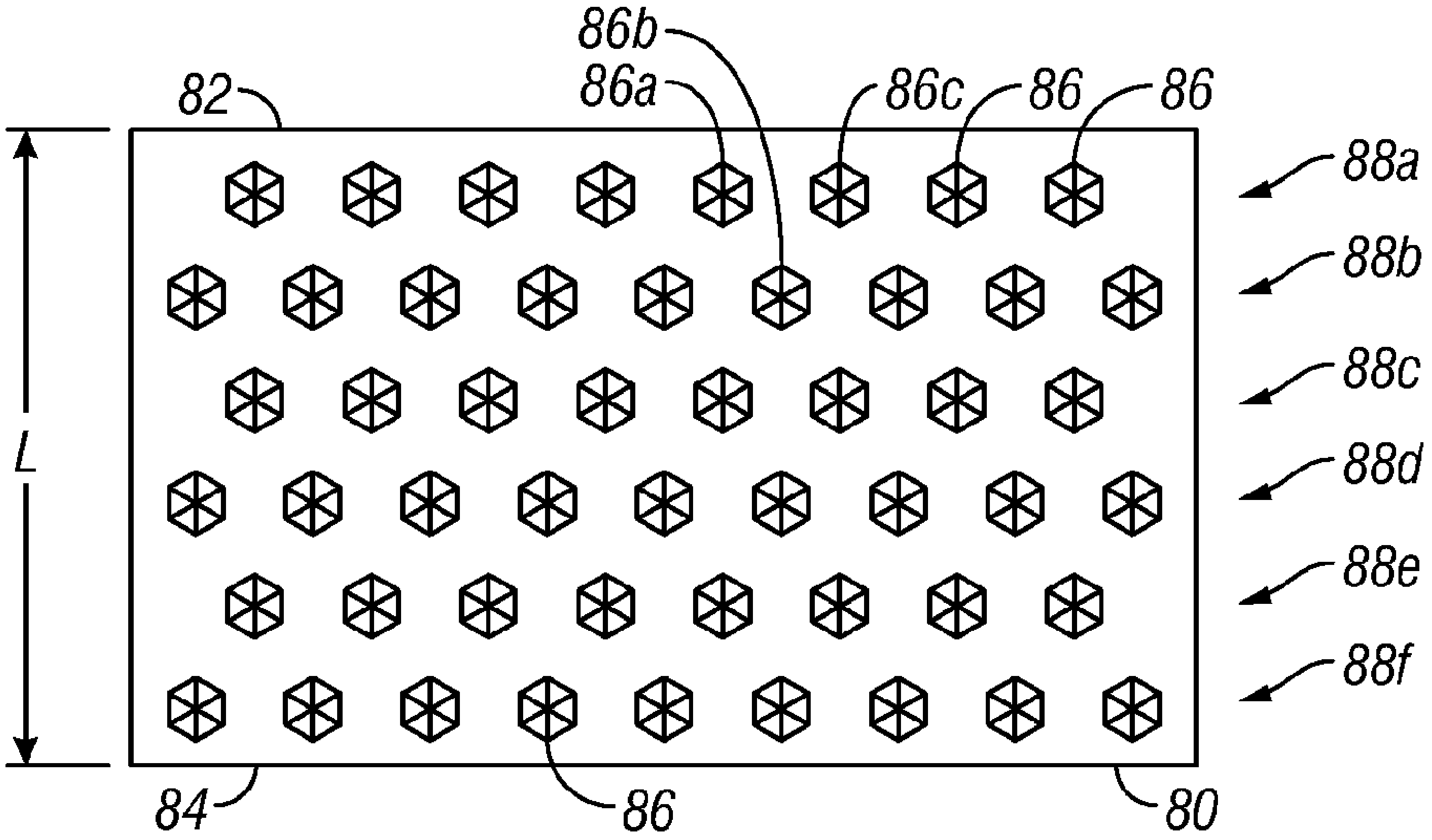
86b
82
86a
86c
86
86
88a
88b
88c
L
88d
88e
88f
84
86
80

FIG. 7

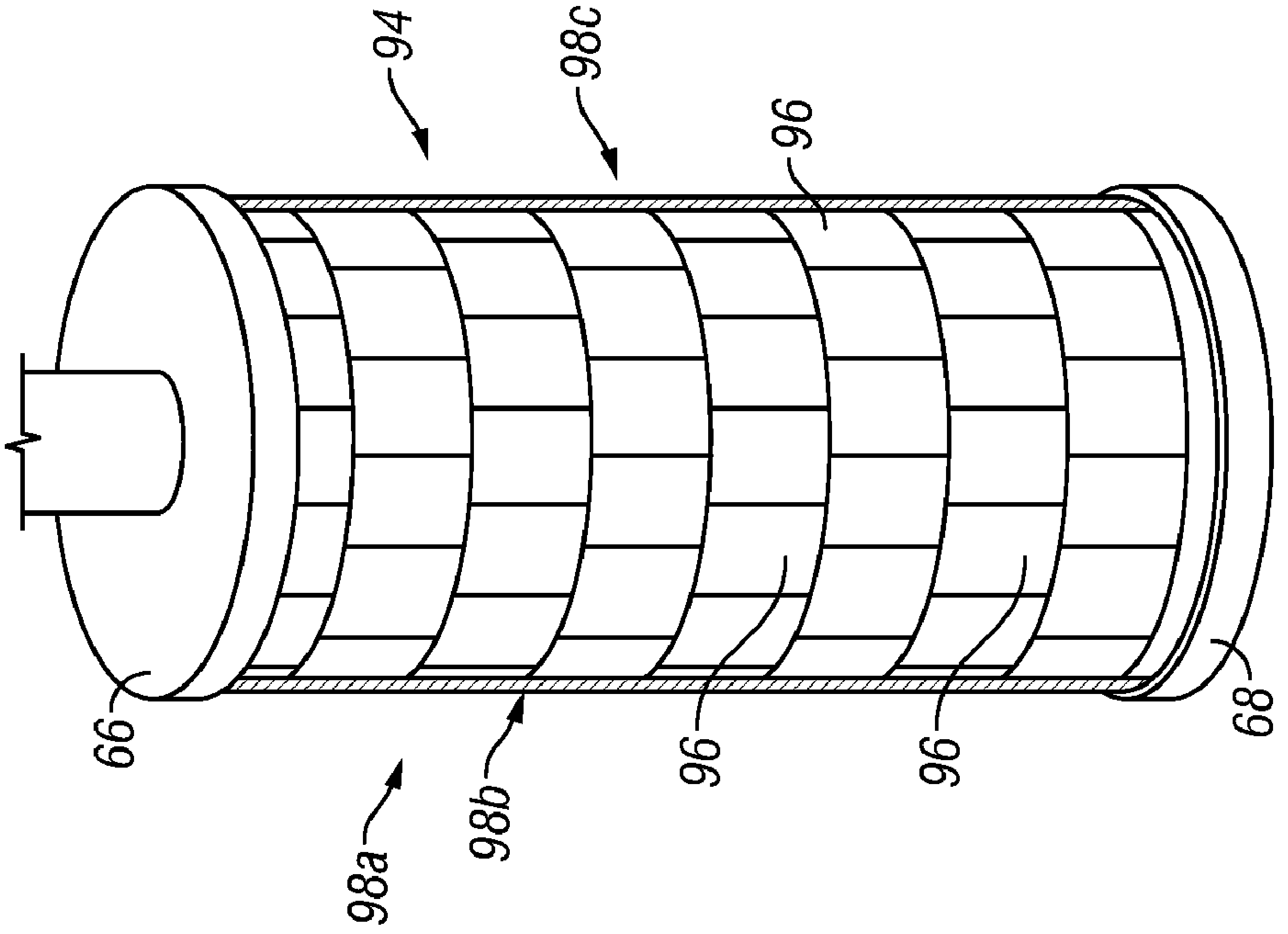

FIG. 9

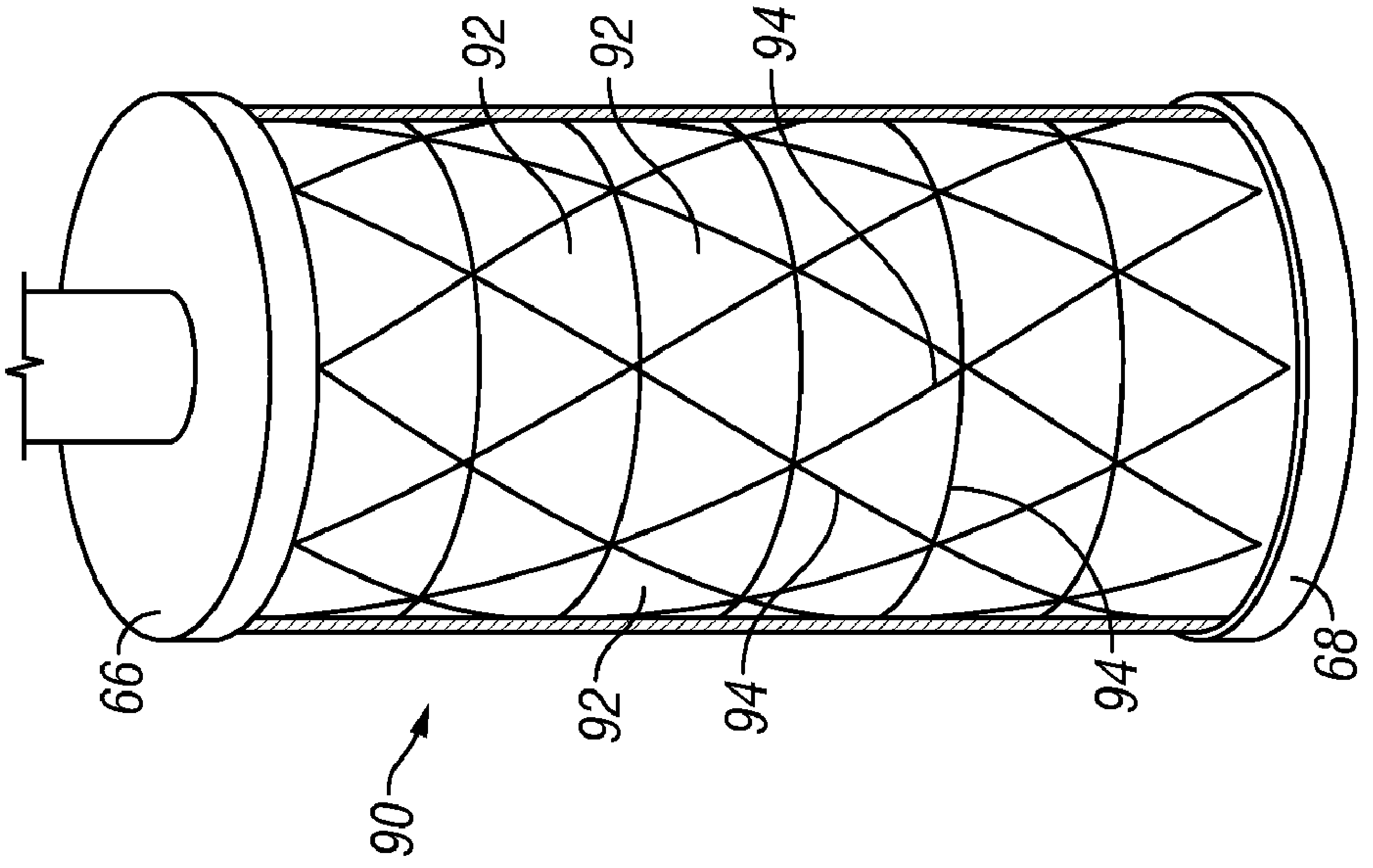

FIG. 8

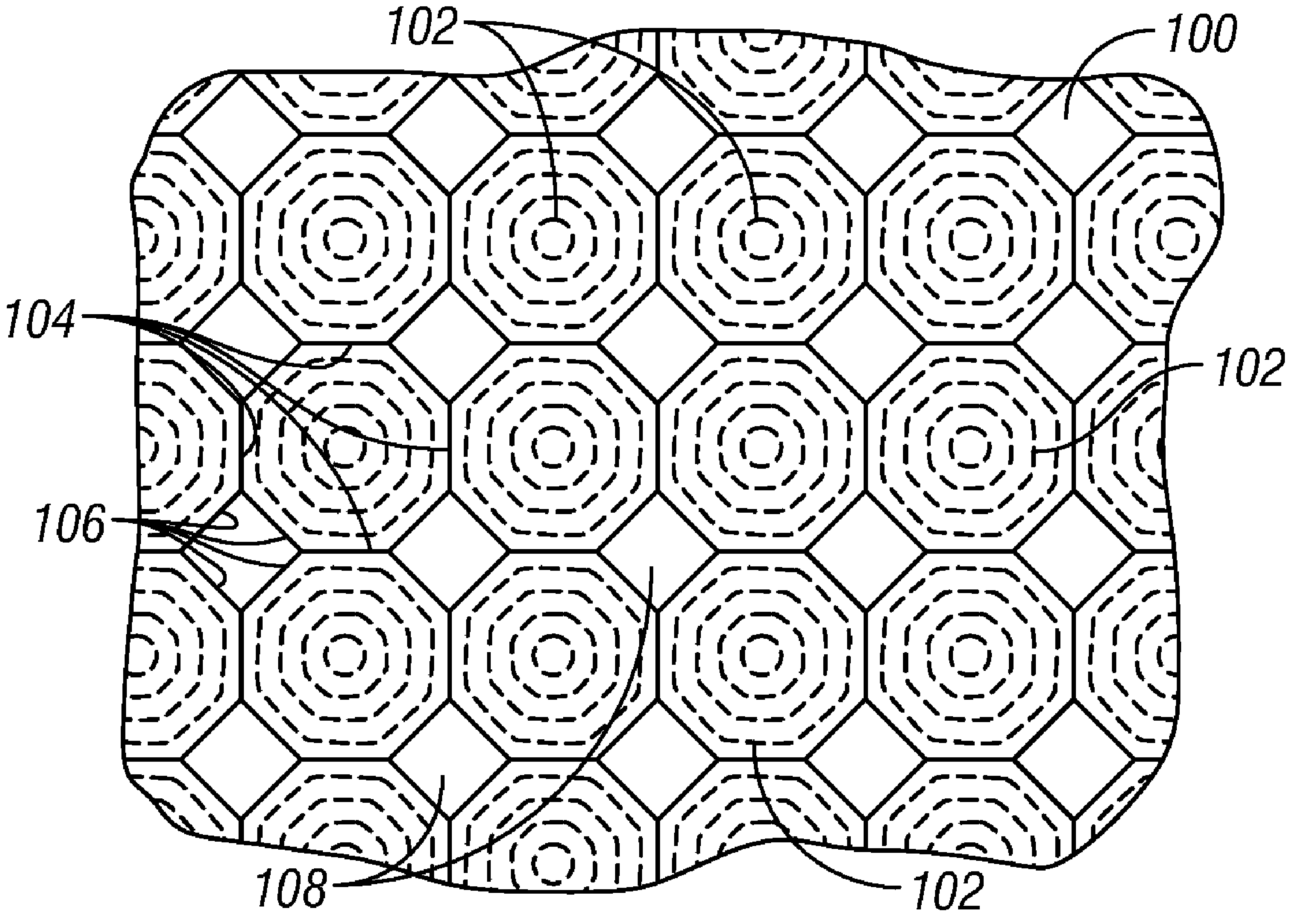

FIG. 10

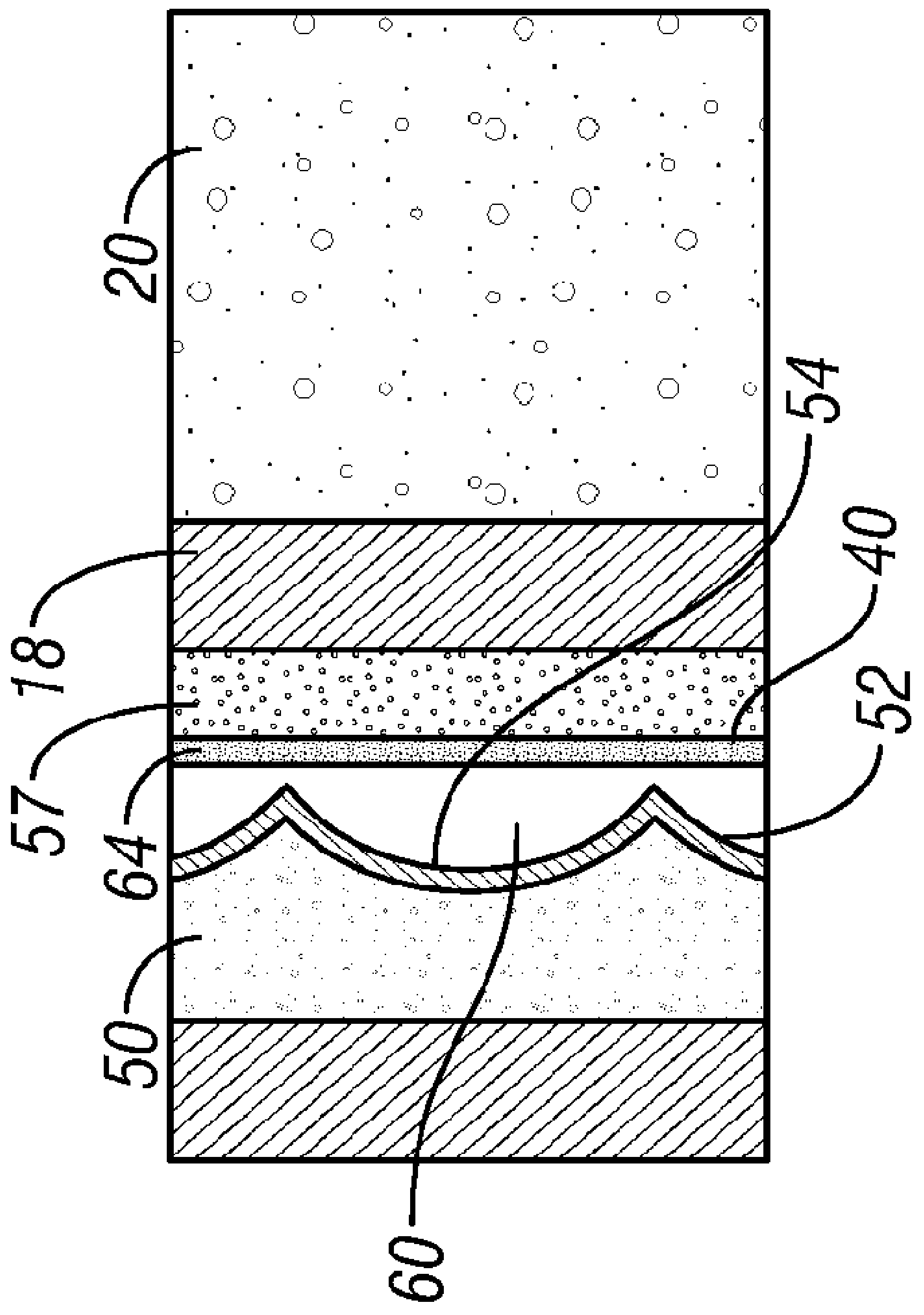

FIG.11

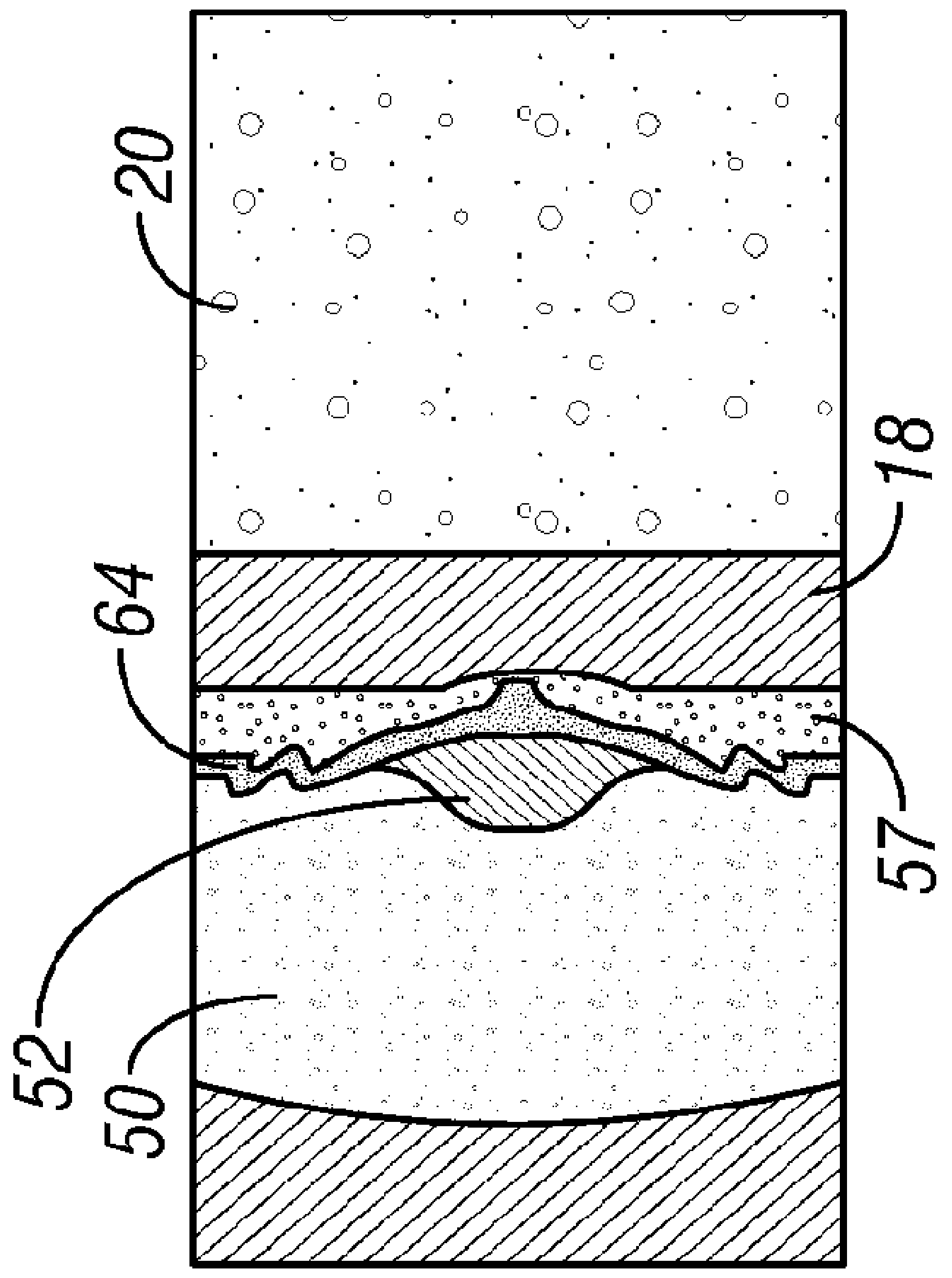

FIG. 12

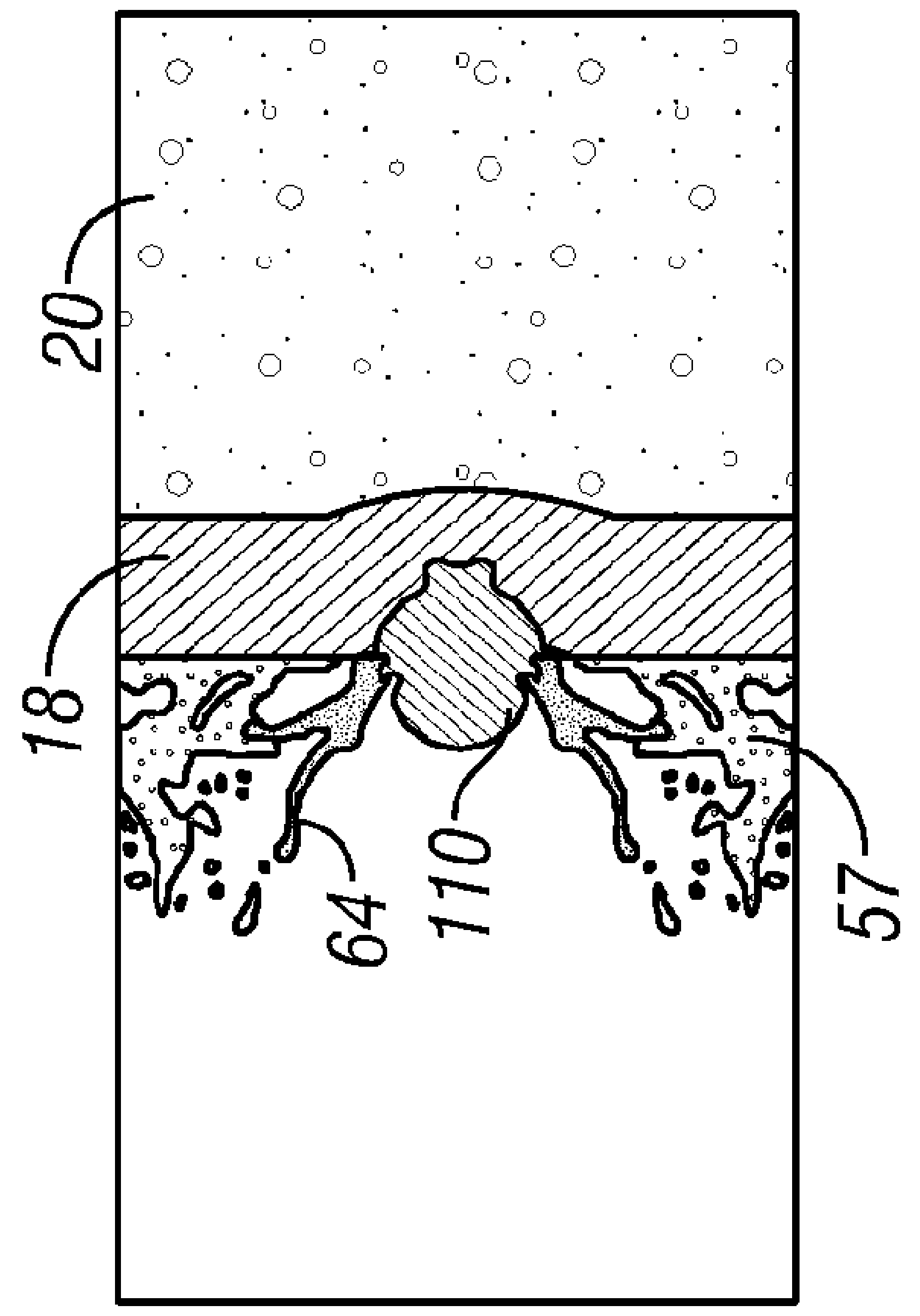

FIG. 13

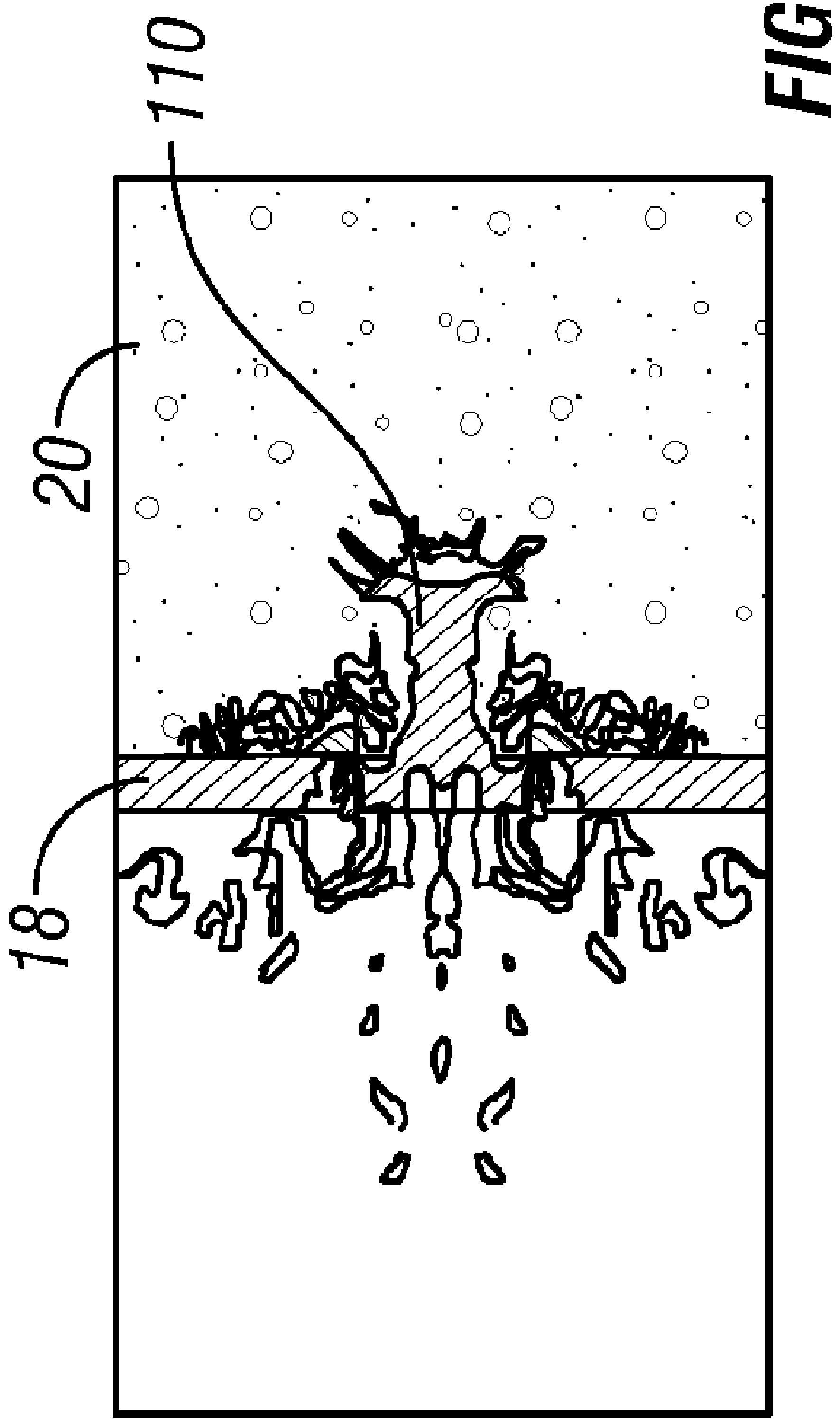

FIG. 14

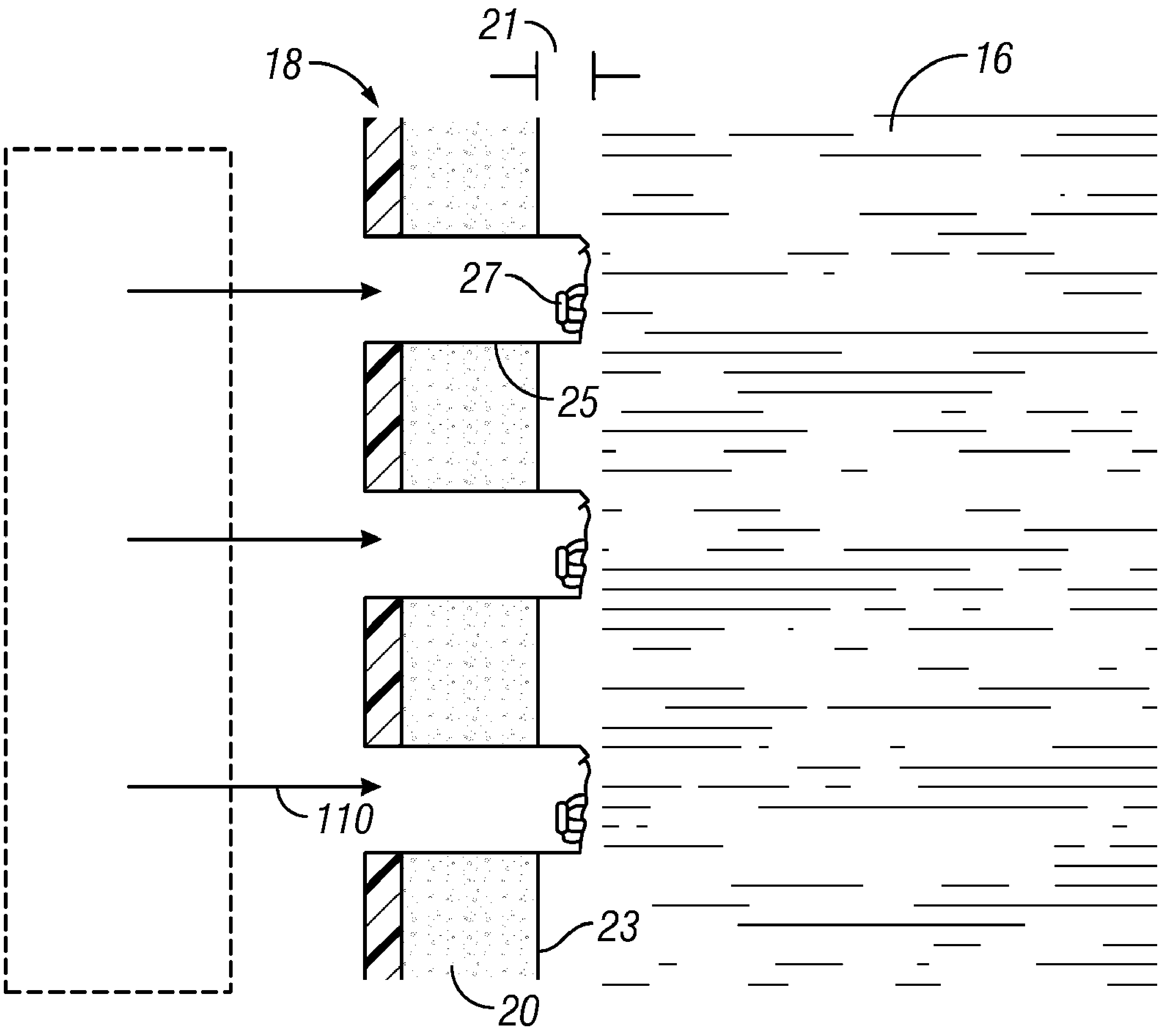

FIG. 15

HIGH DENSITY PERFORATING GUN SYSTEM PRODUCING REDUCED DEBRIS

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of and claims priority to U.S. patent application Ser. No. 11/405,148, filed on Apr. 17, 2006.

BACKGROUND OF THE DISCLOSURE

[0002] 1. Field of the Disclosure

[0003] The disclosure relates generally to the design of perforating tools for use in creating perforations in wellbores to improve the flow of fluids from the wellbore.

[0004] 2. Description of the Related Art

[0005] Commercial development of hydrocarbon fields requires significant amounts of capital. Therefore, before field development begins, operators desire to have as much information as possible in order to evaluate the reservoir for commercial viability. Such information may be acquired at the seismic exploration phase, during well construction, prior to well completion and/or any time thereafter.

[0006] Perforation guns are used within wellbore holes to increase the permeability of the formation surrounding the wellbore. In general, perforation guns producing greater numbers of perforations are considered to be more effective than those producing fewer perforations. It is therefore often desired to maximize the number of penetrating jets within a segment of the wellbore. This may be difficult, however, because there are limitations relating to placement of the charges used for perforation. Standard shaped charges have an outer housing formed of metal or another material that encloses the high explosive charge. The shaped charge holder has openings that have typically circular perimeters. When packing the charges in an adjoining manner in the charge tube, interstitial spaces are unavoidably left between the neighboring charges as a result their shape. This packing of the charges results in significant "dead spaces," that is, areas from which no perforating product, i.e., no jets, is/are provided, between the charges, and limits the density with which the charges can be packed.

[0007] There are a number of known styles and designs for perforation guns. There are, for example, strip guns that include a strip carrier upon which are mounted a number of capsule charges. The capsule charges are individually sealed against corrosive wellbore fluids. Also known are hollow carrier guns that have a sealed outer housing that contains unencapsulated shaped charges. In each case, the shaped charges are arranged such that they will detonate in a radially outward direction to form a specific pattern of perforations.

[0008] An alternative perforation gun design is described in U.S. Pat. No. 5,619,008 to Chawla et al. In this design, a two-layer liner serves to sheath discontinuous loadings of explosive material. The liner is configured with indentations that are each aligned with an individual loading of the explosive material. Upon detonation of the loadings of explosive material, these indentations act in the manner of a shaped charge, creating a directed jet of liner material. The indentations have a circular perimeter and are spaced apart from one another, leaving significant "dead space" between them. Following detonation and any resulting perforation, the housing that surrounds the charges is not completely destroyed and forms debris. This debris is undesirable, both because it must be removed by wireline or by other means in a secondary operation, and because it may clog the perforations that are formed by the perforation operation, thereby making the perforations less effective and sometimes necessitating repeat perforation operations. The Chawla et al. invention thus suffers from problems relating to both "dead space" and debris creation.

[0009] The present disclosure addresses the problems of the prior art.

SUMMARY OF THE DISCLOSURE

[0010] The present disclosure provides a perforating device that produces multiple perforating penetrators from a single high explosive charge. In one embodiment, the perforating module has a central rod with a surrounding cylinder of high explosive. The cylinder of high explosive is contained within a liner having formed indentations. The liner may be of any suitable material, such as a non-explosive material including, for example, an elemental metal or alloy, a composite, a ceramic, a thermoplastic or thermo set polymer, or the like. Finally, a cylindrical outer cover is disposed about the liner. In one embodiment, the indentations are linearly contiguous to one another. In another embodiment, the indentations each have a perimeter that is triangular, square, hexagonal, or octagonal and are disposed in an adjoining fashion to one another.

[0011] In operation and as a result of detonation of the explosive material, the module forms penetrators of liner material that propagate into the formation in a direction that is, in one embodiment, substantially perpendicular to the longitudinal axis of the wellbore. The module thus is capable of providing a relatively dense shot pattern with little or no "dead space" between the locations from which the penetrators are formed. This results in an effective perforation of a wellbore segment.

[0012] During the detonation, the constituent components of the module, the high explosive, the liner, and the outer cover, are largely destroyed. As a result, the amount of debris resulting from the detonation is reduced or eliminated, in contrast with the large amount of debris produced by many conventional perforation devices.

[0013] One embodiment of the disclosure includes a method for perforating a subterranean formation, comprising: lowering a plurality of perforating modules in a wellbore, wherein each of the plurality of perforating modules comprises: a central rod, wherein the central rod comprises: an exterior load bearing portion, and an interior detonation portion including a first explosive, a second explosive adapted to at least partially surround the central rod, and a liner disposed to surround the second explosive, wherein the liner is made of a non-explosive material, and wherein the liner has a plurality of concave arcuate surface indentations; and detonating the plurality of perforating modules in the wellbore.

[0014] Another embodiment of the disclosure includes a method for perforating a subterranean formation, comprising: lowering a plurality of perforating modules in a wellbore, wherein at least one of the plurality of perforating modules is separated from another of the plurality of perforating modules by a spacer, and wherein each of the plurality of perforating modules comprises: a central rod, wherein the central rod comprises: an exterior load bearing portion comprised of a ceramic, an axial passage adapted to receive hydraulic fluid disposed along the length of the exterior load bearing portion, a wire disposed within the axial passage, and an interior detonation portion including a first explosive, a second explosive adapted to at least partially surround the central rod, a liner disposed to surround the second explosive, wherein the liner is made of a non-explosive material, and wherein the liner has a plurality of concave arcuate surface indentations, wherein each of the plurality of concave arcuate surface indentation is polygonal, wherein each of the plurality of concave arcuate surface indentations is configured to face substantially perpendicular to the longitudinal axis of the wellbore, and wherein each of the plurality of concave arcuate surface is linearly contiguous with at least another of the plurality of concave arcuate surface indentations, and a cover disposed about the liner; and detonating the plurality of perforating modules in the wellbore.

[0015] In embodiments, the plurality of shallow concave surface indentations may each have a cavity. The cavity may be defined by a diameter and a depth. In one arrangement, the diameter to depth ratio is approximately not less than two to one. In another embodiment, the diameter to depth ratio is not less than six to one. In still other embodiments, the depth is no greater than a thickness of the liner. The method may also include forming a plurality of perforations in a region adjacent to the perforating modules, wherein the plurality of perforations extend substantially through a cement layer into a formation a distance from a cement face that is no greater than a diameter of the cavity. In some applications, the distance is no greater than one-half of the diameter of the cavity. Also, the method may include at least partially lining the plurality of perforations in the cement layer with a liner material.

[0016] Another embodiment of the disclosure includes a method for perforating a subterranean formation. The method may include lowering a perforating module into a wellbore having a casing incased in cement, the perforating module having at least one explosively formed penetrator forming charge and liner; positioning the plurality of perforating modules in the wellbore and adjacent to a substantially unconsolidated formation; perforating the casing and cement; and perforating the formation to a distance no greater than a diameter of the at least one explosively formed penetrator forming charge and liner, wherein the distance measured from a boundary between the cement and the formation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] For greater understanding of the disclosure, reference is made to the following detailed description of the embodiments of the present disclosure, taken in conjunction with the accompanying drawings in which reference characters designate like or similar elements throughout the several figures of the drawings.

[0018] FIG. **1** is a side, cross-sectional view of a wellbore containing an exemplary perforation system constructed in accordance with the present disclosure.

[0019] FIGS. **1***a* and **1***b* illustrate a pair of alternative constructions for perforation systems constructed in accordance with the present disclosure.

[0020] FIG. **2** is a side, cross-section depiction of a single perforation module of the perforation system shown in FIG. **1**.

[0021] FIG. **3** is an exterior view of the module shown in FIG. **2**.

[0022] FIG. **4** is a detail view of a portion of the liner of an exemplary perforation module showing further details concerning the indentations.

[0023] FIG. **5** is a detail view of a portion of the liner of an exemplary perforation module showing an alternative shape for the indentations.

[0024] FIG. **6** is a side cross-section of the portion of liner shown in FIG. **5**, taken along lines **6**-**6**.

[0025] FIG. **7** depicts an exemplary shot pattern that is created by the perforation module shown in FIGS. **2** and **3**.

[0026] FIG. **8** illustrates an alternative embodiment for a perforation module in accordance with the present disclosure having triangular indentations.

[0027] FIG. **9** illustrates a further alternative embodiment for a perforation module in accordance with the present disclosure having square indentations.

[0028] FIG. **10** depicts a portion of the surface of the liner of a perforation module that utilizes octagonal indentations.

[0029] FIGS. **11**-**15** illustrate an exemplary initiation sequence for a single penetrator of a perforation module in accordance with one embodiment of the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0030] The present disclosure relates to devices and methods for perforating wellbores. The present disclosure is susceptible to embodiments of different forms. These are shown in the drawings, and herein will be described in detail, specific embodiments of the present disclosure with the understanding that the present disclosure is to be considered an exemplification of the principles of the disclosure, and is not intended to limit the disclosure to that illustrated and described herein.

[0031] FIG. **1** illustrates an exemplary perforation system **10** that is configured in accordance with one embodiment of the present disclosure. The perforation system **10** is disposed within a wellbore **12** that has been drilled through the earth **14** and a hydrocarbon-bearing formation **16**. Portions of the wellbore **12** are cased by a steel casing **18** that is secured within the open wellbore hole by cement **20**.

[0032] The hydrocarbon-bearing formation **16** contains two oil-bearing strata **22**, **24**, which are separated by a layer of water **26**. A layer of water **28** also separates the lower oil stratum **24** from a stratum of gas **30**. It is noted that this arrangement of strata in formation **16** is presented only by way of example and that those skilled in the art will recognize that the actual composition and configuration of formations varies.

[0033] The perforation system **10** is disposed into the wellbore **12** on a conveyance string **32**. The conveyance string **32** may be of any known construction for conveying a tool into a wellbore, including a drill pipe, wireline, production tubing, coiled tubing, and the like. The perforation system **10** includes one or more perforating modules that are used to perforate portions of the surrounding formation **16**. In the described embodiment, there are three perforating modules **34**, **36**, **38** that are secured to one another in series. There may, of course, be more or fewer than three modules, depending upon the desired length of wellbore to be perforated. Additionally, it is pointed out that there may be intermediate sections of tubing, or subs **37** (see FIG. **1***a*) interposed between the individual modules **34**, **36**, and **38**, to provide a desired spacing therebetween. In practice, the subs **37** are desirably non-explosive. If desired, the modules **34**, **36**, and **38** may alternatively be secured to one another so as to form an unbroken, contiguous series of modules. FIG. **1***b* illustrates a further alternative perforation system arrangement wherein the perforation modules **34**, **36**, and **38**, of the system are interconnected directly to one another in series.

[0034] An exemplary individual module **40** is depicted in FIGS. **2** and **3**. The module **40** is representative of each of the three modules **34**, **36**, and **38** shown in FIG. **1**. As will be described in further detail below, the module **40** creates a plurality of perforating penetrators from a single explosive charge. The penetrators travel in a direction substantially normal or orthogonal to the longitudinal axis of the wellbore. Advantageously, this arrangement may significantly increase shot density and simultaneously reduce the amount of debris left in the wellbore, relative to many conventional perforation systems. In one embodiment, the module **40** includes a support member such as a central rod **42** having upper and lower axial ends **44**, **46**. The upper and lower axial ends **44**, **46** are provided with threaded connections, as is known in the art, so that they may be secured to the conveying string **32** (see FIG. **1***b*) or to an adjoining module. The central rod **42** is composed of a central load bearing portion **41** and an outer detonation layer **43**. The load-bearing portion **41** of the central rod **42** may be a section of pipe, rod or other load bearing structure. In one embodiment, the load-bearing portion **41** of the central rod **42** is formed of steel. In another embodiment, if the perforation device **10** is not to be withdrawn from the wellbore **12** after detonation, the load-bearing portion **41** of the central rod **42** is formed of a frangible or combustible material that will be readily destroyed during the detonation of the perforating device **10**. Ceramic is just one example of a suitable frangible material.

[0035] The detonation layer **43** comprises, in this embodiment, a primasheet of a type known in the art for initiation of detonations. The load-bearing portion **41** of the central rod **42** may also contain an axial passage **48** along its length to contain electrical wiring (not shown) that is necessary for initiation of the detonation layer **43** which, in turn, results in detonation of the body **50** of high explosive material. The detonation layer **43** may be initiated with a control signal either manually or utilizing some preprogrammed device. For example, suitable initiating systems can include using electrical signals transmitted from the surface via wiring (not shown) in the axial passage **48** to initiate detonation by increasing hydraulic pressure in the wellbore, or by the dropping of a drop bar (not shown) into the axial passage **48**, as is used conventionally with tubing conveyed perforation guns. Other initiating systems can utilize timers or well bore parameter sensitive devices (e.g., pressure, temperature, depth, etc.). Initiation systems for detonating perforating guns are known in the art and will not be discussed in further detail.

[0036] Surrounding the central rod **42** is a substantially unitary body **50** of high explosive material that explosively forms the perforating penetrators using the liner **52**. Suitable high explosive materials may include, for example, conventionally-employed high explosives such as RDX, HMX and HNS. While the size of the module is not a critical aspect thereof, it may be convenient to configure the module **40** such that it is a cylinder about 12 inches in length and about 4.5 inches in diameter. However, the length and diameter may be varied according to the dimensions of the wellbore **12** or other factors. In one embodiment, a tube **51** of cardboard or a similar material is disposed between the central rod **42** and the high explosive body **50**.

[0037] The liner **52** surrounds the body **50** of high explosive and is configured to form a plurality of perforating penetrators. The penetrators formed by the liner **52** may travel in a direction generally perpendicular to the longitudinal axis of the wellbore, although modifications in direction may also be achieved in other embodiments of this disclosure. In one embodiment, the liner **52** may be, in this embodiment, a cylindrical and non-explosive liner formed of a metal, such as, for example, tantalum. Alternatively, the liner **52** may be made from extruded copper, tungsten, steel, depleted uranium, aluminum, or another elemental metal or alloy. In other embodiments blends of elemental metals or alloys with materials such as lead, graphite, and zinc stearate may also be employed. In still other embodiments blends or alloys of aluminum with either titanium or hafnium may be used. Additionally, a frangible material may be used to form the liner **52** in order to further reduce the likelihood that the formed penetrator will plug the perforation created in the surrounding formation. Such may include, for example, the use of pressed, sintered metallic powders, such as those described in U.S. Pat. No. 6,012,392, which is incorporated herein by reference in its entirety, and metal/matrix composites.

[0038] The size, shape, velocity and other characteristics of the perforating penetrators formed by the liner **52** may be controlled, in part, by adjusting the surface contours and/or geometry of the liner **52**. In one embodiment, a plurality of linearly contiguous indentations **54** is formed into the liner **52**. As used herein, the phrase "linearly contiguous" means that the perimeters of every indentation shares at least one common side with an adjacent indentation. In some embodiments a majority of each indentation is linearly contiguous with adjacent indentations, and in other embodiments essentially all of each indentation is linearly contiguous with adjacent indentations. In one embodiment, each indentation **54** has an axis that is substantially perpendicular to the exterior surface of the liner **52**, where such exterior surface is substantially parallel to the longitudinal axis of the wellbore. In other embodiments such indentation axis may be significantly greater or less than ninety degrees to the exterior surface of the liner **52** and/or to the longitudinal axis of the wellbore, in order to direct the penetrators in a specific direction, according to the purposes and goals of the perforation operation.

[0039] FIG. **4** depicts further details concerning one embodiment of the indentations **54**. In this embodiment, each indentation **54** has a hexagonal outer perimeter **56** and therefore adjoins a neighboring indentation **54** on each of its six sides, i.e., all of its six sides are linearly contiguous with neighboring indentations **54**. Because of this fact, there are no "dead spaces" between the indentations **54** from which it is inferable that there is no area from which a penetrator is not, or could not be, transformed. A small linear ridge **58** is formed at each of the adjoining contact areas of the neighboring indentations **54**. A hexagonal shape for the perimeter **56** of the indentations **54** is one possible arrangement, which may offer the additional benefit that, by approximating the shape of a circle, a penetrator that is relatively radially uniform is, upon detonation of the body **50** of high explosive, developed therefrom. Additionally, the hexagonal shape of the perimeter **56** permits relatively closer packing of the indentations **54** to form an adjoining, interlocking honeycomb effect. As a result, the "dead space," that is unavoidable when indentations having circular perimeters are employed, is thereby greatly reduced or eliminated. A further advantage of the honeycomb arrangement of the indentations **54** is that the perforations created may, as a result, be spaced equally in all directions, that is, in circumferential, axial, vertical, and horizontal directions, such as to significantly reduce the possibility of failure of the surrounding casing **18** upon perforation. A high density of perforations may therefore be achieved from the use of such linearly contiguous and interlocking indentations that cover essentially the entire outer surface area of the module **40**. For example, a pattern of hexagonal indentations that are two inches in diameter, i.e., hexagons that can be inscribed within a two-inch diameter circle, may in some embodiments generate a shot pattern of 51 perforations per linear foot of the wellbore from the surface of a 4.5-inch diameter module **40**. In contrast, a similarly sized, conventional carrier-type perforating gun, using conventional shaped charges, will typically provide only about 18 perforations per linear foot. Thus, this embodiment illustrates a capability to increase the perforated area by a factor of three. The size and number of hexagonal indentations **54** may be varied, depending upon factors such as the diameter of the module **40** relative to the size of the annular space between the perforation system **10** and the casing wall **18**; the properties of the formation in which the perforation gun is being used; the presence or absence of fluid in the annular space; the selection of liner material and explosive; and the like. With the benefit of the present teachings, those skilled in the art will be able to determine optimal configurations based upon such skill and without undue experimentation.

[0040] FIGS. **4**, **5** and **6** show additional possible configurations for the liner to enable formation of effective penetrators therefrom. As illustrated therein, the indentations **54** each define a cavity **60**. While the perimeter of the indentations may influence the shape of the cavity **60**, it is not necessarily determinative thereof. Thus, in certain embodiments the shape of the cavity **60** may be of a generally conical or pyramidal configuration, as shown in FIG. **4**, or of a generally spherical or parabolic configuration, as depicted in FIGS. **5** and **6**. The cavity **60** provides a formation distance for a penetrator to form. The cavity **60** provides an apex **62**, i.e., point of greatest indentation, opposite the opening defined by perimeter **56**. In this embodiment, the cavity **60** has six equal planar triangular sides **70**. The sides **70** adjoin one another along junction lines **72**, forming a cavity **60** that is symmetrical along certain axes. The indentations **54** may be formed into the essentially planar liner **52** by stamping, forging or by other known means. Thereafter, the sheet may be formed into a cylinder by bringing opposing ends together and then welding or otherwise connecting the ends. The high explosive body **50** may then be cast into the space between the liner **52** and the inner cardboard tube **51**.

[0041] The shape of the cavity **60** may determine one or more characteristics of the penetrator and may dictate how the penetrator is formed.

[0042] Certain shapes (such as those for conventional shaped charges) produce a Munroe effect, whereby a small fraction (10-15%) of the liner **52** is propelled into a target to cause a narrow and deep penetration. Under the Munroe effect, the tip of the jet formed by a shaped charge liner collapse travels at tremendous velocity (8-10 km/sec). A generally conical or pyramidal cavity **60** produces a jet that forms such a penetration. For the purposes of this disclosure, a Munroe effect penetration may be defined as a penetration wherein a depth of penetration into the formation, i.e., a distance from a cement face, is generally six times or more of the diameter D of the cavity **60**.

[0043] Certain other shapes produce Misznay-Schardin effect, whereby a large fraction (90-100%) of the liner **52** is propelled into a target to cause a wide and shallow perforation. Projectiles formed under the Misznay-Schardin effect are commonly called Explosively Formed Penetrators (EFPs). EFPs travel much more slowly (~1 km/sec.) than the jet of a conventional shaped charge. A generally spherical, shallow curved hollow, a shallow pyramid indentation, or a shallow concave arcuate shaped cavity **60** forms a projectile that makes such a penetration. For the purposes of this disclosure, "shallow" means that the cavity **60** has a diameter D to depth De ratio of greater than two to one. In some embodiments, the diameter to depth ratio may be six to one or greater. The diameter of the cavity **60** may be measured across the outer perimeter **56** (i.e. diameter D), and the depth De of cavity **60** may be measured from the apex **62** and the plane of the ridges **58**. In embodiments where the bottom of the cavity **60** is flattened, then the depth De may be measured between the plane of the flattened area and the plane of the ridges **58**. For a non-circular shape, the diameter D may be considered the diameter of the circle that encompasses or circumscribes that shape. In other aspects, the term "shallow" may include designs wherein the depth De of the cavity **60** is approximately the same as or less than a thickness of the liner **52**. For the purposes of this disclosure, a Misznay-Schardin effect penetration may be defined as a penetration wherein a depth of penetration into the formation is about one-half to one diameter of the cavity **60**. In certain embodiments, the penetration may be less than one-half times the diameter of the cavity **60**.

[0044] Embodiments of this disclosure contemplate the use of a variety of cavity **60** shapes as required to accomplish the desired penetration.

[0045] An alternative method for forming the high explosive body **50** is by pressing a billet to a desired length and diameter, and then machining the billet to match the hexagonal indentations **54** at the outer surface of the liner **52**. A long axial hole is then drilled into the center of the billet and sized to accommodate the tube **51**. As those skilled in the art are aware, a billet of high explosive is a mass of high explosive material that has been pressed or cast into cylindrical shape. Pressed billets can be machined to a desired shape, while cast billets are formed to the desired shape, such as, in this case, a cylinder with an axial passage therethrough.

[0046] FIG. **5** illustrates an alternative design for the indentations **54**, here designated **54'**. The indentations **54'** still have a hexagonal perimeter **56**. However, the side surfaces defining the cavity **60** are smooth and rounded. In side cross-section, the cavity **60** forms a dome-like cap or parabola, as FIGS. **5** and **6**, respectively, depict. The radius and apex of each dome-like cavity **60** depend upon the liner thickness and desired formation distance, with the goal that a penetrator may be transformed therefrom that is optimal for creating a large perforation in the wellbore casing **18**. In alternative embodiments, other cavity shapes, such as a conical shape, may be employed.

[0047] Circumferentially surrounding the liner **52** is a cover **64** that protects the liner **52** and other parts of the module **40** from the harsh wellbore environment. In one embodiment, the cover **64** is a generally cylindrical construction having planar inner and outer surfaces. The cover **64** may be formed of, for example, a thermoplastic or thermoset polymer that is resistant to high wellbore temperatures. The cover **64** may be relatively thin, having a thickness of, for example, just 0.05 inch, and light in weight, such that it will not unduly interfere with the creation of the penetrators from the indentations **54** or **54'**. In some embodiments, an elemental metal or alloy, composite material, thermoplastic or thermoset polymer, or glass, for example, may be used to form the cover **64**. The cover **64** overlies the adjoining ridges **58** between neighboring indentations **54** or **54'** (see FIG. **6**). There is a space disposed between the cover **64** and the ridges **58** to permit the indentations **54**, **54'** to fully develop into penetrators upon detonation. Such space may be relatively small, for example, about 5 mm. Air, at atmospheric pressure, may be trapped within the cavities **60** of the indentations **54**, **54'** between the cover **64** and the outer surface of the liner **52**. The distance between the apex **62** of each indentation **54** or **54'** and the outer cover **64** provides a stand-off for each indentation **54** or **54'** such that a penetrator can more fully develop prior to contact with the well casing **18** (see FIG. **1**).

[0048] Upper and lower end caps **66**, **68** (see FIG. **3**) are secured to the cover **64** and liner **52** of the module **40** and serve to help encapsulate and protect the contents of the module **40**, particularly the explosive body **50**, from fluids within the wellbore **12** prior to detonation.

[0049] In operation, the perforation system **10** is lowered into the wellbore **12** until the modules **34**, **36**, **38** of the perforation system **10** are aligned with the desired strata **22**, **24**, and **30**, respectively, of the formation **14**. The modules **34**, **36**, **38** of the perforation system **10** are then detonated to create penetrators that perforate the casing **18**, cement **20** and formation **14**. Following perforation of the formation **14**, the remains of the perforation system **10** may be removed from the wellbore **12** by pulling upwardly on the conveyance string **32**. It is anticipated that, in many embodiments, the perforation modules **34**, **36**, **38** will be substantially or totally consumed in the detonation.

[0050] During detonation of the perforation modules **34**, **36**, **38**, directional penetrators are formed by the indentations **54**, **54'**. It is noted, however, that the detonation sequence of each module **34**, **36**, **38**, begins at the top end proximate to the central rod **42** and proceeds simultaneously in axially downward and radially outward directions. Each liner indentation **54**, **54'**, when acted upon by the advancing detonation wave, forms a robust EFP, which is particularly well suited for making large and shallow perforation holes in sandy or soft formations. While conventional shaped charges form a relatively fast-moving, low mass jet that accomplishes the perforation, followed by a relatively slow-moving slug that thereafter carries the mass of the remaining charge liner but does not take part in the actual perforation, the EFP of the present disclosure carries essentially all of the mass of the liner **52** forming the indentation **54** or **54'**. This means that the liner mass effectively forms part of the penetrator and takes an active part in the perforation, increasing the relative effectiveness thereof. In one embodiment it has been found that the perforations that result from indentations **54** or **54'** having hexagonal perimeters very closely approximate those created from indentations having circular perimeters.

[0051] FIG. **7** illustrates an exemplary shot pattern that may be formed upon detonation of the perforation module **40** within a section **80** of the wellbore **12**. FIG. **7** depicts the sidewall of the wellbore section **80** in cylindrical projection with the upper end of the section **80** depicted as line **82** and the lower end of the section **80** shown as line **84**. The illustrated wellbore section **80** has a length (L) of approximately one foot. There are fifty-one (51) perforations **86** disposed within the wellbore section **80**, which have been created by penetrators formed from the indentations **54** or **54'** of the perforation module **40**. In practice, those skilled in the art frequently desire perforations having diameters, as measured at the inner surface of the well casing, ranging from about 10 to about 22 mm, but larger or smaller perforations may alternatively be obtained by simply varying the size of the indentations. In one embodiment, the fifty-one (51) perforations **86** are arranged in six horizontal rows **88*a***, **88*b***, **88*c***, **88*d***, **88*e***, and **88*f*** that alternate between eight and nine perforations **86** each. Adjacent rows **88** of perforations **86** are shown herein as horizontally staggered from one another, such that perforations **86** in one row are located diagonal to, i.e., offset diagonally in relation to, perforations **86** in adjacent rows. For example, referring to FIG. **7**, perforation **86*b*** in row **88*b*** is located diagonal to penetrations **86*a*** and **86*c*** in row **88*a***. This staggered pattern may be advantageous in some circumstances. Because the penetrations **86** are more densely concentrated than perforations from conventional shaped charge perforation devices, the staggered arrangement may help to avoid overlapping of adjacent perforations. This may be desirable because, if there were numerous such overlaps, the resultant effect of a linear cut in the casing **18** could theoretically produce a casing failure, such as a casing collapse. The staggered arrangement may therefore avoid such an undesirable event. In another embodiment, some of the indentations may be configured of a material that does not suitably form penetrators, in order to reduce the number of penetrators and, therefore, the number or density of perforations obtained thereby. Such an embodiment may be acceptable in certain applications, wherein relatively increased amounts of post-detonation debris are not problematic.

[0052] Alternative to indentations having hexagonal perimeters, other perimeter shapes may be selected, most commonly polygonal shapes, such that the perimeters may be adjoined in a linearly contiguous fashion. For example, the indentations may be configured to have triangular, square, or octagonal perimeters. FIGS. **8** and **9** illustrate alternative embodiments wherein such triangular and square perimeter indentations, respectively, are used. FIG. **8** depicts an exemplary perforation module **90** having triangular perimeter indentations **92**. As may be seen, the triangular perimeter indentations are located in an adjacent manner such that each of the three sides of a given perimeter borders a side of a neighboring perimeter. Thus, “dead space” between the indentations **92** has thereby been eliminated.

[0053] FIG. **9** depicts an exemplary perforation module **94** having square perimeter indentations **96**. These indentations **96** are arranged in several horizontally-disposed rows, e.g., **98*a***, **98*b***, **98*c***. Adjacent rows of indentations **96** are staggered relative to one another, i.e., offset by half a square, such that indentations **96** in each row are located with their apices diagonal to the apices of indentations **96** in the adjacent row.

[0054] It will be understood by those in the art that each perimeter shape will impart some effect on the configuration of the cavity formed by an indentation, and therefore of the penetrator that will be formed from collapse of the cavity as a result of detonation. Factors such as the fabrication method, and capabilities and limitations thereof, of the liner wherein the indentations are formed, and the material of which the liner is composed, will desirably be taken into account when selecting the perimeter shape and associated packing parameters. For example, triangular and square perimeter indentations may, because of their shape, not collapse as readily during detonation as do hexagonal perimeter indentations in a perforation module wherein all materials and detonation factors are the same. However, modification of such factors may, in some embodiments, offset such disadvantages or even turn such a tendency into an advantage.

[0055] FIG. **10** depicts a portion of an exemplary liner surface for a perforation module wherein octagonal perimeter indentations are used. As may be seen in FIG. **10**, octagonal perimeter indentations cannot completely cover a given area without leaving some "dead space" between the indentations. In this aspect, their use may be less advantageous, in some embodiments, than the use of hexagonal, square or triangular-shaped indentations. However, octagonal perimeter indentations may more readily approximate the collapse sequence and penetrator transformation of indentations having a circular perimeter, and thus may obtain an advantage over triangular and circular perimeter indentations in certain embodiments. FIG. **10** depicts a liner surface section **100** having a plurality of octagonal perimeter indentations **102** that adjoin, i.e., are linearly contiguous to, one another at four of their eight sides **104**. The remaining four sides **106** of the octagonal perimeter indentations **102** define square areas **108** as interstitial spaces. If desired, the interstitial square areas **108** may themselves be indented, in the manner of square indentations **96** (see FIG. **9**), to provide for additional formed penetrators.

[0056] Turning now to FIGS. **11** through **15**, an exemplary initiation sequence is illustrated for a single EFP from a perforation module **40**. FIG. **11** is a cross-sectional view of the indentation **54** prior to detonation of the perforation module **40**. The indentation **54** is formed in liner **52** that surrounds the high explosive body **50**. In this embodiment a thermoplastic cover **64** surrounds liner **52**. The module **40** is disposed within a section of wellbore casing **18** surrounded by cement **20**. Fluid **57** resides in the annular space that is between the casing **18** and the radially exterior portion of the cover **64**. FIG. **12** depicts the beginning portion of the detonation wherein the material forming metallic liner **52** has begun to collapse or coalesce within the space formerly occupied by the cavity **60** of indentation **54**. The cover **64** atop the indentation **54** has begun to bow outward and thin out. In FIG. **13**, the detonation process has progressed to the point where a generally spherical penetrator **110** has been formed from the material making up the liner **52**. The casing **18** and fluid **57** are essentially sheared through by the penetrator **110**. FIG. **14** depicts an advanced stage of the detonation with the penetrator **110** now in a primarily plastic phase and perforating the cement **20** on its way to the formation (not shown). The walls of the perforation cavity may be lined with the liner or EFP material **25** that originally formed at least part of the liner **52** before detonation. Thus, aspects of the present disclosure include at least partially or substantially lining a perforation in the cement with liner material. Some unspent residual liner or EFP material **27** may be present at the end of the perforation.

[0057] Referring now to FIG. **15**, the penetrator **110** has formed a tunnel in the cement **20** and has proceeded a distance **21** into a formation **16**. The distance **21** may be generally measured from a boundary **23** between the cement **20** and the formation **16**. The distance **21** may be approximately a diameter of the cavity **60** or less. In variants, the distance **21** may be one-half or less of the diameter of the cavity **60**.

[0058] Referring now to FIG. **1**, in an illustrative method of perforating a well, the perforation system **10** may be disposed into the wellbore **12** on the conveyance string **32**. As noted previously, the perforation system **10** may include one or more perforating modules that are used to perforate portions of the surrounding formation **16**. The formation **16** may be loosely consolidated, unconsolidated or un-compacted. In one aspect, such a formation includes sediment, rocks, sand, and other granular material that behave more as a fluid than a solid. In another aspect, the particles making up such a formation may move relative to one another. In still another aspect, such a formation is not sufficiently stable to maintain a cavity or conduit formed therein. For example, a tunnel formed into the formation would collapse soon after formation. In a generally unconsolidated formation **16**, it may be desired to perforate the casing and the cement, but leave the formation **16** largely untouched. For such an application, the perforating modules **34**, **36**, **38** may utilize indentations configured to utilize the Misznay-Schardin effect forming EFPs. There may, of course, be more or fewer than three modules, depending upon the desired length of wellbore to be perforated.

[0059] Upon the firing of the perforating modules **34**, **36**, and **38**, perforations will be formed in the casing and cement in a manner as generally shown in FIG. **15**. However, the unconsolidated formation adjacent to the casing and cement are largely untouched. In aspects, therefore, the present disclosure provides a method of forming fluid channels in a well to produce fluids from a subsurface hydrocarbon reservoir that resides in an unconsolidated or substantially unconsolidated formation. In embodiments, the perforations in the cement may be at least partially lined with liner material.

[0060] In summary of the foregoing description, those skilled in the art will appreciate that the design of the perforation system **10** thus provides a number of advantages over conventional perforation systems. Included among these, first, is the fact that the linearly contiguous packing of the indentations combined with the unitary body of high explosive produces a greater number of perforating penetrators over a given axial length of a module **40** and reduced amount of "dead space," as compared with conventional perforation systems using shaped charges and indentations that are physically separated and/or have circular perimeters. The greater number of penetrators results in a desirably greater density in the post-detonation perforation shot pattern. Second, the disclosure provides for a substantial reduction in debris formed during the perforation operation. And third, the perforation module **40** may be created or manufactured and customized relatively easily, without the need for time-consuming placement and orientation of individual shaped charges, as with conventional systems.

[0061] From the above, it should be appreciated that what has been described includes, in part, a method for perforating a subterranean formation. The method may include lowering a plurality of perforating modules in a wellbore and detonating the plurality of perforating modules in the wellbore. Each of the plurality of perforating modules may include a central rod having an exterior load bearing portion, and an interior detonation portion including a first explosive, a second explosive at least partially surrounding the central rod, and a liner surrounding the second explosive, wherein the liner has a plurality of shallow concave surface indentations. The central rod further may include an axial passage. In one arrangement, a conducting wire may be disposed within the axial passage. In another embodiment, the axial passage may receive a hydraulic fluid. In embodiments, the plurality of shallow concave surface indentations may each have a cavity. The cavity may be defined by a diameter and a depth. In one arrangement, the diameter to depth ratio is approximately not less than two to one. In another embodiment, the diameter to depth ratio is not less than six to one. In still other embodiments, the depth is no greater than a thickness of the liner.

[0062] In arrangements, the plurality of shallow concave surface indentations may each have a cavity. The method may include forming a plurality of perforations in a region adjacent to the perforating modules, wherein the plurality of perforations extend substantially through a cement layer into a formation a distance from a cement face that is no greater than a diameter of the cavity. In some applications, the distance is no greater than one-half of the diameter of the cavity. Also, the method may include at least partially lining the plurality of perforations in the cement layer with a liner material.

[0063] In embodiments, the exterior load bearing portion may comprise a frangible material. Also, each of the plurality of shallow concave surface indentations may be linearly contiguous with at least another of the plurality of shallow concave surface indentations. In some arrangements, the shallow concave surface indentations may be arcuate.

[0064] From the above, it should be appreciated that what has been described also includes, in part, a method for perforating a subterranean formation. The method may include lowering a perforating module into a wellbore having a casing incased in cement, the perforating module having at least one explosively formed penetrator forming charge and liner; positioning the plurality of perforating modules in the wellbore and adjacent to a substantially unconsolidated formation; perforating the casing and cement; and perforating the formation to a distance no greater than a diameter of the at least one explosively formed penetrator forming charge and liner, wherein the distance measured from a boundary between the cement and the formation.

[0065] 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 perforating a subterranean formation, comprising:
- lowering a plurality of perforating modules in a wellbore,
  - wherein each of the plurality of perforating modules comprises:
    - a central rod,
      - wherein the central rod comprises:
        - an exterior load bearing portion, and
        - an interior detonation portion including a first explosive,
    - a second explosive at least partially surrounding the central rod, and
    - a liner surrounding the second explosive,
      - wherein the liner has a plurality of shallow concave surface indentations; and
- detonating the plurality of perforating modules in the wellbore.

2. The method of claim **1**, wherein the central rod further comprises:

an axial passage.

3. The method of claim **2**, wherein the central rod further comprises:

a conducting wire disposed within the axial passage.

4. The method of claim **2**, wherein the axial passage is adapted to receive a hydraulic fluid.

5. The method of claim **1**, wherein the plurality of shallow concave surface indentations each have a cavity, the cavity being defined by a diameter and a depth, and wherein the diameter to depth ratio is approximately not less than two to one.

6. The method of claim **5**, wherein the diameter to depth ratio is not less than six to one.

7. The method of claim **1** wherein the plurality of shallow concave surface indentations each have a cavity, the cavity being defined by a depth, wherein the depth is no greater than a thickness of the liner.

8. The method of claim **1**, wherein the plurality of shallow concave surface indentations each have a cavity, and further comprising: forming a plurality of perforations in a region adjacent to the perforating modules, wherein the plurality of perforations extend substantially through a cement layer into a formation a distance from a cement face that is no greater than a diameter of the cavity.

9. The method of claim **8**, wherein the distance is no greater than one-half of the diameter of the cavity.

10. The method of claim **8**, further comprising at least partially lining the plurality of perforations in the cement layer with a liner material.

11. The method of claim **1**, wherein the exterior load bearing portion comprises a frangible material.

12. The method of claim **1**, wherein each of the plurality of shallow concave surface indentations is linearly contiguous with at least another of the plurality of shallow concave surface indentations.

13. The method of claim **1**, wherein the shallow concave surface indentations are arcuate.

14. A method for perforating a subterranean formation, comprising:
- lowering a plurality of perforating modules in a wellbore,
  - wherein at least one of the plurality of perforating modules is separated from another of the plurality of perforating modules by a spacer, and
  - wherein each of the plurality of perforating modules comprises:
    - a central rod,
      - wherein the central rod comprises:
        - an exterior load bearing portion comprised of a frangible material,
        - an axial passage adapted to receive hydraulic fluid disposed along the length of the interior load bearing portion,
        - a wire disposed within the axial passage, and
        - an interior detonation portion including a first explosive,
    - a second explosive adapted to at least partially surround the central rod,
    - a liner disposed to surround the second explosive,
      - wherein the liner is made of a non-explosive material, and
      - wherein the liner has a plurality of shallow concave arcuate surface indentations,
        - wherein each of the plurality of shallow concave arcuate surface indentation is polygonal,
        - wherein each of the plurality of shallow concave arcuate surface indentations is configured to face substantially perpendicular to the longitudinal axis of the wellbore, and

wherein each of the plurality of concave arcuate surface is linearly contiguous with at least another of the plurality of shallow concave arcuate surface indentations, and

a cover disposed about the liner; and

detonating the plurality of perforating modules in the wellbore.

15. A method for perforating a subterranean formation, comprising:

lowering a perforating module into a wellbore having a casing incased in cement, the perforating module having at least one explosively formed penetrator forming charge and liner;

positioning the plurality of perforating modules in the wellbore and adjacent to a substantially unconsolidated formation;

perforating the casing and cement; and

perforating the formation to a distance no greater than a diameter of the at least one explosively formed penetrator forming charge and liner, wherein the distance measured from a boundary between the cement and the formation.

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