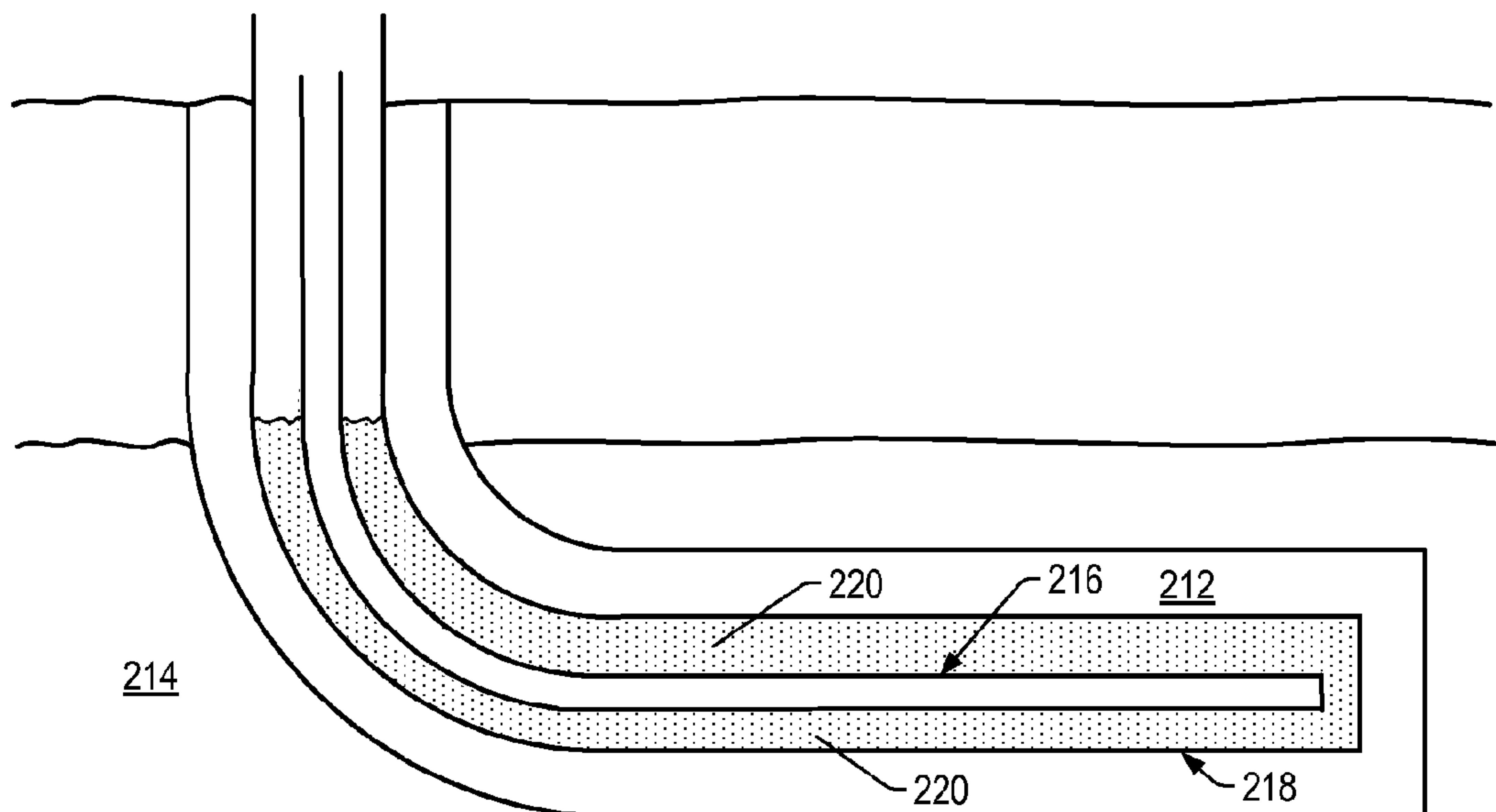




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(54) **Titre : SEL FONDU EN TANT QUE FLUIDE DE TRANSFERT THERMIQUE POUR CHAUFFER UNE FORMATION
SOUTERRAINE**
(54) **Title: MOLTEN SALT AS A HEAT TRANSFER FLUID FOR HEATING A SUBSURFACE FORMATION**



(57) **Abrégé/Abstract:**

A heating system for a subsurface formation includes a conduit located in an opening in the subsurface formation. An insulated conductor is located in the conduit. A material is in the conduit between a portion of the insulated conductor and a portion of the conduit. The material may be a salt. The material is a fluid at operating temperature of the heating system. Heat transfers from the insulated conductor to the fluid, from the fluid to the conduit, and from the conduit to the subsurface formation.

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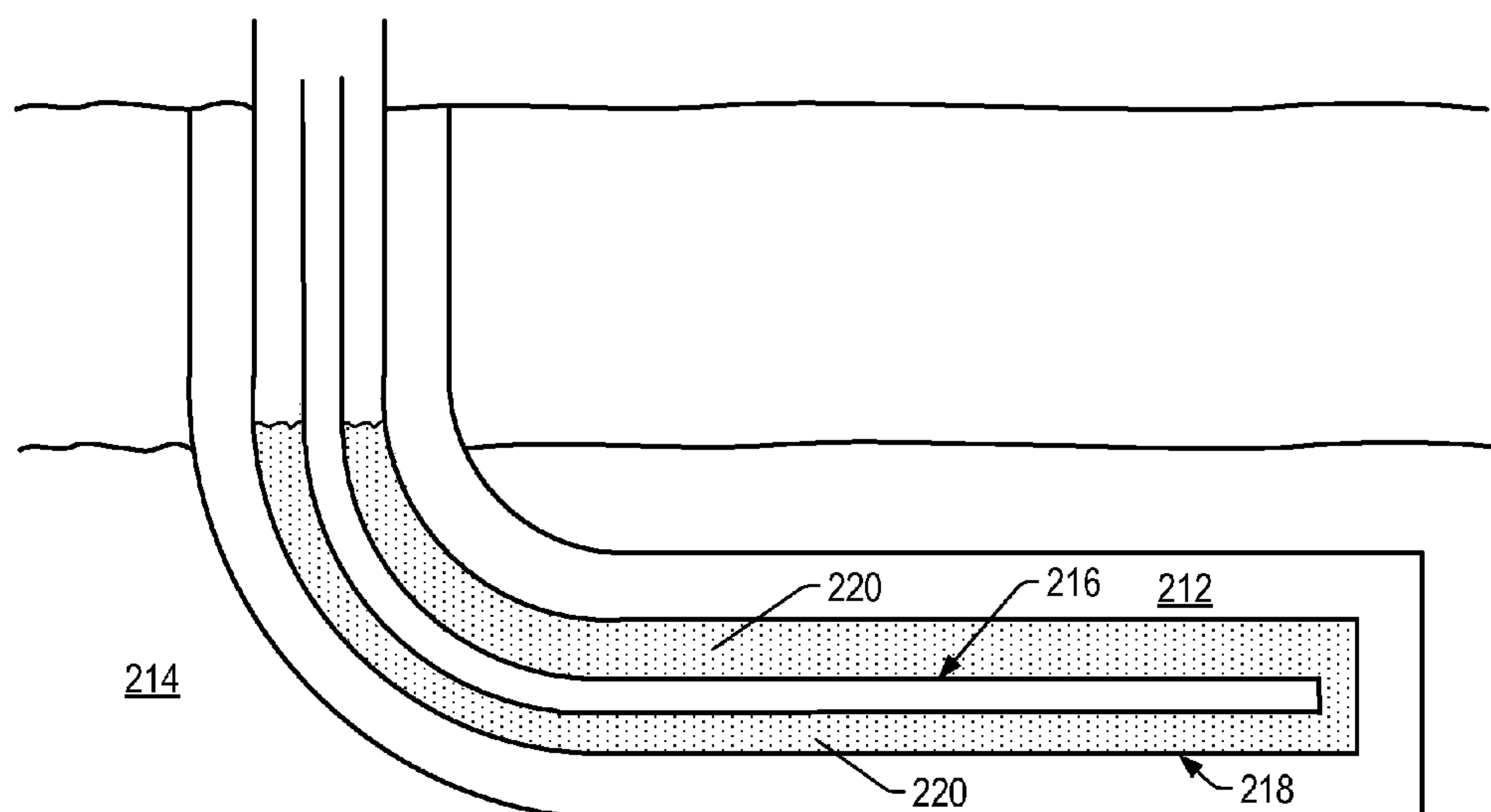
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FIG. 5

(57) Abstract: A heating system for a subsurface formation includes a conduit located in an opening in the subsurface formation. An insulated conductor is located in the conduit. A material is in the conduit between a portion of the insulated conductor and a portion of the conduit. The material may be a salt. The material is a fluid at operating temperature of the heating system. Heat transfers from the insulated conductor to the fluid, from the fluid to the conduit, and from the conduit to the subsurface formation.

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MOLTEN SALT AS A HEAT TRANSFER FLUID FOR HEATING
A SUBSURFACE FORMATION

BACKGROUND

5 1. Field of the Invention

[0001] The present invention relates generally to heating methods and heating systems for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations.

2. Description of Related Art

10 [0002] Hydrocarbons obtained from subterranean formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources and concerns over declining overall quality of produced hydrocarbons have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources. In situ processes may be used to remove
15 hydrocarbon materials from subterranean formations. Chemical and/or physical properties of hydrocarbon material in a subterranean formation may need to be changed to allow hydrocarbon material to be more easily removed from the subterranean formation. The chemical and physical changes may include in situ reactions that produce removable fluids, composition changes, solubility changes, density changes, phase changes, and/or viscosity
20 changes of the hydrocarbon material in the formation. A fluid may be, but is not limited to, a gas, a liquid, an emulsion, a slurry, and/or a stream of solid particles that has flow characteristics similar to liquid flow.

[0003] A wellbore may be formed in a formation. In some embodiments, a casing or other pipe system may be placed or formed in a wellbore. In some embodiments, an expandable
25 tubular may be used in a wellbore. Heaters may be placed in wellbores to heat a formation during an in situ process.

[0004] Application of heat to oil shale formations is described in U.S. Patent Nos. 2,923,535 to Ljungstrom and 4,886,118 to Van Meurs et al. Heat may be applied to the oil shale formation to pyrolyze kerogen in the oil shale formation. The heat may also fracture
30 the formation to increase permeability of the formation. The increased permeability may allow formation fluid to travel to a production well where the fluid is removed from the oil shale formation. In some processes disclosed by Ljungstrom, for example, an oxygen

containing gaseous medium is introduced to a permeable stratum, preferably while still hot from a preheating step, to initiate combustion.

[0005] A heat source may be used to heat a subterranean formation. Electric heaters may be used to heat the subterranean formation by radiation and/or conduction. An electric
5 heater may resistively heat an element. U.S. Patent Nos. 2,548,360 to Germain; 4,716,960 to Eastlund et al.; 4,716,960 to Eastlund et al.; and 5,065,818 to Van Egmond describes an electric heating element placed in a wellbore. U.S. Patent No. 6,023,554 to Vinegar et al. describes an electric heating element that is positioned in a casing. The heating element generates radiant energy that heats the casing.

10 [0006] U.S. Patent No. 4,570,715 to Van Meurs et al. describes an electric heating element. The heating element has an electrically conductive core, a surrounding layer of insulating material, and a surrounding metallic sheath. The conductive core may have a relatively low resistance at high temperatures. The insulating material may have electrical resistance, compressive strength, and heat conductivity properties that are relatively high at high
15 temperatures. The insulating layer may inhibit arcing from the core to the metallic sheath. The metallic sheath may have tensile strength and creep resistance properties that are relatively high at high temperatures. U.S. Patent No. 5,060,287 to Van Egmond describes an electrical heating element having a copper-nickel alloy core.

[0007] Heaters may be manufactured from wrought stainless steels. U.S. Patent No.
20 7,153,373 to Maziasz et al. and U.S. Patent Application Publication No. US 2004/0191109 to Maziasz et al. described modified 237 stainless steels as cast microstructures or fine grained sheets and foils.

[0008] As outlined above, there has been a significant amount of effort to develop heaters, methods and systems to economically produce hydrocarbons, hydrogen, and/or other
25 products from hydrocarbon containing formations. At present, however, there are still many hydrocarbon containing formations from which hydrocarbons, hydrogen, and/or other products cannot be economically produced. Thus, there is still a need for improved heating methods and systems for production of hydrocarbons, hydrogen, and/or other products from various hydrocarbon containing formations.

SUMMARY

[0009] Embodiments described herein generally relate to systems, methods, and heaters for treating a subsurface formation. Embodiments described herein also generally relate to heaters that have novel components therein. Such heaters can be obtained by using the systems and methods described herein.

[0010] In certain embodiments, the invention provides one or more systems, methods, and/or heaters. In some embodiments, the systems, methods, and/or heaters are used for treating a subsurface formation.

[0011] In certain embodiments, the invention provides a method of heating a formation comprising: supplying electricity to an insulated conductor positioned in a conduit to resistively heat at least a portion of the insulated conductor to a temperature that allows heat to transfer from the insulated conductor to a molten salt adjacent to at least a portion of the insulated conductor, wherein the temperature of the insulated conductor is above a melt temperature of the molten salt, wherein heat from the molten salt transfers to the conduit; and wherein heat transfers from the conduit to the formation.

[0012] In certain embodiments, the invention provides a heating system for a subsurface formation, comprising: a conduit located in an opening in the subsurface formation; at least one insulated conductor located in the conduit; a salt in the conduit adjacent to a portion of at least one insulated conductor, and wherein at least one insulated conductor is configured to resistively heat to a temperature sufficient to maintain the salt in a molten phase in the conduit.

[0013] In certain embodiments, the invention provides a heating system for a subsurface formation, comprising: a wellbore in the formation; a heat source in the wellbore; and a material between the formation and the heat source, wherein the material is a liquid at a selected operating temperature of the heat source.

[0014] 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.

[0015] In further embodiments, treating a subsurface formation is performed using any of the methods, systems, or heaters described herein.

[0016] In further embodiments, additional features may be added to the specific embodiments described herein.

[0016a] In accordance with one aspect of the present invention, there is provided a method of heating a formation comprising: supplying electricity to resistively heat an insulated conductor positioned in a conduit located in an opening in the subsurface formation, wherein the conduit is configured to contain a molten salt in the conduit; and allowing heat to transfer from the insulated conductor to the molten salt adjacent to at least a portion of the insulated conductor, wherein a temperature of the insulated conductor is above a melt temperature of the molten salt, wherein heat from the molten salt transfers to the conduit, and wherein heat transfers from the conduit to the formation.

[0016b] In accordance with another aspect of the present invention, there is provided a heating system for a subsurface formation, comprising: a conduit located in an opening in the subsurface formation; at least one insulated conductor located in the conduit; a salt in the conduit adjacent to a portion of at least one insulated conductor, wherein the conduit is configured to contain the salt in the conduit; and wherein at least one insulated conductor is configured to resistively heat to a temperature sufficient to maintain the salt in a molten phase in the conduit.

[0016c] In accordance with yet another aspect of the present invention, there is provided a heating system for a subsurface formation, comprising: a wellbore in the formation; a conduit located in the wellbore; a heat source in the conduit; and a salt in the conduit between the conduit and the heat source, wherein the conduit is configured to contain the salt in the conduit, and wherein the salt is a liquid at a selected operating temperature of the heat source.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] 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:

5 [0018] FIG. 1 depicts an illustration of stages of heating a hydrocarbon containing formation.

[0019] FIG. 2 shows a schematic view of an embodiment of a portion of an in situ heat treatment system for treating a hydrocarbon containing formation.

10 [0020] FIG. 3 depicts an embodiment of an insulated conductor heater in a conduit with a fluid between the insulated conductor and the conduit.

[0021] FIG. 4 depicts an embodiment of an insulated conductor heater in a conduit with conductive fluid between the insulated conductor and the conduit.

[0022] FIG. 5 depicts an embodiment of a substantially horizontal insulated conductor heater in a conduit with molten metal.

15 [0023] FIG. 6 depicts a cross-sectional representation of a ribbed conduit.

[0024] FIG. 7 depicts a perspective representation of a portion of a ribbed conduit.

[0025] FIG. 8 depicts an embodiment of a portion of an insulated conductor heater in a bottom portion of an open wellbore.

20 [0026] FIG. 9 depicts temperature versus radial distance for a heater with air between an insulated conductor and conduit.

[0027] FIG. 10 depicts temperature versus radial distance for a heater with molten solar salt between an insulated conductor and conduit.

[0028] FIG. 11 depicts temperature versus radial distance for a heater with molten tin between an insulated conductor and conduit.

25 [0029] FIG. 12 depicts simulated temperature versus radial distance for various heaters of a first size, with various fluids between the insulated conductors and conduits, and at different temperatures of the outer surfaces of the conduits,

30 [0030] FIG. 13 depicts simulated temperature versus radial distance for various heaters wherein the dimensions of the insulated conductor are half the size of the insulated conductor used to generate FIG. 12, with various fluids between the insulated conductors and conduits, and at different temperatures of the outer surfaces of the conduits.

[0031] FIG. 14 depicts simulated temperature versus radial distance for various heaters wherein the dimensions of the insulated conductor is the same as the insulated conductor

used to generate FIG. 13, and the conduit is larger than the conduit used to generate FIG. 13 with various fluids between the insulated conductors and conduits, and at various temperatures of the outer surfaces of the conduits.

[0032] FIG. 15 depicts simulated temperature versus radial distance for various heaters with molten salt between insulated conductors and conduits of the heaters and a boundary condition of 500 °C.

[0033] 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.

DETAILED DESCRIPTION

[0034] 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.

[0035] “Alternating current (AC)” refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

[0036] “Curie temperature” is the temperature above which a ferromagnetic material loses all of its ferromagnetic properties. In addition to losing all of its ferromagnetic properties above the Curie temperature, the ferromagnetic material begins to lose its ferromagnetic properties when an increasing electrical current is passed through the ferromagnetic material.

[0037] “Fluid pressure” is a pressure generated by a fluid in a formation. “Lithostatic pressure” (sometimes referred to as “lithostatic stress”) is a pressure in a formation equal to a weight per unit area of an overlying rock mass. “Hydrostatic pressure” is a pressure in a formation exerted by a column of water.

[0038] A “formation” includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. “Hydrocarbon layers” refer to layers in the formation that contain hydrocarbons. The hydrocarbon layers may

contain non-hydrocarbon material and hydrocarbon material. The “overburden” and/or the “underburden” include one or more different types of impermeable materials. For example, the overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ heat treatment 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 heat treatment 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 heat treatment process. In some cases, the overburden and/or the underburden may be somewhat permeable.

[0039] “Formation fluids” refer to fluids present in a formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbons, 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 fluids removed from the formation.

[0040] 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.

[0041] 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.

[0042] “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.

[0043] 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.

[0044] An “in situ heat treatment process” refers to a process of heating a hydrocarbon containing formation with heat sources to raise the temperature of at least a portion of the formation above a temperature that results in mobilized fluid, visbreaking, and/or pyrolysis of hydrocarbon containing material so that mobilized fluids, visbroken fluids, and/or pyrolyzation fluids are produced in the formation.

[0045] “Insulated conductor” refers to any elongated material that is able to conduct electricity and that is covered, in whole or in part, by an electrically insulating material.

[0046] “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.

[0047] “Pyrolyzation fluids” 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.

5 [0048] "Superposition of heat" refers to providing heat from two or more heat sources to a selected section of a formation such that the temperature of the formation at least at one location between the heat sources is influenced by the heat sources.

[0049] "Temperature limited heater" generally refers to a heater that regulates heat output (for example, reduces heat output) above a specified temperature without the use of
10 external controls such as temperature controllers, power regulators, rectifiers, or other devices. Temperature limited heaters may be AC (alternating current) or modulated (for example, "chopped") DC (direct current) powered electrical resistance heaters.

[0050] "Thermally conductive fluid" includes fluid that has a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa).

15 [0051] "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.

[0052] "Thickness" of a layer refers to the thickness of a cross section of the layer, wherein the cross section is normal to a face of the layer.

20 [0053] "Time-varying current" refers to electrical current that produces skin effect electricity flow in a ferromagnetic conductor and has a magnitude that varies with time. Time-varying current includes both alternating current (AC) and modulated direct current (DC).

[0054] "Turndown ratio" for the temperature limited heater is the ratio of the highest AC
25 or modulated DC resistance below the Curie temperature to the lowest resistance above the Curie temperature for a given current.

[0055] A "u-shaped wellbore" refers to a wellbore that extends from a first opening in the formation, through at least a portion of the formation, and out through a second opening in the formation. In this context, the wellbore may be only roughly in the shape of a "v" or
30 "u", with the understanding that the "legs" of the "u" do not need to be parallel to each other, or perpendicular to the "bottom" of the "u" for the wellbore to be considered "u-shaped".

[0056] “Upgrade” refers to increasing the quality of hydrocarbons. For example, upgrading heavy hydrocarbons may result in an increase in the API gravity of the heavy hydrocarbons.

5 [0057] 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.”

10 [0058] Hydrocarbons in formations may be treated in various ways to produce many different products. In certain embodiments, hydrocarbons in formations are treated in stages. FIG. 1 depicts an illustration of stages of heating the hydrocarbon containing formation. FIG. 1 also depicts an example of yield (“Y”) in barrels of oil equivalent per ton (y axis) of formation fluids from the formation versus temperature (“T”) of the heated formation in degrees Celsius (x axis).

15 [0059] Desorption of methane and vaporization of water occurs during stage 1 heating. Heating of the formation through stage 1 may be performed as quickly as possible. For example, when the hydrocarbon containing formation is initially heated, hydrocarbons in the formation desorb adsorbed methane. The desorbed methane may be produced from the formation. If the hydrocarbon containing formation is heated further, water in the
20 hydrocarbon containing formation is vaporized. Water may occupy, in some hydrocarbon containing formations, between 10% and 50% of the pore volume in the formation. In other formations, water occupies larger or smaller portions of the pore volume. Water typically is vaporized in a formation between 160 °C and 285 °C at pressures of 600 kPa absolute to 7000 kPa absolute. In some embodiments, the vaporized water produces
25 wettability changes in the formation and/or increased formation pressure. The wettability changes and/or increased pressure may affect pyrolysis reactions or other reactions in the formation. In certain embodiments, the vaporized water is produced from the formation. In other embodiments, the vaporized water is used for steam extraction and/or distillation in the formation or outside the formation. Removing the water from and increasing the
30 pore volume in the formation increases the storage space for hydrocarbons in the pore volume.

[0060] In certain embodiments, after stage 1 heating, the formation is heated further, such that a temperature in the formation reaches (at least) an initial pyrolyzation temperature

(such as a temperature at the lower end of the temperature range shown as stage 2).

Hydrocarbons in the formation may be pyrolyzed throughout stage 2. A pyrolysis temperature range varies depending on the types of hydrocarbons in the formation. The pyrolysis temperature range may include temperatures between 250 °C and 900 °C. The pyrolysis temperature range for producing desired products may extend through only a portion of the total pyrolysis temperature range. In some embodiments, the pyrolysis temperature range for producing desired products may include temperatures between 250 °C and 400 °C or temperatures between 270 °C and 350 °C. If a temperature of hydrocarbons in the formation is slowly raised through the temperature range from 250 °C to 400 °C, production of pyrolysis products may be substantially complete when the temperature approaches 400 °C. Average temperature of the hydrocarbons may be raised at a rate of less than 5 °C per day, less than 2 °C per day, less than 1 °C per day, or less than 0.5 °C per day through the pyrolysis temperature range for producing desired products. Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that slowly raise the temperature of hydrocarbons in the formation through the pyrolysis temperature range.

[0061] The rate of temperature increase through the pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

[0062] In some in situ heat treatment embodiments, a portion of the formation is heated to a desired temperature instead of slowly heating the temperature through a temperature range. In some embodiments, the desired temperature is 300 °C, 325 °C, or 350 °C. Other temperatures may be selected as the desired temperature. Superposition of heat from heat sources allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heat sources may be adjusted to maintain the temperature in the formation substantially at the desired temperature. The heated portion of the formation is maintained substantially at the desired temperature until pyrolysis declines such that production of desired formation fluids from the formation

becomes uneconomical. Parts of the formation that are subjected to pyrolysis may include regions brought into a pyrolysis temperature range by heat transfer from only one heat source.

[0063] In certain embodiments, formation fluids including pyrolyzation fluids are produced from the formation. As the temperature of the formation increases, the amount of condensable hydrocarbons in the produced formation fluid may decrease. At high temperatures, the formation may produce mostly methane and/or hydrogen. If the hydrocarbon containing formation is heated throughout an entire pyrolysis range, the formation may produce only small amounts of hydrogen towards an upper limit of the pyrolysis range. After all of the available hydrogen is depleted, a minimal amount of fluid production from the formation will typically occur.

[0064] After pyrolysis of hydrocarbons, a large amount of carbon and some hydrogen may still be present in the formation. A significant portion of carbon remaining in the formation can be produced from the formation in the form of synthesis gas. Synthesis gas generation may take place during stage 3 heating depicted in FIG. 1. Stage 3 may include heating a hydrocarbon containing formation to a temperature sufficient to allow synthesis gas generation. For example, synthesis gas may be produced in a temperature range from about 400 °C to about 1200 °C, about 500 °C to about 1100 °C, or about 550 °C to about 1000 °C. The temperature of the heated portion of the formation when the synthesis gas generating fluid is introduced to the formation determines the composition of synthesis gas produced in the formation. The generated synthesis gas may be removed from the formation through a production well or production wells.

[0065] Total energy content of fluids produced from the hydrocarbon containing formation may stay relatively constant throughout pyrolysis and synthesis gas generation. During pyrolysis at relatively low formation temperatures, a significant portion of the produced fluid may be condensable hydrocarbons that have a high energy content. At higher pyrolysis temperatures, however, less of the formation fluid may include condensable hydrocarbons. More non-condensable formation fluids may be produced from the formation. Energy content per unit volume of the produced fluid may decline slightly during generation of predominantly non-condensable formation fluids. During synthesis gas generation, energy content per unit volume of produced synthesis gas declines significantly compared to energy content of pyrolyzation fluid. The volume of the

produced synthesis gas, however, will in many instances increase substantially, thereby compensating for the decreased energy content.

[0066] FIG. 2 depicts a schematic view of an embodiment of a portion of the in situ heat treatment system for treating the hydrocarbon containing formation. The in situ heat treatment system may include barrier wells 200. Barrier wells 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 some embodiments, barrier wells 200 are dewatering wells. Dewatering wells may remove liquid water and/or inhibit liquid water from entering a portion of the formation to be heated, or to the formation being heated. In the embodiment depicted in FIG. 2, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells typically encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

[0067] Heat sources 202 are placed in at least a portion of the formation. Heat sources 202 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 202 may also include other types of heaters. Heat sources 202 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 202 through supply lines 204. Supply lines 204 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 204 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. In some embodiments, electricity for an in situ heat treatment process may be provided by a nuclear power plant or nuclear power plants. The use of nuclear power may allow for reduction or elimination of carbon dioxide emissions from the in situ heat treatment process.

[0068] Production wells 206 are used to remove formation fluid from the formation. In some embodiments, production well 206 includes a heat source. The heat source in the production well may heat one or more portions of the formation at or near the production well. In some in situ heat treatment process embodiments, the amount of heat supplied to the formation from the production well per meter of the production well is less than the

amount of heat applied to the formation from a heat source that heats the formation per meter of the heat source.

[0069] In some embodiments, the heat source in production well 206 allows for vapor phase removal of formation fluids from the formation. Providing heating at or through the production well may: (1) inhibit condensation and/or refluxing of production fluid when such production fluid is moving in the production well proximate the overburden, (2) increase heat input into the formation, (3) increase production rate from the production well as compared to a production well without a heat source, (4) inhibit condensation of high carbon number compounds (C6 and above) in the production well, and/or (5) increase formation permeability at or proximate the production well.

[0070] Subsurface pressure in the formation may correspond to the fluid pressure generated in the formation. As temperatures in the heated portion of the formation increase, the pressure in the heated portion may increase as a result of thermal expansion of fluids, increased fluid generation, and vaporization of water. Controlling rate of fluid removal from the formation may allow for control of pressure in the formation. Pressure in the formation may be determined at a number of different locations, such as near or at production wells, near or at heat sources, or at monitor wells.

[0071] In some hydrocarbon containing formations, production of hydrocarbons from the formation is inhibited until at least some hydrocarbons in the formation have been pyrolyzed. Formation fluid may be produced from the formation when the formation fluid is of a selected quality. In some embodiments, the selected quality includes an API gravity of at least about 20°, 30°, or 40°. Inhibiting production until at least some hydrocarbons are pyrolyzed may increase conversion of heavy hydrocarbons to light hydrocarbons. Inhibiting initial production may minimize the production of heavy hydrocarbons from the formation. Production of substantial amounts of heavy hydrocarbons may require expensive equipment and/or reduce the life of production equipment.

[0072] After pyrolysis temperatures are reached and production from the formation is allowed, pressure in the formation may be varied to alter and/or control a composition of formation fluid produced, to control a percentage of condensable fluid as compared to non-condensable fluid in the formation fluid, and/or to control an API gravity of formation fluid being produced. For example, decreasing pressure may result in production of a larger condensable fluid component. The condensable fluid component may contain a larger percentage of olefins.

- [0073] In some in situ heat treatment process embodiments, pressure in the formation may be maintained high enough to promote production of formation fluid with an API gravity of greater than 20°. Maintaining increased pressure in the formation may inhibit formation subsidence during in situ heat treatment. Maintaining increased pressure may facilitate vapor phase production of fluids from the formation. Vapor phase production may allow for a reduction in size of collection conduits used to transport fluids produced from the formation. Maintaining increased pressure may reduce or eliminate the need to compress formation fluids at the surface to transport the fluids in collection conduits to treatment facilities.
- [0074] Maintaining increased pressure in a heated portion of the formation may surprisingly allow for production of large quantities of hydrocarbons of increased quality and of relatively low molecular weight. Pressure may be maintained so that formation fluid produced has a minimal amount of compounds above a selected carbon number. The selected carbon number may be at most 25, at most 20, at most 12, or at most 8. Some high carbon number compounds may be entrained in vapor in the formation and may be removed from the formation with the vapor. Maintaining increased pressure in the formation may inhibit entrainment of high carbon number compounds and/or multi-ring hydrocarbon compounds in the vapor. High carbon number compounds and/or multi-ring hydrocarbon compounds may remain in a liquid phase in the formation for significant time periods. The significant time periods may provide sufficient time for the compounds to pyrolyze to form lower carbon number compounds.
- [0075] Formation fluid produced from production wells 206 may be transported through collection piping 208 to treatment facilities 210. Formation fluids may also be produced from heat sources 202. For example, fluid may be produced from heat sources 202 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 202 may be transported through tubing or piping to collection piping 208 or the produced fluid may be transported through tubing or piping directly to treatment facilities 210. Treatment facilities 210 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. In some embodiments, the transportation fuel may be jet fuel, such as JP-8.

[0076] FIG. 3 depicts an embodiment of a heater in wellbore 212 in formation 214. The heater includes insulated conductor 216 in conduit 218 with material 220 between the insulated conductor and the conduit. In some embodiments, insulated conductor 216 is a mineral insulated conductor. Electricity supplied to insulated conductor 216 resistively
5 heats the insulated conductor. Insulated conductor conductively transfers heat to material 220. Heat may transfer within material 220 by heat conduction and/or by heat convection. Radiant heat from insulated conductor 216 and/or heat from material 220 transfers to conduit 218. Heat may transfer to the formation from the heater by conductive or radiative heat transfer from conduit 218. Material 220 may be molten metal, molten salt, or other
10 liquid. In some embodiments, a gas (for example, nitrogen, carbon dioxide, and/or helium) is in conduit 218 above material 220. The gas may inhibit oxidation or other chemical changes of material 220. The gas may inhibit vaporization of material 220.

[0077] Insulated conductor 216 and conduit 218 may be placed in an opening in a subsurface formation. Insulated conductor 216 and conduit 218 may have any orientation
15 in a subsurface formation (for example, the insulated conductor and conduit may be substantially vertical or substantially horizontally oriented in the formation). Insulated conductor 216 includes core 222, electrical insulator 224, and jacket 226. In some embodiments, core 222 is a copper core. In some embodiments, core 222 includes other electrical conductors or alloys (for example, copper alloys). In some embodiments, core
20 222 includes a ferromagnetic conductor so that insulated conductor 216 operates as a temperature limited heater. In some embodiments, core 222 does not include a ferromagnetic conductor.

[0078] In some embodiments, core 222 of insulated conductor 216 is made of two or more portions. The first portion may be placed adjacent to the overburden. The first portion
25 may be sized and/or made of a highly conductive material so that the first portion does not resistively heat to a high temperature. One or more other portions of core 216 may be sized and/or made of material that resistively heats to a high temperature. These portions of core 216 may be positioned adjacent to sections of the formation that are to be heated by the heater. In some embodiments, the insulated conductor does not include a highly
30 conductive first portion. A lead in cable may be coupled to the insulated conductor to supply electricity to the insulated conductor.

[0079] In some embodiments, core 222 of insulated conductor 216 is a highly conductive material such as copper. Core 222 may be electrically coupled to jacket 226 at or near the

end of the insulated conductor. In some embodiments, insulated conductor 216 is electrically coupled to conduit 218. Electrical current supplied to insulated conductor 216 may resistively heat core 222, jacket 226, material 220, and/or conduit 218. Resistive heating of core 222, jacket 226, material 220, and/or conduit 218 generates heat that may transfer to the formation.

[0080] Electrical insulator 224 may be magnesium oxide, aluminum oxide, silicon dioxide, beryllium oxide, boron nitride, silicon nitride, or combinations thereof. In certain embodiments, electrical insulator 224 is a compacted powder of magnesium oxide. In some embodiments, electrical insulator 224 includes beads of silicon nitride. In certain embodiments, a thin layer of material clad over core 222 to inhibit the core from migrating into the electrical insulator at higher temperatures (i.e., to inhibit copper of the core from migrating into magnesium oxide of the insulation). For example, a small layer of nickel (for example, about 0.5 mm of nickel) may be clad on core 222.

[0081] In some embodiments, material 220 may be relatively corrosive. Jacket 226 and/or at least the inside surface of conduit 218 may be made of a corrosion resistant material such as, but not limited to, nickel, Alloy N (Carpenter Metals), 347 stainless steel, 347H stainless steel, 446 stainless steel, or 825 stainless steel. For example, conduit 218 may be plated or lined with nickel. In some embodiments, material 220 may be relatively non-corrosive. Jacket 226 and/or at least the inside surface of conduit 218 may be made of a material such as carbon steel.

[0082] In some embodiments, jacket 226 of insulated conductor 216 is not used as the main return of electrical current for the insulated conductor. In embodiments where material 220 is a good electrical conductor such as a molten metal, current returns through the molten metal in the conduit and/or through the conduit 218. In some embodiments, conduit 218 is made of a ferromagnetic material, (for example 410 stainless steel). Conduit 218 may function as a temperature limited heater until the temperature of the conduit approaches, reaches or exceeds the Curie temperature or phase transition temperature of the conduit material.

[0083] In some embodiments, material 220 returns electrical current to the surface from insulated conductor 216 (i.e., the material acts as the return or ground conductor for the insulated conductor). Material 220 may provide a current path with low resistance so that a long insulated conductor 216 is useable in conduit 218. The long heater may operate at

low voltages for the length of the heater due to the presence of material 220 that is conductive.

[0084] FIG. 4 depicts an embodiment of a portion of insulated conductor 216 in conduit 218 wherein material 220 is a good conductor (for example, a liquid metal) and current flow is indicated by the arrows. Current flows down core 222 and returns through jacket 226, material 220, and conduit 218. Jacket 226 and conduit 218 may be at approximately constant potential. Current flows radially from jacket 226 to conduit 218 through material 220. Material 220 may resistively heat. Heat from material 220 may transfer through conduit 218 into the formation.

[0085] In embodiments where material 220 is partially electrically conductive (for example, the material is a molten salt), current returns mainly through jacket 226. All or a portion of the current that passes through partially conductive material 220 may pass to ground through conduit 218.

[0086] In the embodiment depicted in FIG. 3, core 222 of insulated conductor 216 has a diameter of about 1 cm, electrical insulator 224 has an outside diameter of about 1.6 cm, and jacket 226 has an outside diameter of about 1.8 cm. In other embodiments, the insulated conductor is smaller. For example, core 222 has a diameter of about 0.5 cm, electrical insulator 224 has an outside diameter of about 0.8 cm, and jacket 226 has an outside diameter of about 0.9 cm. Other insulated conductor geometries may be used. For the same size conduit 218, the smaller geometry of insulated conductor 216 may result in a higher operating temperature of the insulated conductor to achieve the same temperature at the conduit. The smaller geometry insulated conductors may be significantly more economically favorable due to manufacturing cost, weight, and other factors.

[0087] Material 220 may be placed between the outside surface of insulated conductor 216 and the inside surface of conduit 218. In certain embodiments, material 220 is placed in the conduit in a solid form as balls or pellets. Material 220 may melt below the operating temperatures of insulated conductor 216. Material may melt above ambient subsurface formation temperatures. Material 220 may be placed in conduit 218 after insulated conductor 216 is placed in the conduit. In certain embodiments, material 220 is placed in conduit 216 as a liquid. The liquid may be placed in conduit 218 before or after insulated conductor 216 is placed in the conduit (for example, the molten liquid may be poured into the conduit before or after the insulated conductor is placed in the conduit). Additionally, material 220 may be placed in conduit 218 before or after insulated conductor 216 is

energized (i.e., supplied with electricity). Material 220 may be added to conduit 218 or removed from the conduit after operation of the heater is initialized. Material 220 may be added to or removed from conduit 218 to maintain a desired head of fluid in the conduit. In some embodiments, the amount of material 220 in conduit 218 may be adjusted (i.e.,
5 added to or depleted) to adjust or balance the stresses on the conduit. Material 220 may inhibit deformation of conduit 218. The head of material 220 in conduit 218 may inhibit the formation from crushing or otherwise deforming the conduit should the formation expand against the conduit. The head of fluid in conduit 218 allows the wall of the conduit to be relatively thin. Having thin conduits 218 may increase the economic viability of
10 using multiple heaters of this type to heat portions of the formation.

[0088] Material 220 may support insulated conductor 216 in conduit 218. The support provided by material 220 of insulated conductor 216 may allow for the deployment of long insulated conductors as compared to insulated conductors positioned only in a gas in a conduit without the use of special metallurgy to accommodate the weight of the insulated
15 conductor. In certain embodiments, insulated conductor 216 is buoyant in material 220 in conduit 218. For example, insulated conductor may be buoyant in molten metal. The buoyancy of insulated conductor 216 reduces creep associated problems in long, substantially vertical heaters. A bottom weight or tie down may be coupled to the bottom of insulated conductor 216 to inhibit the insulated conductor from floating in material 220.

[0089] Material 220 may remain a liquid at operating temperatures of insulated conductor 216. In some embodiments, material 220 melts at temperatures above about 100 °C, above about 200 °C, or above about 300 °C. The insulated conductor may operate at
20 temperatures greater than 200 °C, greater than 400 °C, greater than 600 °C, or greater than 800 °C. In certain embodiments, material 220 provides enhanced heat transfer from
25 insulated conductor 216 to conduit 218 at or near the operating temperatures of the insulated conductor.

[0090] Material 220 may include metals such as tin, zinc, an alloy such as a 60% by weight tin, 40% by weight zinc alloy; bismuth; indium; cadmium, aluminum; lead; and/or combinations thereof (for example, eutectic alloys of these metals such as binary or ternary
30 alloys). In one embodiment, material 220 is tin. Some liquid metals may be corrosive. The jacket of the insulated conductor and/or at least the inside surface of the canister may need to be made of a material that is resistant to the corrosion of the liquid metal. The jacket of the insulated conductor and/or at least the inside surface of the conduit may be

made of materials that inhibit the molten metal from leaching materials from the insulating conductor and/or the conduit to form eutectic compositions or metal alloys. Molten metals may be highly thermal conductive, but may block radiant heat transfer from the insulated conductor and/or have relatively small heat transfer by natural convection.

- 5 **[0091]** Material 220 may be or include molten salts such as solar salt, salts presented in Table 1, or other salts. The molten salts may be infrared transparent to aid in heat transfer from the insulated conductor to the canister. In some embodiments, solar salt includes sodium nitrate and potassium nitrate (for example, about 60% by weight sodium nitrate and about 40% by weight potassium nitrate). Solar salt melts at about 220 °C and is chemically
- 10 stable up to temperatures of about 593 °C. Other salts that may be used include, but are not limited to LiNO_3 (melt temperature (T_m) of 264 °C and a decomposition temperature of about 600 °C) and eutectic mixtures such as 53% by weight KNO_3 , 40% by weight NaNO_3 and 7% by weight NaNO_2 (T_m of about 142 °C and an upper working temperature of over 500 °C); 45.5% by weight KNO_3 and 54.5% by weight NaNO_2 (T_m of about 142-145 °C
- 15 and an upper working temperature of over 500 °C); or 50% by weight NaCl and 50% by weight SrCl_2 (T_m of about 19 °C and an upper working temperature of over 1200 °C).

TABLE 1

Material	T_m (°C)	T_b (°C)
Zn	420	907
CdBr_2	568	863
CdI_2	388	744
CuBr_2	498	900
PbBr_2	371	892
TlBr	460	819
TlF	326	826
ThI_4	566	837
SnF_2	215	850
SnI_2	320	714
ZnCl_2	290	732

- 20 **[0092]** Some molten salts, such as solar salt, may be relatively non-corrosive so that the conduit and/or the jacket may be made of relatively inexpensive material (for example,

carbon steel). Some molten salts may have good thermal conductivity, may have high heat density, and may result in large heat transfer by natural convection.

[0093] In fluid mechanics, the Rayleigh number is a dimensionless number associated with heat transfer in a fluid. When the Rayleigh number is below the critical value for the fluid, heat transfer is primarily in the form of conduction; and when the Rayleigh number is above the critical value, heat transfer is primarily in the form of convection. The Rayleigh number is the product of the Grashof number (which describes the relationship between buoyancy and viscosity in a fluid) and the Prandtl number (which describes the relationship between momentum diffusivity and thermal diffusivity). For the same size insulated conductors in conduits, and where the temperature of the conduit is 500 °C, the Rayleigh number for solar salt in the conduit is about 10 times the Rayleigh number for tin in the conduit. The higher Rayleigh number implies that the strength of natural convection in the molten solar salt is much stronger than the strength of the natural convection in molten tin. The stronger natural convection of molten salt may distribute heat and inhibit the formation of hot spots at locations along the length of the conduit. Hot spots may be caused by coke build up at isolated locations adjacent to or on the conduit, contact of the conduit by the formation at isolated locations, and/or other high thermal load situations.

[0094] Conduit 218 may be a carbon steel or stainless steel canister. In some embodiments, conduit 218 may include cladding on the outer surface to inhibit corrosion of the conduit by formation fluid. Conduit 218 may include cladding on an inner surface of the conduit that is corrosion resistant to material 220 in the conduit. Cladding applied to conduit 218 may be a coating and/or a liner. If the conduit contains a metal salt, the inner surface of the conduit may include coating of nickel, or the conduit may be or include a liner of a corrosion resistant metal such as Alloy N. If the conduit contains a molten metal, the conduit may include a corrosion resistant metal liner or coating, and/or a ceramic coating (for example, a porcelain coating or fired enamel coating). In an embodiment, conduit 218 is a canister of 410 stainless steel with an outside diameter of about 6 cm. Conduit 218 may not need a thick wall because material 220 may provide internal pressure that inhibits deformation or crushing of the conduit due to external stresses.

[0095] FIG. 5 depicts an embodiment of the heater positioned in wellbore 212 of formation 214 with a portion of insulated conductor 216 and conduit 218 oriented substantially horizontally in the formation. Material 220 may provide a head in conduit 218 due to the pressure of the material. The pressure head may keep material 220 in conduit 218. The

pressure head may also provide internal pressure that inhibits deformation or collapse of conduit 218 due to external stresses.

[0096] In some embodiments, two or more insulated conductors are placed in the conduit. In some embodiments, only one of the insulated conductors is energized. Should the energized conductor fail, one of the other conductors may be energized to maintain the material in a molten phase. The failed insulated conductor may be removed and/or replaced.

[0097] The conduit of the heater may be a ribbed conduit. The ribbed conduit may improve the heat transfer characteristics of the conduit as compared to a cylindrical conduit. FIG. 6 depicts a cross-sectional representation of ribbed conduit 228. FIG. 7 depicts a perspective view of a portion of ribbed conduit 228. Ribbed conduit 228 may include rings 230 and ribs 232. Rings 230 and ribs 232 may improve the heat transfer characteristics of ribbed conduit 228. In an embodiment, the cylinder of conduit has an inner diameter of about 5.1 cm and a wall thickness of about 0.57 cm. Rings 230 may be spaced about every 3.8 cm. Rings 230 may have a height of about 1.9 cm and a thickness of about 0.5 cm. Six ribs 232 may be spaced evenly about conduit 218. Ribs 232 may have a thickness of about 0.5 cm and a height of about 1.6 cm. Other dimensions for the cylinder, rings and ribs may be used. Ribbed conduit 228 may be formed from two or more rolled pieces that are welded together to form the ribbed conduit. Other types of conduit with extra surface area to enhance heat transfer from the conduit to the formation may be used.

[0098] In some embodiments, the ribbed conduit may be used as the conduit of a conductor-in-conduit heater. For example, the conductor may be a 3.05 cm 410 stainless steel rod and the conduit has dimensions as described above. In other embodiments, the conductor is an insulated conductor and a fluid is positioned between the conductor and the ribbed conduit. The fluid may be a gas or liquid at operating temperatures of the insulated conductor.

[0099] In some embodiments, the heat source for the heater is not an insulated conductor. For example, the heat source may be hot fluid circulated through an inner conduit positioned in an outer conduit. The material may be positioned between the inner conduit and the outer conduit. Convection currents in the material may help to more evenly distribute heat to the formation and may inhibit or limit formation of a hot spot where insulation that limits heat transfer to the overburden ends. In some embodiments, the heat

sources are downhole oxidizers. The material is placed between an outer conduit and an oxidizer conduit. The oxidizer conduit may be an exhaust conduit for the oxidizers or the oxidant conduit if the oxidizers are positioned in a u-shaped wellbore with exhaust gases exiting the formation through one of the legs of the u-shaped conduit. The material may help inhibit the formation of hot spots adjacent to the oxidizers of the oxidizer assembly.

[0100] The material to be heated by the insulated conductor may be placed in an open wellbore. FIG. 8 depicts material 220 in open wellbore 212 in formation 214 with insulated conductor 216 in the wellbore. In some embodiments, a gas (for example, nitrogen, carbon dioxide, and/or helium) is placed in wellbore 212 above material 220.

The gas may inhibit oxidation or other chemical changes of material 220. The gas may inhibit vaporization of material 220.

[0101] Material 220 may have a melting point that is above the pyrolysis temperature of hydrocarbons in the formation. The melting point of material 220 may be above 375 °C, above 400 °C, or above 425 °C. The insulated conductor may be energized to heat the formation. Heat from the insulated conductor may pyrolyze hydrocarbons in the formation. Adjacent the wellbore, the heat from insulated conductor 216 may result in coking that reduces the permeability and plugs the formation near wellbore 212. The plugged formation inhibits material 220 from leaking from wellbore 212 into formation 214 when the material is a liquid. In some embodiments, material 220 is a salt.

[0102] Return electrical current for insulated conductor 216 may return through jacket 226 of the insulated conductor. Any current that passes through material 220 may pass to ground. Above the level of material 220, any remaining return electrical current may be confined to jacket 226 of insulated conductor 216.

[0103] In some embodiments, other types of heat sources besides for insulated conductors are used to heat the material placed in the open wellbore. The other types of heat sources may include gas burners, pipes through which hot heat transfer fluid flows, or other types of heaters.

[0104] Simulations were performed for a heater including a vertical insulated conductor in a cylindrical conduit (for example, the heater depicted in FIG. 3) with either air, solar salt, or tin between the insulated conductor and the conduit. The simulation used a vertical steady state, two dimensional axi-symmetric system with a temperature boundary condition and a constant power injection rate by the insulated conductor of 300 watts per foot.

Values of the temperature boundary condition (temperature of the outside surface of the

conduit) were set at 300 °C, 500 °C or 700 °C. Air was assumed to be an ideal gas. Some representative properties of the solar salt and the tin are given in Table 2. The software used for the simulations was ANSYS CFX 11. The turbulence model was a shear stress transport model, which is an accurate model to solve the heat transfer rate in the near wall region. Table 3 shows the heat transfer modes used for each material.

TABLE 2

	Molten solar salt	Molten tin
Density (kg/m ³)	1794	6800
Dynamic viscosity (Pa s)	2.10×10^{-3}	0.001
Specific heat capacity (J/kg K)	1549	3180
Thermal conductivity (W/m K)	0.5365	33.5
Thermal expansivity (1/K)	2.50×10^{-4}	2.00×10^{-4}

TABLE 3

Material	Heat Transfer Modes
Air	Radiation, convection, and conduction
Solar salt	Radiation, convection, and conduction
Tin	Convection and conduction

10

[0105] The simulations were used to examine three different insulated conduit and conduit embodiments. Table 4 shows the sizes of the insulated conductors and conduits used in the simulations.

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TABLE 4

	Case 1	Case 2	Case 3
Insulated conductor:			
core radius (cm):	0.5	0.25	0.25
insulation thickness (cm)	0.3	0.15	0.15
jacket thickness (cm)	0.1	0.05	0.05
Nominal conduit size (inches)	2	2	3.5

[0106] FIGS 9-11 depict temperature profiles for case 1 heaters with the boundary condition temperature set at 500 °C. The temperature axis of the three figures is different to emphasize the shape of the curves. FIG. 9 depicts temperature versus radial distance for the heater with air between the insulated conductor and the conduit. FIG. 10 depicts temperature versus radial distance for the heater with molten solar salt between the insulated conductor and the conduit. FIG. 11 depicts temperature versus radial distance for the heater with molten tin between the insulated conductor and the conduit. As shown by the shape of the curves in FIGS 9-11, the effect of natural convection for the molten salt is much stronger than the effect of natural convection for air or molten tin. Table 5 shows calculated values of the Prandtl number (Pr), Grashof number (Gr) and Rayleigh number (Ra) for the solar salt and tin when the boundary condition was set at 500 °C.

TABLE 5

Material	Pr	Gr	Ra
Solar Salt	6.06	4.33×10^5	2.63×10^6
Tin	0.09	2.98×10^5	2.83×10^5

[0107] FIG. 12 depicts simulation results for case 1 heaters with the three different materials between the insulated conductors and the conduits, and with boundary conditions of 700 °C, 500 °C and 300 °C. Region A is the distance from the center of the insulated conductor to the outside surface of the insulated conductor. Region B is the distance from the outside of the insulated conductor to the inside surface of the conduit. Region C is the distance from the inside surface of the conduit to the outside surface of the conduit. Curve 234 depicts the temperature profile for air between the insulated conductor and the conduit with the boundary condition for the outer surface of the conduit set at 700 °C. Curve 236 depicts the temperature profile for molten solar salt between the insulated conductor and the conduit with the boundary condition for the outer surface of the conduit set at 700 °C. Curve 238 depicts the temperature profile for molten tin between the insulated conductor and the conduit with the boundary condition for the outer surface of the conduit set at 700 °C. Curves 240, 242, and 244 depict the temperature profiles for air, molten salt, and molten tin respectively with the boundary condition for the outer surface of the conduit set at 500 °C. Curves 246, 248, and 250 depict the temperature profiles for air, molten salt,

and molten tin respectively with the boundary condition for the outer surface of the conduit set at 300 °C.

[0108] Having air in the gap between the insulated conductor and the conduit results in the largest temperature difference between the insulated conductor and the conduit for a given boundary condition temperature, especially for the lower boundary condition of 300 °C. For boundary condition temperatures of 500 °C and 700 °C, the temperature difference between the insulated conductor and the conduit for the molten salt and air is significantly reduced because of the increase in radiative heat transfer with increasing temperature.

[0109] FIG. 13 depicts simulation results for case 2 heaters with the three different materials between the insulated conductors and the conduits, and with boundary conditions of 700 °C, 500 °C and 300 °C. Region A is the distance from the center of the insulated conductor to the outside surface of the insulated conductor. Region B is the distance from the outside of the insulated conductor to the inside surface of the conduit. Region C is the distance from the inside surface of the conduit to the outside surface of the conduit.

Curves 234, 236, and 238 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 700 °C. Curves 240, 242, and 244 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 500 °C. Curves 246, 248, and 250 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 300 °C. As can be seen by comparing FIG. 12 with FIG. 13, decreasing the heater radius results in higher insulated conductor temperature and therefore larger temperature differences between the insulated conductor and the conduit. As seen in FIG. 12 and in FIG. 13, the temperature profile in the material between the insulated conductor and the conduit falls rapidly for the molten salt and is only slightly higher in temperature than the temperature profile established when the material is molten metal. The rapid temperature fall for the molten salt may be due to natural convection in the molten salt.

[0110] FIG. 14 depicts simulation results for case 3 heaters with the three different materials between the insulated conductors and the conduits, and with boundary conditions of 700 °C, 500 °C and 300 °C. Region A is the distance from the center of the insulated conductor to the outside surface of the insulated conductor. Region B is the distance from the outside of the insulated conductor to the inside surface of the conduit. Region C is the distance from the inside surface of the conduit to the outside surface of the conduit.

Curves 234, 236, and 238 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 700 °C. Curves 240, 242, and 244 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 500 °C. Curves 246, 248, and 250 depict the temperature profiles for air, molten salt, and molten tin, respectively, with the boundary condition for the outer surface of the conduit set at 300 °C. As can be seen by comparing FIG. 13 with FIG. 14, increasing the size of the conduit results in a lower insulated conductor temperature, and a lower and more uniform temperature in Region *B*.

[0111] FIG. 15 depicts simulation results of temperature (°C) versus radial distance (mm) for the three cases examined in the simulation with molten salt between the insulated conductors and the conduits, and where the boundary condition was set at 500 °C. Curve 252 depicts the results for case 1, curve 254 depicts the results for case 2, and curve 256 depicts the results for case 3. The lower insulated conductor temperature (for example, when $r = 0$) for curve 252 may result from the larger size of the insulated conductor.

[0112] The temperature of insulated conductor (for example, at $r = 0$) is lower for curve 256 than for curve 254. Also, the temperature of the molten salt away from the near insulated conductor and near conduit regions is lower for curve 256 than for curves 252, 254. The Rayleigh number is proportional to x^3 , where x is the radial thickness of the fluid. For the large conduit (i.e., case 3 and curve 256), the Rayleigh number is about 8 times that of the small conduit (i.e., case 2 and curve 254). The larger Rayleigh number implies that natural convection for the salt in the large conduit is much stronger than the natural convection in the smaller conduit. The stronger natural convection may increase the heat transfer through the molten salt and reduce the temperature of the insulated conductor.

[0113] 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. The scope of the claims should not be limited by the preferred embodiments set forth in the examples, but should be given the broadest interpretation consistent with the description as a whole. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS:

1. A method of heating a formation comprising:

supplying electricity to resistively heat an insulated conductor positioned in a conduit located in an opening in the subsurface formation, wherein the conduit is configured to contain a molten salt in the conduit; and

allowing heat to transfer from the insulated conductor to the molten salt adjacent to at least a portion of the insulated conductor, wherein a temperature of the insulated conductor is above a melt temperature of the molten salt, wherein heat from the molten salt transfers to the conduit, and wherein heat transfers from the conduit to the formation.
2. The method of claim 1, further comprising inhibiting formation of hot spots at one or more high thermal load regions of the conduit by transferring heat using natural convection flow in the molten salt.
3. The method of claim 1, further comprising supplying a gas to the conduit above the molten salt, wherein the gas is carbon dioxide, nitrogen, helium or combinations thereof.
4. The method of any one of claims 1 to 3, wherein at least a portion of the heat transferred to the formation mobilizes hydrocarbons in the formation.
5. A heating system for a subsurface formation, comprising:

a conduit located in an opening in the subsurface formation;

at least one insulated conductor located in the conduit;

a salt in the conduit adjacent to a portion of at least one insulated conductor, wherein the conduit is configured to contain the salt in the conduit; and

wherein at least one insulated conductor is configured to resistively heat to a temperature sufficient to maintain the salt in a molten phase in the conduit.
6. The system of claim 5, further comprising a gas in the conduit above the salt, wherein the gas is carbon dioxide, nitrogen, helium or combinations thereof.
7. The system of claim 5, wherein the conduit includes cladding on an inner surface to inhibit corrosion of the conduit by the salt.

8. The system of claim 5, wherein the conduit includes cladding on an outer surface to inhibit corrosion of the conduit by formation fluid in the formation.
9. The system of claim 5, wherein the salt comprises a mixture of salts.
10. A heating system for a subsurface formation, comprising:
 - a wellbore in the formation;
 - a conduit located in the wellbore;
 - a heat source in the conduit; and
 - a salt in the conduit between the conduit and the heat source, wherein the conduit is configured to contain the salt in the conduit, and wherein the salt is a liquid at a selected operating temperature of the heat source.
11. The system of claim 10, wherein the heat source is an insulated conductor.
12. The system of claim 10, wherein the heat source is one or more gas burners.
13. The system of any one of claims 10 to 12, wherein the salt melts at a temperature greater than 350 °C.
14. The system of any one of claims 10 to 12, further comprising a gas in the conduit above the salt, wherein the gas is carbon dioxide, nitrogen, helium or combinations thereof.

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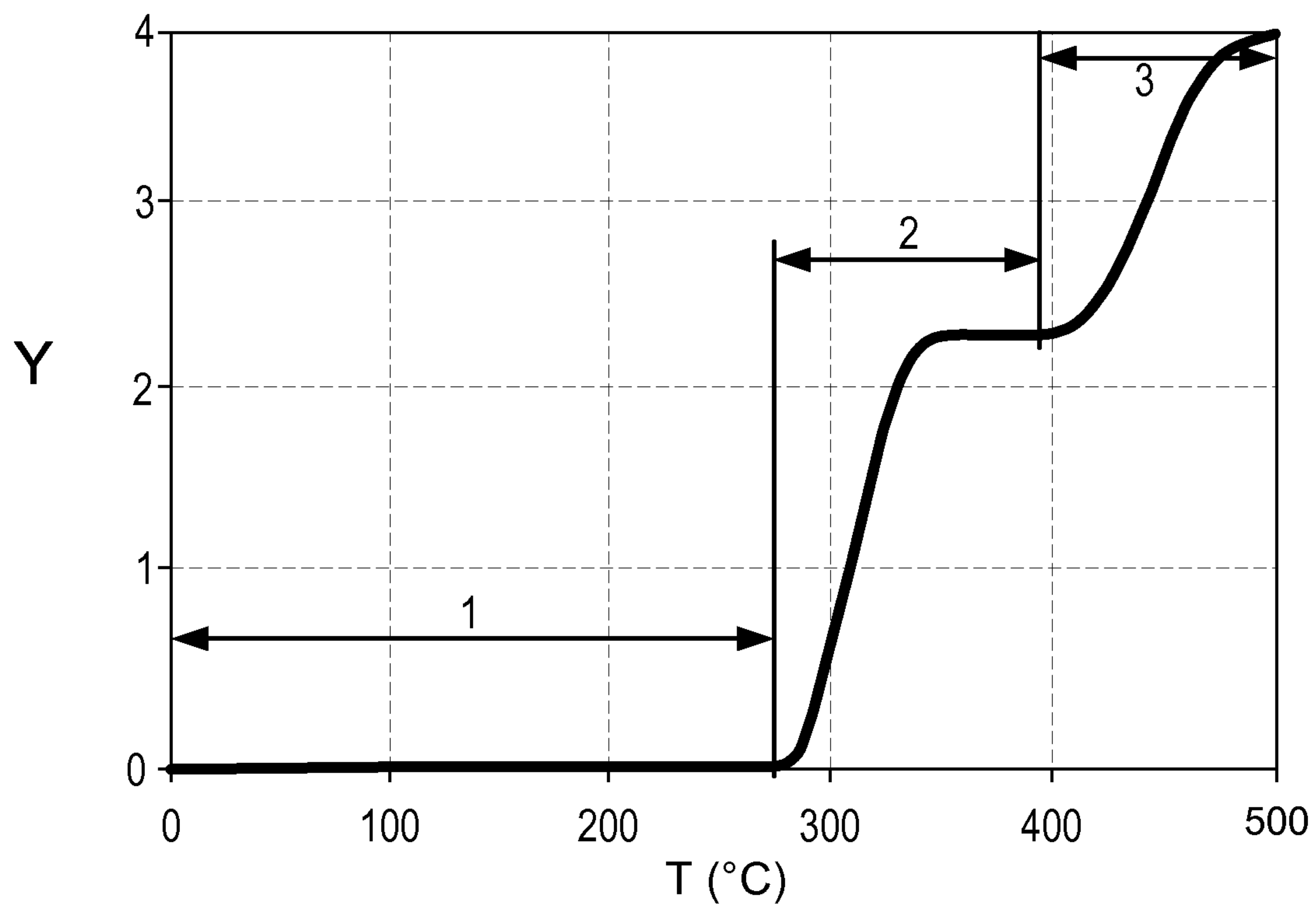


FIG. 1

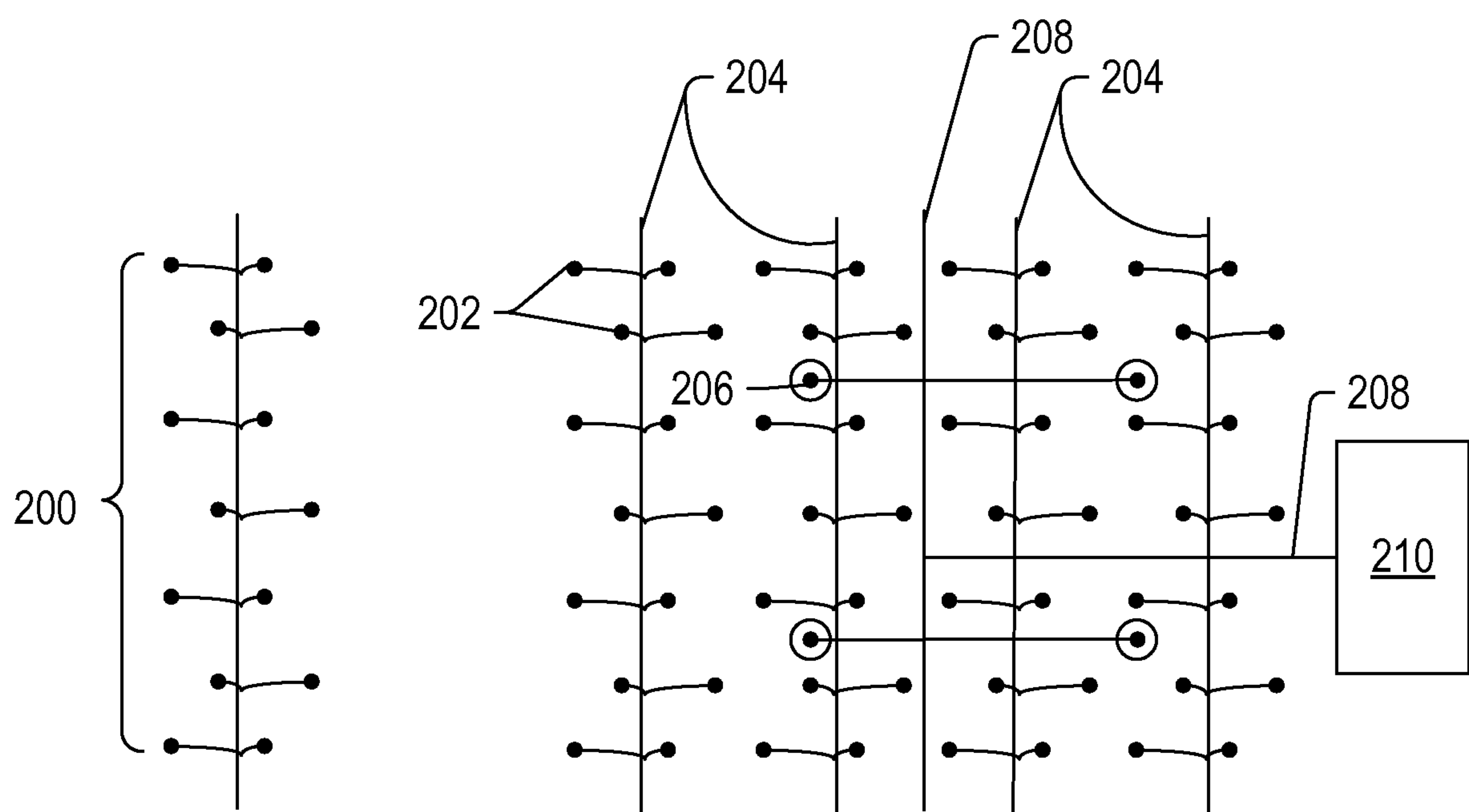
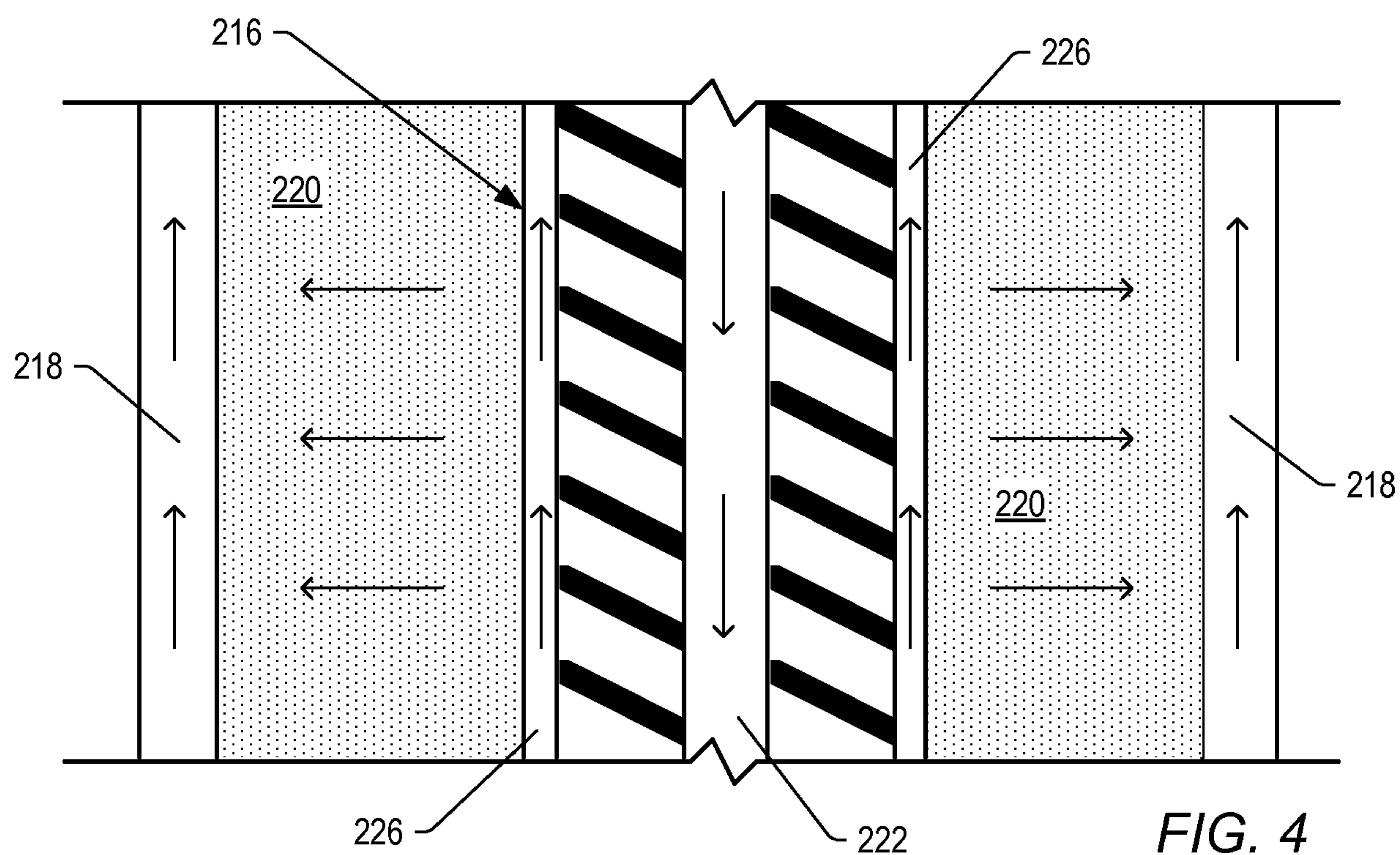
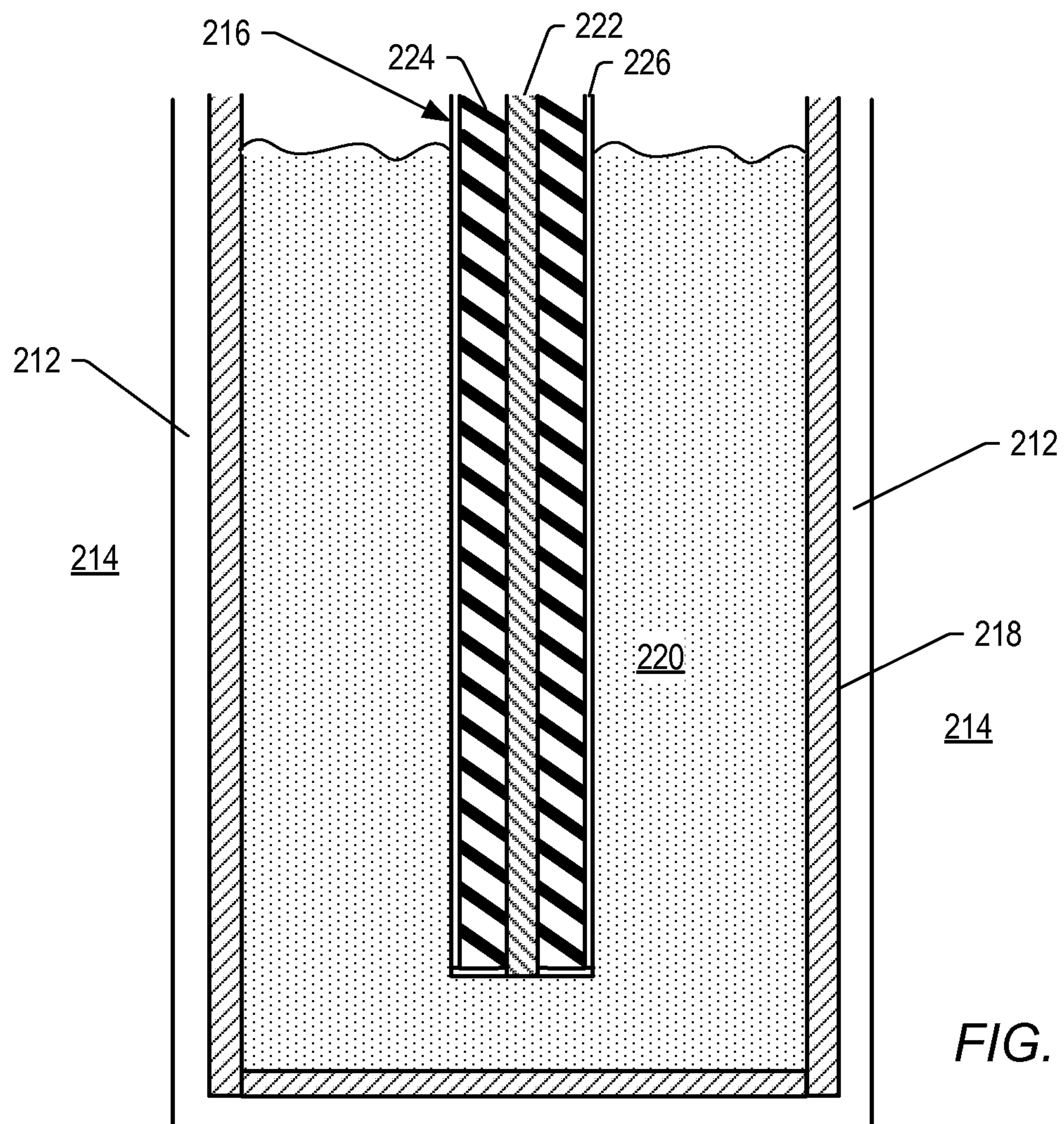


FIG. 2

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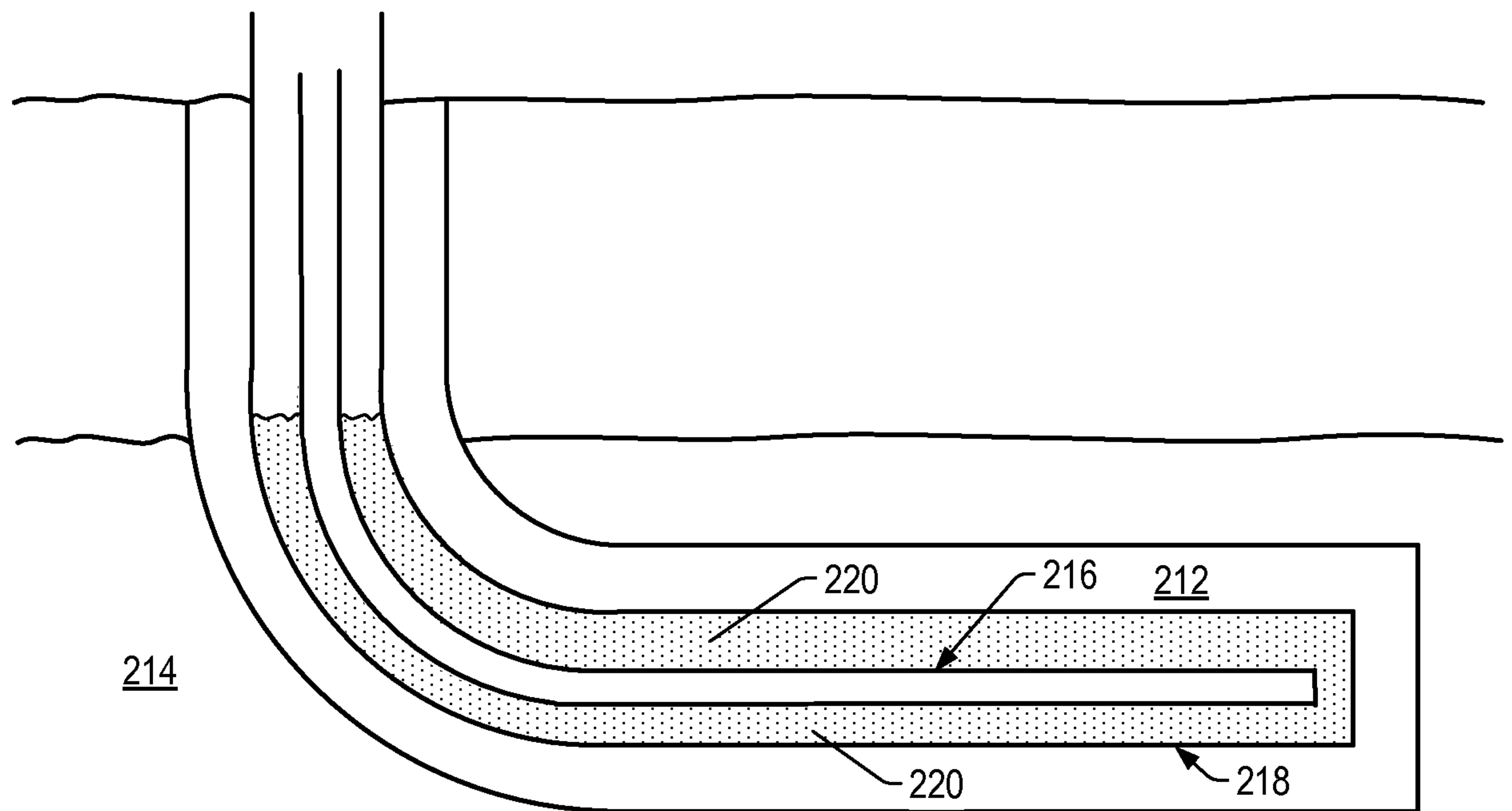


FIG. 5

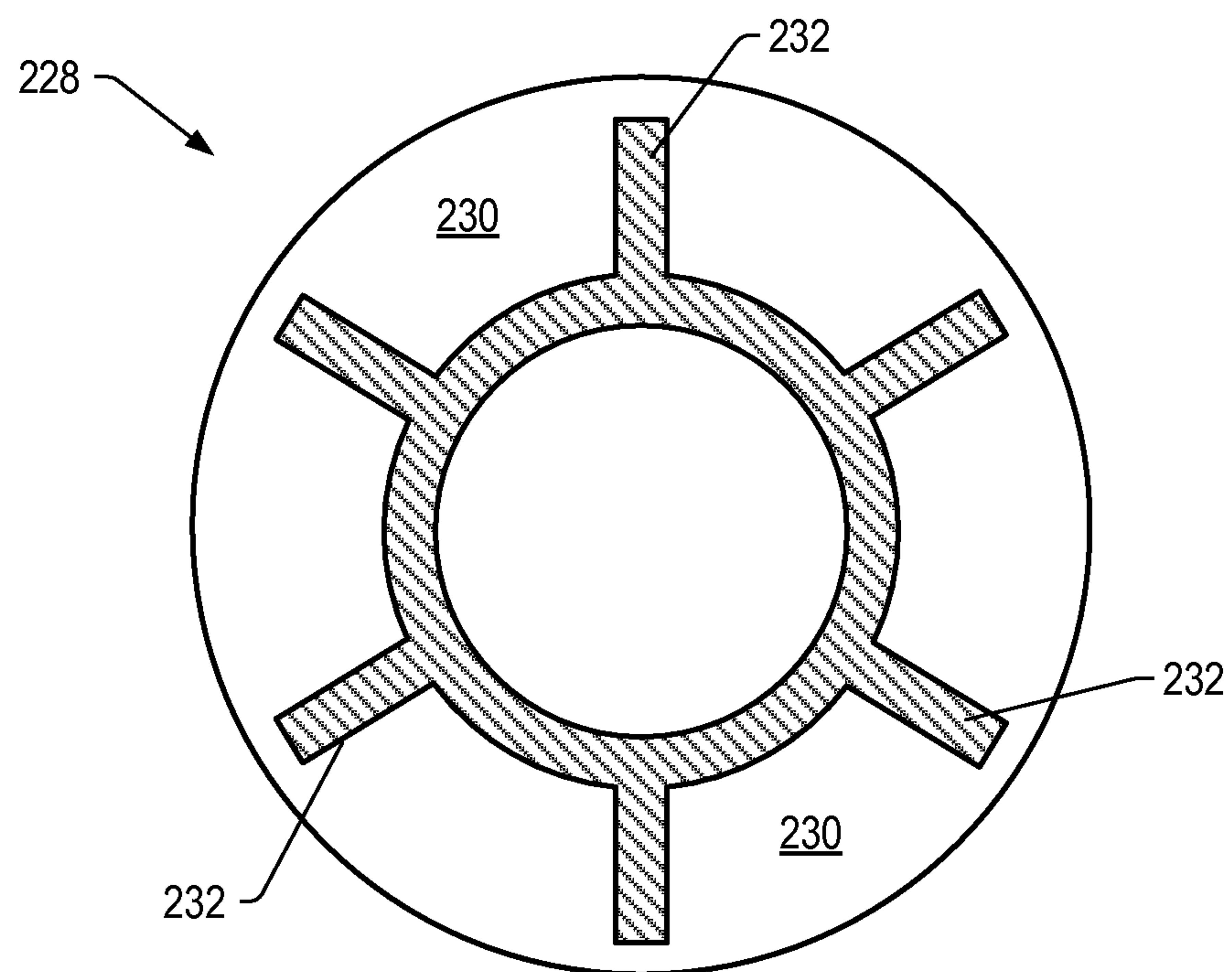


FIG. 6

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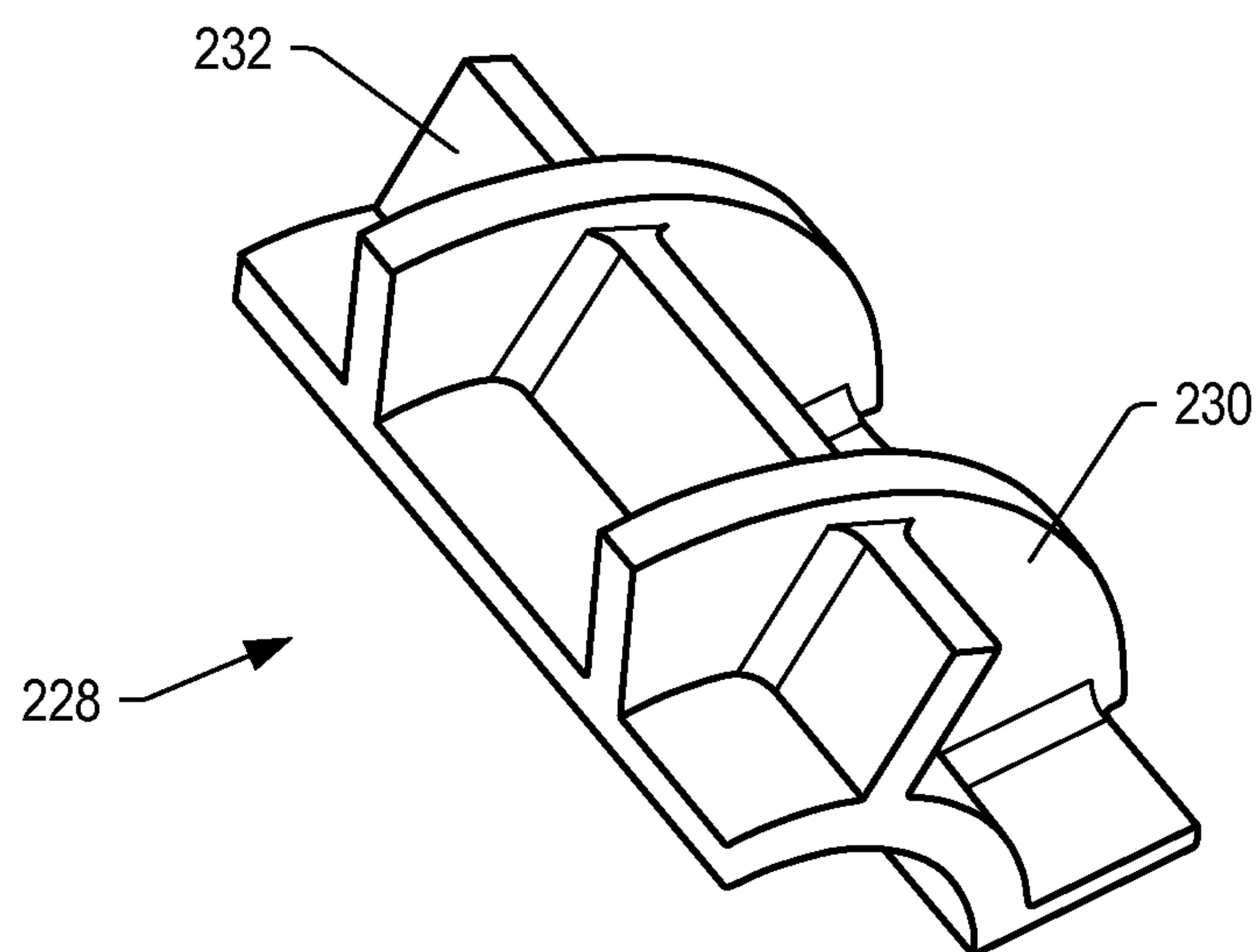


FIG. 7

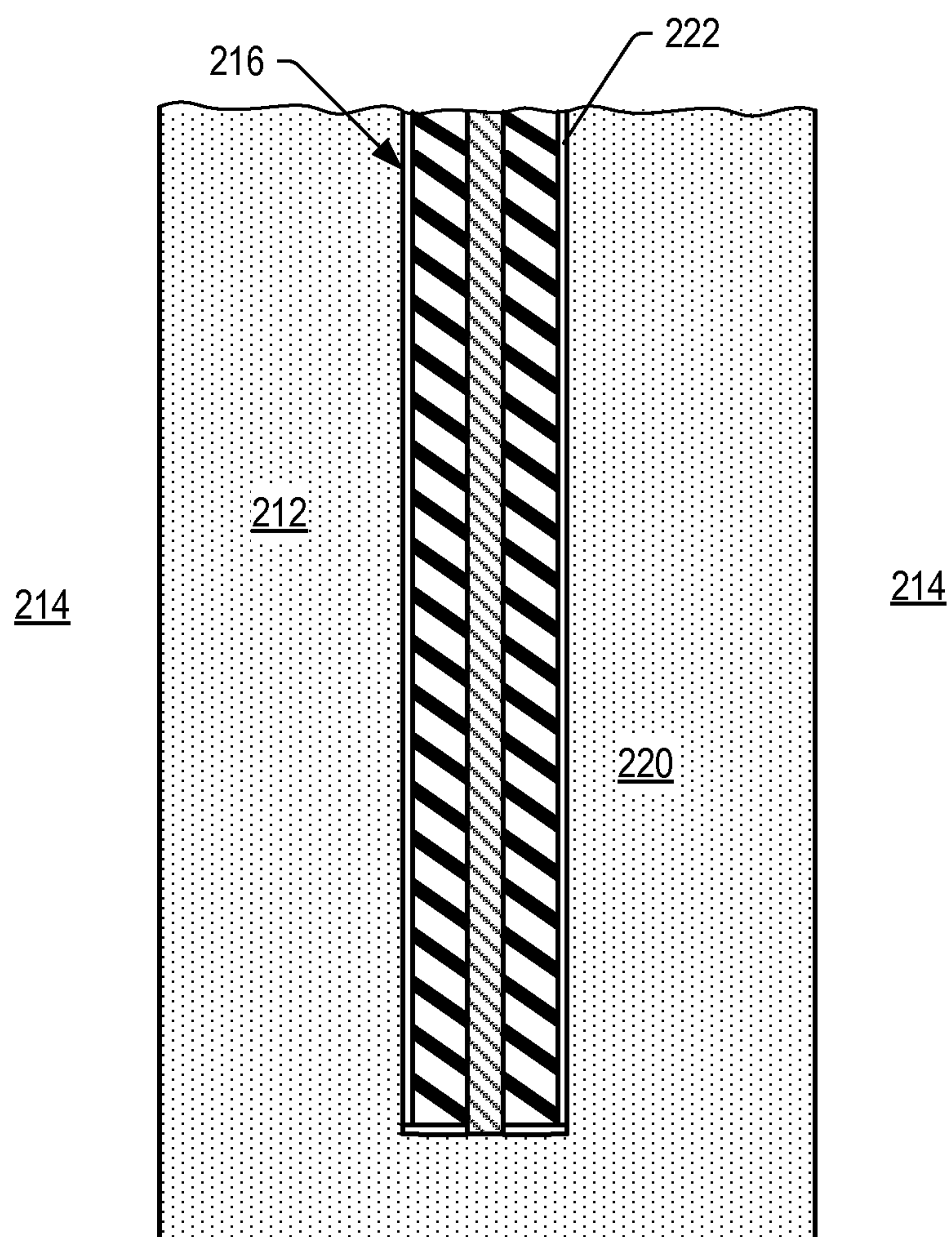


FIG. 8

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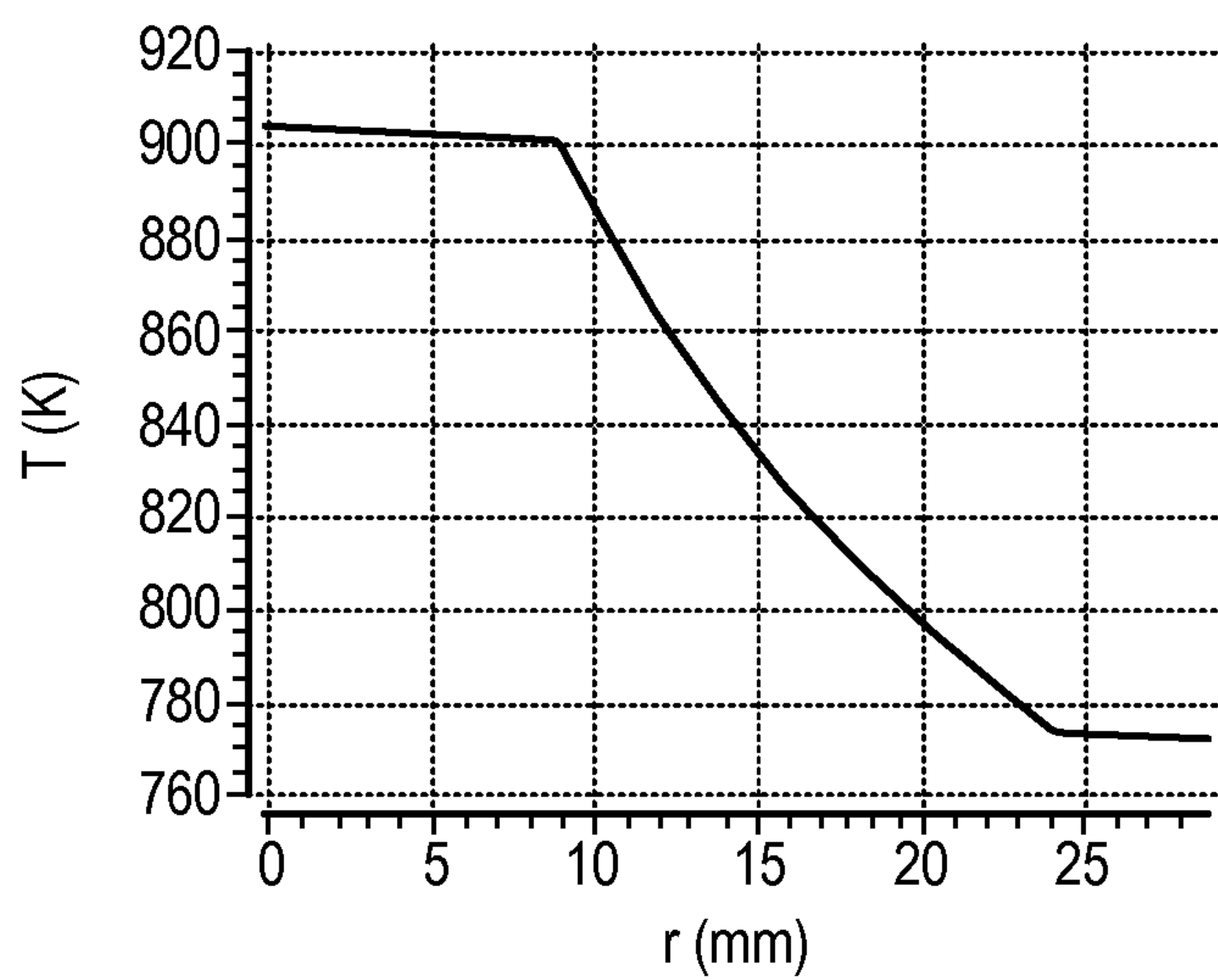


FIG. 9

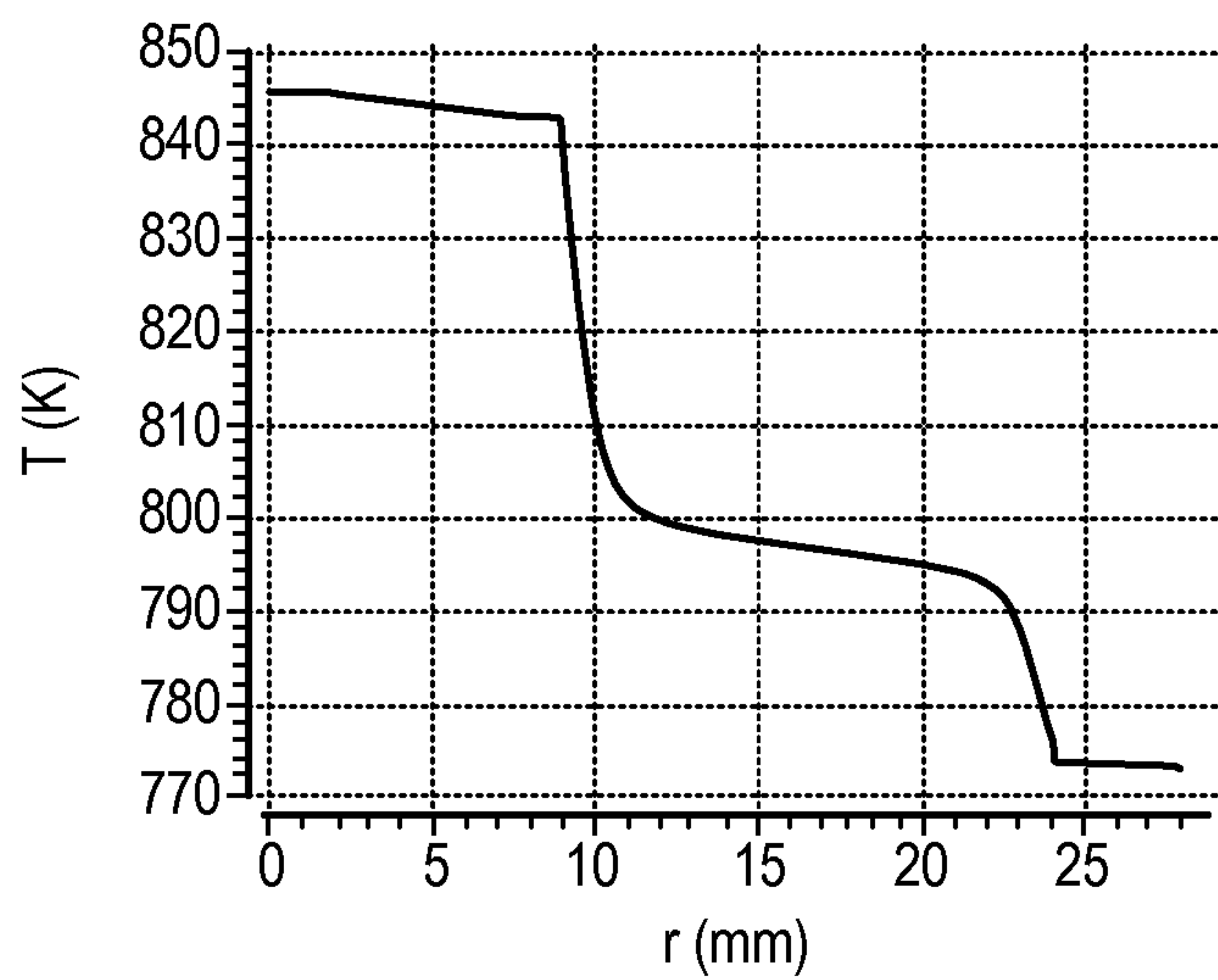


FIG. 10

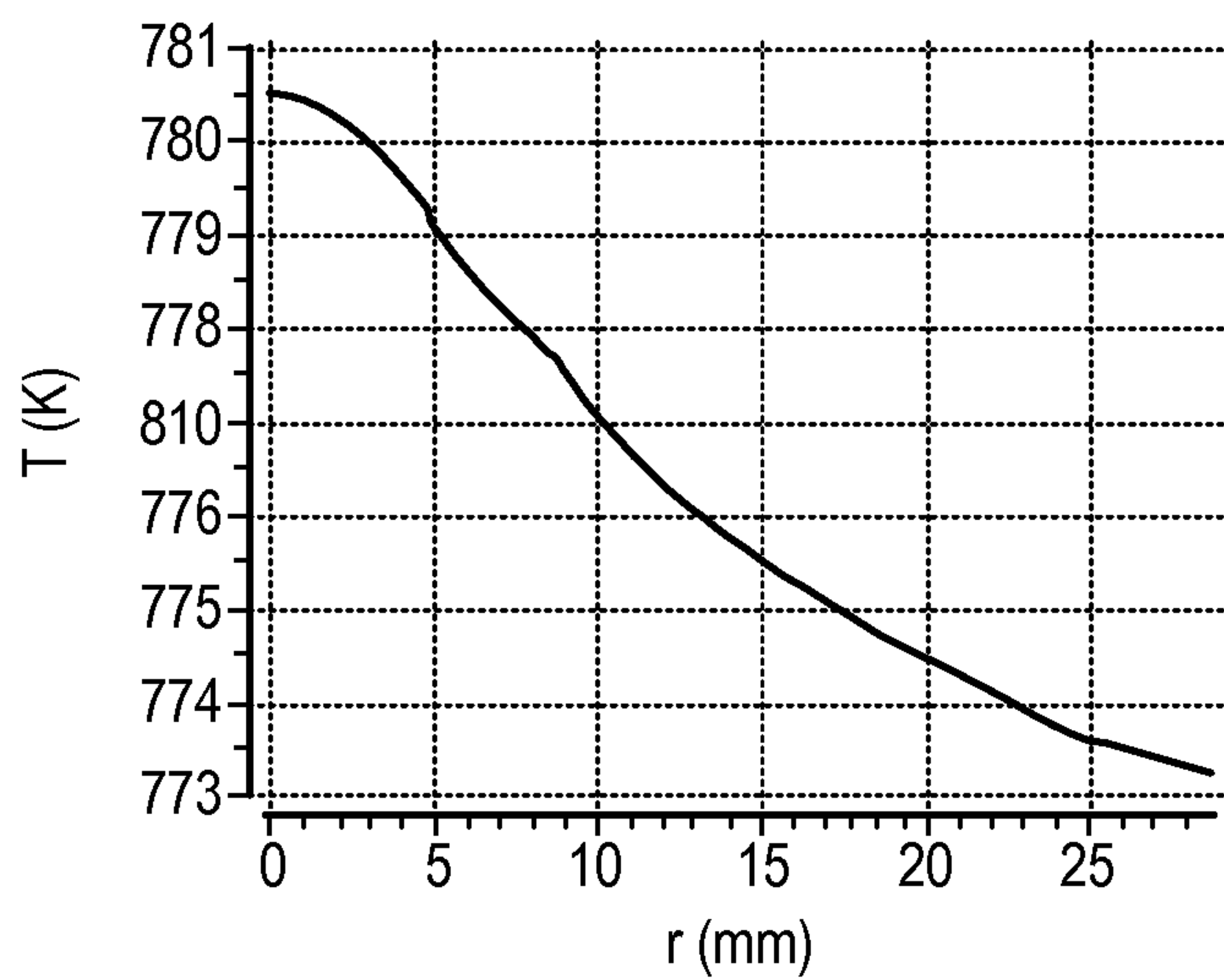


FIG. 11

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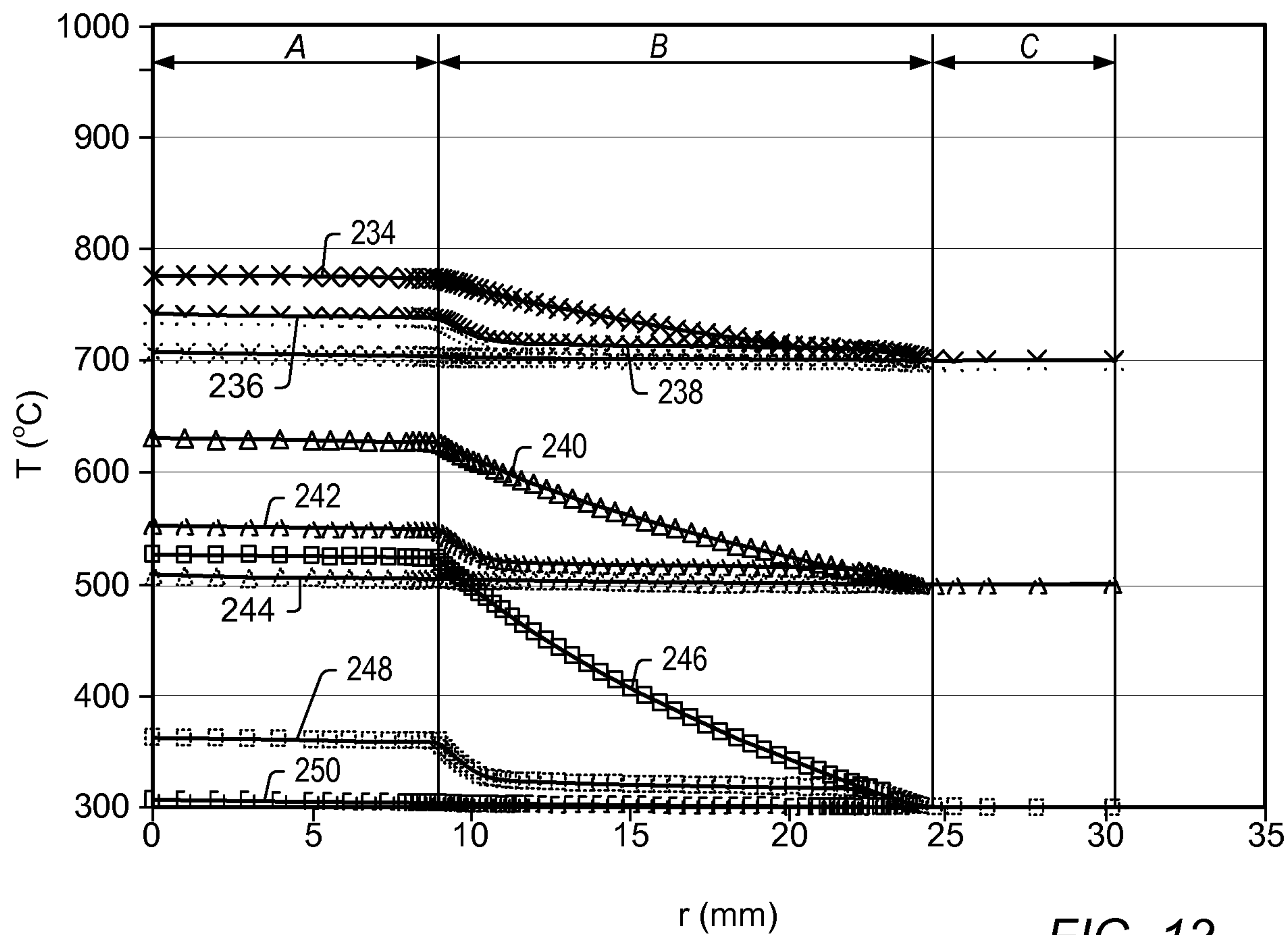


FIG. 12

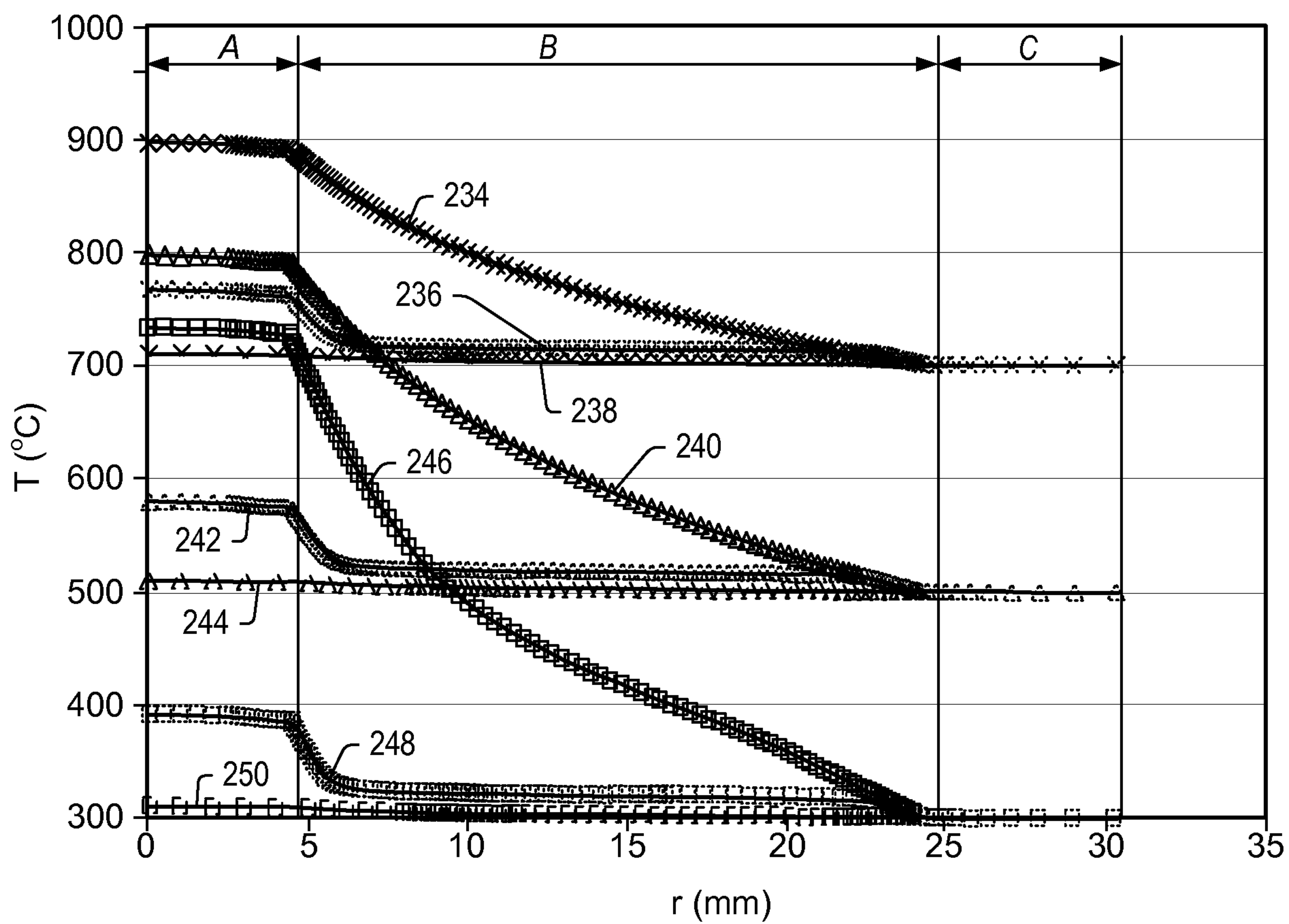


FIG. 13

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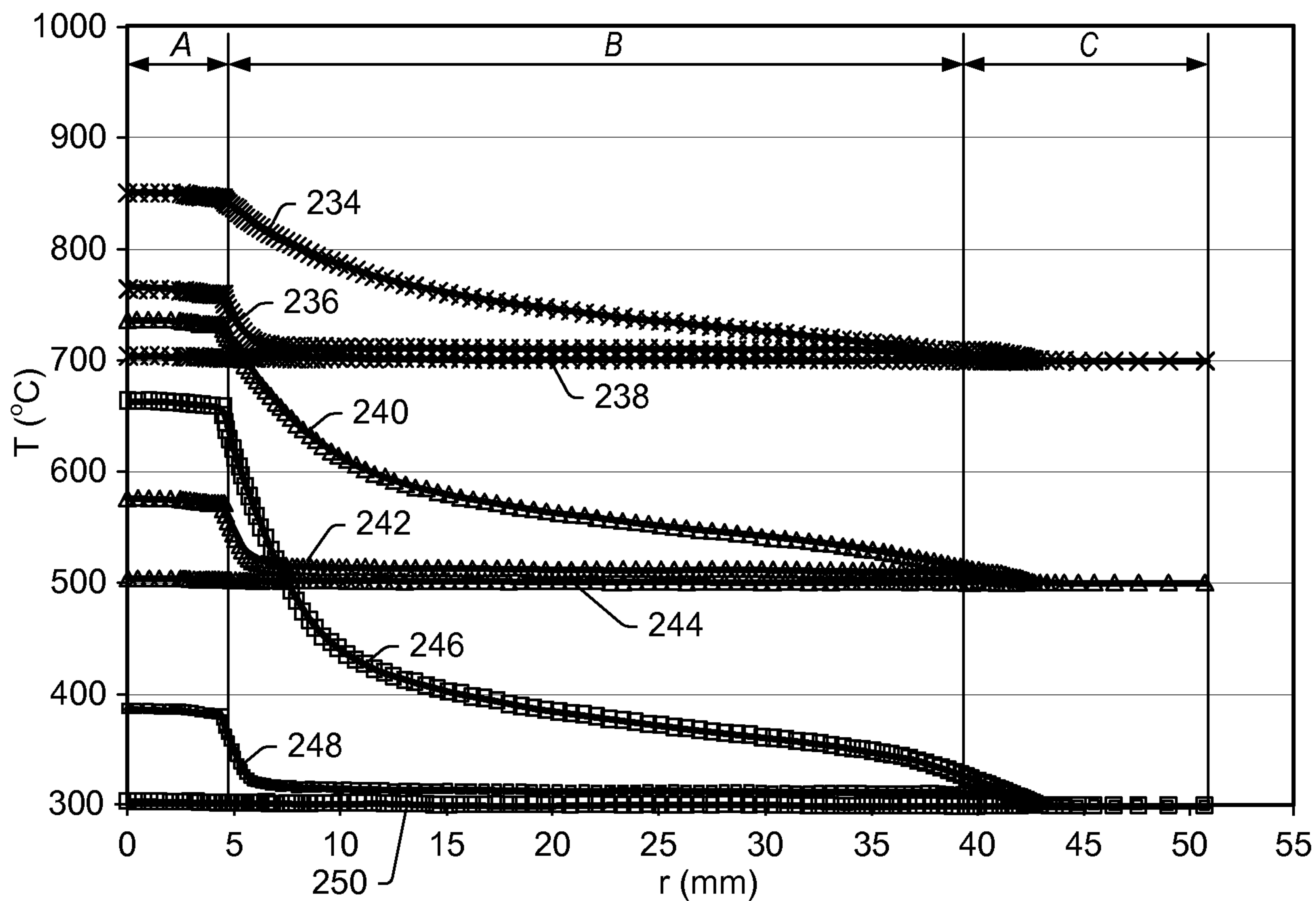


FIG. 14

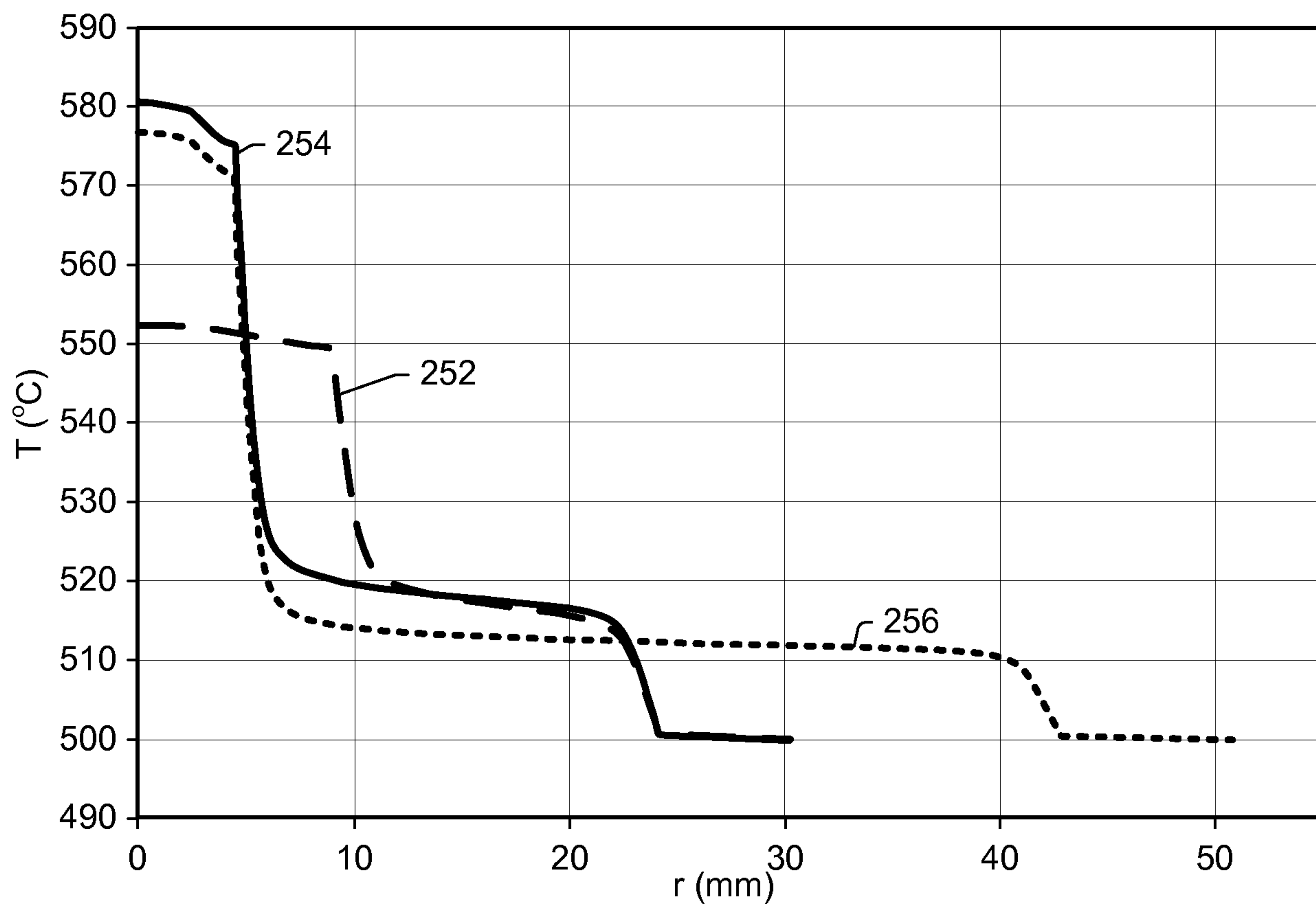


FIG. 15

