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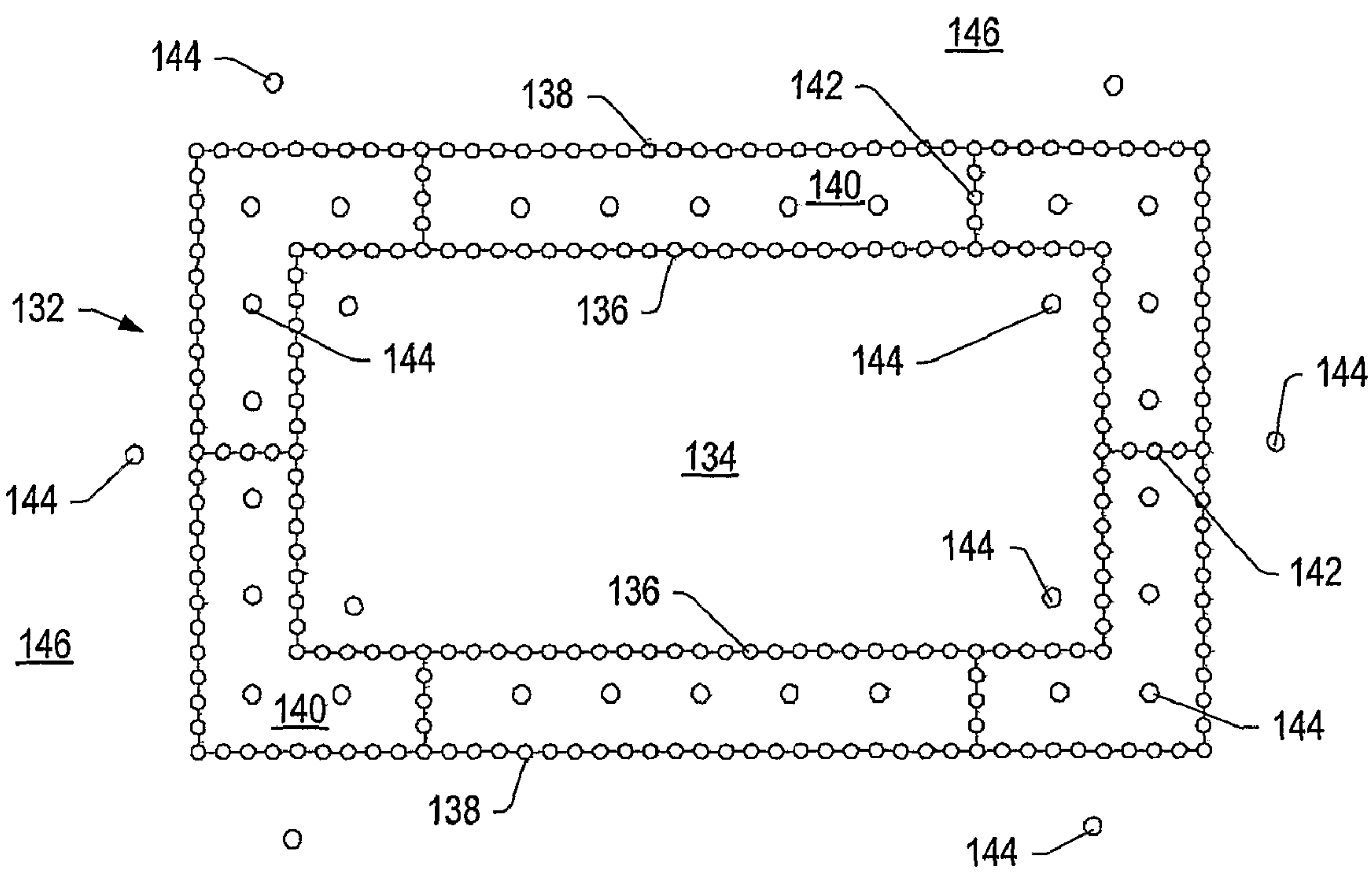

(57) Abrégé/Abstract:
The invention provides a double barrier system (132) for a subsurface treatment area, that includes a first barrier (136) formed around at least a portion of the subsurface treatment area, the first barrier configured to inhibit fluid from exiting or entering the subsurface treatment area; and a second barrier (138) formed around at least a portion of the first barrier, wherein a separation space exists between the first barrier and the second barrier. The invention also provides methods of forming the double barrier system.

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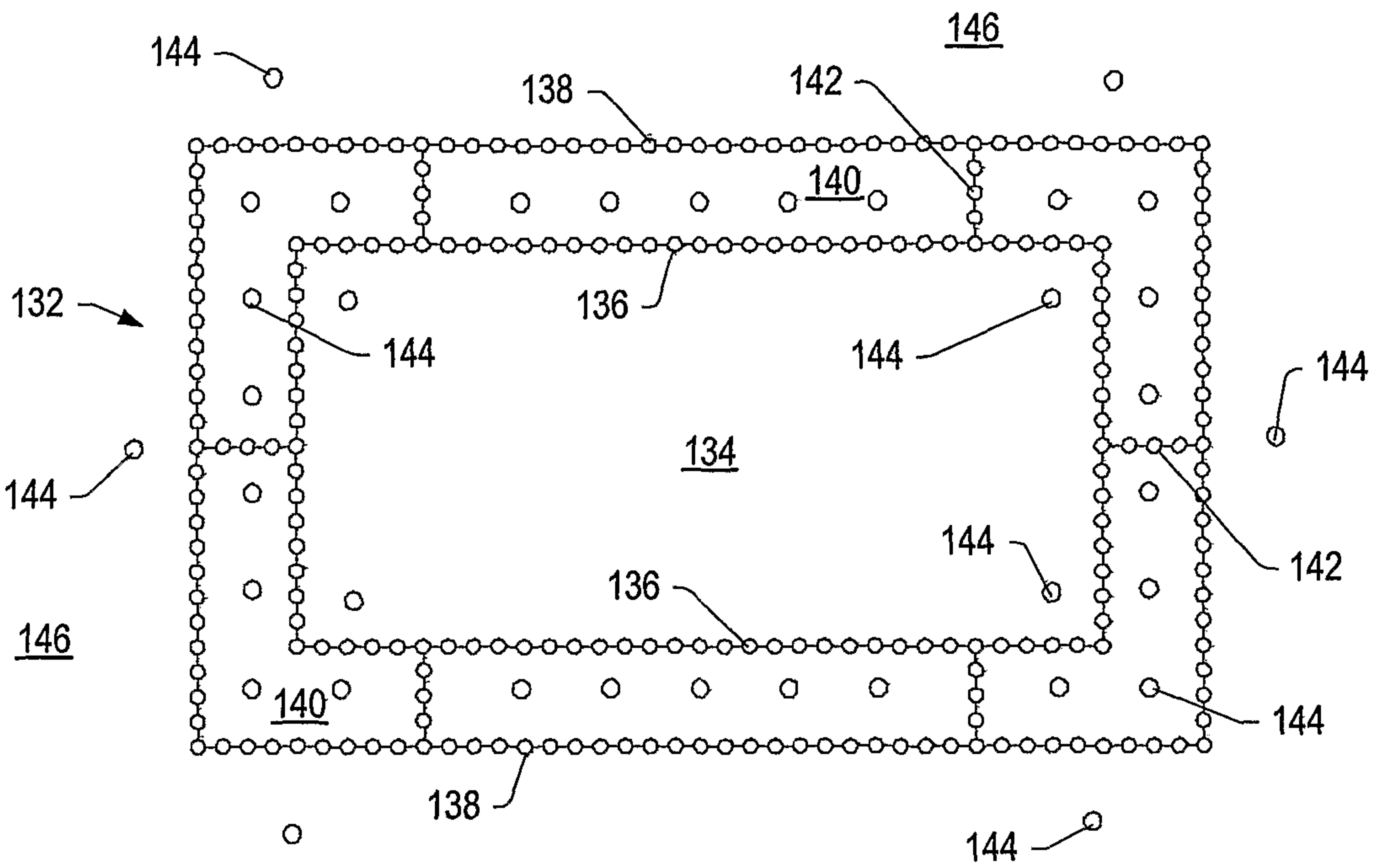

(57) Abstract: The invention provides a double barrier system (132) for a subsurface treatment area, that includes a first barrier (136) formed around at least a portion of the subsurface treatment area, the first barrier configured to inhibit fluid from exiting or entering the subsurface treatment area; and a second barrier (138) formed around at least a portion of the first barrier, wherein a separation space exists between the first barrier and the second barrier. The invention also provides methods of forming the double barrier system.

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DOUBLE BARRIER SYSTEM FOR AN IN SITU CONVERSION PROCESS

BACKGROUND

1. Field of the Invention

The present invention relates generally to methods and systems for providing a barrier for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Embodiments relate to the formation of double barrier around at least a portion of a treatment area.

2. Description of Related Art

In situ processes may be used to treat subsurface formations. During some in situ processes, fluids may be introduced or generated in the formation. Introduced or generated fluids may need to be contained in a treatment area to minimize or eliminate impact of the in situ process on adjacent areas. During some in situ processes, a barrier may be formed around all or a portion of the treatment area to inhibit migration fluids out of or into the treatment area.

A low temperature zone may be used to isolate selected areas of subsurface formation for many purposes. In some systems, ground is frozen to inhibit migration of fluids from a treatment area during soil remediation. U.S. Patent Nos. 4,860,544 to Krieg et al., 4,974,425 to Krieg et al.; 5,507,149 to Dash et al., 6,796,139 to Briley et al.; and 6,854,929 to Vinegar et al. describe systems for freezing ground.

To form a low temperature barrier, spaced apart wellbores may be formed in the formation where the barrier is to be formed. Piping may be placed in the wellbores. A low temperature heat transfer fluid may be circulated through the piping to reduce the temperature adjacent to the wellbores. The low temperature zone around the wellbores may expand outward. Eventually the low temperature zones produced by two adjacent wellbores merge. The temperature of the low temperature zones may be sufficiently low to freeze formation fluid so that a substantially impermeable barrier is formed. The wellbore spacing may be from about 1 m to 3 m or more.

Wellbore spacing may be a function of a number of factors, including formation composition and properties, formation fluid and properties, time available for forming the barrier, and temperature and properties of the low temperature heat transfer fluid. In general, a very cold temperature of the low temperature heat transfer fluid allows for a larger spacing and/or for quicker formation of the barrier. A very cold temperature may be -20° C or less.

Determining when a barrier is formed around a treatment area may be problematic. Also, if a breach in the barrier occurs, determining the location and limiting the impact of the breach on the treatment area or on adjacent areas may be difficult. Therefore, it is desirable to have a barrier system for an in situ process that allows for determination of the formation of the barrier. The barrier system there should be minimal or no effects to the treatment area and/or adjacent areas should a breach of part of the barrier system occur.

SUMMARY

The present invention relates generally to methods and systems for providing a barrier for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Embodiments relate to the formation of double barrier around at least a portion of a treatment area.

In some embodiments, the invention provides a barrier system for a subsurface treatment area, that includes: a first barrier formed around at least a portion of the subsurface treatment area, the first barrier configured to inhibit fluid from exiting or entering the subsurface treatment area; and a second barrier formed around at least a portion of the first barrier, wherein a separation space exists between the first barrier and the second barrier.

The invention also provides methods that use the described inventions to establish a double barrier around a subsurface treatment area.

In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments.

In further embodiments, treating a subsurface formation is performed using any of the methods or systems described herein.

In further embodiments, additional features may be added to the specific embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating a hydrocarbon containing formation.

FIG. 2 depicts an embodiment of a freeze well for a circulated liquid refrigeration system, wherein a cutaway view of the freeze well is represented below ground surface.

FIG. 3 depicts a schematic representation of a double barrier containment system.

FIG. 4 depicts a cross-sectional view of a double barrier containment system.

FIG. 5 depicts a schematic representation of a breach in the first barrier of a double barrier containment system.

FIG. 6 depicts a schematic representation of a breach in the second barrier of a double barrier containment system.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and may herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION

The following description generally relates to systems and methods for treating hydrocarbons in the formations. Such formations may be treated to yield hydrocarbon products, hydrogen, and other products.

"Hydrocarbons" are generally defined as molecules formed primarily by carbon and hydrogen atoms. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbons may be, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. "Hydrocarbon fluids" are fluids that include hydrocarbons. Hydrocarbon fluids may include, entrain, or be entrained in non-hydrocarbon fluids such as hydrogen, nitrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, water, and ammonia.

A "formation" includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. The "overburden" and/or the "underburden" include one or more different types of impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ conversion processes, the overburden and/or the underburden may include a hydrocarbon containing layer or hydrocarbon containing layers that are relatively impermeable and are not subjected to temperatures during in situ conversion processing that result in significant characteristic changes of the hydrocarbon containing layers of the overburden and/or the underburden. For example, the underburden may contain shale or mudstone, but the underburden is not allowed to heat to pyrolysis temperatures during the in situ conversion process. In some cases, the overburden and/or the underburden may be somewhat permeable.

"Formation fluids" refer to fluids present in a formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbon, and water (steam). Formation fluids may include hydrocarbon fluids as well as non-hydrocarbon fluids. The term "mobilized fluid" refers to fluids in a hydrocarbon containing formation that are able to flow as a result of thermal treatment of the formation. "Produced fluids" refer to formation fluids removed from the formation.

A "heat source" is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and/or a conductor disposed in a conduit. A heat source may also include systems that generate heat by burning a fuel external to or in a formation. The systems may be surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In some embodiments, heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer medium that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. Thus, for example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (for example, chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (for example, an oxidation reaction). A heat source may also include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

A "heater" is any system or heat source for generating heat in a well or a near wellbore region. Heaters may be, but are not limited to, electric heaters, burners, combustors that react with material in or produced from a formation, and/or combinations thereof.

An "in situ conversion process" refers to a process of heating a hydrocarbon containing formation from heat sources to raise the temperature of at least a portion of the formation above a pyrolysis temperature so that pyrolyzation fluid is produced in the formation.

The term "wellbore" refers to a hole in a formation made by drilling or insertion of a conduit into the formation. A wellbore may have a substantially circular cross section, or another cross-sectional shape. As used herein, the terms "well" and "opening," when referring to an opening in the formation may be used interchangeably with the term "wellbore."

"Pyrolysis" is the breaking of chemical bonds due to the application of heat. For example, pyrolysis may include transforming a compound into one or more other substances by heat alone. Heat may be transferred to a section of the formation to cause pyrolysis. In some formations, portions of the formation and/or other materials in the formation may promote pyrolysis through catalytic activity.

"Pyrolyzation fluid" or "pyrolysis products" refers to fluid produced substantially during pyrolysis of hydrocarbons. Fluid produced by pyrolysis reactions may mix with other fluids in a formation. The mixture would be considered pyrolyzation fluid or pyrolyzation product. As used herein, "pyrolysis zone" refers to a volume of a formation (for example, a relatively permeable formation such as a tar sands formation) that is reacted or reacting to form a pyrolyzation fluid.

"Thermal conductivity" is a property of a material that describes the rate at which heat flows, in steady state, between two surfaces of the material for a given temperature difference between the two surfaces.

Hydrocarbons or other desired products in a formation may be produced using various in situ processes. Some in situ processes that may be used to produce hydrocarbons or desired products are in situ conversion processes, steam flooding, fire flooding, steam-assisted gravity drainage, and solution mining. During some in situ processes, barriers may be needed or required. Barriers may inhibit fluid, such as formation water, from entering a treatment area. Barriers may also inhibit undesired exit of fluid from the treatment area. Inhibiting undesired exit of fluid from the treatment area may minimize or eliminate impact of the in situ process on areas adjacent to the treatment area.

FIG. 1 depicts a schematic view of an embodiment of a portion of in situ conversion system 100 for treating a hydrocarbon containing formation. In situ conversion system 100 may include barrier wells 102. Barrier wells 102 are used to form a barrier around a treatment area. The barrier inhibits fluid flow into and/or out of the treatment area. Barrier wells include, but are not limited to, dewatering wells, vacuum wells, capture wells, injection wells, grout wells, freeze wells, or combinations thereof. In the embodiment depicted in FIG. 1, barrier wells 102 are shown extending only along one side of heat sources 104, but the barrier wells typically encircle all heat sources 104 used, or to be used, to heat a treatment area of the formation.

Heat sources 104 are placed in at least a portion of the formation. Heat sources 104 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 104 may also include other types of heaters. Heat sources 104 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 104 through supply lines 106. Supply lines 106 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 106 for heat sources may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated in the formation.

Production wells 108 are used to remove formation fluid from the formation. In some embodiments, production well 108 may include one or more heat sources. A heat source in the production well may heat one or more portions of the formation at or near the production well. A heat source in a production well may inhibit condensation and reflux of formation fluid being removed from the formation.

Formation fluid produced from production wells 108 may be transported through collection piping 110 to treatment facilities 112. Formation fluids may also be produced from heat sources 104. For example, fluid may be produced from heat sources 104 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 104 may be transported through tubing or piping to collection piping 110 or the produced fluid may be transported through tubing or piping directly to treatment facilities 112. Treatment facilities 112 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids. The treatment facilities may form transportation fuel from at least a portion of the hydrocarbons produced from the formation.

Some wellbores formed in the formation may be used to facilitate formation of a perimeter barrier around a treatment area. The perimeter barrier may be, but is not limited to, a low temperature or frozen barrier formed by freeze wells, dewatering wells, a grout wall formed in the formation, a sulfur cement barrier, a barrier formed by a gel produced in the formation, a barrier formed by precipitation of salts in the formation, a barrier formed by a polymerization reaction in the formation, and/or sheets driven into the formation. Heat sources, production wells, injection wells, dewatering wells, and/or monitoring wells may be installed in the treatment area defined by the barrier prior to, simultaneously with, or after installation of the barrier.

A low temperature zone around at least a portion of a treatment area may be formed by freeze wells. In an embodiment, refrigerant is circulated through freeze wells to form low temperature zones around each freeze well. The freeze wells are placed in the formation so that the low temperature zones overlap and form a low temperature zone around the treatment area. The low temperature zone established by freeze wells is maintained below the freezing temperature of aqueous fluid in the formation. Aqueous fluid entering the low temperature zone freezes and forms the frozen barrier. In other embodiments, the freeze barrier is formed by batch operated freeze wells. A cold fluid, such as liquid nitrogen, is introduced into the freeze wells to form low temperature zones around the freeze wells. The fluid is replenished as needed.

In some embodiments, two or more rows of freeze wells are located about all or a portion of the perimeter of the treatment area to form a thick interconnected low temperature zone. Thick low temperature zones may be formed adjacent to areas in the formation where there is a high flow rate of aqueous fluid in the formation. The thick barrier may ensure that breakthrough of the frozen barrier established by the freeze wells does not occur.

Vertically positioned freeze wells and/or horizontally positioned freeze wells may be positioned around sides of the treatment area. If the upper layer (the overburden) or the lower layer (the underburden) of the formation is likely to allow fluid flow into the treatment area or out of the treatment area, horizontally positioned freeze wells may be used to form an upper and/or a lower barrier for the treatment area. In some embodiments, an upper barrier and/or a lower barrier may not be necessary if the upper layer and/or the lower layer are at least substantially impermeable. If the upper freeze barrier is formed, portions of heat sources, production wells, injection wells, and/or dewatering wells that pass through the low temperature zone created by the freeze wells forming the upper freeze barrier wells may be insulated and/or heat traced so that the low temperature zone does not adversely affect the functioning of the heat sources, production wells, injection wells and/or dewatering wells passing through the low temperature zone.

Spacing between adjacent freeze wells may be a function of a number of different factors. The factors may include, but are not limited to, physical properties of formation material, type of refrigeration system, coldness and thermal properties of the refrigerant, flow rate of material into or out of the treatment area, time for forming the low temperature zone, and economic considerations. Consolidated or partially consolidated formation material may allow for a large separation distance between freeze wells. A separation distance between freeze wells in consolidated or partially consolidated formation material may be from about 3 m to about 20 m, about 4 m to about 15 m, or about 5 m to about 10 m. In an embodiment, the spacing between adjacent freeze wells is about 5 m. Spacing between freeze wells in unconsolidated or substantially unconsolidated formation material, such as in tar sand, may need to be smaller than spacing in consolidated formation material. A separation distance between freeze wells in unconsolidated material may be from about 1 m to about 5 m.

Freeze wells may be placed in the formation so that there is minimal deviation in orientation of one freeze well relative to an adjacent freeze well. Excessive deviation may create a large separation distance between adjacent freeze wells that may not permit formation of an interconnected low temperature zone between the adjacent freeze wells. Factors that influence the manner in which freeze wells are inserted into the ground include, but are not limited to, freeze well insertion time, depth that the freeze wells are to be inserted, formation properties, desired well orientation, and economics.

Relatively low depth wellbores for freeze wells may be impacted and/or vibrationally inserted into some formations. Wellbores for freeze wells may be impacted and/or vibrationally inserted into formations to depths from about 1 m to about 100 m without excessive deviation in orientation of freeze wells relative to adjacent freeze wells in some types of formations.

Wellbores for freeze wells placed deep in the formation, or wellbores for freeze wells placed in formations with layers that are difficult to impact or vibrate a well through, may be placed in the formation by directional drilling and/or geosteering. Acoustic signals, electrical signals, magnetic signals, and/or other signals produced in a first wellbore may be used to guide drilling of adjacent wellbores so that desired spacing between adjacent wells is maintained. Tight control of the spacing between wellbores for freeze wells is an important factor in minimizing the time for completion of barrier formation.

After formation of the wellbore for the freeze well, the wellbore may be backflushed with water adjacent to the part of the formation that is to be reduced in temperature to form a portion of the freeze barrier. The water may displace drilling fluid remaining in the wellbore. The water may displace indigenous gas in cavities adjacent to the formation. In some embodiments, the wellbore is filled with water from a conduit up to the level of the overburden. In some embodiments, the wellbore is backflushed with water in sections. The wellbore maybe treated in sections having lengths of about 6 m, 10 m, 14 m, 17 m, or greater. Pressure of the water in the wellbore is maintained below the fracture pressure of the formation. In some embodiments, the water, or a portion of the water is removed from the wellbore, and a freeze well is placed in the formation.

FIG. 2 depicts an embodiment of freeze well 114. Freeze well 114 may include canister 116, inlet conduit 118, spacers 120, and wellcap 122. Spacers 120 may position inlet conduit 118 in canister 116 so that an annular space is formed between the canister and the conduit. Spacers 120 may promote turbulent flow of refrigerant in the annular space between inlet conduit 118 and canister 116, but the spacers may also cause a significant fluid pressure drop. Turbulent fluid flow in the annular space may be promoted by roughening the inner surface of canister 116, by roughening the outer surface of inlet conduit 118, and/or by having a small cross-sectional area annular space that allows for high refrigerant velocity in the annular space. In some embodiments, spacers are not used.

Formation refrigerant may flow through cold side conduit 124 from a refrigeration unit to inlet conduit 118 of freeze well 114. The formation refrigerant may flow through an annular space between inlet conduit 118 and canister 116 to warm side conduit 126. Heat may transfer from the formation to canister 116 and from the canister to the formation refrigerant in the annular space. Inlet conduit 118 may be insulated to inhibit heat transfer to the formation refrigerant during passage of the formation refrigerant into freeze well 114. In an embodiment, inlet conduit 118 is a high density polyethylene tube. At cold temperatures, some polymers may exhibit a large amount of thermal contraction. For example, a 260 m initial length of polyethylene conduit subjected to a temperature of about -25 °C may contract by 6 m or more. If a high density polyethylene conduit, or other polymer conduit, is used, the large thermal contraction of the material must be taken into account in determining the final depth of the freeze well. For example, the freeze well may be drilled deeper than needed, and the conduit may be allowed to shrink back during use. In some embodiments, inlet conduit 118 is an insulated metal tube. In some embodiments, the insulation may be a polymer coating, such as, but not limited to, polyvinylchloride, high density polyethylene, and/or polystyrene.

Freeze well 114 may be introduced into the formation using a coiled tubing rig. In an embodiment, canister 116 and inlet conduit 118 are wound on a single reel. The coiled tubing rig introduces the canister and inlet conduit 118 into the formation. In an embodiment, canister 116 is wound on a first reel and inlet conduit 118 is wound on a second reel. The coiled tubing rig introduces canister 116 into the formation. Then, the coiled tubing rig is used to introduce inlet conduit 118 into the canister. In other embodiments, freeze well is assembled in sections at the wellbore site and introduced into the formation.

An insulated section of freeze well 114 may be placed adjacent to overburden 128. An uninsulated section of freeze well 114 may be placed adjacent to layer or layers 130 where a low temperature zone is to be formed. In some embodiments, uninsulated sections of the freeze wells may be positioned adjacent only to aquifers or other permeable portions of the formation that would allow fluid to flow into or out of the treatment area. Portions of the formation where uninsulated sections of the freeze wells are to be placed may be determined using analysis of cores and/or logging techniques.

Various types of refrigeration systems may be used to form a low temperature zone. Determination of an appropriate refrigeration system may be based on many factors, including, but not limited to: type of freeze well; a distance between adjacent freeze wells; refrigerant; time frame in which to form a low temperature zone; depth of the low temperature zone; temperature differential to which the refrigerant will be subjected; chemical and physical properties of the refrigerant; environmental concerns related to potential refrigerant releases, leaks, or spills; economics; formation water flow in the formation; composition and properties of formation water, including the salinity of the formation water; and various properties of the formation such as thermal conductivity, thermal diffusivity, and heat capacity.

A circulated fluid refrigeration system may utilize a liquid refrigerant (formation refrigerant) that is circulated through freeze wells. Some of the desired properties for the formation refrigerant are: low working temperature, low viscosity at and near the working temperature, high density, high specific heat capacity, high thermal conductivity, low cost, low corrosiveness, and low toxicity. A low working temperature of the formation refrigerant allows a large low temperature zone to be established around a freeze well. The low working temperature of formation refrigerant should be about -20 °C or lower. Formation refrigerants having low working temperatures of at least -60 °C may include aqua ammonia, potassium formate solutions such as Dynalene® HC-50 (Dynalene® Heat Transfer Fluids (Whitehall, Pennsylvania, U.S.A.)) or FREEZIUM® (Kemira Chemicals (Helsinki, Finland)); silicone heat transfer fluids such as Syltherm XLT® (Dow Corning Corporation (Midland, Michigan, U.S.A.); hydrocarbon refrigerants such as propylene; and chlorofluorocarbons such as R-22. Aqua ammonia is a solution of ammonia and water with a weight percent of ammonia between about 20% and about 40%. Aqua ammonia has several properties and characteristics that make use of aqua ammonia as the formation refrigerant desirable. Such properties and characteristics include, but are not limited to, a very low freezing point, a low viscosity, ready availability, and low cost.

Formation refrigerant that is capable of being chilled below a freezing temperature of aqueous formation fluid may be used to form the low temperature zone around the treatment area. The following equation (the Sanger equation) may be used to model the time t_1 needed to form a frozen barrier of radius R around a freeze well having a surface temperature of T_s:

(1) $$t_1 = \frac{R^2 L_1}{4k_f v_s}\left(2\ln\frac{R}{r_o} - 1 + \frac{c_{vf} v_s}{L_1}\right)$$

in which:

$$L_1 = L\frac{a_r^2 - 1}{2\ln a_r} c_{vu} v_o$$

$$a_r = \frac{R_A}{R}.$$

In these equations, k_f is the thermal conductivity of the frozen material; c_{vf} and c_{vu} are the volumetric heat capacity of the frozen and unfrozen material, respectively; r_o is the radius of the freeze well; v_s is the temperature difference between the freeze well surface temperature T_s and the freezing point of water T_o; v_o is the temperature difference between the ambient ground temperature T_g and the freezing point of water T_o; L is the volumetric latent heat of freezing of the formation; R is the radius at the frozen-unfrozen interface; and R_A is a radius at which there is no influence from the refrigeration pipe. The Sanger equation may provide a conservative estimate of the time needed to form a frozen barrier of radius R because the equation does not take into consideration superposition of cooling from other freeze wells. The temperature of the formation refrigerant is an adjustable variable that may significantly affect the spacing between freeze wells.

EQN. 1 implies that a large low temperature zone may be formed by using a refrigerant having an initial temperature that is very low. The use of formation refrigerant having an initial cold temperature of about -30 °C or lower is desirable. Formation refrigerants having initial temperatures warmer than about -30 °C may also be used, but such formation refrigerants require longer times for the low temperature zones produced by individual freeze wells to connect. In addition, such formation refrigerants may require the use of closer freeze well spacings and/or more freeze wells.

The physical properties of the material used to construct the freeze wells may be a factor in the determination of the coldest temperature of the formation refrigerant used to form the low temperature zone around the treatment area. Carbon steel may be used as a construction material of freeze wells. ASTM A333 grade 6 steel alloys and ASTM A333 grade 3 steel alloys may be used for low temperature applications. ASTM A333 grade 6 steel alloys typically contain little or no nickel and have a low working temperature limit of about -50 °C. ASTM A333 grade 3 steel alloys typically contain nickel and have a much colder low working temperature limit. The nickel in the ASTM A333 grade 3 alloy adds ductility at cold temperatures, but also significantly raises the cost of the metal. In some embodiments, the coldest temperature of the refrigerant is from about -35 °C to about -55 °C, from about -38 °C to about -47 °C, or from about -40 °C to about -45 °C to allow for the use of ASTM A333 grade 6 steel alloys for construction of canisters for freeze wells. Stainless steels, such as 304 stainless steel, may be used to form freeze wells, but the cost of stainless steel is typically much more than the cost of ASTM A333 grade 6 steel alloy.

In some embodiments, the metal used to form the canisters of the freeze wells may be provided as pipe. In some embodiments, the metal used to form the canisters of the freeze wells may be provided in sheet form. The sheet metal may be longitudinally welded to form pipe and/or coiled tubing. Forming the canisters from sheet metal may improve the economics of the system by allowing for coiled tubing insulation and by reducing the equipment and manpower needed to form and install the canisters using pipe.

A refrigeration unit may be used to reduce the temperature of formation refrigerant to the low working temperature. In some embodiments, the refrigeration unit may utilize an ammonia vaporization cycle. Refrigeration units are available from Cool Man Inc. (Milwaukee, Wisconsin, U.S.A.), Gartner Refrigeration & Manufacturing (Minneapolis, Minnesota, U.S.A.), and other suppliers. In some embodiments, a cascading refrigeration system may be utilized with a first stage of ammonia and a second stage of carbon dioxide. The circulating refrigerant through the freeze wells may be 30% by weight ammonia in water (aqua ammonia). Alternatively, a single stage carbon dioxide refrigeration system may be used.

In some embodiments, a double barrier system is used to isolate a treatment area. The double barrier system may be formed with a first barrier and a second barrier. The first barrier may be formed around at least a portion of the treatment area to inhibit fluid from entering or exiting the treatment area. The second barrier may be formed around at least a portion of the first barrier to isolate an inter-barrier zone between the first barrier and the second barrier. The double barrier system may allow greater project depths than a single barrier system. Greater depths are possible with the double barrier system because the stepped differential pressures across the first barrier and the second barrier is less than the differential pressure across a single barrier. The smaller differential pressures across the first barrier and the second barrier make a breach of the double barrier system less likely to occur at depth for the double barrier system as compared to the single barrier system.

The double barrier system reduces the probability that a barrier breach will affect the treatment area or the formation on the outside of the double barrier. That is, the probability that the location and/or time of occurrence of the breach in the first barrier will coincide with the location and/or time of occurrence of the breach in the second barrier is low, especially if the distance between the first barrier and the second barrier is relatively large (for example, greater than about 15 m). Having a double barrier may reduce or eliminate influx of fluid into the treatment area following a breach of the first barrier or the second barrier. The treatment area may not be affected if the second barrier breaches. If the first barrier breaches, only a portion of the fluid in the inter-barrier zone is able to enter the contained zone. Also, fluid from the contained zone will not pass the second barrier. Recovery from a breach of a barrier of the double barrier system may require less time and fewer resources than recovery from a breach of a single barrier system. For example, reheating a treatment area zone following a breach of a double barrier system may require less energy than reheating a similarly sized treatment area zone following a breach of a single barrier system.

The first barrier and the second barrier may be the same type of barrier or different types of barriers. In some embodiments, the first barrier and the second barrier are formed by freeze wells. In some embodiments, the first barrier is formed by freeze wells, and the second barrier is a grout wall. The grout wall may be formed of cement, sulfur, sulfur cement, or combinations thereof. In some embodiments, a portion of the first barrier and/or a portion of the second barrier is a natural barrier, such as an impermeable rock formation.

FIG. 3 depicts an embodiment of double barrier system 132. The perimeter of treatment area 134 may be surrounded by first barrier 136. First barrier 136 may be surrounded by second barrier 138. Inter-barrier zones 140 may be isolated between first barrier 136, second barrier 138 and partitions 142. Creating sections with partitions 142 between first barrier 136 and second barrier 138 limits the amount of fluid held in individual inter-barrier zones 140. Partitions 142 may strengthen double barrier system 132. In some embodiments, the double barrier system may not include partitions.

The inter-barrier zone may have a thickness from about 1 m to about 300 m. In some embodiments, the thickness of the inter-barrier zone is from about 10 m to about 100 m, or from about 20 m to about 50 m.

 Pumping/monitor wells 144 may be positioned in contained zone 134, inter-barrier zones 140, and/or outer zone 146 outside of second barrier 138. Pumping/monitor wells 144 allow for removal of fluid from treatment area 134, inter-barrier zones 140, or outer zone 146. Pumping/monitor wells 144 also allow for monitoring of fluid levels in treatment area 134, inter-barrier zones 140, and outer zone 146.

In some embodiments, a portion of treatment area 134 is heated by heat sources. The closest heat sources to first barrier 136 may be installed a desired distance away from the first barrier. In some embodiments, the desired distance between the closest heat sources and first barrier 136 is in a range between about 5 m and about 300 m, between about 10 m and about 200 m, or between about 15 m and about 50 m. For example, the desired distance between the closest heat sources and first barrier 136 may be about 40 m.

FIG. 4 depicts a cross-sectional view of double barrier system 132 used to isolate treatment area 134 in the formation. The formation may include one or more fluid bearing zones 148 and one or more impermeable zones 150. First barrier 136 may at least partially surround treatment area 134. Second barrier 138 may at least partially surround first barrier 136. In some embodiments, impermeable zones 150 are located above and/or below treatment area 134. Thus, treatment area 134 is sealed around the sides and from the top and bottom. In some embodiments, one or more paths 152 are formed to allow communication between two or more fluid bearing zones 148 in treatment area 134. Fluid in treatment area 134 may be pumped from the zone. Fluid in inter-barrier zone 140 and fluid in outer zone 146 is inhibited from reaching the treatment area. During in situ conversion of hydrocarbons in treatment area 134, formation fluid generated in the treatment area is inhibited from passing into inter-barrier zone 140 and outer zone 146.

After sealing treatment area 134, fluid levels in a given fluid bearing zone 148 may be changed so that the fluid head in inter-barrier zone 140 and the fluid head in outer zone 146 are different. The amount of fluid and/or the pressure of the fluid in individual fluid bearing zones 148 may be adjusted after first barrier 136 and second barrier 138 are formed. The ability to maintain different amounts of fluid and/or pressure in fluid bearing zones 148 may indicate the formation and completeness of first barrier 136 and second barrier 138. Having different fluid head levels in treatment area 134, fluid bearing zones 148 in inter-barrier zone 140, and in the fluid bearing zones in outer zone 146 allows for determination of the occurrence of a breach in first barrier 136 and/or second barrier 138. In some embodiments, the differential pressure across first barrier 136 and second barrier 138 is adjusted to reduce stresses applied to first barrier 136 and/or second barrier 138, or stresses on certain strata of the formation.

Some fluid bearing zones 148 may contain native fluid that is difficult to freeze because of a high salt content or compounds that reduce the freezing point of the fluid. If first barrier 136 and/or second barrier 138 are low temperature zones established by freeze wells, the native fluid that is difficult to freeze may be removed from fluid bearing zones 148 in inter-barrier zone 140 through pumping/monitor wells 144. The native fluid is replaced with a fluid that the freeze wells are able to more easily freeze.

In some embodiments, pumping/monitor wells 144 may be positioned in treatment area 134, inter-barrier zone 140, and/or outer zone 146. Pumping/monitor wells 144 may be used to test for freeze completion of frozen barriers and/or for pressure testing frozen barriers and/or strata. Pumping/monitor wells 144 may be used to remove fluid and/or to monitor fluid levels in treatment area 134, inter-barrier zone 140, and/or outer zone 146. Using pumping/monitor wells 144 to monitor fluid levels in contained zone 134, inter-barrier zone 140, and/or outer zone 146 may allow detection of a breach in first barrier 136 and/or second barrier 138. Pumping/monitor wells 144 allow pressure in treatment area 134, each fluid bearing zone 148 in inter-barrier zone 140, and each fluid bearing zone in outer zone 146 to be independently monitored so that the occurrence and/or the location of a breach in first barrier 136 and/or second barrier 138 can be determined.

In some embodiments, fluid pressure in inter-barrier zone 140 is maintained greater than the fluid pressure in treatment area 134, and less than the fluid pressure in outer zone 146. If a breach of first barrier 136 occurs, fluid from inter-barrier zone 140 flows into treatment area 134, resulting in a detectable fluid level drop in the inter-barrier zone. If a breach of second barrier 138 occurs, fluid from the outer zone flows into inter-barrier zone 140, resulting in a detectable fluid level rise in the inter-barrier zone.

A breach of first barrier 136 may allow fluid from inter-barrier zone 140 to enter treatment area 134. FIG. 5 depicts breach 154 in first barrier 136 of double barrier containment system 132. Arrow 156 indicates flow direction of fluid 158 from inter-barrier zone 140 to treatment area 134 through breach 154. The fluid level in fluid bearing zone 148 proximate breach 154 of inter-barrier zone 140 falls to the height of the breach.

Path 152 allows fluid 158 to flow from breach 154 to the bottom of treatment area 134, increasing the fluid level in the bottom of the contained zone. The volume of fluid that flows into treatment area 134 from inter-barrier zone 140 is typically small compared to the volume of the treatment area. The volume of fluid able to flow into treatment area 134 from inter-barrier zone 140 is limited because second barrier 138 inhibits recharge of fluid 158 into the affected fluid bearing zone. In some embodiments, the fluid that enters treatment area 134 may be pumped from the treatment area using pumping/monitor wells 144 in the treatment area. In some embodiments, the fluid that enters treatment area 134 may be evaporated by heaters in the treatment area that are part of the in situ conversion process system. The recovery time for the heated portion of treatment area 134 from cooling caused by the introduction of fluid from inter-barrier zone 140 is brief. The recovery time may be less than a month, less than a week, or less than a day.

Pumping/monitor wells 144 in inter-barrier zone 140 may allow assessment of the location of breach 154. When breach 154 initially forms, fluid flowing into treatment area 134 from fluid bearing zone 148 proximate the breach creates a cone of depression in the fluid level of the affected fluid bearing zone in inter-barrier zone 140. Time analysis of fluid level data from pumping/monitor wells 144 in the same fluid bearing zone as breach 154 can be used to determine the general location of the breach.

When breach 154 of first barrier 136 is detected, pumping/monitor wells 144 located in the fluid bearing zone that allows fluid to flow into treatment area 134 may be activated to pump fluid out of the inter-barrier zone. Pumping the fluid out of the inter-barrier zone reduces the amount of fluid 158 that can pass through breach 154 into treatment area 134.

Breach 154 may be caused by ground shift. If first barrier 136 is a low temperature zone formed by freeze wells, the temperature of the formation at breach 154 in the first barrier is below the freezing point of fluid 158 in inter-barrier zone 140. Passage of fluid 158 from inter-barrier zone 140 through breach 154 may result in freezing of the fluid in the breach and self-repair of first barrier 136.

A breach of the second barrier may allow fluid in the outer zone to enter the inter-barrier zone. The first barrier may inhibit fluid entering the inter-barrier zone from reaching the treatment area. FIG. 6 depicts breach 154 in second barrier 138 of double barrier system 132. Arrow 156 indicates flow direction of fluid 158 from outside of second barrier 138 to inter-barrier zone 140 through breach 154. As fluid 158 flows through breach 154 in second barrier 138, the fluid level in the portion of inter-barrier zone 140 proximate the breach rises from initial level 160 to a level that is equal to level 162 of fluid in the same fluid bearing zone in outer zone 146. An increase of fluid 158 in fluid bearing zone 148 may be detected by pumping/monitor well 144 positioned in the fluid bearing zone proximate breach 154.

Breach 154 may be caused by ground shift. If second barrier 138 is a low temperature zone formed by freeze wells, the temperature of the formation at breach 154 in the second barrier is below the freezing point of fluid 158 entering from outer zone 146. Fluid from outer zone 146 in breach 154 may freeze and self-repair second barrier 138.

First barrier and second barrier of the double barrier containment system may be formed by freeze wells. In an embodiment, first barrier is formed first. The cooling load needed to maintain the first barrier is significantly less than the cooling load needed to form the first barrier. After formation of the first barrier, the excess cooling capacity that the refrigeration system used to form the first barrier may be used to form a portion of the second barrier. In some embodiments, the second barrier is formed first and the excess cooling capacity that the refrigeration system used to form the second barrier is used to form a portion of the first barrier. After the first and second barriers are formed, excess cooling capacity supplied by the refrigeration system or refrigeration systems used to form the first barrier and the second barrier may be used to form a barrier or barriers around the next contained zone that is to be processed by the in situ conversion process.

Grout may be used in combination with freeze wells to provide a barrier for the in situ conversion process. The grout fills cavities (vugs) in the formation and reduces the permeability of the formation. Grout may have better thermal conductivity than gas and/or formation fluid that fills cavities in the formation. Placing grout in the cavities may allow for faster low temperature zone formation. The grout forms a perpetual barrier in the formation that may strengthen the formation. The use of grout in unconsolidated or substantially unconsolidated formation material may allow for larger well spacing than is possible without the use of grout. The combination of grout and the low temperature zone formed by freeze wells may constitute a double barrier for environmental regulation purposes.

Grout may be introduced into the formation through freeze well wellbores. The grout may be allowed to set. The integrity of the grout wall may be checked. The integrity of the grout wall may be checked by logging techniques and/or by hydrostatic testing. If the permeability of a grouted section is too high, additional grout may be introduced into the formation through freeze well wellbores. After the permeability of the grouted section is sufficiently reduced, freeze wells may be installed in the freeze well wellbores.

Grout may be injected into the formation at a pressure that is high, but below the fracture pressure of the formation. In some embodiments, grouting is performed in 16 m increments in the freeze wellbore. Larger or smaller increments may be used if desired. In some embodiments, grout is only applied to certain portions of the formation. For example, grout may be applied to the formation through the freeze wellbore only adjacent to aquifer zones and/or to relatively high permeability zones (for example, zones with a permeability greater than about 0.1 darcy). Applying grout to aquifers may inhibit migration of water from one aquifer to a different aquifer when an established low temperature zone thaws.

Grout used in the formation may be any type of grout including, but not limited to, fine cement, micro fine cement, sulfur, sulfur cement, viscous thermoplastics, or combinations thereof. Fine cement may be ASTM type 3 Portland cement. Fine cement may be less expensive than micro fine cement. In an embodiment, a freeze wellbore is formed in the formation. Selected portions of the freeze wellbore are grouted using fine cement. Then, micro fine cement is injected into the formation through the freeze wellbore. The fine cement may reduce the permeability down to about 10 millidarcy. The micro fine cement may further reduce the permeability to about 0.1 millidarcy.

After the grout is introduced into the formation, a freeze wellbore canister may be inserted into the formation. The process may be repeated for each freeze well that will be used to form the barrier.

In some embodiments, fine cement is introduced into every other freeze wellbore. Micro fine cement is introduced into the remaining wellbores. For example, grout may be used in a formation with freeze wellbores set at about 5 m spacing. A first wellbore is drilled and fine cement is introduced into the formation through the wellbore. A freeze well canister is positioned in the first wellbore. A second wellbore is drilled 10 m away from the first wellbore. Fine cement is introduced into the formation through the second wellbore. A freeze well canister is positioned in the second wellbore. A third wellbore is drilled between the first wellbore and the second wellbore. In some embodiments, grout from the first and/or second wellbores may be detected in the cuttings of the third wellbore. Micro fine cement is introduced into the formation through the third wellbore. A freeze wellbore canister is positioned in the third wellbore. The same procedure is used to form the remaining freeze wells that will form the barrier around the treatment area.

Further modifications and alternative embodiments of various aspects of the invention may be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS

1. A double barrier system for a subsurface treatment area, comprising:

a first barrier formed around at least a portion of the subsurface treatment area, the first barrier configured to inhibit fluid from exiting or entering the subsurface treatment area; and

a second barrier formed around at least a portion of the first barrier, wherein a separation space exists between the first barrier and the second barrier.

2. The barrier system as claimed in claim 1, wherein the first barrier is a freeze barrier established by freeze wells.

3. The barrier system as claimed in claim 2, further comprising grout introduced in the formation through at least one freeze well wellbore of a freeze well used to form the first barrier.

4. The barrier system as claimed in any of claims 1-3, wherein the second barrier is a freeze barrier established by freeze wells.

5. The barrier system as claimed in claim 4, further comprising grout introduced in the formation through at least one freeze well wellbore of a freeze well used to form the second barrier.

6. The barrier system as claimed in any of claims 1-5, wherein the treatment area comprises a hydrocarbon containing formation, and further comprising a plurality of heaters in the treatment area, the heaters configured to heat a hydrocarbon layer of the hydrocarbon containing formation.

7. The barrier system as claimed in any of claims 1-6, further comprising barrier segments formed between the first barrier and the second barrier, wherein the barrier segments are configured to section the space between the first barrier and the second barrier.

8. The barrier system as claimed in any of claims 1-7, further comprising at least one monitor well in the space between the first barrier and the second barrier, wherein at least one monitor well is configured to monitor integrity of the first barrier and/or the second barrier.

9. The barrier system as claimed in any of claims 1-7, further comprising a first monitor well in the space between the first barrier and the second barrier, and a second monitor well located on an opposite of the first barrier, wherein the first monitor well and the second monitor well are configured to monitor integrity of the first barrier.

10. The barrier system as claimed in any of claims 1-7, further comprising a first monitor well in the space between the first barrier and the second barrier, and a second monitor well located outside of the second barrier, wherein the first monitor well and the second monitor well are configured to monitor integrity of the second barrier.

11. A method of establishing a double barrier as claimed in any of claims 1-8, comprising:

forming a first barrier around at least a portion of the subsurface treatment area; and

forming a second barrier around the first barrier, wherein a space exists between the first barrier and the second barrier.

12. The method as claimed in claim 11, further comprising forming one or more barrier segments between the first barrier and the second barrier to section the space between the first barrier and the second barrier into different sections.

13. The method as claimed in claim 12, further comprising monitoring one or more of the sections to monitor the integrity of the first barrier and/or the second barrier.

14. The method as claimed in any of claims 11-13, further comprising heating hydrocarbons in the subsurface treatment area.

15. The method as claimed in any of claims 11-14, further comprising reducing salinity of water in the space between the first barrier and the second barrier.

16. The method as claimed in any of claims 11-15, further comprising monitoring the space to monitor integrity of the first barrier and/or the second barrier.

17. The method as claimed in any of claims 11-16, further comprising introducing grout in the formation.

18. A composition comprising hydrocarbons produced from a subsurface formation, the subsurface formation including a double barrier system as claimed in any of claims 1-10 or including a double barrier formed using the methods as claimed in any of claims 11-17.

19. A transportation fuel comprising hydrocarbons made from the composition as claimed in claim 18.

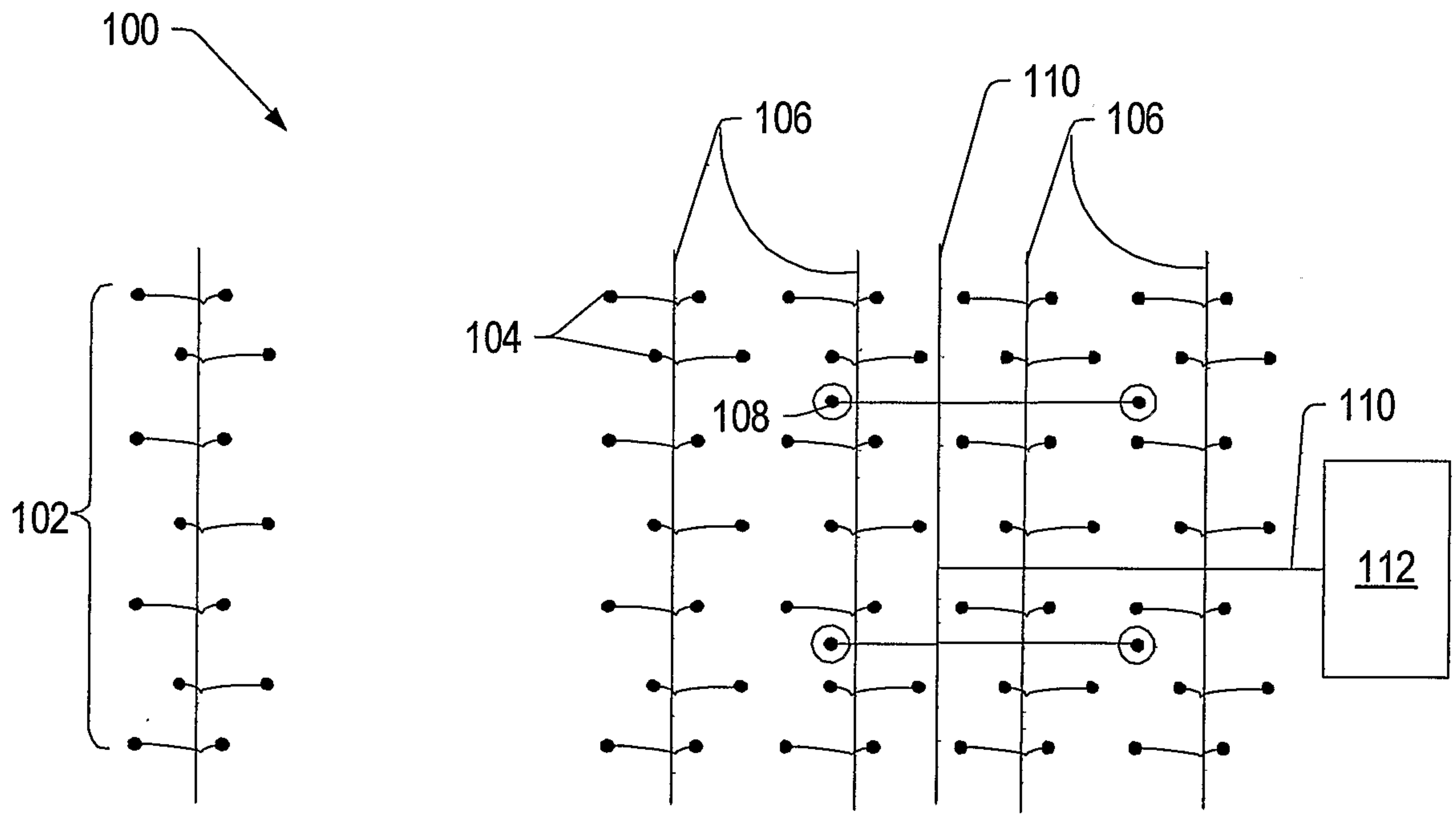

FIG. 1

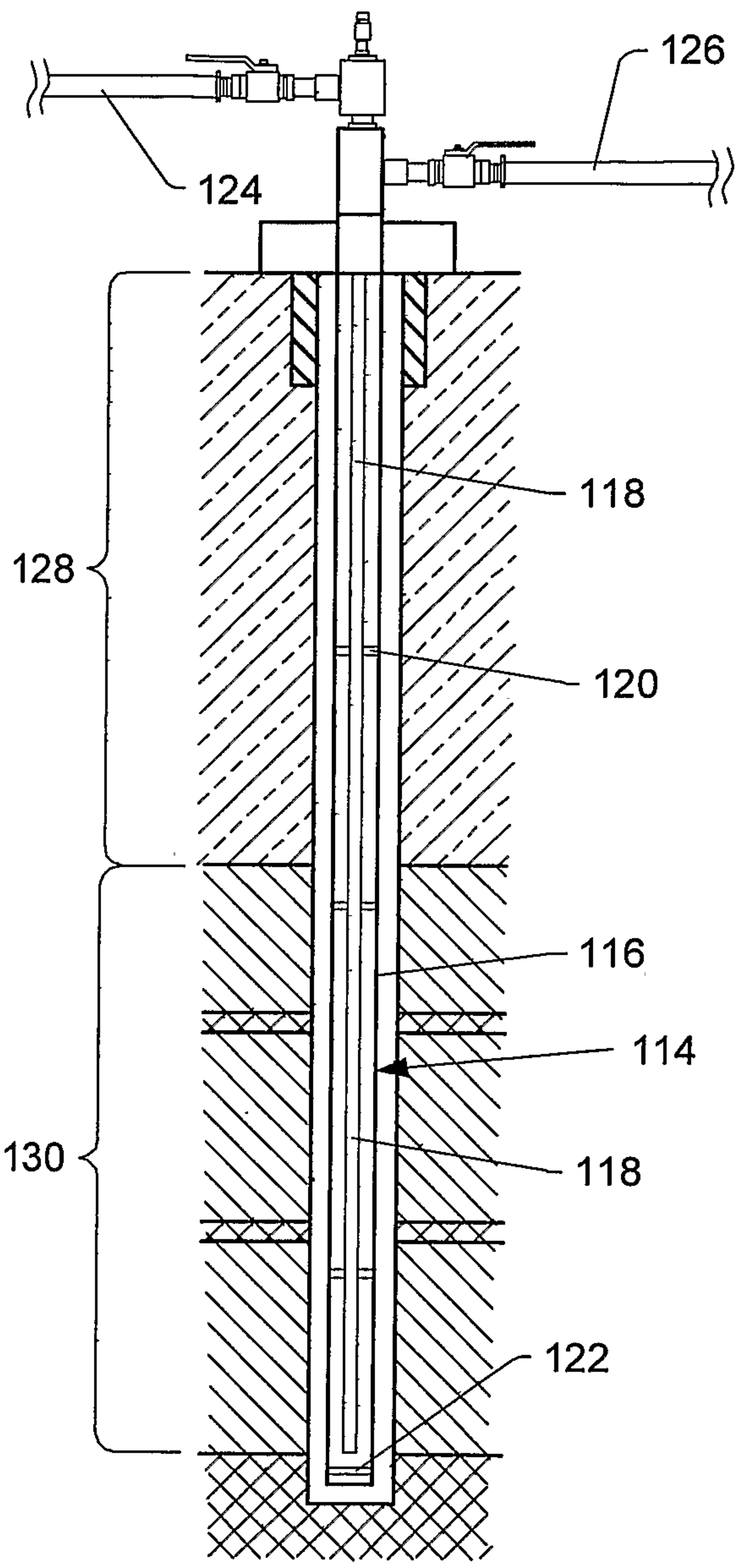

FIG. 2

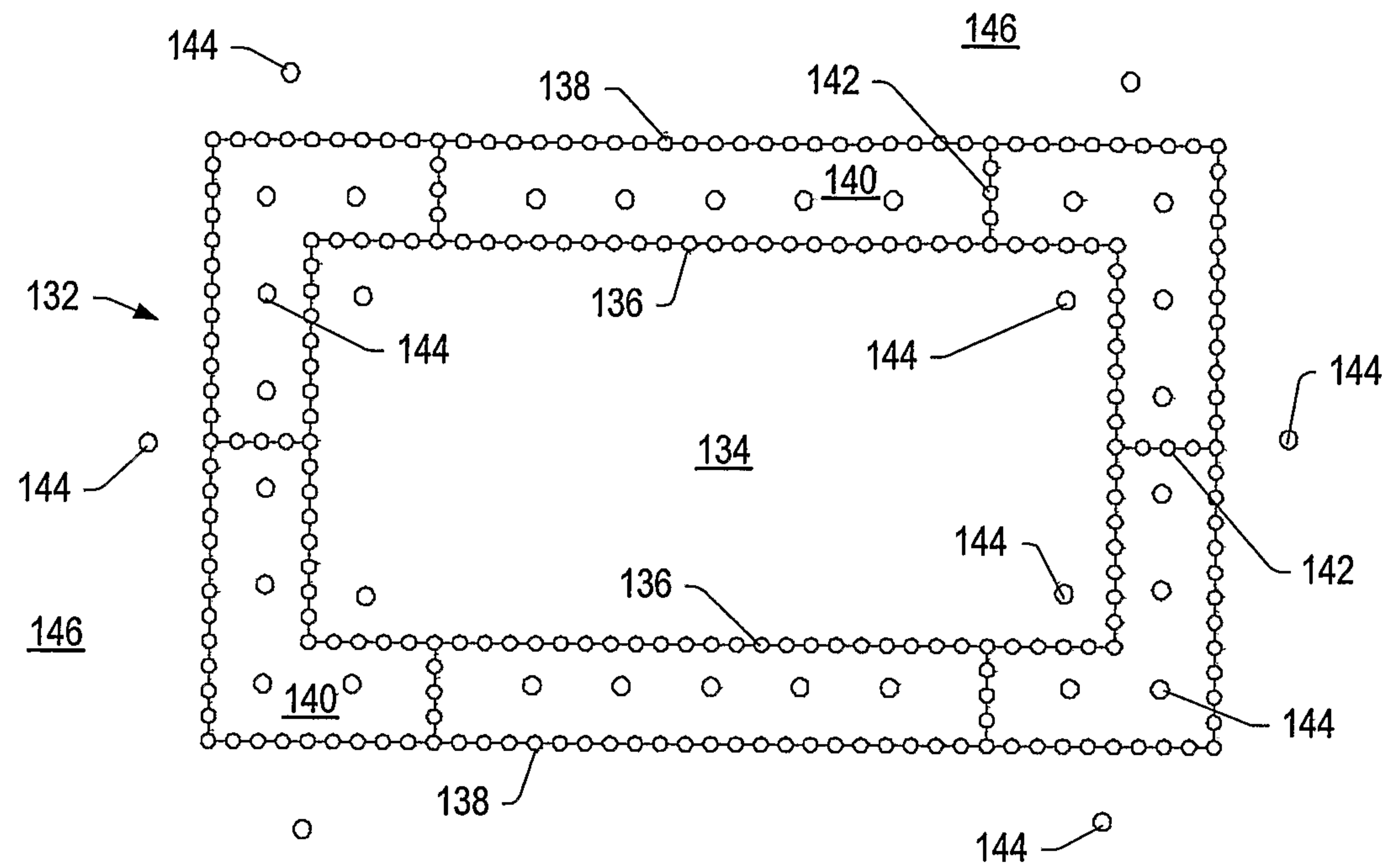
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FIG. 3

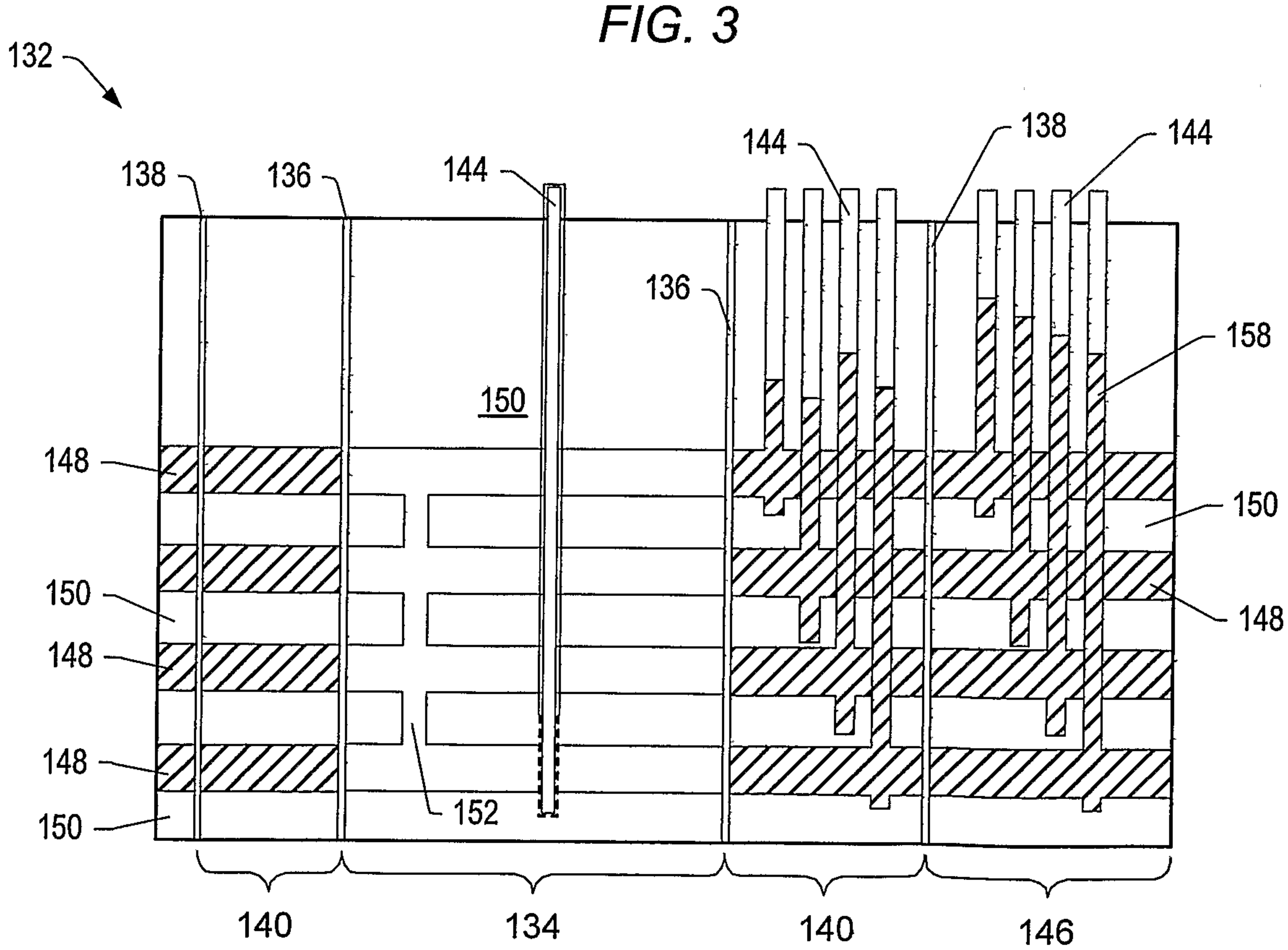
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FIG. 4

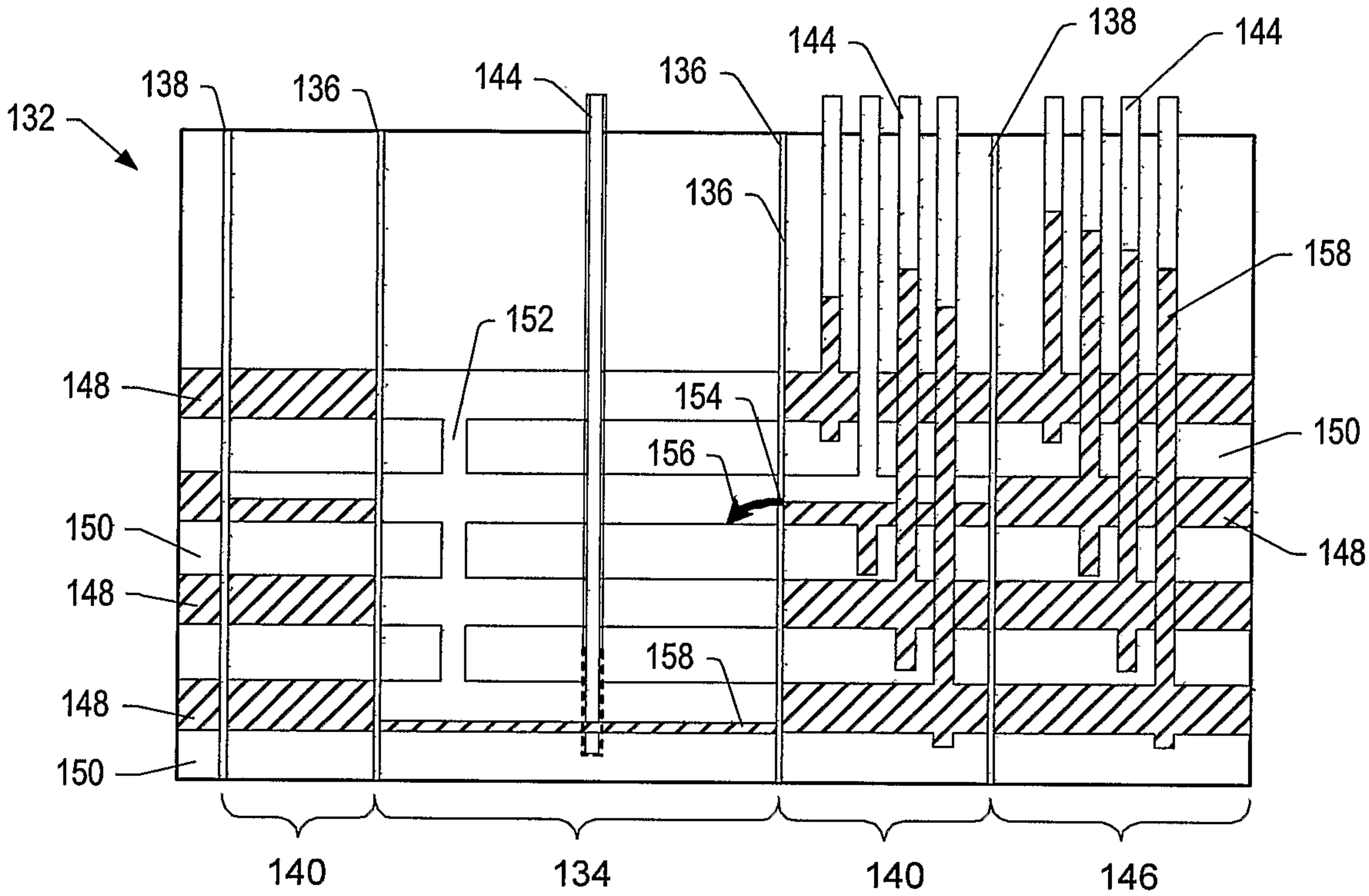
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FIG. 5

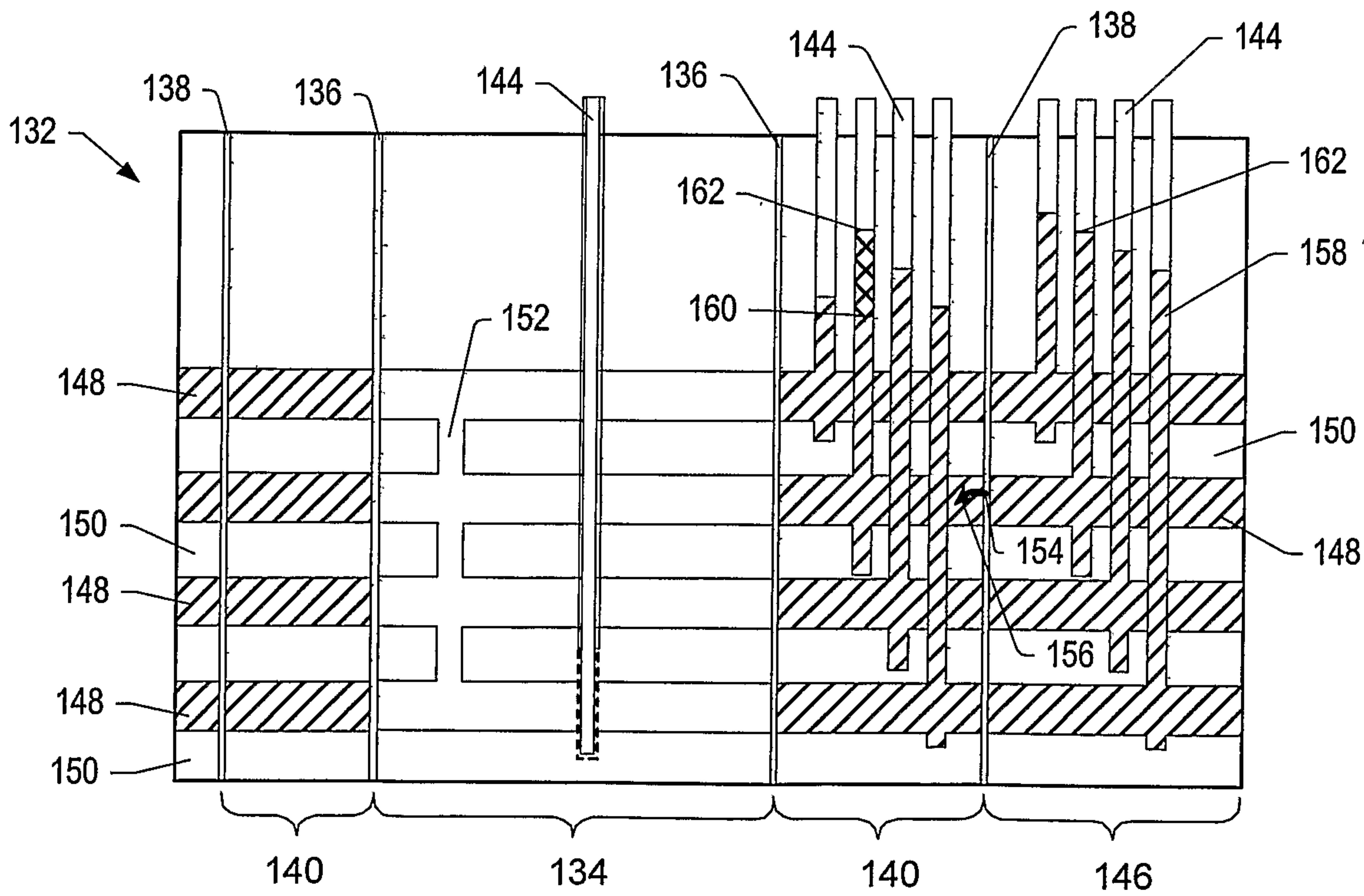
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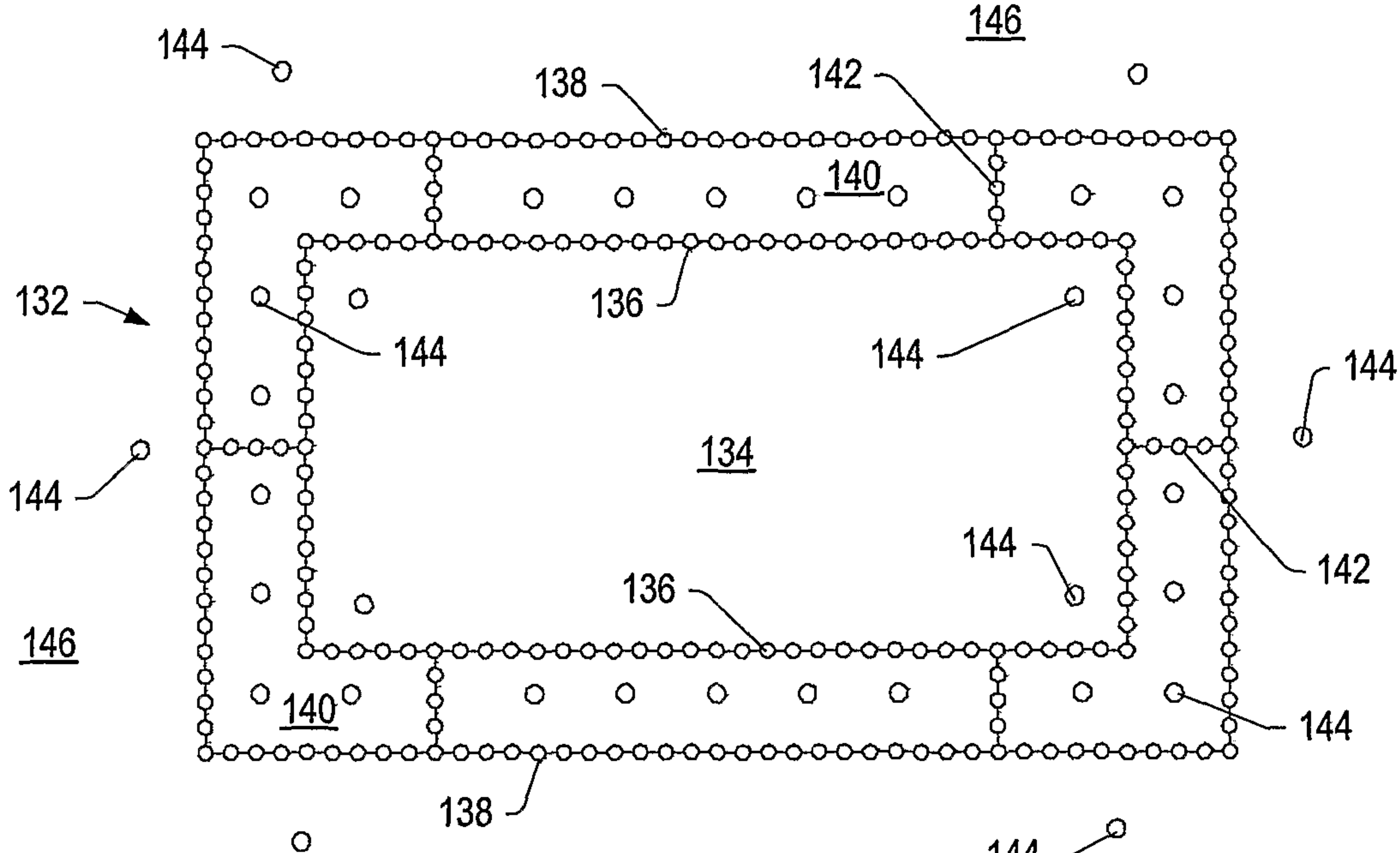
FIG. 6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