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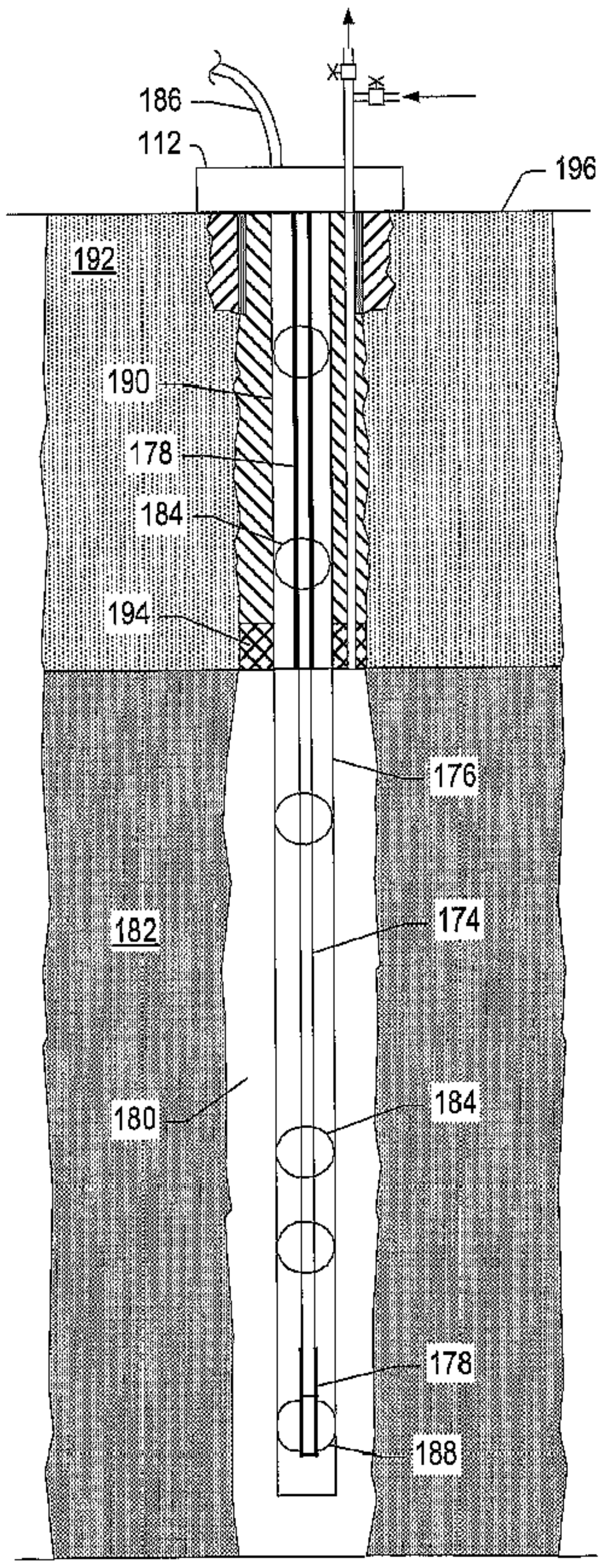
(54) Titre : DISPOSITIFS DE CHAUFFAGE A TEMPERATURE LIMITEE COMPRENANT UN LIQUIDE THERMIQUEMENT CONDUCTEUR UTILISES POUR CHAUFFER DES FORMATIONS SOUTERRAINES

(54) Title: TEMPERATURE LIMITED HEATERS WITH THERMALLY CONDUCTIVE FLUID USED TO HEAT SUBSURFACE FORMATIONS



(57) **Abrégé/Abstract:**

The invention provides a system that includes a heater comprising one or more electrical conductors. The heater is configured to generate a heat output during application of electrical current to the heater. The heater comprises a ferromagnetic material. A

(57) **Abrégé(suite)/Abstract(continued):**

conduit at least partially surrounds the heater. A fluid is located in a space between the heater and the conduit. The fluid has a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa). The system is configured to provide (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater.

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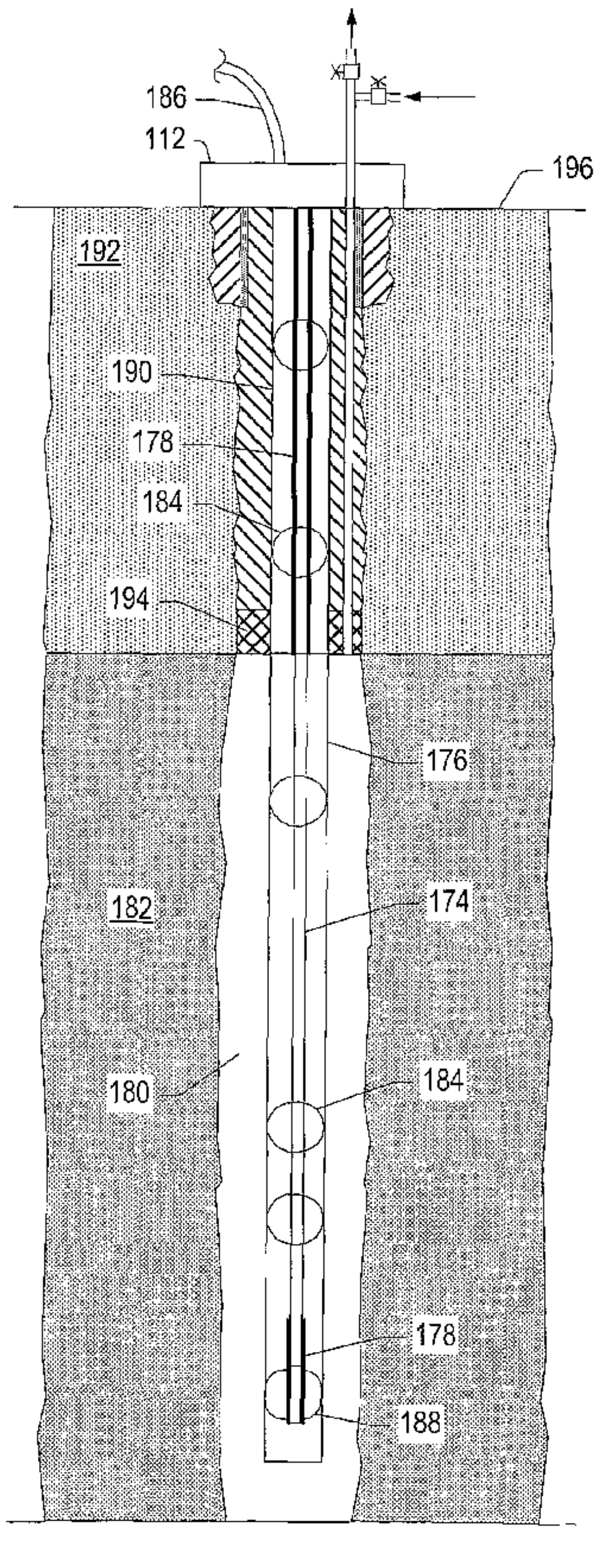
# (54) Title: TEMPERATURE LIMITED HEATERS WITH THERMALLY CONDUCTIVE FLUID USED TO HEAT SUBSURFACE FORMATIONS



**(57) Abstract:** The invention provides a system that includes a heater comprising one or more electrical conductors. The heater is configured to generate a heat output during application of electrical current to the heater. The heater comprises a ferromagnetic material. A conduit at least partially surrounds the heater. A fluid is located in a space between the heater and the conduit. The fluid has a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa). The system is configured to provide (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater.

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# TEMPERATURE LIMITED HEATERS WITH THERMALLY CONDUCTIVE FLUID USED TO HEAT SUBSURFACE FORMATIONS

## BACKGROUND

### Field of the Invention

The present invention relates generally to methods and systems for heating subsurface formations. Certain embodiments relate to methods and systems for using temperature limited heaters with a thermally conductive fluid in the annulus to heat subsurface formations such as hydrocarbon containing formations.

### Description of Related Art

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 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 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.

Heaters may be placed in wellbores to heat a formation during an in situ process. Examples of in situ processes utilizing downhole heaters are illustrated in U.S. Patent Nos. 2,634,961 to Ljungstrom; 2,732,195 to Ljungstrom; 2,780,450 to Ljungstrom; 2,789,805 to Ljungstrom; 2,923,535 to Ljungstrom; and 4,886,118 to Van Meurs et al.

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 heater may resistively heat an element. U.S. Patent No. 2,548,360 to Germain describes an electric heating element placed in a viscous oil in a wellbore. The heater element heats and thins the oil to allow the oil to be pumped from the wellbore. U.S. Patent No. 4,716,960 to Eastlund et al. describes electrically heating tubing of a petroleum well by passing a relatively low voltage current through the tubing to prevent formation of solids. U.S. Patent No. 5,065,818 to Van Egmond describes an electric heating element that is cemented into a well borehole without a casing surrounding the heating element.

Some heaters may break down or fail due to hot spots in the formation. The power supplied to the entire heater may need to be reduced if a temperature along any point of the heater exceeds, or is about to exceed, a maximum operating temperature of the heater to avoid failure of the heater and/or overheating of the formation at or near hot spots in the formation. Some heaters may not provide uniform heat along a length of the heater until the heater reaches a certain temperature limit. Some heaters may not heat a subsurface formation efficiently. Thus, it is advantageous to have a heater that provides uniform heat along a length of the heater; heats the subsurface formation efficiently; and/or provides automatic temperature adjustment when a portion of the heater approaches a selected temperature. It may also be advantageous to use a fluid with a high thermal conductivity in the heater.

## Summary of the Invention

The invention provides a system comprising: a heater comprising one or more electrical conductors, the heater configured to generate a heat output during application of electrical current to the heater, wherein the heater comprises a ferromagnetic material; a conduit at least partially surrounding the heater; a fluid having a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa) located in a space between the heater and the conduit, a source of electrical power; and wherein the system is configured to provide (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater and (c) the electrical conductor at least partially surrounds a non-ferromagnetic material the non-ferromagnetic material has a higher electrical conductivity than the ferromagnetic material; and wherein a fluid pressure in the space between the electrical conductor and the conduit is at least 1000 kPa and is sufficient to inhibit arcing in the space

The invention also provides in combination with the above invention: (i) the fluid is an electrically insulating fluid, for example, helium; and (ii) the fluid is helium and the space between the electrical conductor and the conduit is at least 50% by volume helium, at least 75% by volume helium, or at least 90% by volume helium.

The invention also provides in combination with one or more of the above inventions: (a) the source of electrical power comprises an AC power supply or a modulated DC power supply; and (b) the system has a turndown ratio of at least 1.1 to 1, at least 2 to 1, or at least 3 to 1.

The invention also provides in combination with one or more of the above inventions: a) the system comprises in addition a non-ferromagnetic material coupled to the ferromagnetic material; (b) the selected temperature is approximately the Curie temperature of the ferromagnetic material or is within 25 °C of the Curie temperature of the ferromagnetic material; and (c) at least one of the electrical conductors is elongated and configured such that electrically resistive sections at or near the selected temperature will automatically provide the second heat output.

In another aspect of the invention there is provided a method for heating a subsurface formation, the method comprising: arranging in a heater well a heating system of the invention; providing electrical current to the heater to provide an electrically resistive heat output; and allowing heat to transfer from the heater to at least part of the subsurface formation such that the heater provides (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater.

## Brief Description of the Drawings

Advantages of the present invention will 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 depicts an illustration of stages of heating hydrocarbons in the formation.

FIG. 2 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating hydrocarbons in the formation.

FIGS. 3, 4, and 5 depict cross-sectional representations of an embodiment of a temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section.

FIGS. 6, 7, 8, and 9 depict cross-sectional representations of an embodiment of a temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section placed inside a sheath.

FIGS. 10, 11, and 12 depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor.

FIGS. 13, 14, and 15 depict cross-sectional representations of an embodiment of a temperature limited heater with an outer conductor.

FIGS. 16A and 16B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic inner conductor.

FIGS. 17A and 17B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic inner conductor and a non-ferromagnetic core.

FIGS. 18A and 18B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor.

FIGS. 19A and 19B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor that is clad with a corrosion resistant alloy.

FIGS. 20A and 20B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor.

FIG. 21 depicts a cross-sectional representation of an embodiment of a composite conductor with a support member.

FIG. 22 depicts a cross-sectional representation of an embodiment of a composite conductor with a support member separating the conductors.

FIG. 23 depicts a cross-sectional representation of an embodiment of a composite conductor surrounding a support member.

FIG. 24 depicts a cross-sectional representation of an embodiment of a composite conductor surrounding a conduit support member.

FIG. 25 depicts a cross-sectional representation of an embodiment of a conductor-in-conduit heater.

FIG. 26A and FIG. 26B depict an embodiment of an insulated conductor heater.

FIG. 27 and FIG. 27B depict an embodiment of an insulated conductor heater with a jacket located outside an outer conductor.

FIG. 28 depicts an embodiment of an insulated conductor located inside a conduit.

FIGS. 29, 30, 31, 32, 33, 34, 35, and 36 show heater rod temperature as a function of the power generated within a rod for a base case in which both the rod and conduit emissivities were 0.8, and a low emissivity case in which the rod emissivity was lowered to 0.4.

FIG. 37 shows a plot of center heater rod (with 0.8 emissivity) temperature versus conduit temperature for various heater powers with air or helium in the annulus.

FIG. 38 shows a plot of center heater rod (with 0.4 emissivity) temperature versus conduit temperature for various heater powers with air or helium in the annulus.

FIG. 39 depicts spark gap breakdown voltages versus pressure at different temperatures for a conductor-in-conduit heater with air in the annulus.

FIG. 40 depicts spark gap breakdown voltages versus pressure at different temperatures for a conductor-in-conduit heater with helium in the annulus.

FIG. 41 depicts electrical resistance versus temperature at various applied electrical currents for a 446 stainless steel rod.

FIG. 42 depicts electrical resistance versus temperature at various applied electrical currents for a temperature limited heater.

FIG. 43 depicts data of electrical resistance versus temperature for a solid 2.54 cm diameter, 1.8 m long 410 stainless steel rod at various applied electrical currents.

FIG. 44 depicts data for values of skin depth versus temperature for a solid 2.54 cm diameter, 1.8 m long 410 stainless steel rod at various applied AC electrical currents.

FIG. 45 depicts temperature versus time for a temperature limited heater.

FIG. 46 depicts temperature versus log time data for a 2.5 cm solid 410 stainless steel rod and a 2.5 cm solid 304 stainless steel rod.

FIG. 47 displays temperature of the center conductor of a conductor-in-conduit heater as a function of formation depth for a temperature limited heater with a turndown ratio of 2:1.

FIG. 48 displays heater heat flux through a formation for a turndown ratio of 2:1 along with the oil shale richness profile.

FIG. 49 displays heater temperature as a function of formation depth for a turndown ratio of 3:1.

FIG. 50 displays heater heat flux through a formation for a turndown ratio of 3:1 along with the oil shale richness profile.

FIG. 51 displays heater temperature as a function of formation depth for a turndown ratio of 4:1.

FIG. 52 depicts heater temperature versus depth for heaters used in a simulation for heating oil shale.

FIG. 53 depicts heater heat flux versus time for heaters used in a simulation for heating oil shale.

FIG. 54 depicts cumulative heat input versus time in a simulation for heating oil shale.

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 of the Invention

The above problems may be addressed using systems, methods, and heaters described herein. For example, a system includes an electrical conductor configured to generate an electrically resistive heat output during application of electrical current to the electrical conductor. The electrical conductor may include an electrically resistive ferromagnetic material. A conduit may at least partially surround the electrical conductor. A fluid may be located in a space between the electrical conductor and the conduit. The fluid has a higher thermal conductivity than air at 101 kPa and a temperature in the space. The system is configured to provide a reduced amount of heat above or near a selected temperature.

Certain embodiments of the inventions described herein in more detail relate to systems and methods for treating hydrocarbons in the formations. Such formations may be treated to yield hydrocarbon products, hydrogen, and other products. Terms used herein are defined as follows.

"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 (for example, 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 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 results 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" and "produced fluids" refer to fluids removed from the 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.

"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).

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

"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 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.

"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.

"Time-varying current" refers to an electrical current that has a magnitude that varys with time. Time-varying current includes both alternating current (AC) and modulated direct current (DC).

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

"Modulated direct current (DC)" refers to any substantially non-sinusoidal time-varying current that produces skin effect electricity flow in a ferromagnetic conductor.

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

The term "wellbore" refers to a hole in a formation made by drilling or insertion of a conduit into the formation. As used herein, the terms "well" and "opening," when referring to an opening in the formation may be used interchangeably with the term "wellbore."

"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. The term "self-controls" refers to controlling an output of a heater without external control of any type.

In the context of reduced heat output heating systems, apparatus, and methods, the term "automatically" means such systems, apparatus, and methods function in a certain way without the use of external control (for example, external controllers such as a controller with a temperature sensor and a feedback loop, PID controller, or predictive controller).

Hydrocarbons in formations may be treated in various ways to produce many different products. In certain embodiments, such formations are treated in stages. FIG. 1 illustrates several stages of heating a portion of the formation that contains hydrocarbons. FIG. 1 also depicts an example of yield ("Y") in barrels of oil equivalent per ton (y axis) of formation versus temperature ("T") of the heated formation in degrees Celsius (x axis).

Desorption of methane and vaporization of water occurs during stage 1 heating. Heating the formation through stage 1 may be performed as quickly as possible. When the formation is initially heated, hydrocarbons in the formation desorb adsorbed methane. The desorbed methane may be produced from the formation. If the formation is heated further, water in the formation is vaporized. Water typically is vaporized in the formation between 160 °C and 285 °C at pressures of 600 kPa absolute to 7000 kPa absolute. In some embodiments, the vaporized water produces 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 the formation and increasing the pore volume in the formation increases the storage space for hydrocarbons in the pore volume.

In certain embodiments, after stage 1 heating, the portion of the formation is heated further, such that the temperature in the portion of 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, temperatures between 250 °C and 350 °C, or temperatures between 325 °C and 400 °C. If the 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. Heating the formation with a plurality of heaters may establish superposition of heat that slowly raises the temperature of hydrocarbons in the formation through the pyrolysis temperature range.

In some in situ conversion embodiments, a portion of the formation is heated to the desired temperature instead of slowly heating the temperature through the pyrolysis temperature range. In some embodiments, the desired temperature is 300 °C. In some embodiments, the desired temperature is 325 °C. In some embodiments, the desired temperature is 350 °C. Other temperatures may be selected as the desired temperature. Superposition of heat from heaters allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heaters may be adjusted to maintain the temperature in the formation 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 the pyrolysis temperature range by heat transfer from only one heater.

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 very high temperatures, the formation may produce mostly methane and/or hydrogen. If the 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 most of the available hydrogen is depleted, a minimal amount of fluid production will occur from the formation.

After pyrolysis of hydrocarbons, a large amount of carbon and some hydrogen may still be present in the heated portion of the formation. A portion of carbon remaining in the heated portion of the formation may 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 the heated portion of the formation to a temperature sufficient to allow synthesis gas generation. Synthesis gas may be produced in a temperature range from 400 °C to 1200 °C, 500 °C to 1100 °C, or 550 °C to 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. Generated synthesis gas may be removed from the formation through one or more production wells.

FIG. 2 depicts a schematic view of an embodiment of a portion of the in situ conversion system for treating the formation that contains hydrocarbons. Heaters 100 are placed in at least a portion of the formation. Heaters 100 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heaters 100 through supply lines 102. Supply lines 102 may be structurally different depending on the type of heater or heaters used to heat the formation. Supply lines 102 for heaters 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 104 are used to remove formation fluid from the formation. Formation fluid produced from production wells 104 may be transported through collection piping 106 to treatment facilities 108. Formation fluids may also be produced from heaters 100. For example, fluid may be produced from heaters 100 to control pressure in the formation adjacent to the heaters. Fluid produced from heaters 100 may be transported through tubing or piping to collection piping 106 or the produced fluid may be transported through tubing or piping directly to treatment facilities 108. Treatment facilities 108 may include separation units, reaction units, upgrading units, sulfur removal from gas units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids.

The in situ conversion system for treating hydrocarbons may include barrier wells 110. 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 110 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 dewatering wells are shown extending only along one side of heaters 100, but dewatering wells typically encircle all heaters 100 used, or to be used, to heat the formation.

As shown in FIG. 2, in addition to heaters 100, one or more production wells 104 are placed in the formation. Formation fluids may be produced through production well 104. In some embodiments, production well 104 includes a heater. The heater in the production well may heat one or more portions of the formation at or near the production well and allow for vapor phase removal of formation fluids. The need for high temperature pumping of liquids from the production well may be reduced or eliminated. Avoiding or limiting high temperature pumping of liquids may significantly decrease production costs. 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, and/or (3) increase formation permeability at or proximate the production well. In some in situ conversion process embodiments, an amount of heat supplied to the formation from a production well per meter of the production well is less than the amount of heat applied to the formation from a heater that heats the formation per meter of the heater.

Some embodiments of heaters include switches (for example, fuses and/or thermostats) that turn off power to a heater or portions of a heater when a certain condition is reached in the heater. In certain embodiments, a temperature limited heater is used to provide heat to hydrocarbons in the formation.

Temperature limited heaters may be in configurations and/or may include materials that provide automatic temperature limiting properties for the heater at certain temperatures. In certain embodiments, ferromagnetic materials are used in temperature limited heaters. Ferromagnetic material may self-limit temperature at or near the Curie temperature of the material to provide a reduced amount of heat at or near the Curie temperature when an time-varying current is applied to the material. In certain embodiments, the ferromagnetic material self-limits temperature of the temperature limited heater at a selected temperature that is approximately the Curie temperature. In certain embodiments, the selected temperature is within about 35 °C, within about 25 °C, within about 20 °C, or within about 10 °C of the Curie temperature. In certain embodiments, ferromagnetic materials are coupled with other materials (for example, highly conductive materials, high strength materials, corrosion resistant materials, or combinations thereof) to provide various electrical and/or mechanical properties. Some parts of the temperature limited heater may have a lower resistance (caused by different geometries and/or by using different ferromagnetic and/or non-ferromagnetic materials) than other parts of the temperature limited heater. Having parts of the temperature limited heater with various materials and/or dimensions allows for tailoring the desired heat output from each part of the heater.

Temperature limited heaters may be more reliable than other heaters. Temperature limited heaters may be less apt to break down or fail due to hot spots in the formation. In some embodiments, temperature limited heaters allow for substantially uniform heating of the formation. In some embodiments, temperature limited heaters are able to heat the formation more efficiently by operating at a higher average heat output along the entire length of the heater. The temperature limited heater operates at the higher average heat output along the entire length of the heater because power to the heater does not have to be reduced to the entire heater, as is the case with typical constant wattage heaters, if a temperature along any point of the heater exceeds, or is about to exceed, a maximum operating temperature of the heater. Heat output from portions of a temperature limited heater approaching a Curie temperature of the heater automatically reduces without controlled adjustment of current applied to the heater. The heat output automatically reduces due to changes in electrical properties (for example, electrical resistance) of portions of the temperature limited heater. Thus, more power is supplied by the temperature limited heater during a greater portion of a heating process.

In certain embodiments, the system including temperature limited heaters initially provides a first heat output and then provides a reduced (second heat output) heat output, near, at, or above the Curie temperature of an electrically resistive portion of the heater when the temperature limited heater is energized by a time-varying current. The first heat output is the heat output at temperatures below which the temperature limited heater begins to self-limit. In some embodiments, the first heat output is the heat output at a temperature 50 °C, 75 °C, 100 °C, or 125 °C below the Curie temperature of the ferromagnetic material in the temperature limited heater.

The temperature limited heater may be energized by time-varying current (alternating current or modulated direct current) supplied at the wellhead. The wellhead may include a power source and other components (for example, modulation components, transformers, and/or capacitors) used in supplying power to the temperature limited heater. The temperature limited heater may be one of many heaters used to heat a portion of the formation.

In certain embodiments, the temperature limited heater includes a conductor that operates as a skin effect or proximity effect heater when time-varying current is applied to the conductor. The skin effect limits the depth of current penetration into the interior of the conductor. For ferromagnetic materials, the skin effect is dominated by the magnetic permeability of the conductor. The relative magnetic permeability of ferromagnetic materials is typically between 10 and 1000 (for example, the relative magnetic permeability of ferromagnetic materials is typically at least 10 and may be at least 50, 100, 500, 1000 or greater). As the temperature of the ferromagnetic material is raised above the Curie temperature and/or as the applied electrical current is increased, the magnetic permeability of the ferromagnetic material decreases substantially and the skin depth expands rapidly (for example, the skin depth expands as the inverse square root of the magnetic permeability). The reduction in magnetic permeability results in a decrease in the AC or modulated DC resistance of the conductor near, at, or above the Curie temperature and/or as the applied electrical current is increased. When the temperature limited heater is powered by a substantially constant current source, portions of the heater that approach, reach, or are above the Curie temperature may have reduced heat dissipation. Sections of the temperature limited heater that are not at or near the Curie temperature may be dominated by skin effect heating that allows the heater to have high heat dissipation due to a higher resistive load.

Curie temperature heaters have been used in soldering equipment, heaters for medical applications, and heating elements for ovens. Some of these uses are disclosed in U.S. Patent Nos. 5,579,575 to Lamome et al.; 5,065,501 to Henschen et al.; and 5,512,732 to Yagnik et al. U.S. Patent No. 4,849,611 to Whitney et al. describes a plurality of discrete, spaced-apart heating units including a reactive component, a resistive heating component, and a temperature responsive component.

An advantage of using the temperature limited heater to heat hydrocarbons in the formation is that the conductor is chosen to have a Curie temperature in a desired range of temperature operation. Operation within the desired operating temperature range allows substantial heat injection into the formation while maintaining the temperature of the temperature limited heater, and other equipment, below design limit temperatures. Design limit temperatures are temperatures at which properties such as corrosion, creep, and/or deformation are adversely affected. The temperature limiting properties of the temperature limited heater inhibits overheating or burnout of the heater adjacent to low thermal conductivity "hot spots" in the formation. In some embodiments, the temperature limited heater is able to lower or control heat output and/or withstand heat at temperatures above 25 °C, 37 °C, 100 °C, 250 °C, 500 °C, 700 °C, 800 °C, 900 °C, or higher up to 1131 °C, depending on the materials used in the heater.

The temperature limited heater allows for more heat injection into the formation than constant wattage heaters because the energy input into the temperature limited heater does not have to be limited to accommodate low thermal conductivity regions adjacent to the heater. For example, in Green River oil shale there is a difference of at least a factor of 3 in the thermal conductivity of the lowest richness oil shale layers and the highest richness oil shale layers. When heating such a formation, substantially more heat is transferred to the formation with the temperature limited heater than with the conventional heater that is limited by the temperature at low thermal conductivity layers. The heat output along the entire length of the conventional heater needs to accommodate the low thermal conductivity layers so that the heater does not overheat at the low thermal conductivity layers and burn out. The heat output adjacent to the low thermal conductivity layers that are at high temperature will reduce for the temperature limited heater, but the remaining portions of the temperature limited heater that are not at high temperature will still provide high heat output. Because heaters for heating hydrocarbon formations typically have long lengths (for example, at least 10 m, 100 m, 300 m, at least 500 m, 1 km or more up to 10 km), the majority of the length of the temperature limited heater may be operating below the Curie temperature while only a few portions are at or near the Curie temperature of the temperature limited heater.

The use of temperature limited heaters allows for efficient transfer of heat to the formation. Efficient transfer of heat allows for reduction in time needed to heat the formation to a desired temperature. For example, in Green River oil shale, pyrolysis typically requires 9.5 years to 10 years of heating when using a 12 m heater well spacing with conventional constant wattage heaters. For the same heater spacing, temperature limited heaters may allow a larger average heat output while maintaining heater equipment temperatures below equipment design limit temperatures. Pyrolysis in the formation may occur at an earlier time with the larger average heat output provided by temperature limited heaters than the lower average heat output provided by constant wattage heaters. For example, in Green River oil shale, pyrolysis may occur in 5 years using temperature limited heaters with a 12 m heater well spacing. Temperature limited heaters counteract hot spots due to inaccurate well spacing or drilling where heater wells come too close together. In certain embodiments, temperature limited heaters allow for increased power output over time for heater wells that have been spaced too far apart, or limit power output for heater wells that are spaced too close together. Temperature limited heaters also supply more power in regions adjacent the overburden and underburden to compensate for temperature losses in the regions.

Temperature limited heaters may be advantageously used in many types of formations. For example, in tar sands formations or relatively permeable formations containing heavy hydrocarbons, temperature limited heaters may be used to provide a controllable low temperature output for reducing the viscosity of fluids, mobilizing fluids, and/or enhancing the radial flow of fluids at or near the wellbore or in the formation.

Temperature limited heaters may be used to inhibit excess coke formation due to overheating of the near wellbore region of the formation.

The use of temperature limited heaters, in some embodiments, eliminates or reduces the need for expensive temperature control circuitry. For example, the use of temperature limited heaters eliminates or reduces the need to perform temperature logging and/or the need to use fixed thermocouples on the heaters to monitor potential overheating at hot spots.

In some embodiments, temperature limited heaters are more economical to manufacture or make than standard heaters. Typical ferromagnetic materials include iron, carbon steel, or ferritic stainless steel. Such materials are inexpensive as compared to nickel-based heating alloys (such as nichrome, Kanthal™ (Bulten-Kanthal AB, Sweden), and/or LOHM™ (Driver-Harris Company, Harrison, NJ)) typically used in insulated conductor (mineral insulated cable) heaters. In one embodiment of the temperature limited heater, the temperature limited heater is manufactured in continuous lengths as an insulated conductor heater to lower costs and improve reliability.

In certain embodiments, a thermally conductive fluid such as helium may be placed inside the temperature limited heater to improve thermal conduction inside the heater. Thermally conductive fluids include, but are not limited to, gases that are thermally conductive, electrically insulating, and radiantly transparent. In certain embodiments, thermally conductive fluid in the void volumes has a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa). Radiantly transparent gases include gases with diatomic or single atoms that do not absorb a significant amount of infrared energy. In certain embodiments, thermally conductive fluids include helium and/or hydrogen. Thermally conductive fluids may also be thermally stable. For example, thermally conductive fluids may not thermally crack and form unwanted residue.

Thermally conductive fluid may be placed inside a conductor, inside a conduit, and/or inside a jacket of a temperature limited heater. The thermally conductive fluid may be placed in the space (the annulus) between one or more components (for example, conductor, conduit, or jacket) of the temperature limited heater. In some embodiments, thermally conductive fluid is placed in the space (the annulus) between the temperature limited heater and a conduit.

In certain embodiments, air and/or other fluid in the space (the annulus) is displaced by a flow of thermally conductive fluid during introduction of the thermally conductive fluid into the space. In some embodiments, air and/or other fluid is removed (for example, vacuumed, flushed, or pumped out) from the space before introducing thermally conductive fluid in the space. Reducing the partial pressure of air in the space reduces the rate of oxidation of heater components in the space. The thermally conductive fluid is introduced in a specific volume and/or to a selected pressure in the space. Thermally conductive fluid may be introduced such that the space has at least a minimum volume percentage of thermally conductive fluid above a selected value. In certain embodiments, the space has at least 50%, 75%, or 90% by volume of thermally conductive fluid

Placing thermally conductive fluid inside the space of the temperature limited heater increases thermal heat transfer in the space. The increased thermal heat transfer is caused by reducing resistance to heat transfer in the space with the thermally conductive fluid. Reducing resistance to heat transfer in the space allows for increased power output from the temperature limited heater to the subsurface formation. Reducing the resistance to heat transfer inside the space with the thermally conductive fluid allows for smaller diameter electrical conductors (for example, a smaller diameter inner conductor, a smaller diameter outer conductor, and/or a smaller diameter conduit), a larger outer radius (for example, a larger radius of a conduit or a jacket), and/or an increased space width. Reducing the diameter of electrical conductors reduces material costs. Increasing the outer radius of the conduit or the jacket and/or increasing the annulus space width provides additional annular space. Additional annular space may accommodate deformation of the conduit and/or the jacket without causing heater failure. Increasing the outer radius of the conduit or the jacket and/or increasing the annulus width may provide additional annular space to protect components (for example, spacers, connectors, and/or conduits) in the annulus.

As the annular width of the temperature limited heater is increased, however, greater heat transfer is needed across the annular space to maintain good heat output properties for the heater. In some embodiments, especially for low temperature heaters, radiative heat transfer is minimally effective in transferring heat across the annular space of the heater. Conductive heat transfer in the annular space is important in such embodiments to maintain good heat output properties for the heater. A thermally conductive fluid provides increased heat transfer across the annular space.

In certain embodiments, the thermally conductive fluid located in the space is also electrically insulating to inhibit arcing between conductors in the temperature limited heater. Arcing across the space or gap is a problem with longer heaters that require higher operating voltages. Arcing may be a problem with shorter heaters and/or at lower voltages depending on the operating conditions of the heater. Increasing the pressure of the fluid in the space increases the spark gap breakdown voltage in the space and inhibits arcing across the space.

Pressure of thermally conductive fluid in the space may be increased to a pressure between 500 kPa and 50,000 kPa, between 700 kPa and 45,000 kPa, or between 1000 kPa and 40,000 kPa. In an embodiment, the pressure of the thermally conductive fluid is increased to at least 700 kPa or at least 1000 kPa. In certain embodiments, the pressure of the thermally conductive fluid needed to inhibit arcing across the space depends on the temperature in the space. Electrons may track along surfaces (for example, insulators, connectors, or shields) in the space and cause arcing or electrical degradation of the surfaces. High pressure fluid in the space may inhibit electron tracking along surfaces in the space.

The ferromagnetic alloy or ferromagnetic alloys used in the temperature limited heater determine the Curie temperature of the heater. Curie temperature data for various metals is listed in "American Institute of Physics Handbook," Second Edition, McGraw-Hill, pages 5-170 through 5-176. Ferromagnetic conductors may include one or more of the ferromagnetic elements (iron, cobalt, and nickel) and/or alloys of these elements. In some embodiments, ferromagnetic conductors include iron-chromium (Fe-Cr) alloys that contain tungsten (W) (for example, HCM12A and SAVE12 (Sumitomo Metals Co., Japan) and/or iron alloys that contain chromium (for example, Fe-Cr alloys, Fe-Cr-W alloys, Fe-Cr-V (vanadium) alloys, Fe-Cr-Nb (Niobium) alloys). Of the three main ferromagnetic elements, iron has a Curie temperature of approximately 770 °C; cobalt (Co) has a Curie temperature of approximately 1131 °C; and nickel has a Curie temperature of approximately 358 °C. An iron-cobalt alloy has a Curie temperature higher than the Curie temperature of iron. For example, iron-cobalt alloy with 2% by weight cobalt has a Curie temperature of approximately 800 °C; iron-cobalt alloy with 12% by weight cobalt has a Curie temperature of approximately 900 °C; and iron-cobalt alloy with 20% by weight cobalt has a Curie temperature of approximately 950 °C. Iron-nickel alloy has a Curie temperature lower than the Curie temperature of iron. For example, iron-nickel alloy with 20% by weight nickel has a Curie temperature of approximately 720 °C, and iron-nickel alloy with 60% by weight nickel has a Curie temperature of approximately 560 °C.

Some non-ferromagnetic elements used as alloys raise the Curie temperature of iron. For example, an iron-vanadium alloy with 5.9% by weight vanadium has a Curie temperature of approximately 815 °C. Other non-ferromagnetic elements (for example, carbon, aluminum, copper, silicon, and/or chromium) may be alloyed with iron or other ferromagnetic materials to lower the Curie temperature. Non-ferromagnetic materials that raise the Curie temperature may be combined with non-ferromagnetic materials that lower the Curie temperature and alloyed with iron or other ferromagnetic materials to produce a material with a desired Curie temperature and other desired physical and/or chemical properties. In some embodiments, the Curie temperature material is a ferrite such as $NiFe_2O_4$. In other embodiments, the Curie temperature material is a binary compound such as $FeNi_3$ or $Fe_3Al$.

Certain embodiments of temperature limited heaters may include more than one ferromagnetic material. Such embodiments are within the scope of embodiments described herein if any conditions described herein apply to at least one of the ferromagnetic materials in the temperature limited heater.

Magnetic properties generally decay as the Curie temperature is approached. The "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995) shows a typical curve for 1% carbon steel (steel with 1% carbon by weight). The loss of magnetic permeability starts at temperatures above 650 °C and tends to be complete when temperatures exceed 730 °C. Thus, the self-limiting temperature may be somewhat below the actual Curie temperature of the ferromagnetic conductor. The skin depth for current flow in 1% carbon steel is 0.132 cm (centimeters) at room temperature and increases to 0.445 cm at 720 °C. From 720 °C to 730 °C, the skin depth sharply increases to over 2.5 cm. Thus, a temperature limited heater embodiment using 1% carbon steel self-limits between 650 °C and 730 °C.

Skin depth generally defines an effective penetration depth of time-varying current into the conductive material. In general, current density decreases exponentially with distance from an outer surface to the center along the radius of the conductor. The depth at which the current density is approximately 1/*e* of the surface current density is called the skin depth. For a solid cylindrical rod with a diameter much greater than the penetration depth, or for hollow cylinders with a wall thickness exceeding the penetration depth, the skin depth, $\delta$, is:

(1) $\delta = 1981.5 * (\rho/(\mu * f))^{1/2}$;

in which: $\delta$ = skin depth in inches;
$\rho$ = resistivity at operating temperature (ohm-cm);
$\mu$ = relative magnetic permeability; and
f = frequency (Hz).

EQN. 1 is obtained from "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995). For most metals, resistivity ($\rho$) increases with temperature. The relative magnetic permeability generally varies with temperature and with current. Additional equations may be used to assess the variance of magnetic permeability and/or skin depth on both temperature and/or current. The dependence of $\mu$ on current arises from the dependence of $\mu$ on the magnetic field.

Materials used in the temperature limited heater may be selected to provide a desired turndown ratio. Turndown ratios of at least 1.1:1, 2:1, 3:1, 4:1, 5:1, 10:1, 30:1, or 50:1 may be selected for temperature limited heaters. Larger turndown ratios may also be used. The selected turndown ratio depends on a number of factors including, but not limited to, the type of formation in which the temperature limited heater is located and/or a temperature limit of materials used in the wellbore. In some embodiments, the turndown ratio is increased by coupling additional copper or another good electrical conductor to the ferromagnetic material (for example, adding copper to lower the resistance above the Curie temperature).

The temperature limited heater may provide a minimum heat output (power output) below the Curie temperature of the heater. In certain embodiments, the minimum heat output is at least 400 W/m (Watts per meter), 600 W/m, 700 W/m, 800 W/m, or higher up to 2000 W/m. The temperature limited heater reduces the amount of heat output by a section of the heater when the temperature of the section of the heater approaches or is above the Curie temperature. The reduced amount of heat may be substantially less than the heat output below the Curie temperature. In some embodiments, the reduced amount of heat is at most 400 W/m, 200 W/m, 100 W/m or may approach 0 W/m.

In certain embodiments, the temperature limited heater operates substantially independently of the thermal load on the heater in a certain operating temperature range. "Thermal load" is the rate that heat is transferred from a heating system to its surroundings. It is to be understood that the thermal load may vary with temperature of the surroundings and/or the thermal conductivity of the surroundings. In an embodiment, the temperature limited heater operates at or above the Curie temperature of the temperature limited heater such that the operating temperature of the heater increases at most by 3 °C, 2 °C, 1.5 °C, 1 °C, or 0.5 °C for a decrease in thermal load of 1 W/m proximate to a portion of the heater. In certain embodiments, the temperature limited heater operates in such a manner at a relatively constant current.

The AC or modulated DC resistance and/or the heat output of the temperature limited heater may decrease sharply above the Curie temperature due to the Curie effect. In certain embodiments, the value of the electrical resistance or heat output above or near the Curie temperature is at most one-half of the value of electrical resistance or heat output at a certain point below the Curie temperature. In some embodiments, the heat output above or near the Curie temperature is at most 40%, 30%, 20%, 10%, or less (down to 1%) of the heat output at a certain point below the Curie temperature (for example, 30 °C below the Curie temperature, 40 °C below the Curie temperature, 50 °C below the Curie temperature, or 100 °C below the Curie temperature). In certain embodiments, the electrical resistance above or near the Curie temperature decreases to 80%, 70%, 60%, 50%, or less (down to 1%) of the electrical resistance at a certain point below the Curie temperature (for example, 30 °C below the Curie temperature, 40 °C below the Curie temperature, 50 °C below the Curie temperature, or 100 °C below the Curie temperature).

In some embodiments, AC frequency is adjusted to change the skin depth of the ferromagnetic material. For example, the skin depth of 1% carbon steel at room temperature is 0.132 cm at 60 Hz, 0.0762 cm at 180 Hz, and 0.046 cm at 440 Hz. Since heater diameter is typically larger than twice the skin depth, using a higher frequency (and thus a heater with a smaller diameter) reduces heater costs. For a fixed geometry, the higher frequency results in a higher turndown ratio. The turndown ratio at a higher frequency is calculated by multiplying the turndown ratio at a lower frequency by the square root of the higher frequency divided by the lower frequency. In some embodiments, a frequency between 100 Hz and 1000 Hz, between 140 Hz and 200

Hz, or between 400 Hz and 600 Hz is used (for example, 180 Hz, 540 Hz, or 720 Hz). In some embodiments, high frequencies may be used. The frequencies may be greater than 1000 Hz.

To maintain a substantially constant skin depth until the Curie temperature of the temperature limited heater is reached, the heater may be operated at a lower frequency when the heater is cold and operated at a higher frequency when the heater is hot. Line frequency heating is generally favorable, however, because there is less need for expensive components such as power supplies, transformers, or current modulators that alter frequency. Line frequency is the frequency of a general supply of current. Line frequency is typically 60 Hz, but may be 50 Hz or another frequency depending on the source for the supply of the current. Higher frequencies may be produced using commercially available equipment such as solid state variable frequency power supplies. Transformers that convert three-phase power to single-phase power with three times the frequency are commercially available. For example, high voltage three-phase power at 60 Hz may be transformed to single-phase power at 180 Hz and at a lower voltage. Such transformers are less expensive and more energy efficient than solid state variable frequency power supplies. In certain embodiments, transformers that convert three-phase power to single-phase power are used to increase the frequency of power supplied to the temperature limited heater.

In certain embodiments, modulated DC (for example, chopped DC, waveform modulated DC, or cycled DC) may be used for providing electrical power to the temperature limited heater. A DC modulator or DC chopper may be coupled to a DC power supply to provide an output of modulated direct current. In some embodiments, the DC power supply may include means for modulating DC. One example of a DC modulator is a DC-to-DC converter system. DC-to-DC converter systems are generally known in the art. DC is typically modulated or chopped into a desired waveform. Waveforms for DC modulation include, but are not limited to, square-wave, sinusoidal, deformed sinusoidal, deformed square-wave, triangular, and other regular or irregular waveforms.

The modulated DC waveform generally defines the frequency of the modulated DC. Thus, the modulated DC waveform may be selected to provide a desired modulated DC frequency. The shape and/or the rate of modulation (such as the rate of chopping) of the modulated DC waveform may be varied to vary the modulated DC frequency. DC may be modulated at frequencies that are higher than generally available AC frequencies. For example, modulated DC may be provided at frequencies of at least 1000 Hz. Increasing the frequency of supplied current to higher values advantageously increases the turndown ratio of the temperature limited heater.

In certain embodiments, the modulated DC waveform is adjusted or altered to vary the modulated DC frequency. The DC modulator may be able to adjust or alter the modulated DC waveform at any time during use of the temperature limited heater and at high currents or voltages. Thus, modulated DC provided to the temperature limited heater is not limited to a single frequency or even a small set of frequency values. Waveform selection using the DC modulator typically allows for a wide range of modulated DC frequencies and for discrete control of the modulated DC frequency. Thus, the modulated DC frequency is more easily set at a distinct value whereas AC frequency is generally limited to incremental values of the line frequency. Discrete control of the modulated DC frequency allows for more selective control over the turndown ratio of the temperature limited heater. Being able to selectively control the turndown ratio of the temperature limited heater allows for a broader range of materials to be used in designing and constructing the temperature limited heater.

In some embodiments, the modulated DC frequency or the AC frequency is adjusted to compensate for changes in properties (for example, subsurface conditions such as temperature or pressure) of the temperature limited heater during use. The modulated DC frequency or the AC frequency provided to the temperature limited heater is varied based on assessed downhole condition conditions. For example, as the temperature of the temperature limited heater in the wellbore increases, it may be advantageous to increase the frequency of the current provided to the heater, thus increasing the turndown ratio of the heater. In an embodiment, the downhole temperature of the temperature limited heater in the wellbore is assessed.

In certain embodiments, the modulated DC frequency, or the AC frequency, is varied to adjust the turndown ratio of the temperature limited heater. The turndown ratio may be adjusted to compensate for hot spots occurring along a length of the temperature limited heater. For example, the turndown ratio is increased because the temperature limited heater is getting too hot in certain locations. In some embodiments, the modulated DC frequency, or the AC frequency, are varied to adjust a turndown ratio without assessing a subsurface condition.

Temperature limited heaters may generate an inductive load. The inductive load is due to some applied electrical current being used by the ferromagnetic material to generate a magnetic field in addition to generating a resistive heat output. As downhole temperature changes in the temperature limited heater, the inductive load of the heater changes due to changes in the magnetic properties of ferromagnetic materials in the heater with temperature. The inductive load of the temperature limited heater may cause a phase shift between the current and the voltage applied to the heater.

A reduction in actual power applied to the temperature limited heater may be caused by a time lag in the current waveform (for example, the current has a phase shift relative to the voltage due to an inductive load) and/or by distortions in the current waveform (for example, distortions in the current waveform caused by introduced harmonics due to a non-linear load). Thus, it may take more current to apply a selected amount of power due to phase shifting or waveform distortion. The ratio of actual power applied and the apparent power that would have been transmitted if the same current were in phase and undistorted is the power factor. The power factor is always less than or equal to 1. The power factor is 1 when there is no phase shift or distortion in the waveform.

Actual power applied to a heater due to a phase shift is described by EQN. 2:

$$(2)\qquad P = I \times V \times \cos(\theta);$$

in which P is the actual power applied to the temperature limited heater; I is the applied current; V is the applied voltage; and $\theta$ is the phase angle difference between voltage and current. If there is no distortion in the waveform, then $\cos(\theta)$ is equal to the power factor. At higher frequencies (for example, modulated DC frequencies at least 1000 Hz, 1500 Hz, or 2000 Hz), the problem with phase shifting and/or distortion is more pronounced.

In some embodiments, electrical voltage and/or electrical current is adjusted to change the skin depth of the ferromagnetic material. Increasing the voltage and/or decreasing the current may decrease the skin depth of the ferromagnetic material. A smaller skin depth allows the temperature limited heater with a smaller diameter to be used, thereby reducing equipment costs. In certain embodiments, the applied current is at least 1 amp, 10 amps, 70 amps, 100 amps, 200 amps, 500 amps, or greater up to 2000 amps. In some embodiments, current is supplied at voltages above 200 volts, above 480 volts, above 650 volts, above 1000 volts, above 1500 volts, or higher up to 10000 volts.

In an embodiment, the temperature limited heater includes an inner conductor inside an outer conductor. The inner conductor and the outer conductor are radially disposed about a central axis. The inner and outer conductors may be separated by an insulation layer. In certain embodiments, the inner and outer conductors are coupled at the bottom of the temperature limited heater. Electrical current may flow into the temperature limited heater through the inner conductor and return through the outer conductor. One or both conductors may include ferromagnetic material.

The insulation layer may comprise an electrically insulating ceramic with high thermal conductivity, such as magnesium oxide, aluminum oxide, silicon dioxide, beryllium oxide, boron nitride, silicon nitride, or combinations thereof. The insulating layer may be a compacted powder (for example, compacted ceramic powder). Compaction may improve thermal conductivity and provide better insulation resistance. For lower temperature applications, polymer insulation made from, for example, fluoropolymers, polyimides, polyamides, and/or polyethylenes, may be used. In some embodiments, the polymer insulation is made of perfluoroalkoxy (PFA) or polyetheretherketone (PEEK™ (Victrex Ltd, England)). The insulating layer may be chosen to be substantially infrared transparent to aid heat transfer from the inner conductor to the outer conductor. In an embodiment, the insulating layer is transparent quartz sand. The insulation layer may be air or a non-reactive gas such as helium, nitrogen, or sulfur hexafluoride. If the insulation layer is air or a non-reactive gas, there may be insulating spacers designed to inhibit electrical contact between the inner conductor and the outer conductor. The insulating spacers may be made of, for example, high purity aluminum oxide or another thermally conducting, electrically insulating material such as silicon nitride. The insulating spacers may be a fibrous ceramic material such as Nextel™ 312 (3M Corporation, St. Paul, Minnesota), mica tape, or glass fiber. Ceramic material may be made of alumina, alumina-silicate, alumina-borosilicate, silicon nitride, boron nitride, or other materials.

In certain embodiments, the outer conductor is chosen for corrosion and/or creep resistance. In one embodiment, austentitic (non-ferromagnetic) stainless steels such as 304H, 347H, 347HH, 316H, 310H, 347HP, NF709 (Nippon Steel Corp., Japan) stainless steels, or combinations thereof may be used in the outer conductor. The outer conductor may also include a clad conductor. For example, a corrosion resistant alloy such as 800H or 347H stainless steel may be clad for corrosion protection over a ferromagnetic carbon steel tubular. If high temperature strength is not required, the outer conductor may be constructed from the ferromagnetic metal with good corrosion resistance such as one of the ferritic stainless steels. In one embodiment, a ferritic alloy of 82.3% by weight iron with 17.7% by weight chromium (Curie temperature of 678 °C) provides desired corrosion resistance.

The Metals Handbook, vol. 8, page 291 (American Society of Materials (ASM)) includes a graph of Curie temperature of iron-chromium alloys versus the amount of chromium in the alloys. In some temperature limited heater embodiments, a separate support rod or tubular (made from 347H stainless steel) is coupled to the temperature limited heater made from an iron-chromium alloy to provide strength and/or creep resistance. The support material and/or the ferromagnetic material may be selected to provide a 100,000 hour creep-rupture strength of at least 20.7 MPa at 650 °C. In some embodiments, the 100,000 hour creep-rupture strength is at least 13.8 MPa at 650 °C or at least 6.9 MPa at 650 °C. For example, 347H steel has a favorable creep-rupture strength at or above 650°C. In some embodiments, the 100,000 hour creep-rupture strength ranges from 6.9 MPa to 41.3 MPa or more for longer heaters and/or higher earth or fluid stresses.

In temperature limited heater embodiments with the inner ferromagnetic conductor and the outer ferromagnetic conductor, the skin effect current path occurs on the outside of the inner conductor and on the inside of the outer conductor. Thus, the outside of the outer conductor may be clad with the corrosion resistant alloy, such as stainless steel, without affecting the skin effect current path on the inside of the outer conductor.

A ferromagnetic conductor with a thickness at least the skin depth at the Curie temperature allows a substantial decrease in resistance of the ferromagnetic material as the skin depth increases sharply near the Curie temperature. In certain embodiments when the ferromagnetic conductor is not clad with a highly conducting material such as copper, the thickness of the conductor may be 1.5 times the skin depth near the Curie temperature, 3 times the skin depth near the Curie temperature, or even 10 or more times the skin depth near the Curie temperature. If the ferromagnetic conductor is clad with copper, thickness of the ferromagnetic conductor may be substantially the same as the skin depth near the Curie temperature. In some embodiments, the ferromagnetic conductor clad with copper has a thickness of at least three-fourths of the skin depth near the Curie temperature.

In certain embodiments, the temperature limited heater includes a composite conductor with a ferromagnetic tubular and a non-ferromagnetic, high electrical conductivity core. The non-ferromagnetic, high electrical conductivity core reduces a required diameter of the conductor. For example, the conductor may be composite 1.19 cm diameter conductor with a core of 0.575 cm diameter copper clad with a 0.298 cm thickness of ferritic stainless steel or carbon steel surrounding the core. A composite conductor allows the electrical resistance of the temperature limited heater to decrease more steeply near the Curie temperature. As the skin depth increases near the Curie temperature to include the copper core, the electrical resistance decreases very sharply.

The composite conductor may increase the conductivity of the temperature limited heater and/or allow the heater to operate at lower voltages. In an embodiment, the composite conductor exhibits a relatively flat resistance versus temperature profile at temperatures below a region near the Curie temperature of the ferromagnetic conductor of the composite conductor. In some embodiments, the temperature limited heater exhibits a relatively flat resistance versus temperature profile between 100 °C and 750 °C or between 300 °C and 600 °C. The relatively flat resistance versus temperature profile may also be exhibited in other temperature ranges by adjusting, for example, materials and/or the configuration of materials in the temperature limited heater. In certain embodiments, the relative thickness of each material in the composite conductor is selected to produce a desired resistivity versus temperature profile for the temperature limited heater.

FIGS. 3-28 depict various embodiments of temperature limited heaters. One or more features of an embodiment of the temperature limited heater depicted in any of these figures may be combined with one or more features of other embodiments of temperature limited heaters depicted in these figures. In certain embodiments described herein, temperature limited heaters are dimensioned to operate at a frequency of 60 Hz AC. It is to be understood that dimensions of the temperature limited heater may be adjusted from those described herein in order for the temperature limited heater to operate in a similar manner at other AC frequencies or with modulated DC.

FIG. 3 depicts a cross-sectional representation of an embodiment of the temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section. FIGS. 4 and 5 depict transverse cross-sectional views of the embodiment shown in FIG. 3. In one embodiment, ferromagnetic section 140 is used to provide heat to hydrocarbon layers in the formation. Non-ferromagnetic section 142 is used in the overburden of the formation. Non-ferromagnetic section 142 provides little or no heat to the overburden, thus inhibiting heat losses in the overburden and improving heater efficiency. Ferromagnetic section 140 includes a ferromagnetic material such as 409 stainless steel or 410 stainless steel. Ferromagnetic section 140 has a thickness of 0.3 cm. Non-ferromagnetic section 142 is copper with a thickness of 0.3 cm. Inner conductor 144 is copper. Inner conductor 144 has a diameter of 0.9 cm. Electrical insulator 146 is silicon nitride, boron nitride, magnesium oxide powder, or another suitable insulator material. Electrical insulator 146 has a thickness of 0.1 cm to 0.3 cm.

FIG. 6 depicts a cross-sectional representation of an embodiment of a temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section placed inside a sheath. FIGS. 7, 8, and 9 depict transverse cross-sectional views of the embodiment shown in FIG. 6. Ferromagnetic section 140 is 410 stainless steel with a thickness of 0.6 cm. Non-ferromagnetic section 142 is copper with a thickness of 0.6 cm. Inner conductor 144 is copper with a diameter of 0.9 cm. Outer conductor 148 includes ferromagnetic material. Outer conductor 148 provides some heat in the overburden section of the heater. Providing some heat in the overburden inhibits condensation or refluxing of fluids in the overburden. Outer conductor 148 is 409, 410, or 446 stainless steel with an outer diameter of 3.0 cm and a thickness of 0.6 cm. Electrical insulator 146 is magnesium oxide powder with a thickness of 0.3 cm. In some embodiments, electrical insulator 146 is silicon nitride, boron nitride, or hexagonal type boron nitride. Conductive section 150 may couple inner conductor 144 with ferromagnetic section 140 and/or outer conductor 148.

FIG. 10 depicts a cross-sectional representation of an embodiment of a temperature limited heater with a ferromagnetic outer conductor. The heater is placed in a corrosion resistant jacket. A conductive layer is placed between the outer conductor and the jacket. FIGS. 11 and 12 depict transverse cross-sectional views of the embodiment shown in FIG. 10. Outer conductor 148 is a ¾" Schedule 80 446 stainless steel pipe. In an embodiment, conductive layer 152 is placed between outer conductor 148 and jacket 154. Conductive layer 152 is a copper layer. Outer conductor 148 is clad with conductive layer 152. In certain embodiments, conductive layer 152 includes one or more segments (for example, conductive layer 152 includes one or more copper tube segments). Jacket 154 is a 1-¼" Schedule 80 347H stainless steel pipe or a 1-½" Schedule 160 347H stainless steel pipe. In an embodiment, inner conductor 144 is 4/0 MGT-1000 furnace cable with stranded nickel-coated copper wire with layers of mica tape and glass fiber insulation. 4/0 MGT-1000 furnace cable is UL type 5107 (available from Allied Wire and Cable (Phoenixville, Pennsylvania)). Conductive section 150 couples inner conductor 144 and jacket 154. In an embodiment, conductive section 150 is copper.

FIG. 13 depicts a cross-sectional representation of an embodiment of a temperature limited heater with an outer conductor. The outer conductor includes a ferromagnetic section and a non-ferromagnetic section. The heater is placed in a corrosion resistant jacket. A conductive layer is placed between the outer conductor and the jacket. FIGS. 14 and 15 depict transverse cross-sectional views of the embodiment shown in FIG. 13. Ferromagnetic section 140 is 409, 410, or 446 stainless steel with a thickness of 0.9 cm. Non-ferromagnetic section 142 is copper with a thickness of 0.9 cm. Ferromagnetic section 140 and non-ferromagnetic section 142 are placed in jacket 154. Jacket 154 is 304 stainless steel with a thickness of 0.1 cm. Conductive layer 152 is a copper layer. Electrical insulator 146 is silicon nitride, boron nitride, or magnesium oxide with a thickness of 0.1 to 0.3 cm. Inner conductor 144 is copper with a diameter of 1.0 cm.

In an embodiment, ferromagnetic section 140 is 446 stainless steel with a thickness of 0.9 cm. Jacket 154 is 410 stainless steel with a thickness of 0.6 cm. 410 stainless steel has a higher Curie temperature than 446 stainless steel. Such a temperature limited heater may "contain" current such that the current does not easily flow from the heater to the surrounding formation and/or to any surrounding water (for example, brine, groundwater, or formation water). In this embodiment, a majority of the current flows through ferromagnetic section 140 until the Curie temperature of the ferromagnetic section is reached. After the Curie temperature of ferromagnetic section 140 is reached, a majority of the current flows through conductive layer 152. The ferromagnetic properties of jacket 154 (410 stainless steel) inhibit the current from flowing outside the jacket and "contain" the current. Jacket 154 may also have a thickness that provides strength to the temperature limited heater.

FIG. 16A and FIG. 16B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic inner conductor. Inner conductor 144 is a 1" Schedule XXS 446 stainless steel pipe. In some embodiments, inner conductor 144 includes 409 stainless steel, 410 stainless steel, Invar 36, alloy 42-6, alloy 52, or other ferromagnetic materials. Inner conductor 144 has a diameter of 2.5 cm. Electrical insulator 146 is silicon nitride, boron nitride, magnesium oxide, polymers, Nextel ceramic fiber, mica, or glass fibers. Outer conductor 148 is copper or any other non-ferromagnetic material such as aluminum. Outer conductor 148 is coupled to jacket 154. Jacket 154 is 304H, 316H, or 347H stainless steel. In this embodiment, a majority of the heat is produced in inner conductor 144.

FIG. 17A and FIG. 17B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic inner conductor and a non-ferromagnetic core. Inner conductor 144 includes 446 stainless steel, 409 stainless steel, 410 stainless steel or other ferromagnetic materials. Core 168 is tightly bonded inside inner conductor 144. Core 168 is a rod of copper or other non-ferromagnetic material. Core 168 is inserted as a tight fit inside inner conductor 144 before a drawing operation. In some embodiments, core 168 and inner conductor 144 are coextrusion bonded. Outer conductor 148 is 347H stainless steel. A drawing or rolling operation to compact electrical insulator 146 may ensure good electrical contact between inner conductor 144 and core 168. In this embodiment, heat is produced primarily in inner conductor 144 until the Curie temperature is approached. Resistance then decreases sharply as current penetrates core 168.

FIG. 18A and FIG. 18B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor. Inner conductor 144 is nickel-clad copper. Electrical insulator 146 is silicon nitride, boron nitride, or magnesium oxide. Outer conductor 148 is a 1" Schedule XXS carbon steel pipe. In this embodiment, heat is produced primarily in outer conductor 148, resulting in a small temperature differential across electrical insulator 146.

FIG. 19A and FIG. 19B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor that is clad with a corrosion resistant alloy. Inner conductor 144 is copper. Outer conductor 148 is a 1" Schedule XXS 446 stainless steel pipe. Outer conductor 148 is coupled to jacket 154. Jacket 154 is made of corrosion resistant material (for example, 347H stainless steel). Jacket 154 provides protection from corrosive fluids in the wellbore (for example, sulfidizing and carburizing gases). Heat is produced primarily in outer conductor 148, resulting in a small temperature differential across electrical insulator 146.

FIG. 20A and FIG. 20B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic outer conductor. The outer conductor is clad with a conductive layer and a corrosion resistant alloy. Inner conductor 144 is copper. Electrical insulator 146 is silicon nitride, boron nitride, or magnesium oxide. Outer conductor 148 is a 1" Schedule 80 446 stainless steel pipe. Outer conductor 148 is coupled to jacket 154. Jacket 154 is made from corrosion resistant material. In an embodiment, conductive layer 152 is placed between outer conductor 148 and jacket 154. Conductive layer 152 is a copper layer. Heat is produced primarily in outer conductor 148, resulting in a small temperature differential across electrical insulator 146. Conductive layer 152 allows a sharp decrease in the resistance of outer conductor 148 as the outer conductor approaches the Curie temperature. Jacket 154 provides protection from corrosive fluids in the wellbore.

In some embodiments, the conductor (for example, an inner conductor, an outer conductor, or a ferromagnetic conductor) is the composite conductor that includes two or more different materials. In certain embodiments, the composite conductor includes two or more ferromagnetic materials. In some embodiments, the composite ferromagnetic conductor includes two or more radially disposed materials. In certain embodiments, the composite conductor includes a ferromagnetic conductor and a non-ferromagnetic conductor. In some embodiments, the composite conductor includes the ferromagnetic conductor placed over a non-ferromagnetic core. Two or more materials may be used to obtain a relatively flat electrical resistivity versus temperature profile in a temperature region below the Curie temperature and/or a sharp decrease (a high turndown ratio) in the electrical resistivity at or near the Curie temperature. In some cases, two or more materials are used to provide more than one Curie temperature for the temperature limited heater.

The composite electrical conductor may be used as the conductor in any electrical heater embodiment described herein. For example, the composite conductor may be used as the conductor in a conductor-in-conduit heater or an insulated conductor heater. In certain embodiments, the composite conductor may be coupled to a support member such as a support conductor. The support member may be used to provide support to the composite conductor so that the composite conductor is not relied upon for strength at or near the Curie temperature. The support member may be useful for heaters of lengths of at least 100 m. The support member may be a non-ferromagnetic member that has good high temperature creep strength. Examples of materials that are used for a support member include, but are not limited to, Haynes® 625 alloy and Haynes® HR120® alloy (Haynes International, Kokomo, IN), NF709, Incoloy® 800H alloy and 347H alloy (Allegheny Ludlum Corp., Pittsburgh, PA). In some embodiments, materials in a composite conductor are directly coupled (for example, brazed, metallurgically bonded, or swaged) to each other and/or the support member. Using a support member may decouple the ferromagnetic member from having to provide support for the temperature limited heater, especially at or near the Curie temperature. Thus, the temperature limited heater may be designed with more flexibility in the selection of ferromagnetic materials.

FIG. 21 depicts a cross-sectional representation of an embodiment of the composite conductor with the support member. Core 168 is surrounded by ferromagnetic conductor 166 and support member 172. In some embodiments, core 168, ferromagnetic conductor 166, and support member 172 are directly coupled (for example, brazed together or metallurgically bonded together). In one embodiment, core 168 is copper, ferromagnetic conductor 166 is 446 stainless steel, and support member 172 is 347H alloy. In certain embodiments, support member 172 is a Schedule 80 pipe. Support member 172 surrounds the composite conductor having ferromagnetic conductor 166 and core 168. Ferromagnetic conductor 166 and core 168 are joined to form the composite conductor by, for example, a coextrusion process. For example, the composite conductor is a 1.9 cm outside diameter 446 stainless steel ferromagnetic conductor surrounding a 0.95 cm diameter copper core. This composite conductor inside a 1.9 cm Schedule 80 support member produces a turndown ratio of 1.7.

In certain embodiments, the diameter of core 168 is adjusted relative to a constant outside diameter of ferromagnetic conductor 166 to adjust the turndown ratio of the temperature limited heater. For example, the diameter of core 168 may be increased to 1.14 cm while maintaining the outside diameter of ferromagnetic conductor 166 at 1.9 cm to increase the turndown ratio of the heater to 2.2.

In some embodiments, conductors (for example, core 168 and ferromagnetic conductor 166) in the composite conductor are separated by support member 172. FIG. 22 depicts a cross-sectional representation of an embodiment of the composite conductor with support member 172 separating the conductors. In one embodiment, core 168 is copper with a diameter of 0.95 cm, support member 172 is 347H alloy with an outside diameter of 1.9 cm, and ferromagnetic conductor 166 is 446 stainless steel with an outside diameter of 2.7 cm. Such a conductor produces a turndown ratio of at least 3. The support member depicted in FIG. 22 has a higher creep strength relative to other support members depicted in FIGS. 21, 23, and 24.

In certain embodiments, support member 172 is located inside the composite conductor. FIG. 23 depicts a cross-sectional representation of an embodiment of the composite conductor surrounding support member 172. Support member 172 is made of 347H alloy. Inner conductor 144 is copper. Ferromagnetic conductor 166 is 446 stainless steel. In one embodiment, support member 172 is 1.25 cm diameter 347H alloy, inner conductor 144 is 1.9 cm outside diameter copper, and ferromagnetic conductor 166 is 2.7 cm outside diameter 446 stainless steel. Such a conductor produces a turndown ratio larger than 3, and the turndown ratio is higher than the turndown ratio for the embodiments depicted in FIGS. 21, 22, and 24 for the same outside diameter.

In some embodiments, the thickness of inner conductor 144, which is copper, is reduced to reduce the turndown ratio. For example, the diameter of support member 172 is increased to 1.6 cm while maintaining the outside diameter of inner conductor 144 at 1.9 cm to reduce the thickness of the conduit. This reduction in thickness of inner conductor 144 results in a decreased turndown ratio relative to the thicker inner conductor embodiment. The turndown ratio, however, remains at least 3.

In one embodiment, support member 172 is a conduit (or pipe) inside inner conductor 144 and ferromagnetic conductor 166. FIG. 24 depicts a cross-sectional representation of an embodiment of the composite conductor surrounding support member 172. In one embodiment, support member 172 is 347H alloy with a 0.63 cm diameter center hole. In some embodiments, support member 172 is a preformed conduit. In certain embodiments, support member 172 is formed by having a dissolvable material (for example, copper dissolvable by nitric acid) located inside the support member during formation of the composite conductor. The dissolvable material is dissolved to form the hole after the conductor is assembled. In an embodiment, support member 172 is 347H alloy with an inside diameter of 0.63 cm and an outside diameter of 1.6 cm, inner conductor 144 is copper with an outside diameter of 1.8 cm, and ferromagnetic conductor 166 is 446 stainless steel with an outside diameter of 2.7 cm.

In certain embodiments, the composite electrical conductor is used as the conductor in the conductor-in-conduit heater. For example, the composite electrical conductor may be used as conductor 174 in FIG. 25.

FIG. 25 depicts a cross-sectional representation of an embodiment of the conductor-in-conduit heater. Conductor 174 is disposed in conduit 176. Conductor 174 is a rod or conduit of electrically conductive material. Low resistance sections 178 is present at both ends of conductor 174 to generate less heating in these sections. Low resistance section 178 is formed by having a greater cross-sectional area of conductor 174 in that section, or the sections are made of material having less resistance. In certain embodiments, low resistance section 178 includes a low resistance conductor coupled to conductor 174.

Conduit 176 is made of an electrically conductive material. Conduit 176 is disposed in opening 180 in hydrocarbon layer 182. Opening 180 has a diameter that accommodates conduit 176.

Conductor 174 may be centered in conduit 176 by centralizers 184. Centralizers 184 electrically isolate conductor 174 from conduit 176. Centralizers 184 inhibit movement and properly locate conductor 174 in conduit 176. Centralizers 184 are made of ceramic material or a combination of ceramic and metallic materials. Centralizers 184 inhibit deformation of conductor 174 in conduit 176. Centralizers 184 are touching or spaced at intervals between approximately 0.1 m (meters) and approximately 3 m or more along conductor 174.

A second low resistance section 178 of conductor 174 may couple conductor 174 to wellhead 112, as depicted in FIG. 25. Electrical current may be applied to conductor 174 from power cable 186 through low resistance section 178 of conductor 174. Electrical current passes from conductor 174 through sliding connector 188 to conduit 176. Conduit 176 may be electrically insulated from overburden casing 190 and from wellhead 112 to return electrical current to power cable 186. Heat may be generated in conductor 174 and conduit 176. The generated heat may radiate in conduit 176 and opening 180 to heat at least a portion of hydrocarbon layer 182.

Overburden casing 190 may be disposed in overburden 192. Overburden casing 190 is, in some embodiments, surrounded by materials (for example, reinforcing material and/or cement) that inhibit heating of overburden 192. Low resistance section 178 of conductor 174 may be placed in overburden casing 190. Low resistance section 178 of conductor 174 is made of, for example, carbon steel. Low resistance section 178 of conductor 174 may be centralized in overburden casing 190 using centralizers 184. Centralizers 184 are spaced at intervals of approximately 6 m to approximately 12 m or, for example, approximately 9 m along low resistance section 178 of conductor 174. In a heater embodiment, low resistance section 178 of conductor 174 is coupled to conductor 174 by one or more welds. In other heater embodiments, low resistance sections are threaded, threaded and welded, or otherwise coupled to the conductor. Low resistance section 178 generates little and/or no heat in overburden casing 190. Packing 194 may be placed between overburden casing 190 and opening 180. Packing 194 may be used as a cap at the junction of overburden 192 and hydrocarbon layer 182 to allow filling of materials in the annulus between overburden casing 190 and opening 180. In some embodiments, packing 194 inhibits fluid from flowing from opening 180 to surface 196.

In certain embodiments, the composite electrical conductor may be used as a conductor in an insulated conductor heater. FIG. 26A and FIG. 26B depict an embodiment of the insulated conductor heater. Insulated conductor 200 includes core 168 and inner conductor 144. Core 168 and inner conductor 144 are a composite electrical conductor. Core 168 and inner conductor 144 are located within insulator 146. Core 168, inner conductor 144, and insulator 146 are located inside outer conductor 148. Insulator 146 is silicon nitride, boron nitride, magnesium oxide, or another suitable electrical insulator. Outer conductor 148 is copper, steel, or any other electrical conductor.

In some embodiments, jacket 154 is located outside outer conductor 148, as shown in FIG. 27A and FIG. 27B. In some embodiments, jacket 154 is 304 stainless steel and outer conductor 148 is copper. Jacket 154 provides corrosion resistance for the insulated conductor heater. In some embodiments, jacket 154 and outer conductor 148 are preformed strips that are drawn over insulator 146 to form insulated conductor 200.

In certain embodiments, insulated conductor 200 is located in a conduit that provides protection (for example, corrosion and degradation protection) for the insulated conductor. In FIG. 28, insulated conductor 200 is located inside conduit 176 with gap 202 separating the insulated conductor from the conduit.

In some embodiments, the temperature limited heater is used to achieve lower temperature heating (for example, for heating fluids in a production well, heating a surface pipeline, or reducing the viscosity of fluids in a wellbore or near wellbore region). Varying the ferromagnetic materials of the temperature limited heater allows for lower temperature heating. In some embodiments, the ferromagnetic conductor is made of material with a lower Curie temperature than that of 446 stainless steel. For example, the ferromagnetic conductor may be an alloy of iron and nickel. The alloy may have between 30% by weight and 42% by weight nickel with the rest being iron. In one embodiment, the alloy is Invar 36. Invar 36 is 36% by weight nickel in iron and has a Curie temperature of 277 °C. In some embodiments, an alloy is a three component alloy with, for example, chromium, nickel, and iron. For example, an alloy may have 6% by weight chromium, 42% by weight nickel, and 52% by weight iron. The ferromagnetic conductor made of these types of alloys provides a heat output between 250 watts per meter and 350 watts per meter. A 2.5 cm diameter rod of Invar 36 has a turndown ratio of approximately 2 to 1 at the Curie temperature. Placing the Invar 36 alloy over a copper core may allow for a smaller rod diameter. A copper core may result in a high turndown ratio.

For temperature limited heaters that include a copper core or copper cladding, the copper may be protected with a relatively diffusion-resistant layer such as nickel. In some embodiments, the composite inner conductor includes iron clad over nickel clad over a copper core. The relatively diffusion-resistant layer inhibits migration of copper into other layers of the heater including, for example, an insulation layer. In some embodiments, the relatively impermeable layer inhibits deposition of copper in a wellbore during installation of the heater into the wellbore.

The temperature limited heater may be a single-phase heater or a three-phase heater. In a three-phase heater embodiment, the temperature limited heater has a delta or a wye configuration. Each of the three ferromagnetic conductors in the three-phase heater may be inside a separate sheath. A connection between conductors may be made at the bottom of the heater inside a splice section. The three conductors may remain insulated from the sheath inside the splice section.

In some three-phase heater embodiments, three ferromagnetic conductors are separated by insulation inside a common outer metal sheath. The three conductors may be insulated from the sheath or the three conductors may be connected to the sheath at the bottom of the heater assembly. In another embodiment, a single outer sheath or three outer sheaths are ferromagnetic conductors and the inner conductors may be non-ferromagnetic (for example, aluminum, copper, or a highly conductive alloy). Alternatively, each of the three non-ferromagnetic conductors are inside a separate ferromagnetic sheath, and a connection between the conductors is made at the bottom of the heater inside a splice section. The three conductors may remain insulated from the sheath inside the splice section.

In some embodiments, the three-phase heater includes three legs that are located in separate wellbores. The legs may be coupled in a common contacting section (for example, a central wellbore, a connecting wellbore, or an solution filled contacting section).

In an embodiment, the temperature limited heater includes a hollow core or hollow inner conductor. Layers forming the heater may be perforated to allow fluids from the wellbore (for example, formation fluids or water) to enter the hollow core. Fluids in the hollow core may be transported (for example, pumped or gas lifted) to the surface through the hollow core. In some embodiments, the temperature limited heater with the hollow core or the hollow inner conductor is used as a heater/production well or a production well. Fluids such as steam may be injected into the formation through the hollow inner conductor.

## EXAMPLES

Non-restrictive examples of temperature limited heaters and properties of temperature limited heaters are set forth below.

Calculations may be made to determine the effect of a thermally conductive fluid in an annulus of a temperature limited heater. The equations below (EQNS. 3-13) are used to relate a heater center rod temperature in a heated section to a conduit temperature adjacent to the heater center rod. In this example, the heater center rod is a 347H stainless steel tube with outer radius *b*. The conduit is made of 347 H stainless steel and has inner radius R. The center heater rod and the conduit are at uniform temperatures $T_H$ and $T_C$, respectively. $T_C$ is maintained constant and a constant heat rate, *Q*, per unit length is supplied to the center heater rod. $T_H$ is the value at which the rate of heat per unit length transferred to the conduit by conduction and radiation balances the rate of heat generated, *Q*. Conduction across a gap between the center heater rod and inner surface of the conduit is assumed to take place in parallel with radiation across the gap. For simplicity, radiation across the gap is assumed to be radiation across a vacuum. The equations are thus:

$$(3)\ Q = Q_C + Q_R;$$

where $Q_C$ and $Q_R$ represent the conductive and radiative components of the heat flux across the gap. Denoting the inner radius of the conduit by *R*, conductive heat transport satisfies the equation:

$$(4)\ Q_C = -2\pi r k_g \frac{dT}{dr};\ b \le r \le R;$$

subject to the boundary conditions:

$$(5)\ T(b) = T_H; T(R) = T_C.$$

The thermal conductivity of the gas in the gap, $k_g$, is well described by the equation:

$$(6)\ k_g = a_g + b_g T$$

Substituting EQN. 6 into EQN. 4 and integrating subject to the boundary conditions in EQN. 5 gives:

$$(7)\ \frac{Q_C}{2\pi}\ln(R/b) = k_g^{(eff)}(T_H - T_C);$$

with (8) $k_g^{(eff)} = a_g + \tfrac{1}{2} b_g (T_H + T_C)$.

The rate of radiative heat transport across the gap per unit length, $Q_R$, is given by:

$$(9)\ Q_R = 2\pi\sigma b \varepsilon_R \varepsilon_{bR} \{T_H{}^4 - T_C{}^4\};$$

where (10) $\varepsilon_{bR} = \varepsilon_b / \{\varepsilon_R + (b/R)\varepsilon_b(1-\varepsilon_R)\}$.

In EQNS. 9 and 10, $\varepsilon_b$ and $\varepsilon_R$ denote the emissivities of the center heater rod and inner surface of the conduit, respectively, and $\sigma$ is the Stefan-Boltzmann constant.

Substituting EQNS. 7 and 9 back into EQN. 3, and rearranging gives:

$$(11)\ \frac{Q}{2\pi} = \frac{k_g^{eff}(T_H - T_C)}{\ln(R/b)} + \sigma b \varepsilon_R \varepsilon_{bR} \{T_H{}^4 - T_C{}^4\}.$$

To solve EQN. 11, $t$ is denoted as the ratio of radiative to conductive heat flux across the gap:

$$(12)\ t = \frac{\sigma b \varepsilon_R \varepsilon_{bR} \{T_H{}^2 + T_C{}^2\}(T_H + T_C)\ln(R/b)}{k_g^{eff}}.$$

Then EQN. 11 is written in the form:

$$(13)\ \frac{Q}{2\pi} = \frac{k_g^{eff}(T_H - T_C)}{\ln(R/b)}\{1 + t\}.$$

EQNS. 13 and 11 are solved iteratively for $T_H$ given $Q$ and $T_C$. The numerical values of the parameters $\sigma$, $a_g$, and $b_g$ are given in TABLE 1. A list of heater dimensions are given in TABLE 2. The emissivities $\epsilon_S$ and $\epsilon_a$ may be taken to be in the range 0.4-0.8.

TABLE 1

*Material Parameters Used in the Calculations*

| Parameter | $\sigma$ | $a_g$ (air) | $b_g$ (air) | $a_g$ (He) | $b_g$ (He) |
|---|---|---|---|---|---|
| Unit | $Wm^{-2}K^{-4}$ | $Wm^{-1}K^{-1}$ | $Wm^{-1}K^{-2}$ | $Wm^{-1}K^{-1}$ | $Wm^{-1}K^{-2}$ |
| Value | $5.67\times10^{-8}$ | 0.01274 | $5.493 \times 10^{-5}$ | 0.07522 | $2.741\times10^{-4}$ |

TABLE 2

*Set of Heater Dimensions*

| Dimension | Inches | Meters |
|---|---|---|
| Heater rod outer radius $b$ | ½ × 0.75 | $9.525 \times 10^{-3}$ |
| Conduit inner radius $R$ | ½ × 1.771 | $2.249 \times 10^{-2}$ |

FIG. 29 shows heater rod temperature (°C) as a function of the power (W/m) generated within the heater rod for a base case in which both the heater rod and conduit emissivities were 0.8, and a low emissivity case in which the heater rod emissivity was lowered to 0.4. The conduit temperature was set at 260 °C. Cases in which the annular space is filled with air and with helium are compared in FIG. 29. Plot 204 is for the base case in air. Plot 206 is for the base case in helium. Plot 208 is for the low emissivity case in air. Plot 210 is for the low emissivity case in helium. FIGS. 30-36 repeat the same cases for conduit temperatures of 315 °C to 649

°C inclusive, with incremental steps of 55 °C in each figure. Note that the temperature scale in FIGS. 34-36 is offset by 111 °C with respect to the scale in FIGS. 29-33. FIGS. 29-36 show that helium in the annular space, which has a higher thermal conductivity than air, reduces the rod temperature for similar power generation.

FIG. 37 shows a plot of center heater rod (with 0.8 emissivity) temperature (vertical axis) versus conduit temperature (horizontal axis) for various heater powers with air or helium in the annulus. FIG. 38 shows a plot of center heater rod (with 0.4 emissivity) temperature (vertical axis) versus conduit temperature (horizontal axis) for various heater powers with air or helium in the annulus. Plots 212 are for air and a heater power of 500 W/m. Plots 214 are for air and a heater power of 833 W/m. Plots 216 are for air and a heater power of 1167 W/m. Plots 218 are for helium and a heater power of 500 W/m. Plots 220 are for helium and a heater power of 833 W/m. Plots 222 are for helium and a heater power of 1167 W/m. FIGS. 37-38 show that helium in the annular space, as compared to air in the annulus, reduces temperature difference between the heater and the canister.

FIG. 39 depicts spark gap breakdown voltages (V) versus pressure (atm) at different temperatures for a conductor-in-conduit heater with air in the annulus. FIG. 40 depicts spark gap breakdown voltages (V) versus pressure (atm) at different temperatures for a conductor-in-conduit heater with helium in the annulus. FIGS. 39 and 40 show breakdown voltages for a conductor-in-conduit heater with a 2.5 cm diameter center conductor and a 7.6 cm gap to the inner radius of the conduit. Plot 224 is for a temperature of 300 K. Plot 226 is for a temperature of 700 K. Plot 228 is for a temperature of 1050 K. 480 V RMS is shown as a typical applied voltage. FIGS. 39 and 40 show that helium has a spark gap breakdown voltage smaller than the spark gap breakdown voltage for air at 1 atm. Thus, the pressure of helium may need to be increased to achieve spark gap breakdown voltages on the order of breakdown voltages for air.

FIGS. 41-43 depict experimental data for temperature limited heaters. FIG. 41 depicts electrical resistance (Ω) versus temperature (°C) at various applied electrical currents for a 446 stainless steel rod with a diameter of 2.5 cm and a 410 stainless steel rod with a diameter of 2.5 cm. Both rods had a length of 1.8 m. Curves 230-236 depict resistance profiles as a function of temperature for the 446 stainless steel rod at 440 amps AC (curve 230), 450 amps AC (curve 232), 500 amps AC (curve 234), and 10 amps DC (curve 236). Curves 238-244 depict resistance profiles as a function of temperature for the 410 stainless steel rod at 400 amps AC (curve 238), 450 amps AC (curve 240), 500 amps AC (curve 242), 10 amps DC (curve 244). For both rods, the resistance gradually increased with temperature until the Curie temperature was reached. At the Curie temperature, the resistance fell sharply. Above the Curie temperature, the resistance decreased slightly with increasing temperature. Both rods show a trend of decreasing resistance with increasing AC current. Accordingly, the turndown ratio decreased with increasing current. Thus, the rods provide a reduced amount of heat near and above the Curie temperature of the rods. In contrast, the resistance gradually increased with temperature through the Curie temperature with the applied DC current.

FIG. 42 depicts electrical resistance (mΩ) versus temperature (°C) at various applied electrical currents for a temperature limited heater. The temperature limited heater included a copper rod with a diameter of 1.3 cm inside an outer conductor of 2.5 cm Schedule 80 410 stainless steel pipe with a 0.15 cm thick copper Everdur™ (DuPont Engineering, Wilmington, DE) welded sheath over the 410 stainless steel pipe and a length of 1.8 m. Curves 264-274 show resistance profiles as a function of temperature for AC applied currents ranging from 300 amps to 550 amps (264: 300 amps; 266: 350 amps; 268: 400 amps; 270: 450 amps; 272: 500 amps;

274: 550 amps). For these AC applied currents, the resistance gradually increases with increasing temperature up to the Curie temperature. At the Curie temperature, the resistance falls sharply. In contrast, curve 276 shows resistance for an applied DC electrical current of 10 amps. This resistance shows a steady increase with increasing temperature, and little or no deviation at the Curie temperature.

FIG. 43 depicts data of electrical resistance (mΩ) versus temperature (°C) for a solid 2.54 cm diameter, 1.8 m long 410 stainless steel rod at various applied electrical currents. Curves 278, 280, 282, 284, and 286 depict resistance profiles as a function of temperature for the 410 stainless steel rod at 40 amps AC (curve 284), 70 amps AC (curve 286), 140 amps AC (curve 278), 230 amps AC (curve 280), and 10 amps DC (curve 282). For the applied AC currents of 140 amps and 230 amps, the resistance increased gradually with increasing temperature until the Curie temperature was reached. At the Curie temperature, the resistance fell sharply. In contrast, the resistance showed a gradual increase with temperature through the Curie temperature for an applied DC current.

FIG. 44 depicts data for values of skin depth (cm) versus temperature (°C) for a solid 2.54 cm diameter, 1.8 m long 410 stainless steel rod at various applied AC electrical currents. The skin depth was calculated using EQN. 14:

$$(14) \qquad \delta = R_1 - R_1 \times (1 - (1/R_{AC}/R_{DC}))^{1/2};$$

where $\delta$ is the skin depth, $R_1$ is the radius of the cylinder, $R_{AC}$ is the AC resistance, and $R_{DC}$ is the DC resistance. In FIG. 44, curves 320-338 show skin depth profiles as a function of temperature for applied AC electrical currents over a range of 50 amps to 500 amps (320: 50 amps; 322: 100 amps; 324: 150 amps; 326: 200 amps; 328: 250 amps; 330: 300 amps; 332: 350 amps; 334: 400 amps; 336: 450 amps; 338: 500 amps). For each applied AC electrical current, the skin depth gradually increased with increasing temperature up to the Curie temperature. At the Curie temperature, the skin depth increased sharply.

FIG. 45 depicts temperature (°C) versus time (hrs) for a temperature limited heater. The temperature limited heater was a 1.83 m long heater that included a copper rod with a diameter of 1.3 cm inside a 2.5 cm Schedule XXH 410 stainless steel pipe and a 0.325 cm copper sheath. The heater was placed in an oven for heating. Alternating current was applied to the heater when the heater was in the oven. The current was increased over two hours and reached a relatively constant value of 400 amps for the remainder of the time. Temperature of the stainless steel pipe was measured at three points at 0.46 m intervals along the length of the heater. Curve 340 depicts the temperature of the pipe at a point 0.46 m inside the oven and closest to the lead-in portion of the heater. Curve 342 depicts the temperature of the pipe at a point 0.46 m from the end of the pipe and furthest from the lead-in portion of the heater. Curve 344 depicts the temperature of the pipe at about a center point of the heater. The point at the center of the heater was further enclosed in a 0.3 m section of 2.5 cm thick Fiberfrax® (Unifrax Corp., Niagara Falls, NY) insulation. The insulation was used to create a low thermal conductivity section on the heater (a section where heat transfer to the surroundings is slowed or inhibited (a "hot spot")). The temperature of the heater increased with time as shown by curves 344, 342, and 340. Curves 344, 342, and 340 show that the temperature of the heater increased to about the same value for all three points along the length of the heater. The resulting temperatures were substantially independent of the added Fiberfrax® insulation. Thus, the operating temperatures of the temperature limited heater were substantially the same despite the differences in thermal load (due to the insulation) at each of the three points along the length of the heater. Thus, the temperature limited heater did not exceed the selected temperature limit in the presence of a low thermal conductivity section.

FIG. 46 depicts temperature (°C) versus log time (hrs) data for a 2.5 cm solid 410 stainless steel rod and a 2.5 cm solid 304 stainless steel rod. At a constant applied AC electrical current, the temperature of each rod increased with time. Curve 346 shows data for a thermocouple placed on an outer surface of the 304 stainless steel rod and under a layer of insulation. Curve 348 shows data for a thermocouple placed on an outer surface of the 304 stainless steel rod without a layer of insulation. Curve 350 shows data for a thermocouple placed on an outer surface of the 410 stainless steel rod and under a layer of insulation. Curve 352 shows data for a thermocouple placed on an outer surface of the 410 stainless steel rod without a layer of insulation. A comparison of the curves shows that the temperature of the 304 stainless steel rod (curves 346 and 348) increased more rapidly than the temperature of the 410 stainless steel rod (curves 350 and 352). The temperature of the 304 stainless steel rod (curves 346 and 348) also reached a higher value than the temperature of the 410 stainless steel rod (curves 350 and 352). The temperature difference between the non-insulated section of the 410 stainless steel rod (curve 352) and the insulated section of the 410 stainless steel rod (curve 350) was less than the temperature difference between the non-insulated section of the 304 stainless steel rod (curve 348) and the insulated section of the 304 stainless steel rod (curve 346). The temperature of the 304 stainless steel rod was increasing at the termination of the experiment (curves 346 and 348) while the temperature of the 410 stainless steel rod had leveled out (curves 350 and 352). Thus, the 410 stainless steel rod (the temperature limited heater) provided better temperature control than the 304 stainless steel rod (the non-temperature limited heater) in the presence of varying thermal loads (due to the insulation).

A numerical simulation (FLUENT available from Fluent USA, Lebanon, NH) was used to compare operation of temperature limited heaters with three turndown ratios. The simulation was done for heaters in an oil shale formation (Green River oil shale). Simulation conditions were:

- 61 m length conductor-in-conduit Curie heaters (center conductor (2.54 cm diameter), conduit outer diameter 7.3 cm)
- downhole heater test field richness profile for an oil shale formation
- 16.5 cm (6.5 inch) diameter wellbores at 9.14 m spacing between wellbores on triangular spacing
- 200 hours power ramp-up time to 820 watts/m initial heat injection rate
- constant current operation after ramp up
- Curie temperature of 720.6 °C for heater
- formation will swell and touch the heater canisters for oil shale richnesses at least 0.14 L/kg (35 gals/ton)

FIG. 47 displays temperature (°C) of a center conductor of a conductor-in-conduit heater as a function of formation depth (m) for a temperature limited heater with a turndown ratio of 2:1. Curves 354-376 depict temperature profiles in the formation at various times ranging from 8 days after the start of heating to 675 days after the start of heating (354: 8 days, 356: 50 days, 358: 91 days, 360: 133 days, 362: 216 days, 364: 300 days, 366: 383 days, 368: 466 days, 370: 550 days, 372: 591 days, 374: 633 days, 376: 675 days). At a turndown ratio of 2:1, the Curie temperature of 720.6 °C was exceeded after 466 days in the richest oil shale layers. FIG. 48 shows the corresponding heater heat flux (W/m) through the formation for a turndown ratio of 2:1 along with the oil shale richness (l/kg) profile (curve 378). Curves 380-412 show the heat flux profiles at various times from 8 days after the start of heating to 633 days after the start of heating (380: 8 days; 382: 50 days; 384: 91 days; 386: 133 days; 388: 175 days; 390: 216 days; 392: 258 days; 394: 300 days; 396: 341 days; 398: 383 days; 400: 425 days; 402: 466 days; 404: 508 days; 406: 550 days; 408: 591 days; 410: 633 days; 412: 675 days). At a turndown ratio of 2:1, the center conductor temperature exceeded the Curie temperature in the richest oil shale layers.

FIG. 49 displays heater temperature (°C) as a function of formation depth (m) for a turndown ratio of 3:1. Curves 414-436 show temperature profiles through the formation at various times ranging from 12 days after the start of heating to 703 days after the start of heating (414: 12 days; 416: 33 days; 418: 62 days; 420: 102 days; 422: 146 days; 424: 205 days; 426: 271 days; 428: 354 days; 430: 467 days; 432: 605 days; 434: 662 days; 436: 703 days). At a turndown ratio of 3:1, the Curie temperature was approached after 703 days. FIG. 50 shows the corresponding heater heat flux (W/m) through the formation for a turndown ratio of 3:1 along with the oil shale richness (l/kg) profile (curve 438). Curves 440-460 show the heat flux profiles at various times from 12 days after the start of heating to 605 days after the start of heating (440: 12 days, 442: 32 days, 444: 62 days, 446: 102 days, 448: 146 days, 450: 205 days, 452: 271 days, 454: 354 days, 456: 467 days, 458: 605 days, 460: 749 days). The center conductor temperature never exceeded the Curie temperature for the turndown ratio of 3:1. The center conductor temperature also showed a relatively flat temperature profile for the 3:1 turndown ratio.

FIG. 51 shows heater temperature (°C) as a function of formation depth (m) for a turndown ratio of 4:1. Curves 462-482 show temperature profiles through the formation at various times ranging from 12 days after the start of heating to 467 days after the start of heating (462: 12 days; 464: 33 days; 466: 62 days; 468: 102 days, 470: 147 days; 472: 205 days; 474: 272 days; 476: 354 days; 478: 467 days; 480: 606 days, 482: 678 days). At a turndown ratio of 4:1, the Curie temperature was not exceeded even after 678 days. The center conductor temperature never exceeded the Curie temperature for the turndown ratio of 4:1. The center conductor showed a temperature profile for the 4:1 turndown ratio that was somewhat flatter than the temperature profile for the 3:1 turndown ratio. These simulations show that the heater temperature stays at or below the Curie temperature for a longer time at higher turndown ratios. For this oil shale richness profile, a turndown ratio of at least 3:1 may be desirable.

Simulations have been performed to compare the use of temperature limited heaters and non-temperature limited heaters in an oil shale formation. Simulation data was produced for conductor-in-conduit heaters placed in 16.5 cm (6.5 inch) diameter wellbores with 12.2 m (40 feet) spacing between heaters a formation simulator (for example, STARS from Computer Modelling Group, LTD., Houston, TX), and a near wellbore simulator (for example, ABAQUS from ABAQUS, Inc., Providence, RI). Standard conductor-in-conduit heaters included 304 stainless steel conductors and conduits. Temperature limited conductor-in-conduit heaters included a metal with a Curie temperature of 760 °C for conductors and conduits. Results from the simulations are depicted in FIGS. 52-54.

FIG. 52 depicts heater temperature (°C) at the conductor of a conductor-in-conduit heater versus depth (m) of the heater in the formation for a simulation after 20,000 hours of operation. Heater power was set at 820 watts/meter until 760 °C was reached, and the power was reduced to inhibit overheating. Curve 484 depicts the conductor temperature for standard conductor-in-conduit heaters. Curve 484 shows that a large variance in conductor temperature and a significant number of hot spots developed along the length of the conductor. The temperature of the conductor had a minimum value of 490 °C. Curve 486 depicts conductor temperature for temperature limited conductor-in-conduit heaters. As shown in FIG. 52, temperature distribution along the length of the conductor was more controlled for the temperature limited heaters. In addition, the operating temperature of the conductor was 730 °C for the temperature limited heaters. Thus, more heat input would be provided to the formation for a similar heater power using temperature limited heaters.

FIG. 53 depicts heater heat flux (W/m) versus time (yrs) for the heaters used in the simulation for heating oil shale. Curve 488 depicts heat flux for standard conductor-in-conduit heaters. Curve 490 depicts heat flux for temperature limited conductor-in-conduit heaters. As shown in FIG. 53, heat flux for the temperature limited heaters was maintained at a higher value for a longer period of time than heat flux for standard heaters. The higher heat flux may provide more uniform and faster heating of the formation.

FIG. 54 depicts cumulative heat input (kJ/m)(kilojoules per meter) versus time (yrs) for the heaters used in the simulation for heating oil shale. Curve 492 depicts cumulative heat input for standard conductor-in-conduit heaters. Curve 494 depicts cumulative heat input for temperature limited conductor-in-conduit heaters. As shown in FIG. 54, cumulative heat input for the temperature limited heaters increased faster than cumulative heat input for standard heaters. The faster accumulation of heat in the formation using temperature limited heaters may decrease the time needed for retorting the formation. Onset of retorting of the oil shale formation may begin around an average cumulative heat input of $1.1 \times 10^8$ kJ/meter. This value of cumulative heat input is reached around 5 years for temperature limited heaters and between 9 and 10 years for standard heaters.

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.

CLAIMS:

1. A system, comprising:

a heater comprising one or more electrical conductors (174), the heater configured to generate a heat output during application of electrical current to the heater, wherein the heater comprises a ferromagnetic material (166);

a conduit (176) at least partially surrounding the heater;

a fluid having a higher thermal conductivity than air at a standard temperature of 0 °C and standard pressure of 101.325 kPa, located in a space (180) between the heater and the conduit (176);

a source of electrical power; and wherein:

the system is configured to provide (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater;

at least one electrical conductor (174) comprises a ferromagnetic material (166), which at least partially surrounds a non-ferromagnetic material (172);

the non-ferromagnetic material (172) has a higher electrical conductivity than the ferromagnetic material (166) a fluid pressure in the space (180) between the electrical conductor (174) and the conduit (176) is at least 1000 kPa and is sufficient to inhibit arcing in the space (180).

2. The system as claimed in claim 1, wherein the fluid is helium or hydrogen.

3. The system as claimed in claim 1 or 2, wherein the fluid is helium and the space (180) between the electrical conductor (174) and the conduit (176) is at least 50% by volume helium, at least 75% by volume helium, or at least 90% by volume helium.

4. The system as claimed in any one of claims 1 to 3, wherein the source of electrical power comprises an AC power supply or a modulated DC power supply.

5. The system as claimed in any one of claims 1 to 4, wherein the second heat output is at most 90%, at most 80%, or at most 50% of the first heat output, the first heat output being at about 50 °C below the selected temperature.

6. The system as claimed in any one of claims 1 to 5, wherein the non-ferromagnetic material (172) is coupled to the ferromagnetic material (166).

7. The system as claimed in any one of claims 1 to 6, wherein the selected temperature is approximately the Curie temperature of the ferromagnetic material (166) or is within 25 °C of the Curie temperature of the ferromagnetic material (166).

8. The system as claimed in any one of claims 1 to 7, wherein the system has a turndown ratio being the highest electrical resistance below the Curie temperature to the lowest resistance above the Curie temperature for a given current of at least 1.1 to 1, at least 2 to 1, or at least 3 to 1.

9. The system as claimed in any one of claims 1 to 8, wherein at least one of the electrical conductors (174) is elongated and configured such that electrically resistive sections at or near the selected temperature will automatically provide the second heat output.

10. The system as claimed in any one of claims 1 to 9, wherein at least one of the electrical conductors (174) is elongated and configured to provide heat output along a length of at least a portion of a wellbore.

11. The system as claimed in any one of claims 1 to 10, wherein at least one of the electrical conductors (174) is at least 10 m, at least 50 m, or at least 100 m in length.

12. The system as claimed in any one of claims 1 to 11, wherein the system is configured to allow heat to transfer from the heater to a part of a subsurface formation (182).

13. The system as claimed in any one of claims 1 to 12, wherein the system is configured to be placed in an opening in a subsurface formation (182).

14. A method for heating a subsurface formation (182), the method comprising:

arranging in a heater well a heating system, which comprises:

a heater comprising one or more electrical conductors (174), the heater configured to generate a heat output during application of electrical current to the heater, wherein the heater comprises a ferromagnetic material (166);

a conduit (176) at least partially surrounding the heater;

a fluid having a higher thermal conductivity than air at standard temperature and pressure (STP) (0 °C and 101.325 kPa).located in a space (180) between the heater and the conduit (176);

a source of electrical power; and wherein:

the system is configured to provide (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater;

at least one electrical conductor (174) comprises a ferromagnetic material (166), which at least partially surrounds a non-ferromagnetic material (172);

the non-ferromagnetic material (172) has a higher electrical conductivity than the ferromagnetic material (166); and

a fluid pressure in the space (180) between the electrical conductor (174) and the conduit (176) is at least 1000 kPa and is sufficient to inhibit arcing in the space (180);

providing electrical current to the heater to provide an electrically resistive heat output; and

allowing heat to transfer from the heater to at least part of the subsurface formation such that the heater

provides (a) a first heat output below a selected temperature when time-varying electrical current is applied to the heater, and (b) a second heat output near or above the selected temperature when time-varying electrical current is applied to the heater.

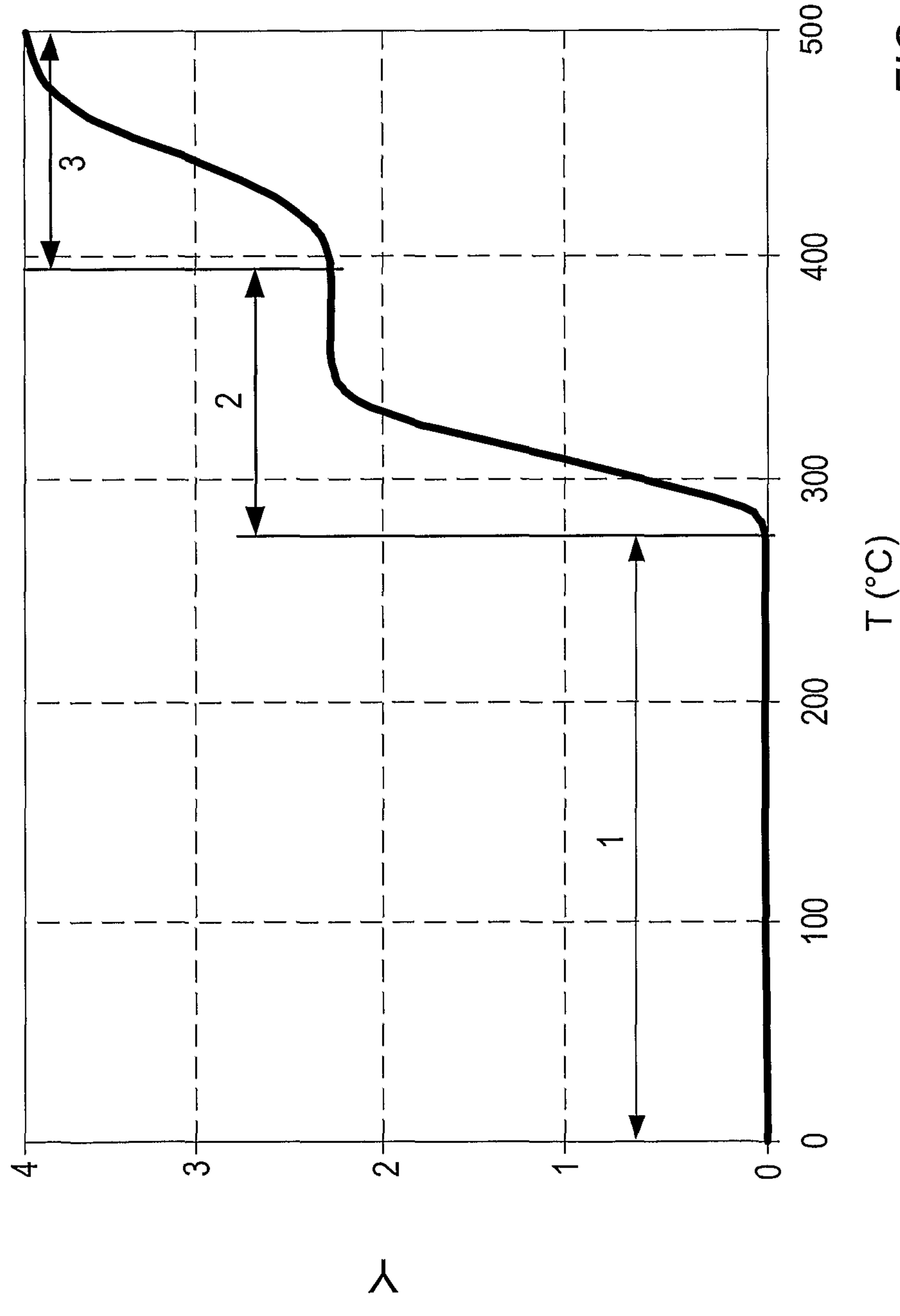


FIG. 1

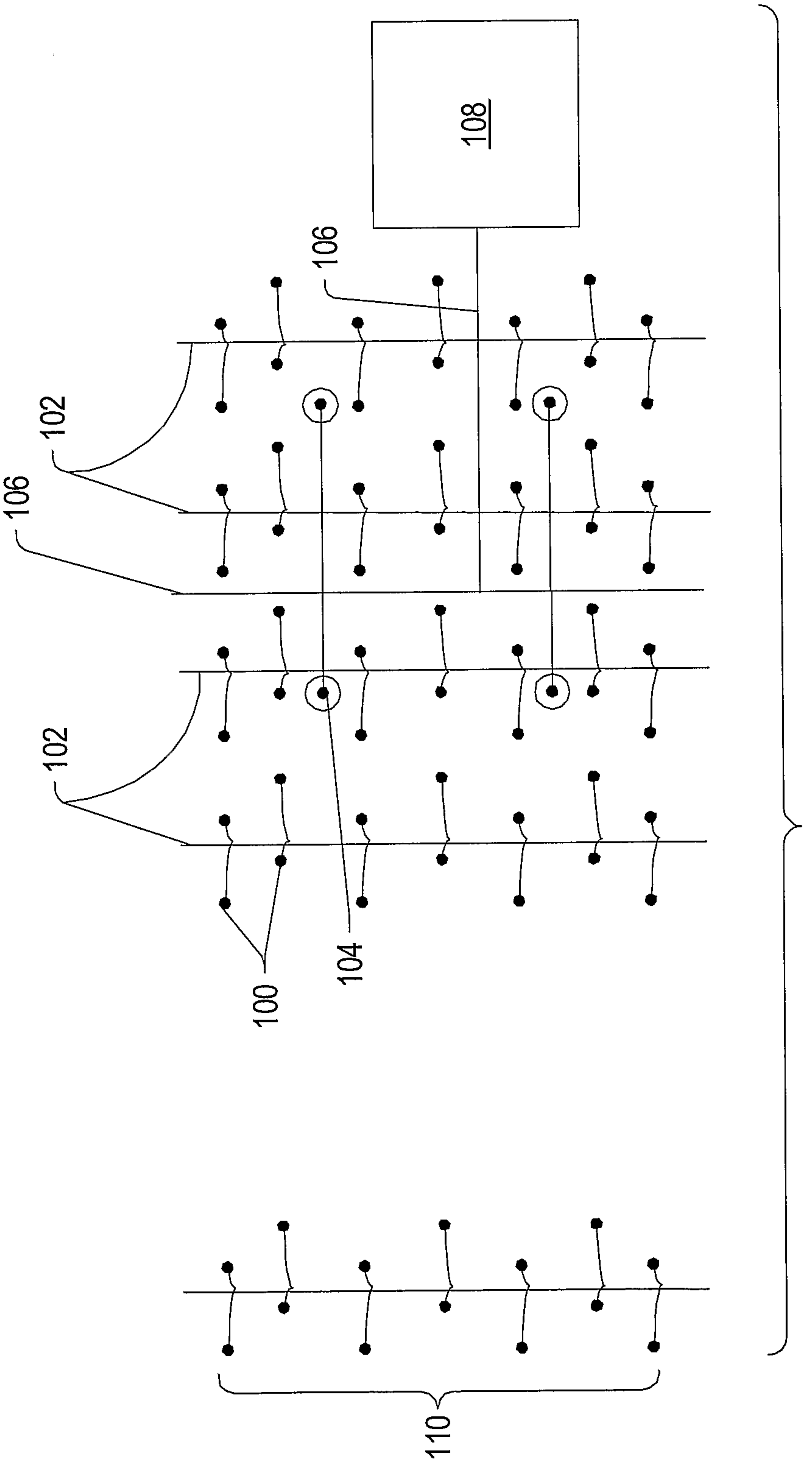


FIG. 2

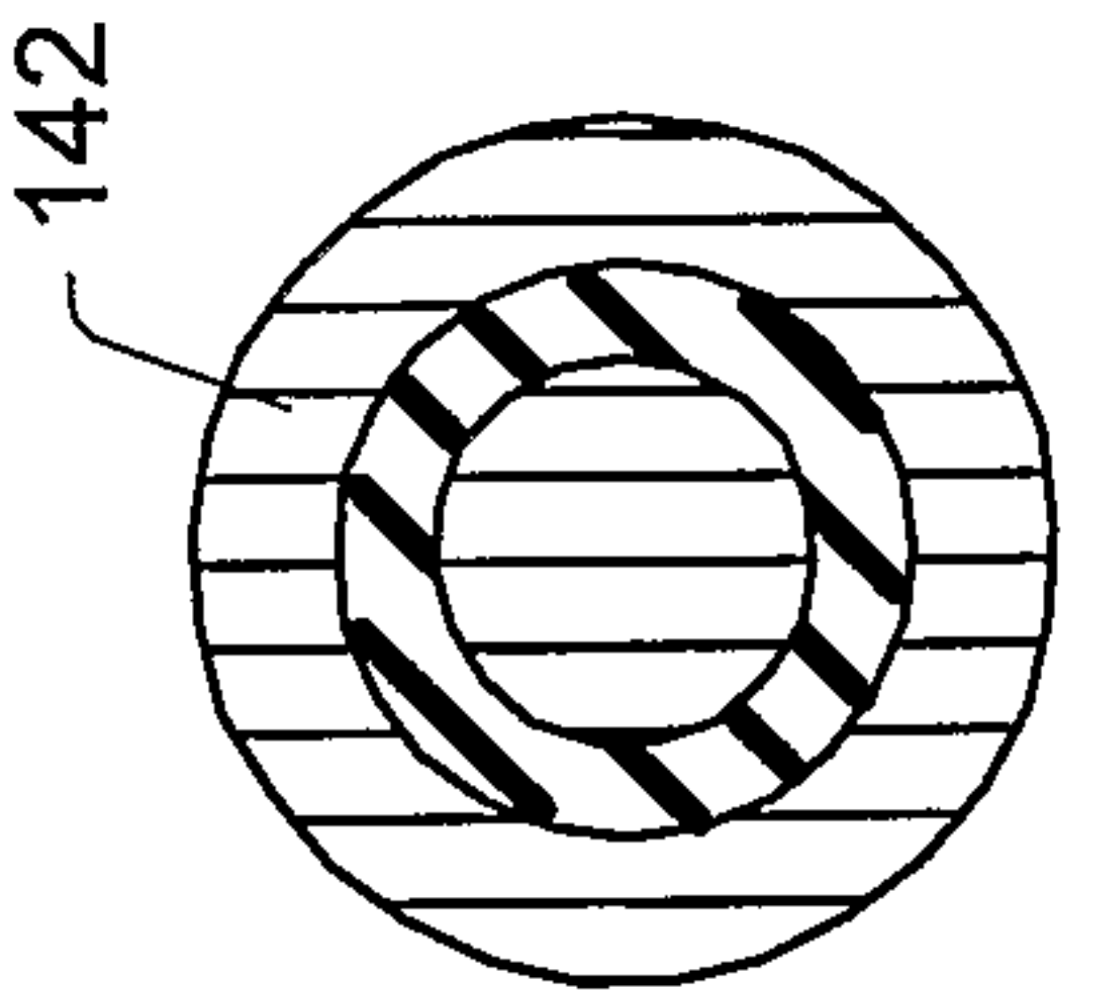


FIG. 5

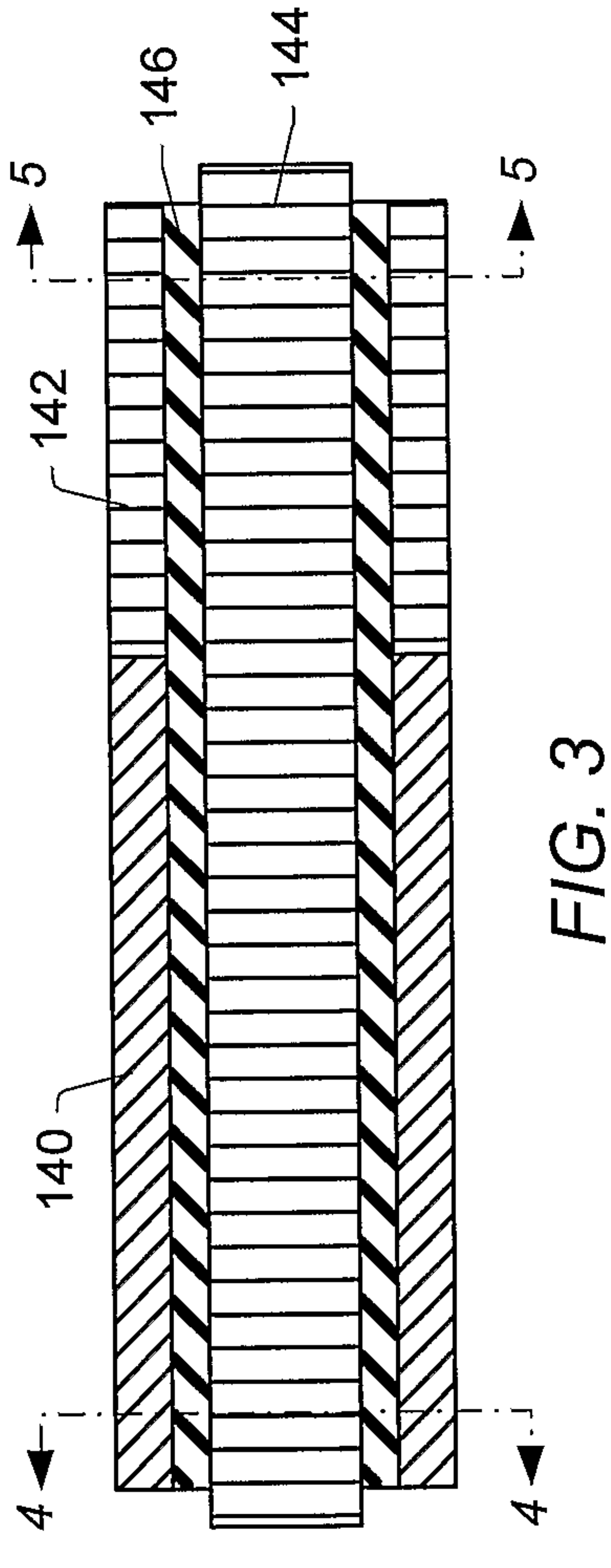


FIG. 3

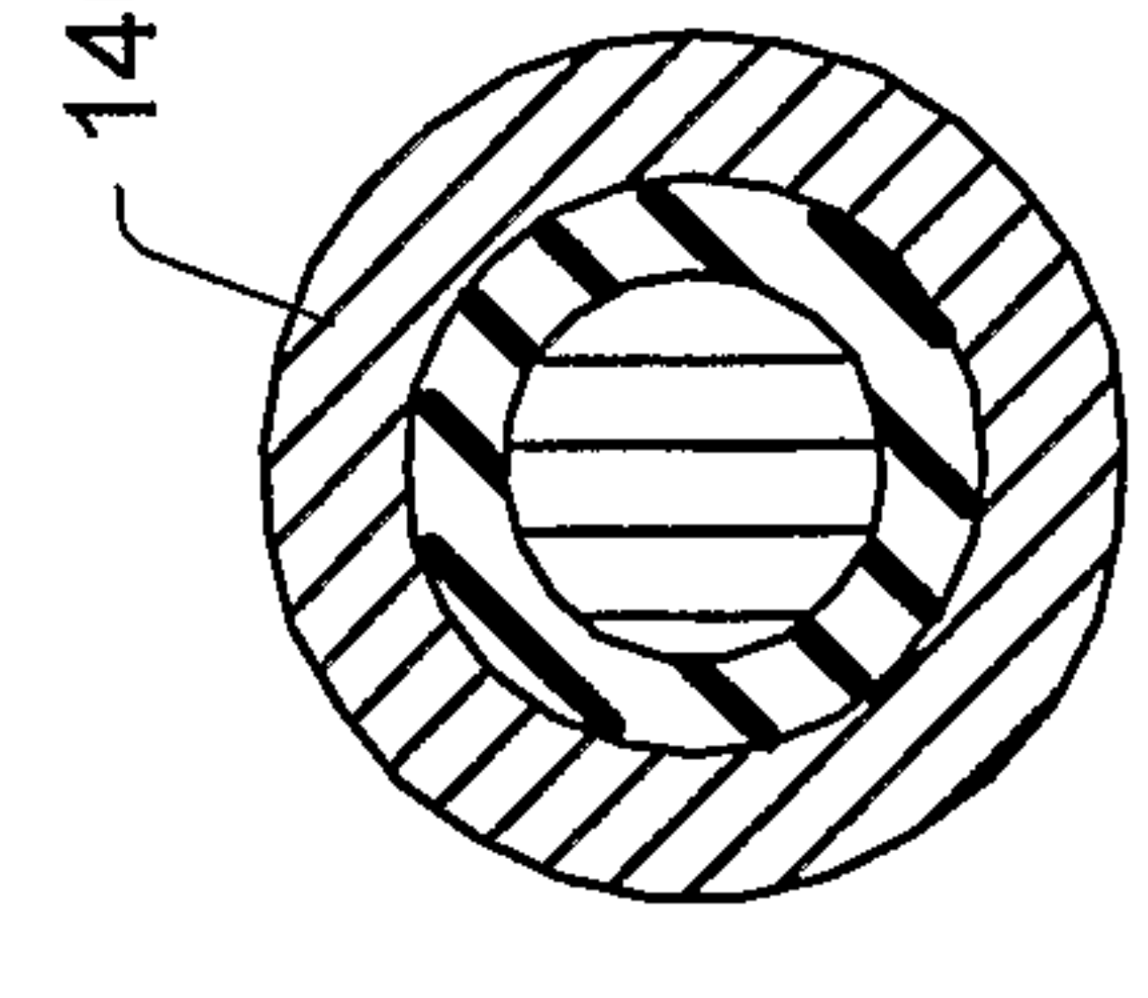


FIG. 4

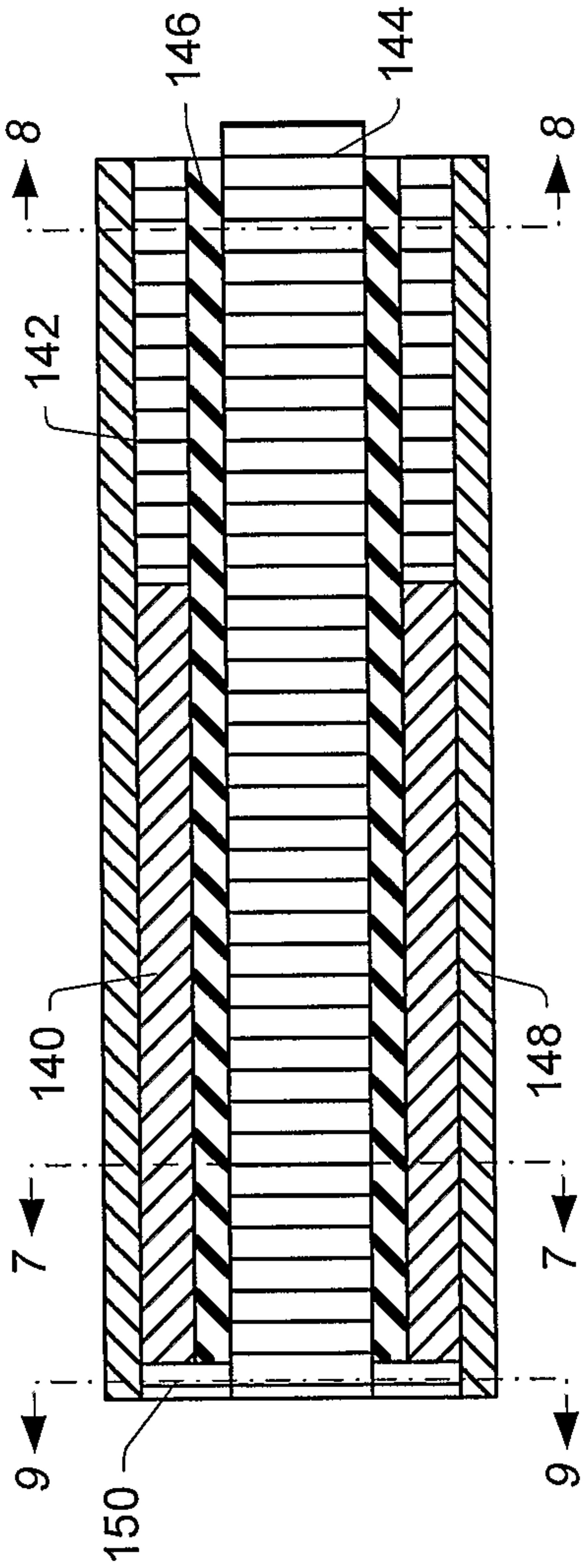


FIG. 6

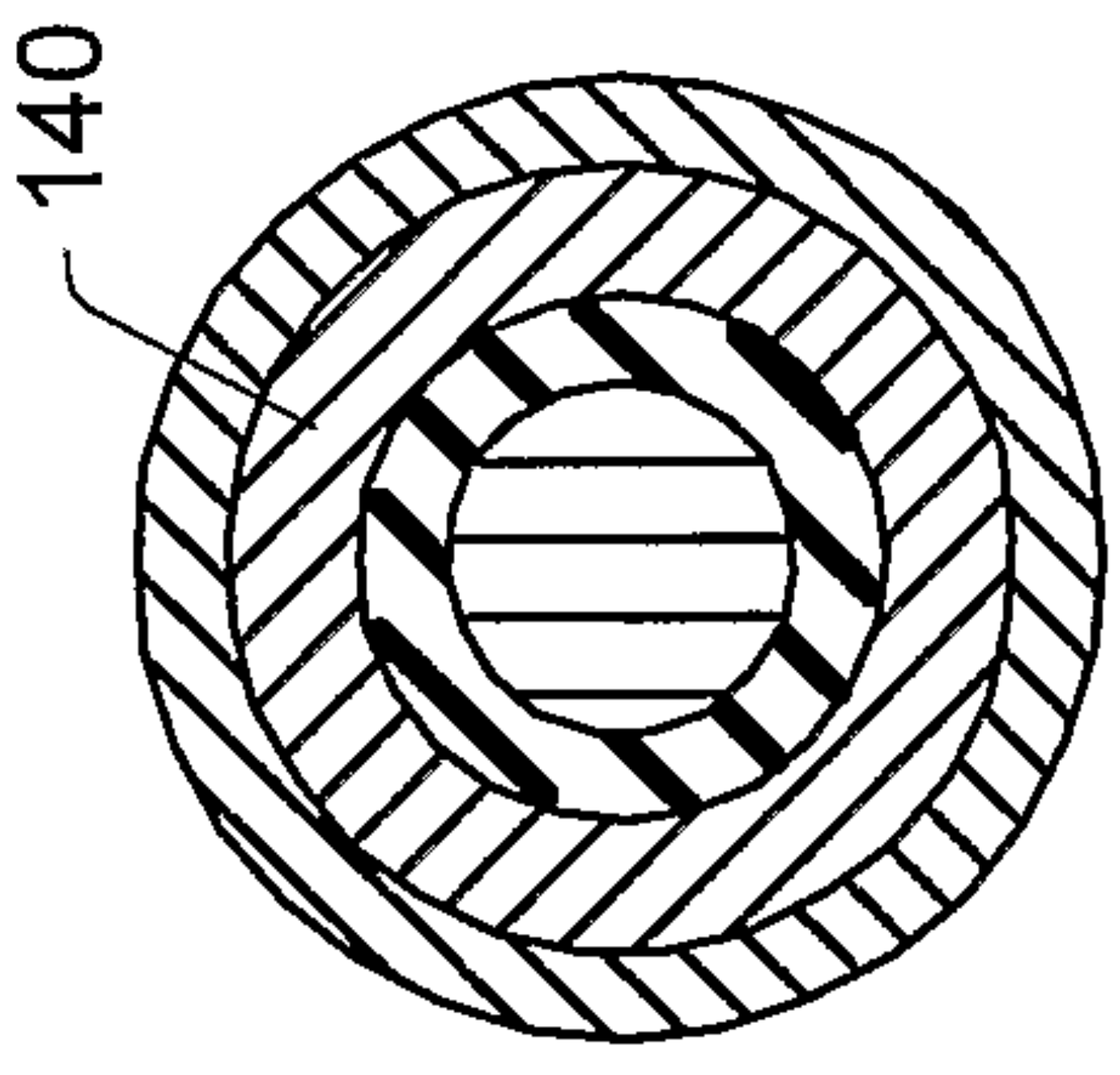


FIG. 7

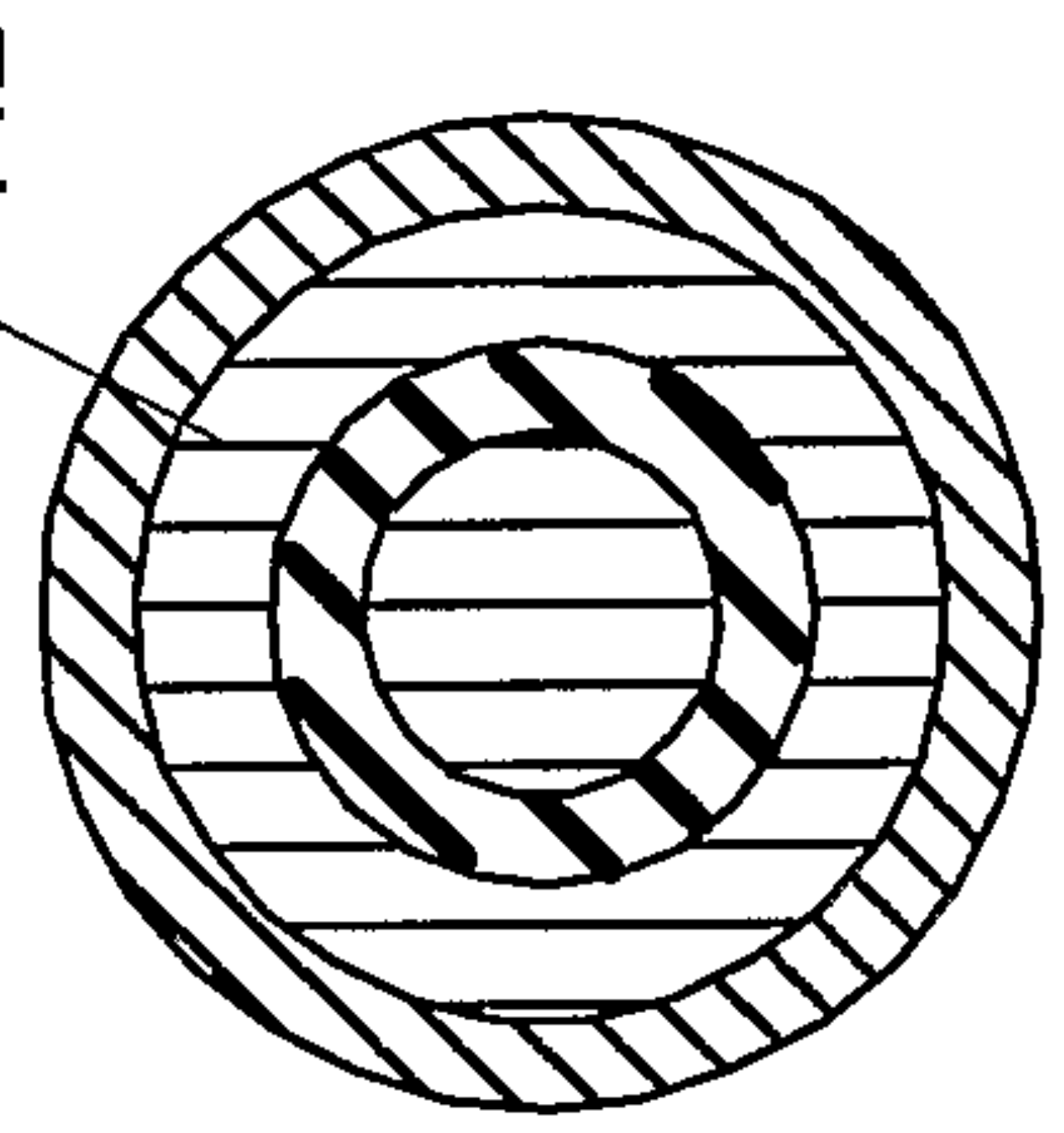


FIG. 8

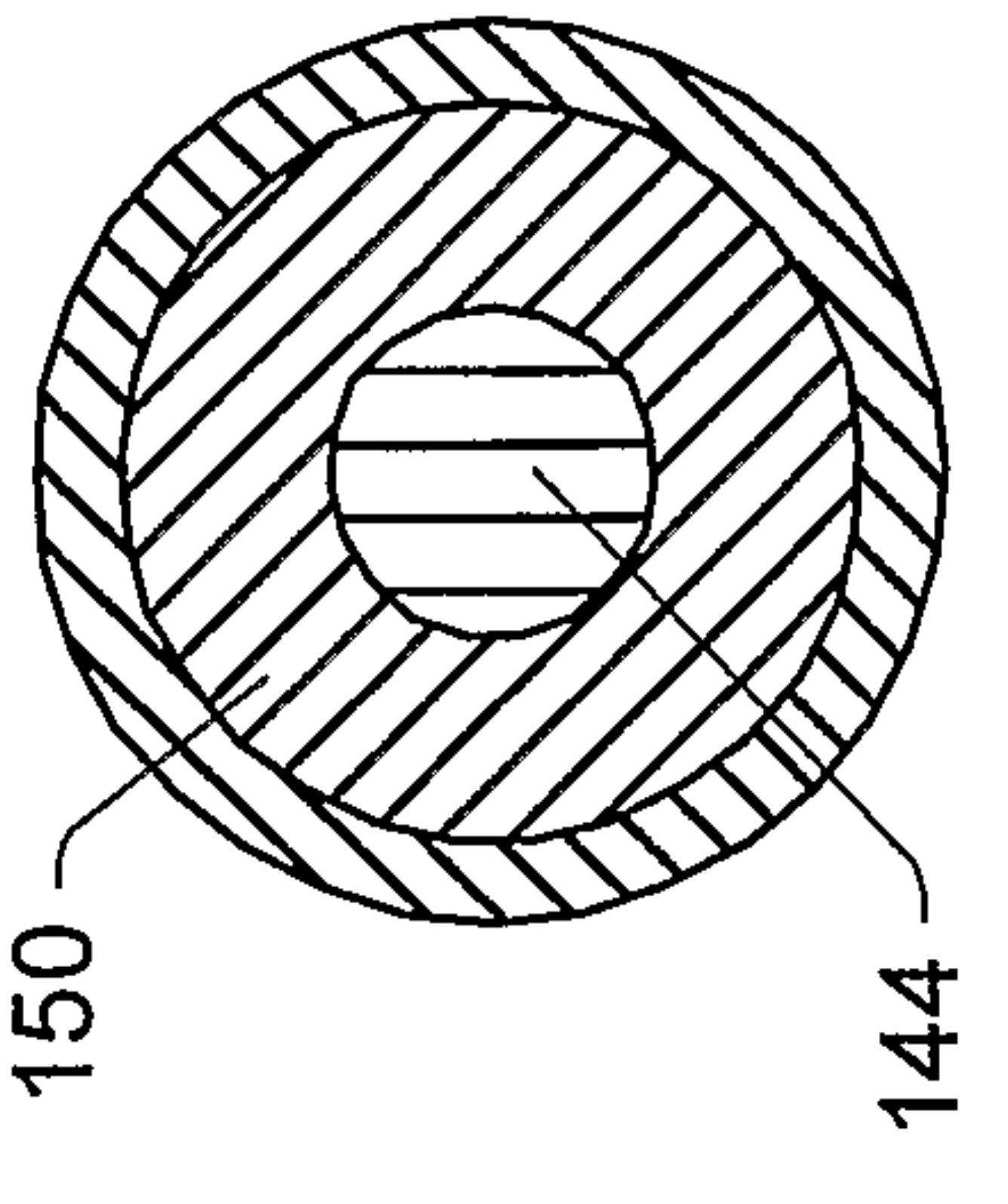


FIG. 9

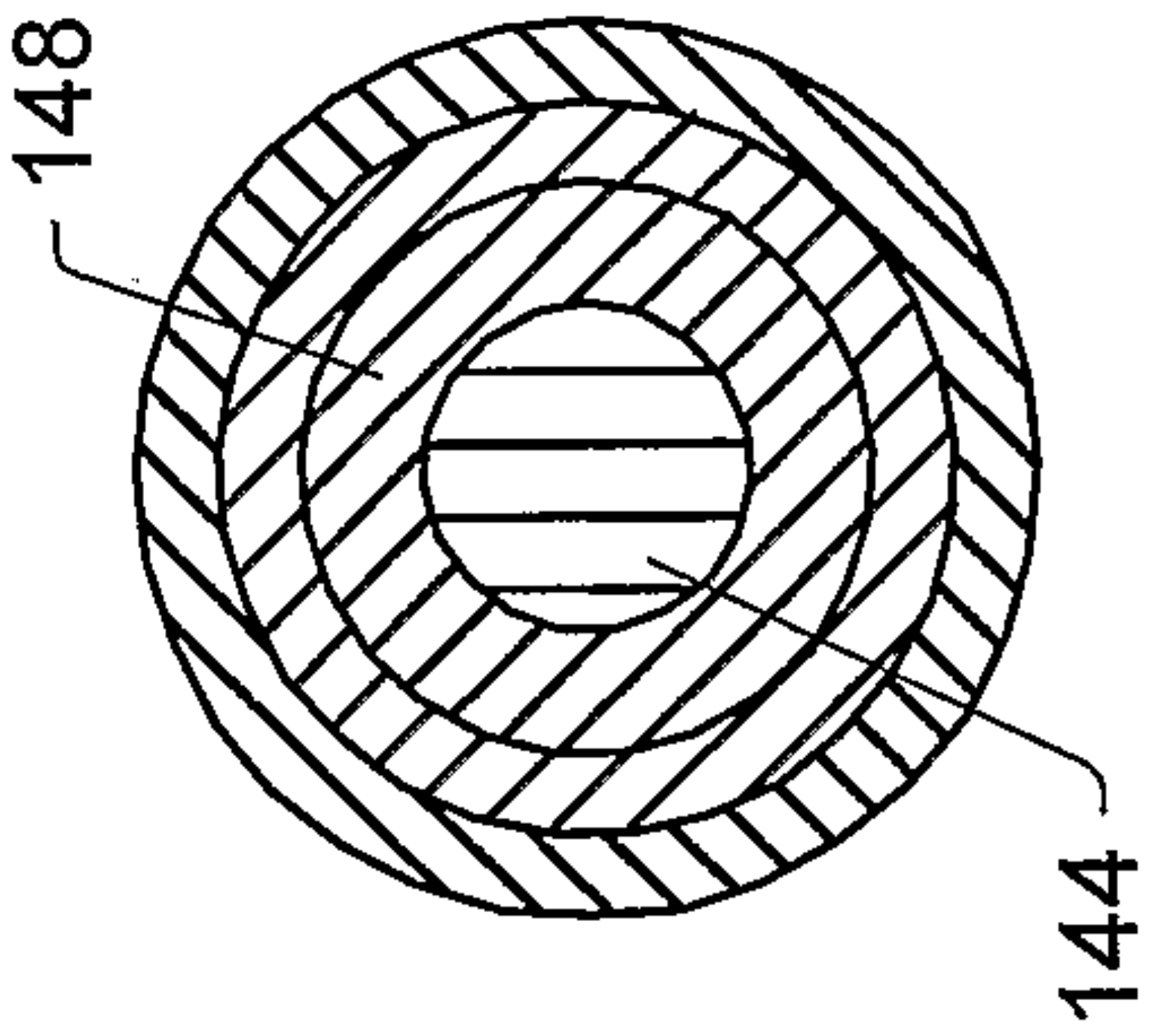


FIG. 12

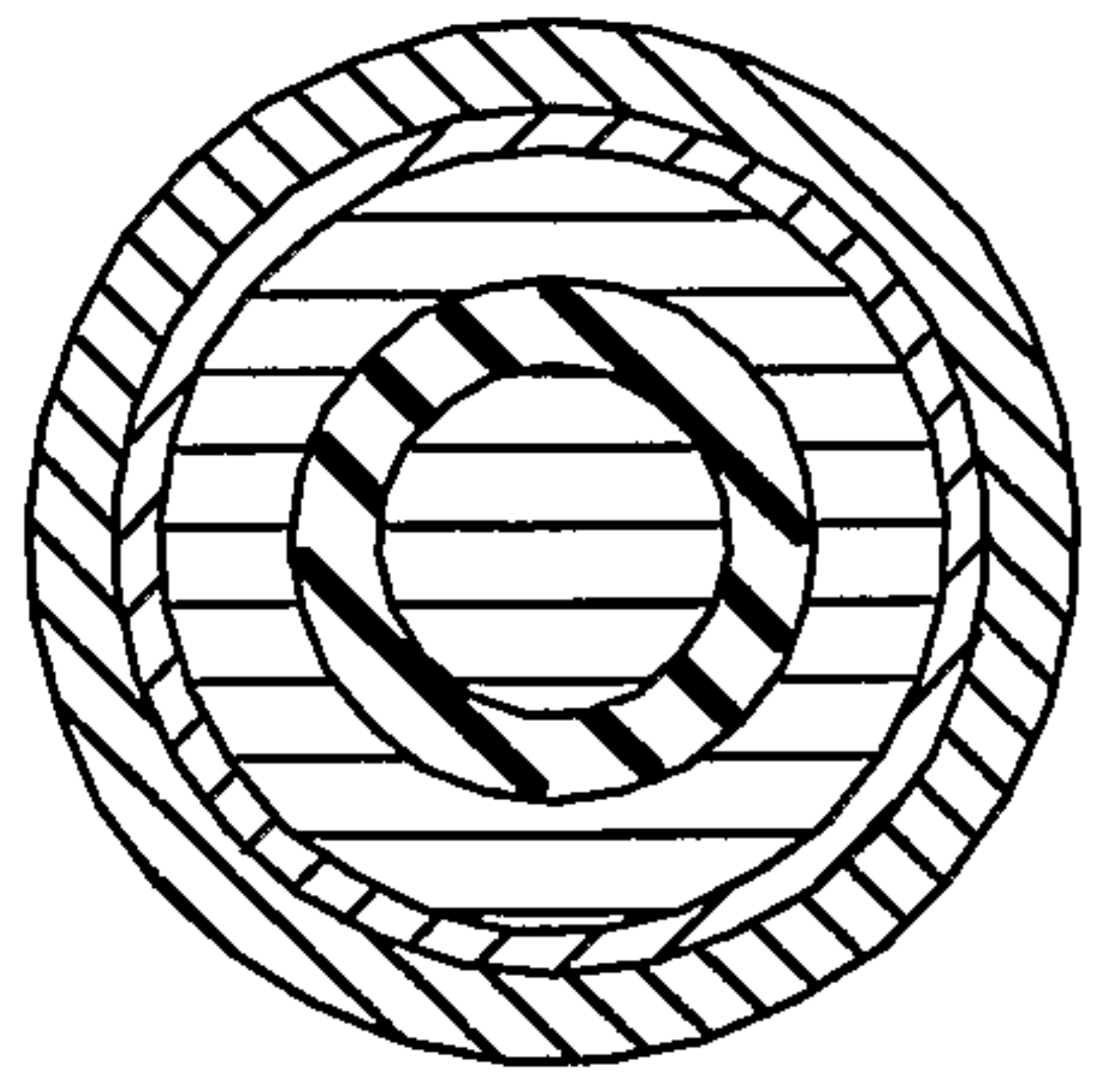


FIG. 15

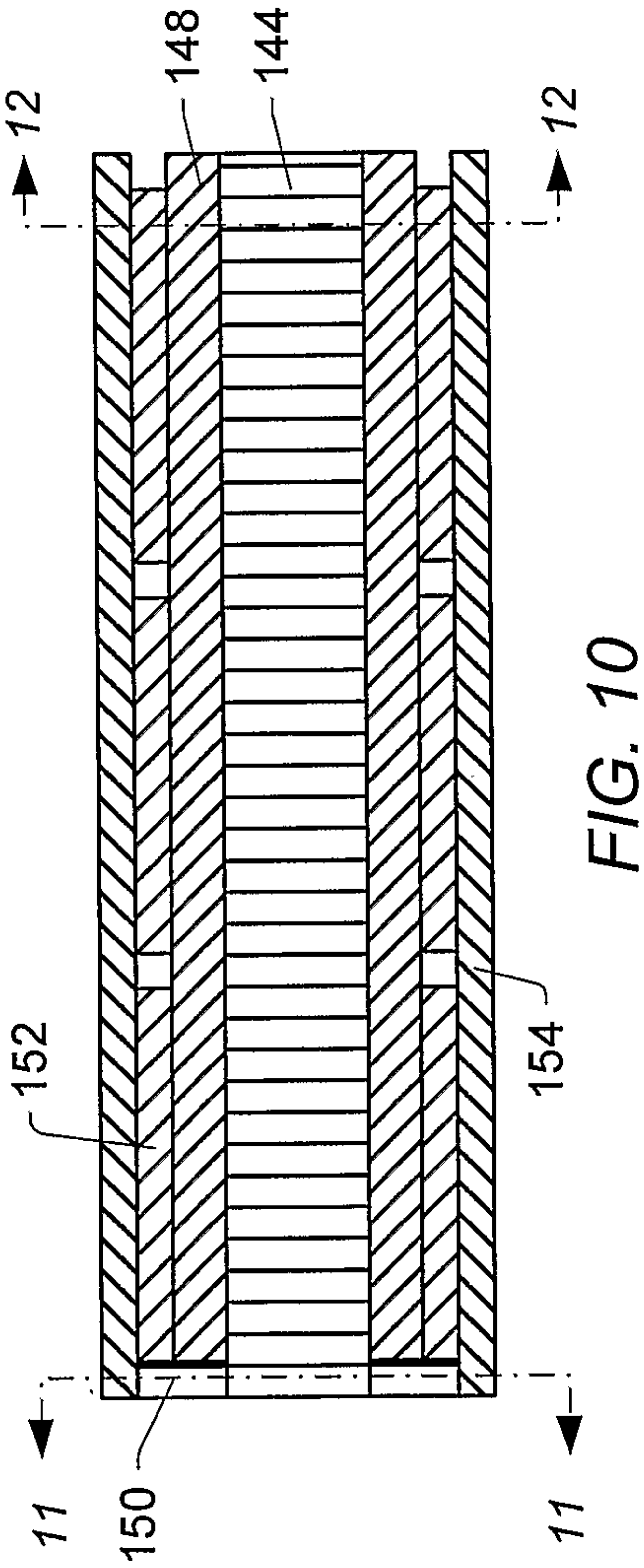


FIG. 10

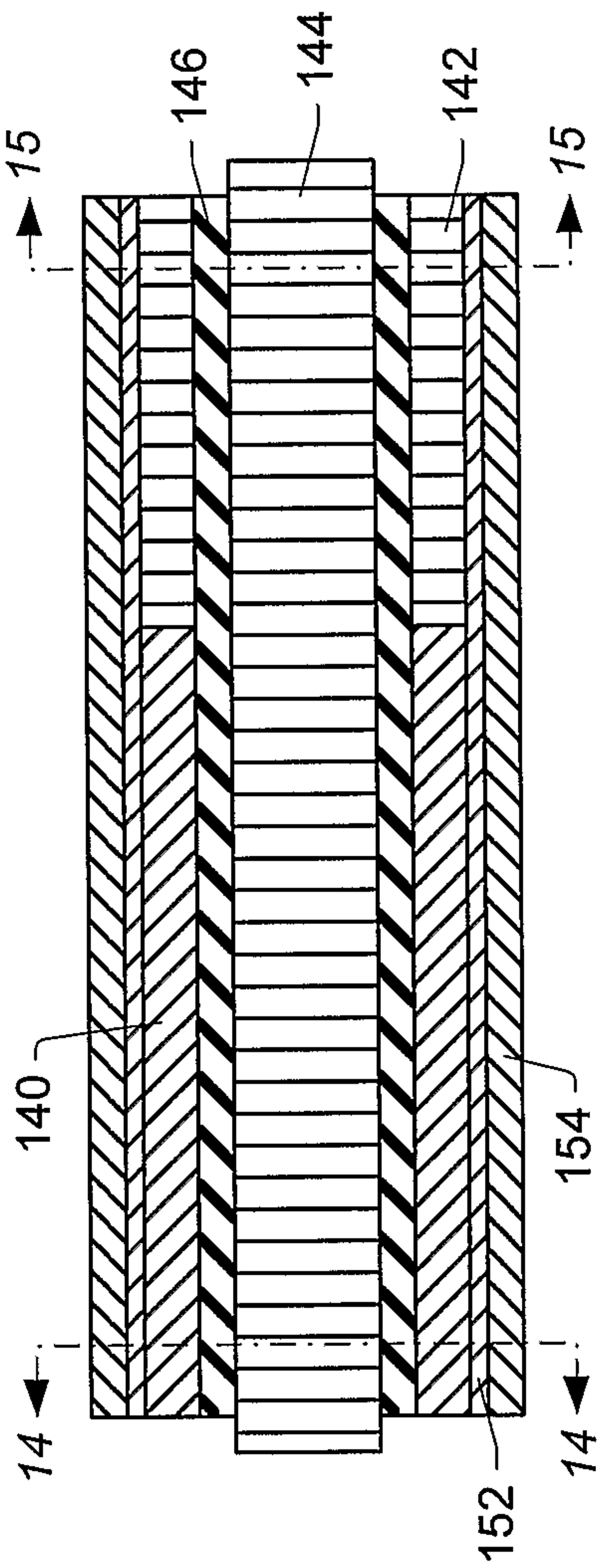


FIG. 13

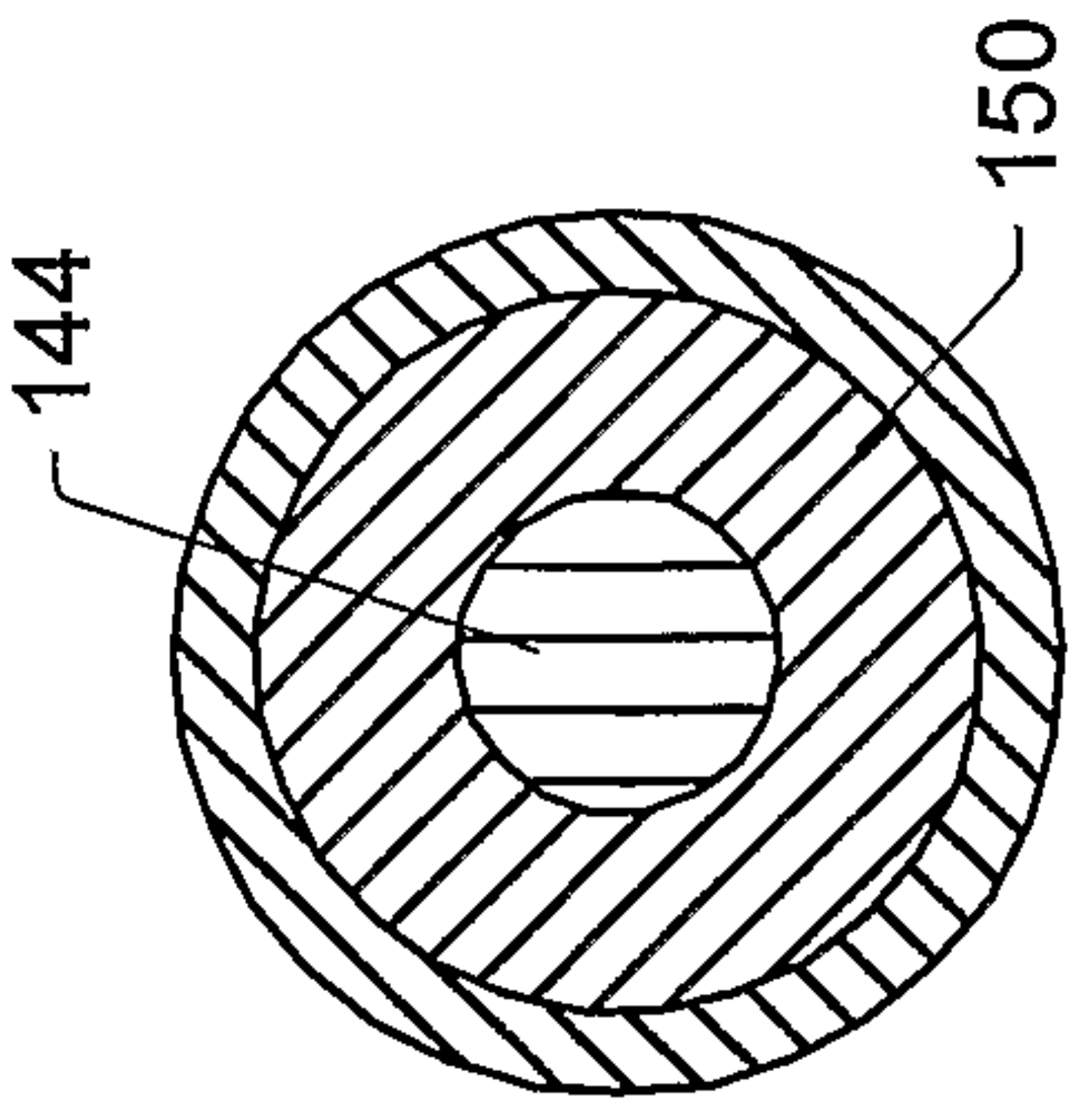


FIG. 11

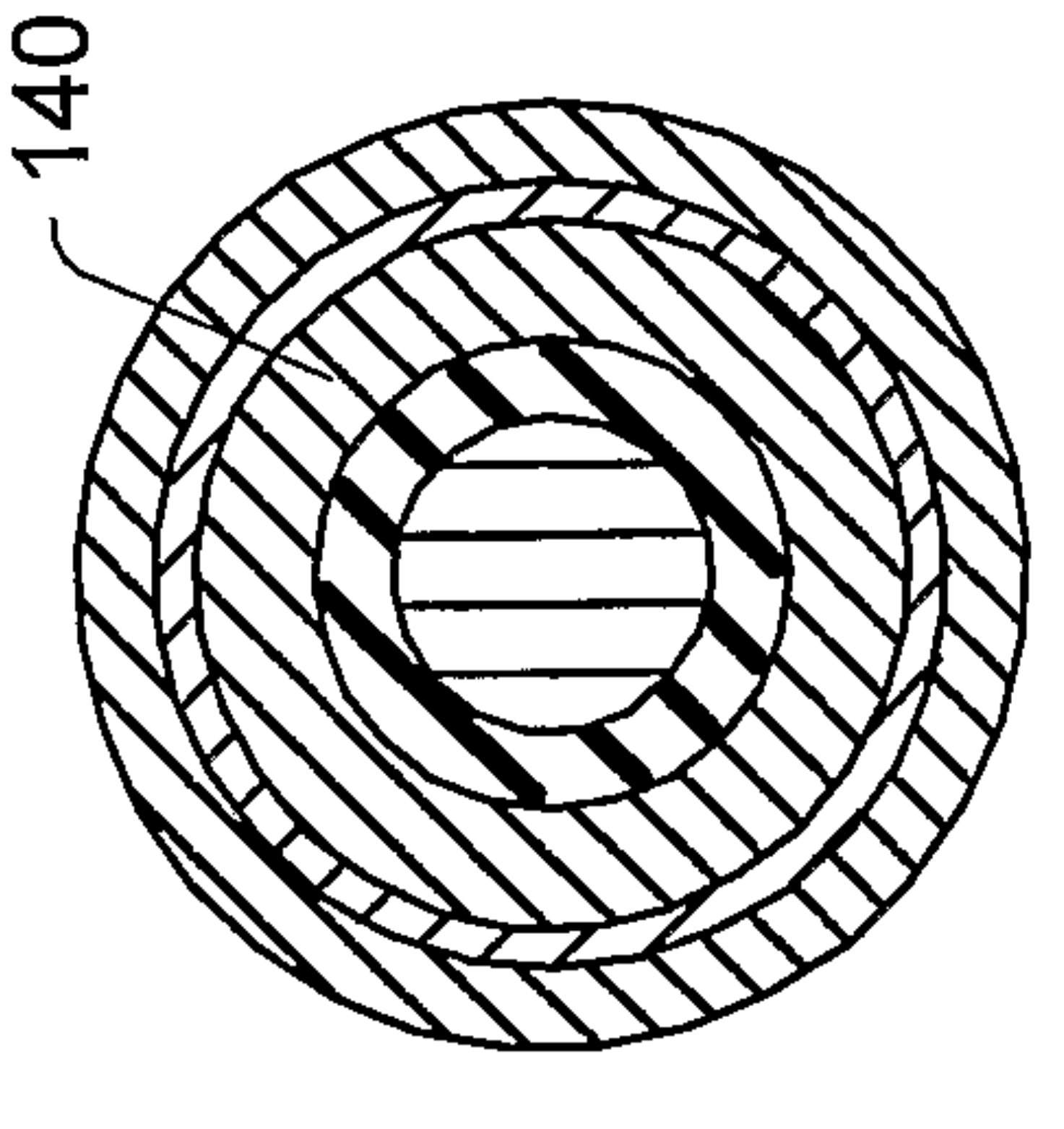


FIG. 14

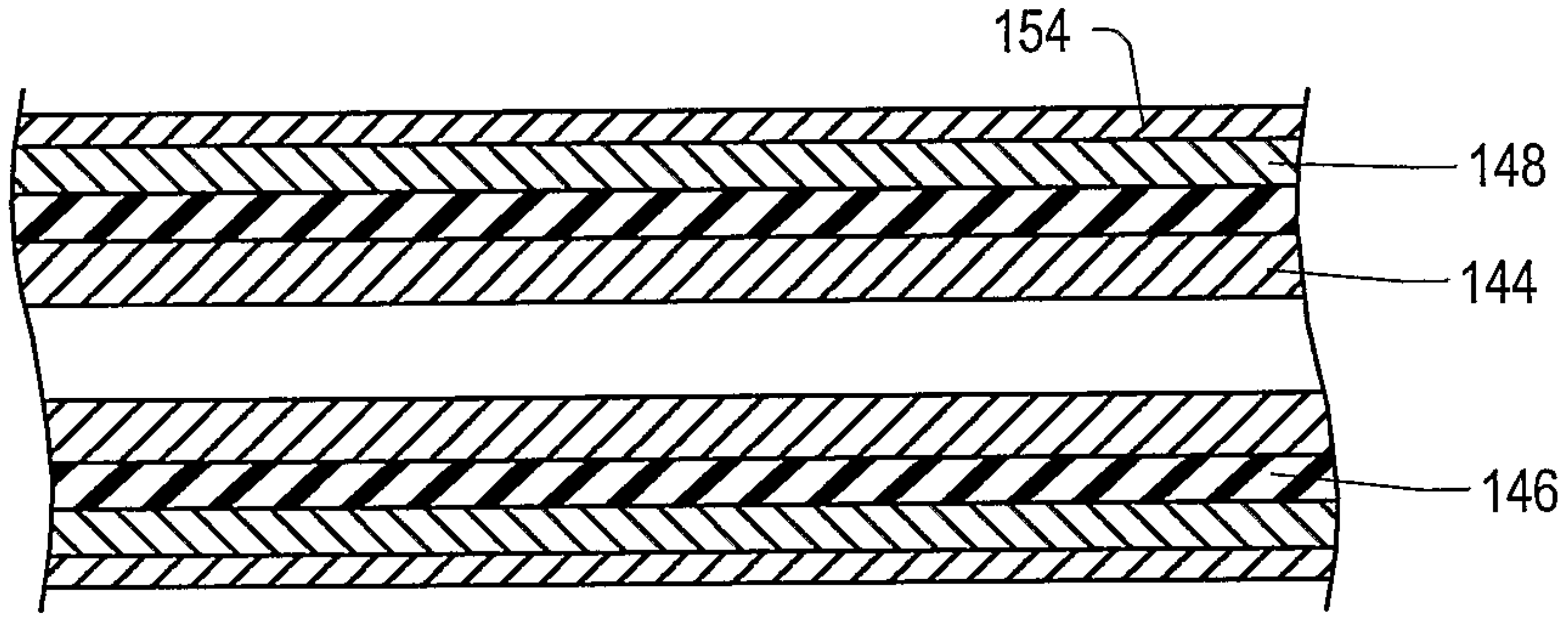


FIG. 16A

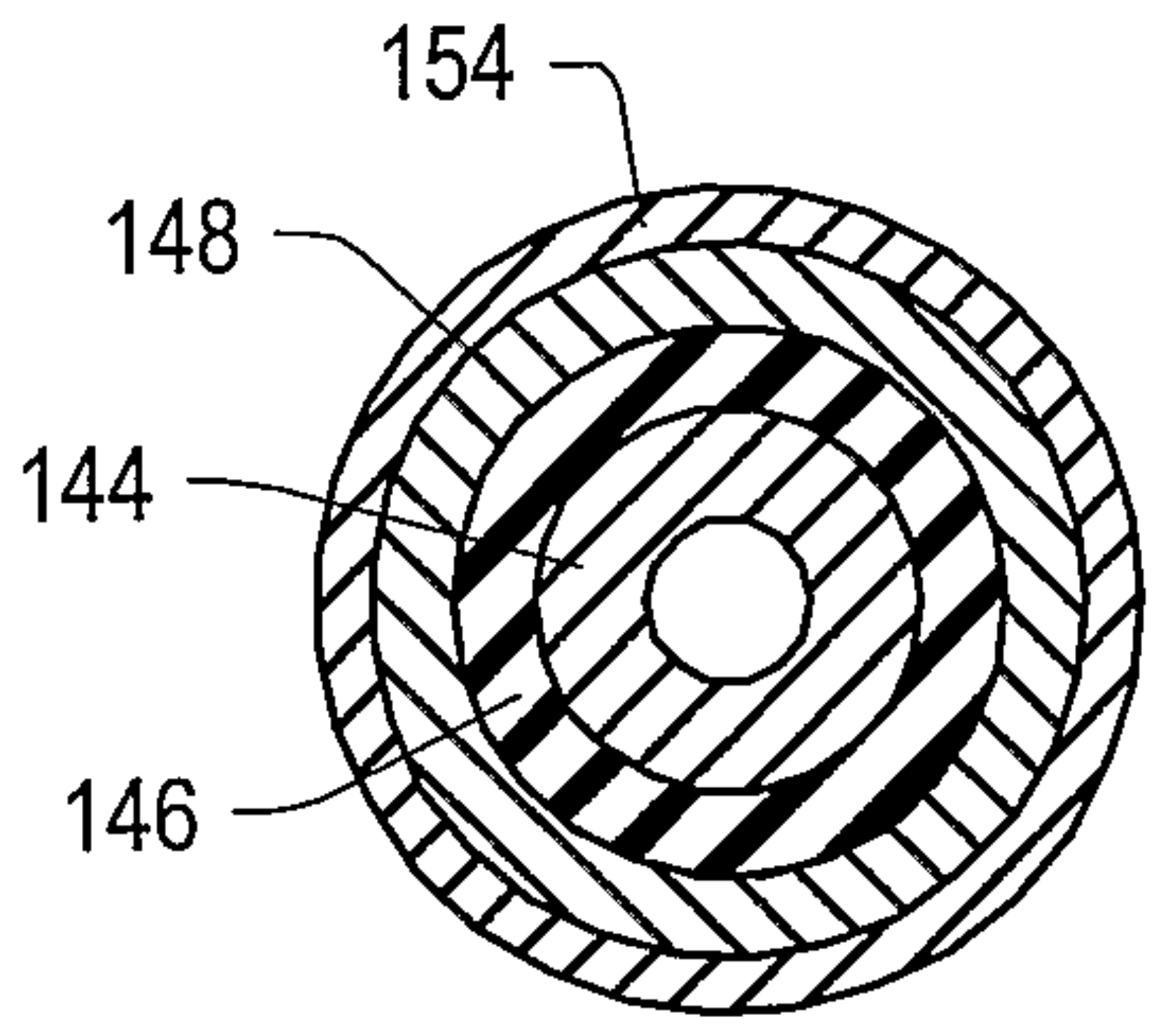


FIG. 16B

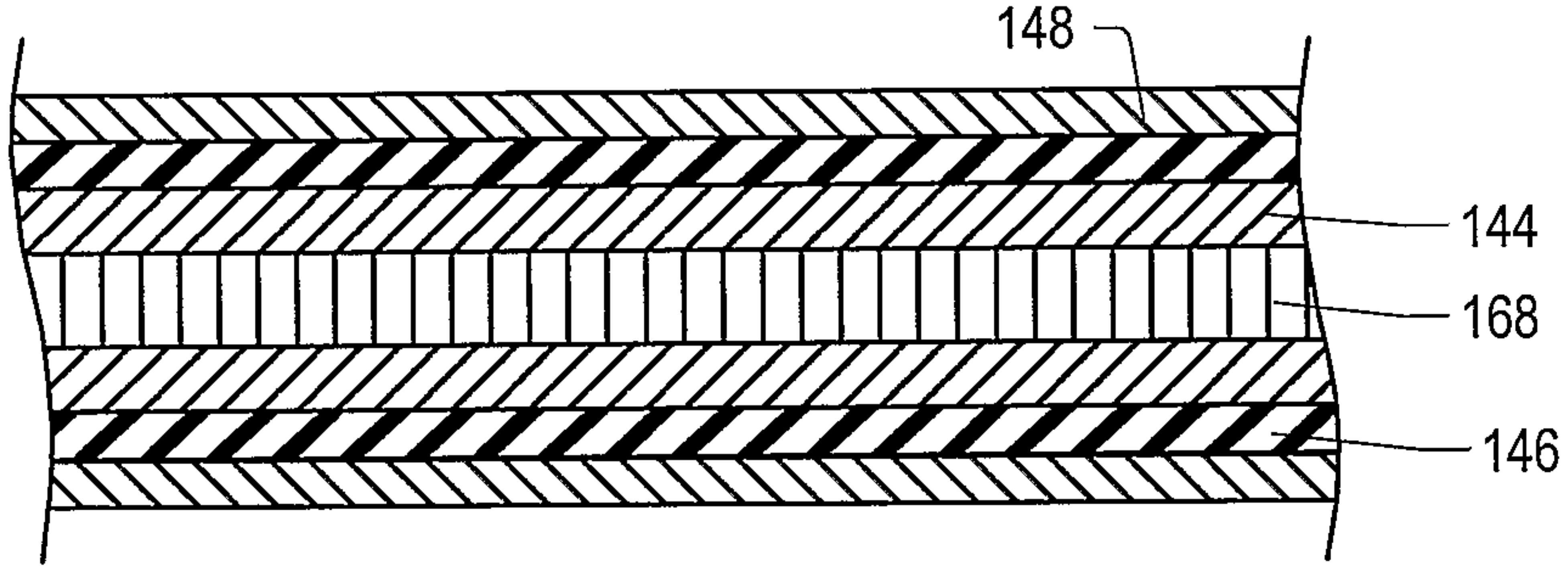


FIG. 17A

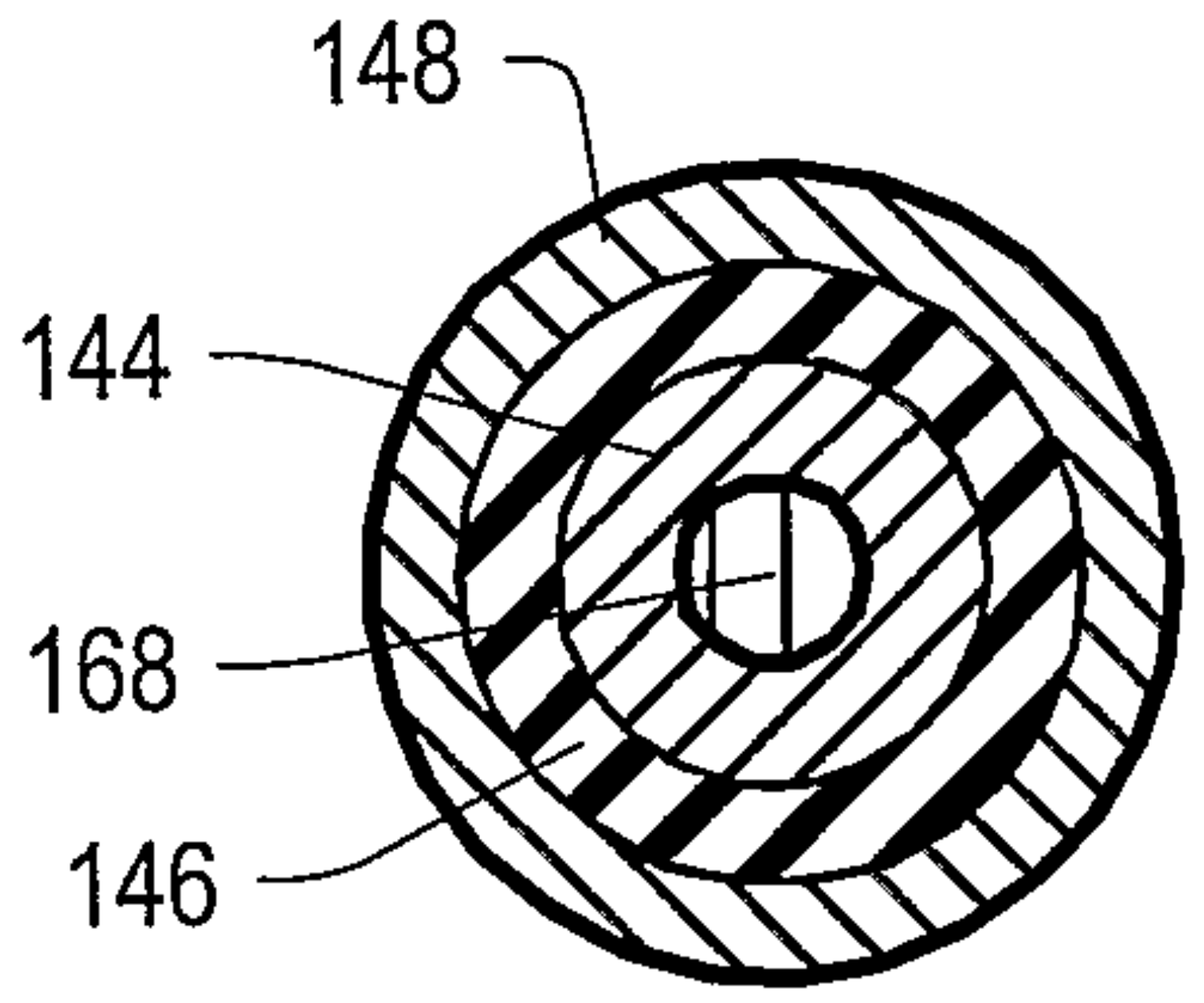


FIG. 17B

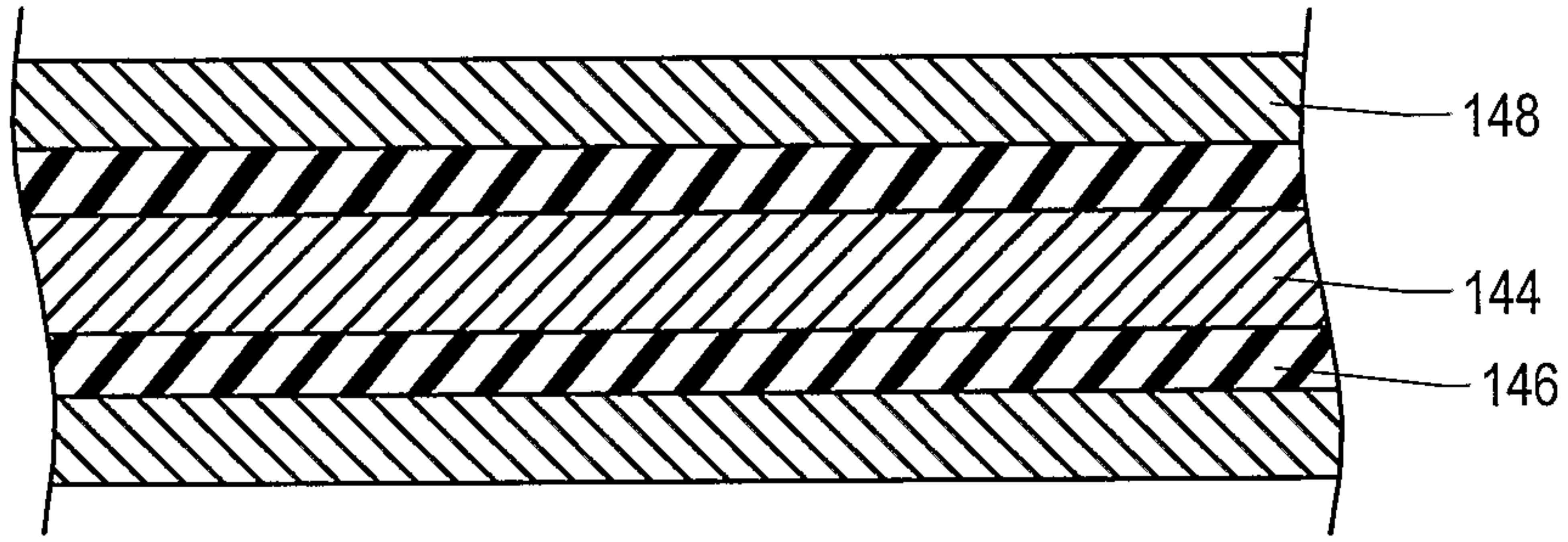


FIG. 18A

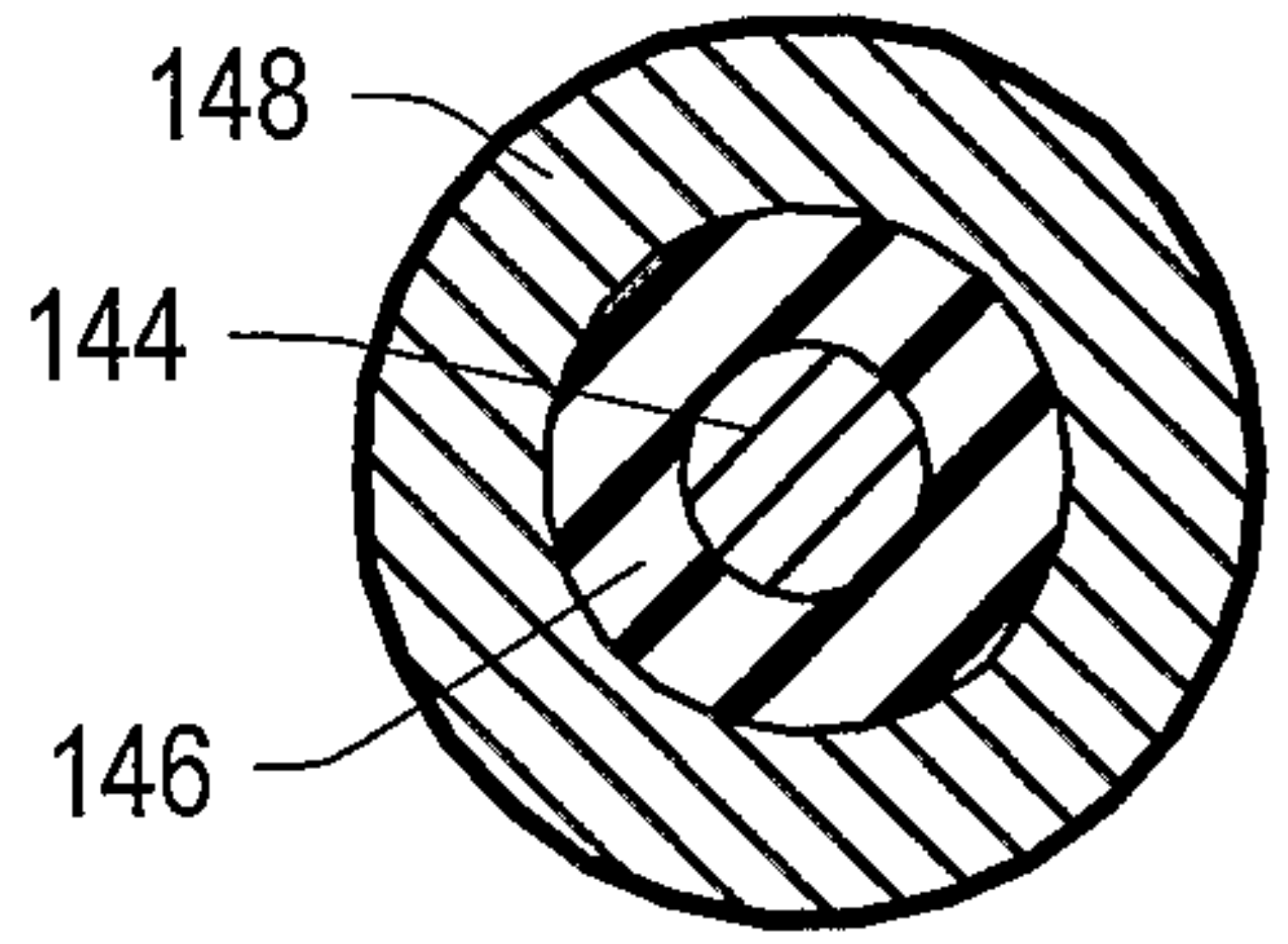


FIG. 18B

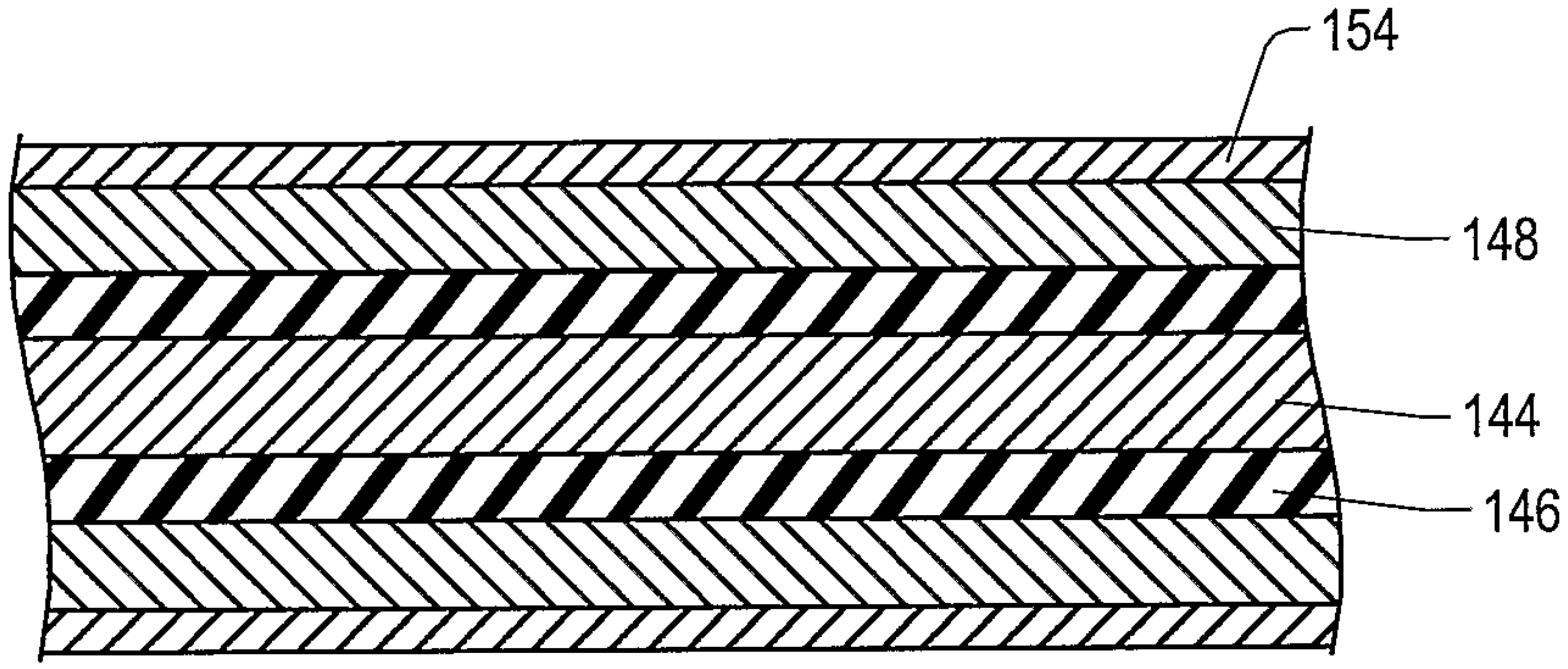


FIG. 19A

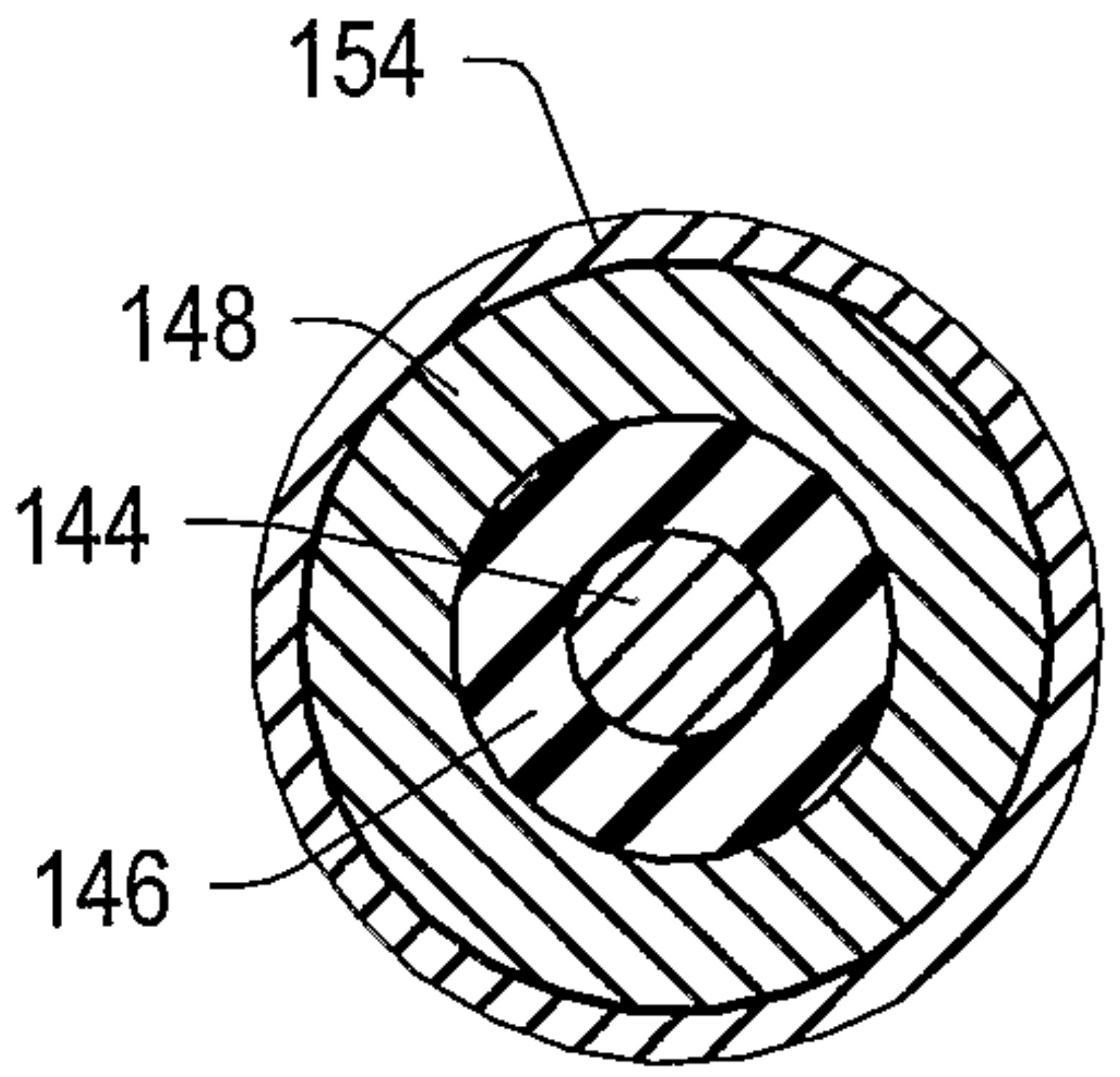


FIG. 19B

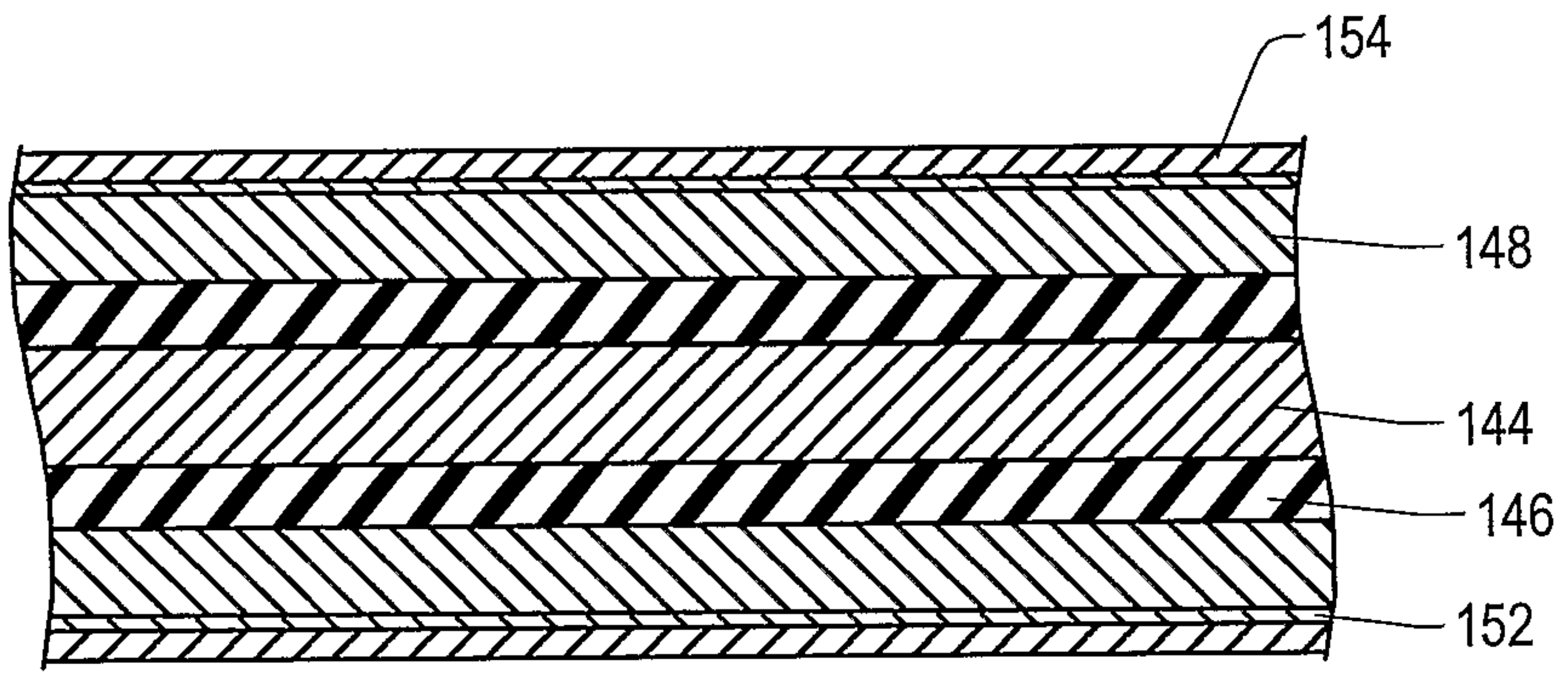


FIG. 20A

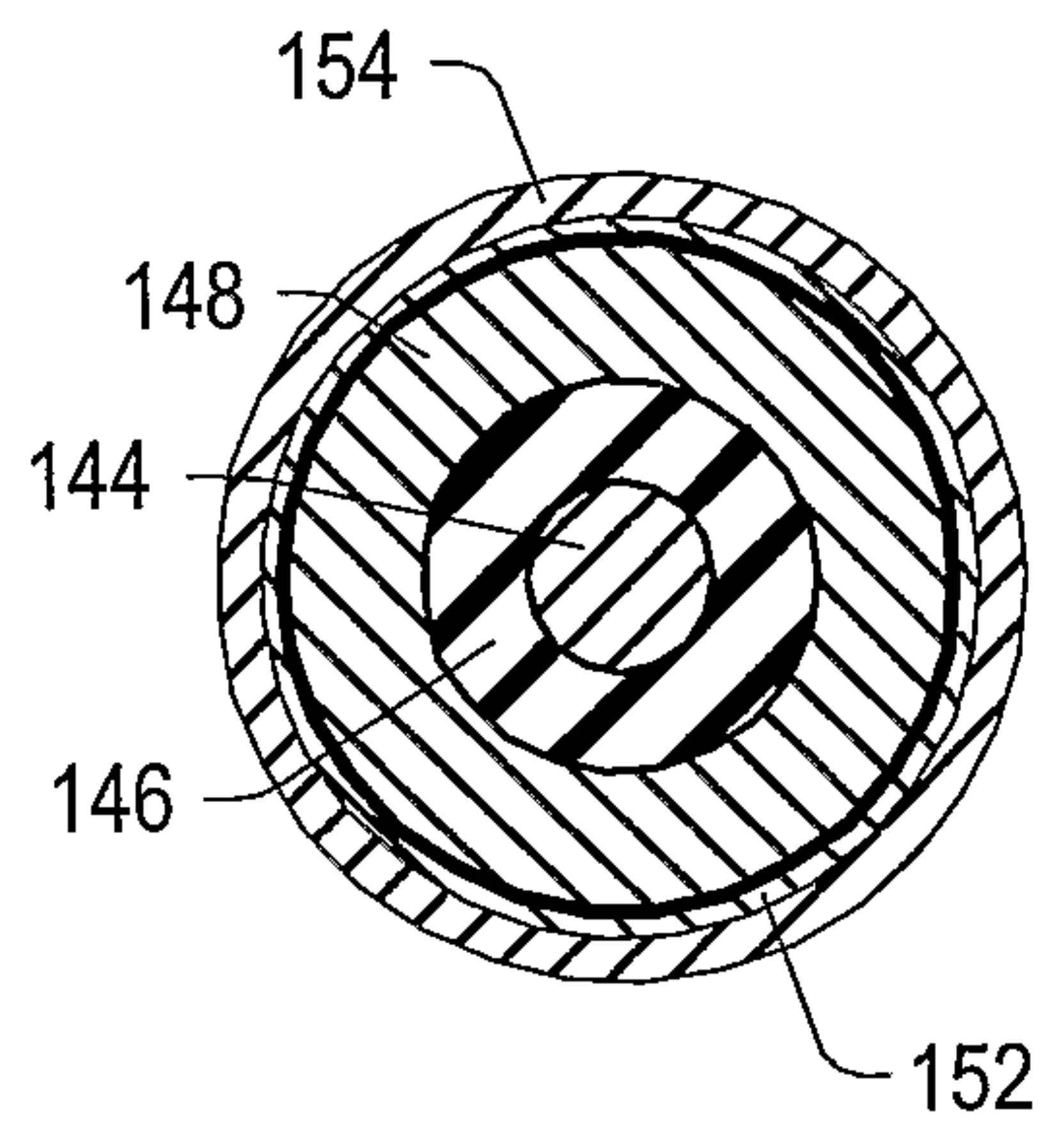


FIG. 20B

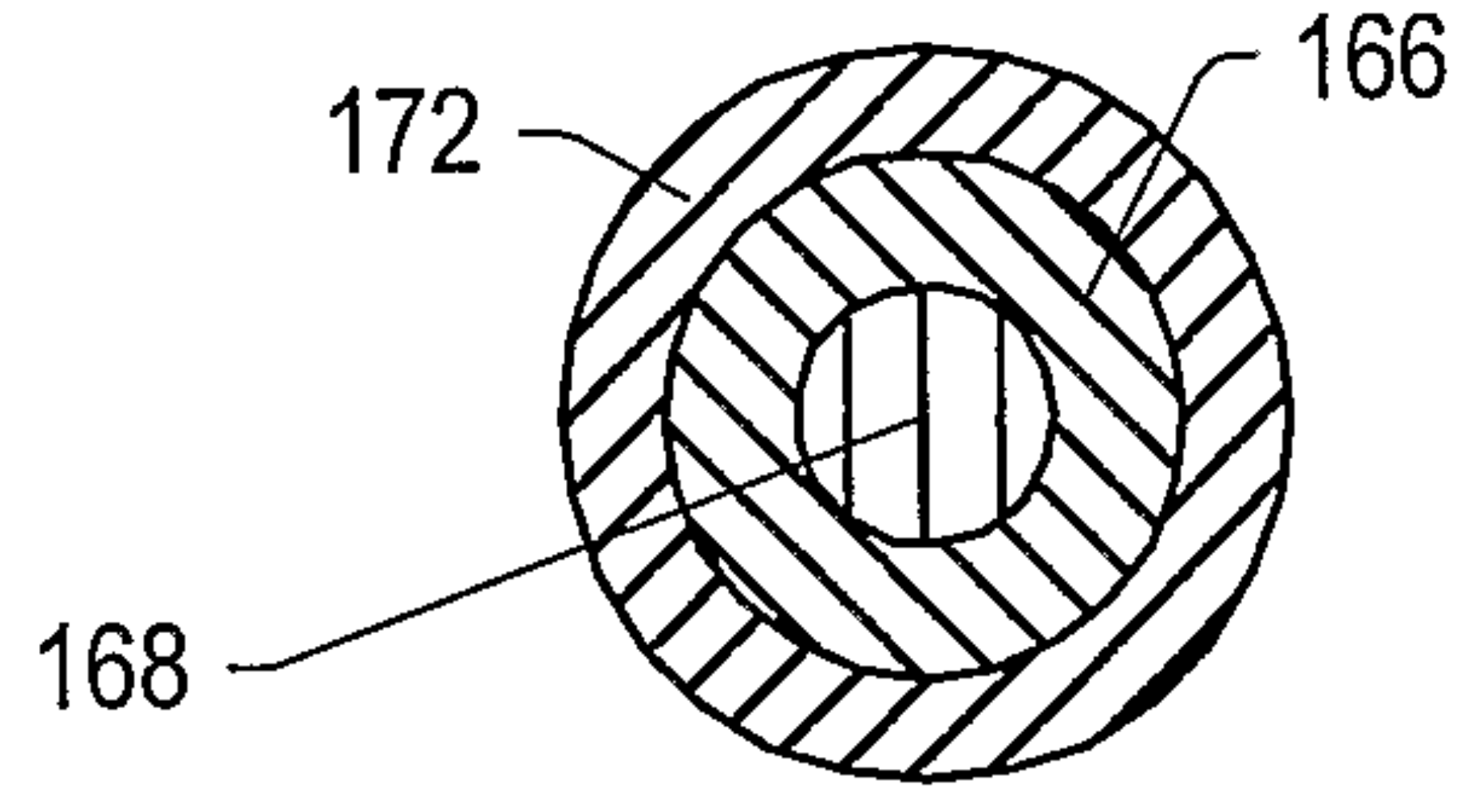


FIG. 21

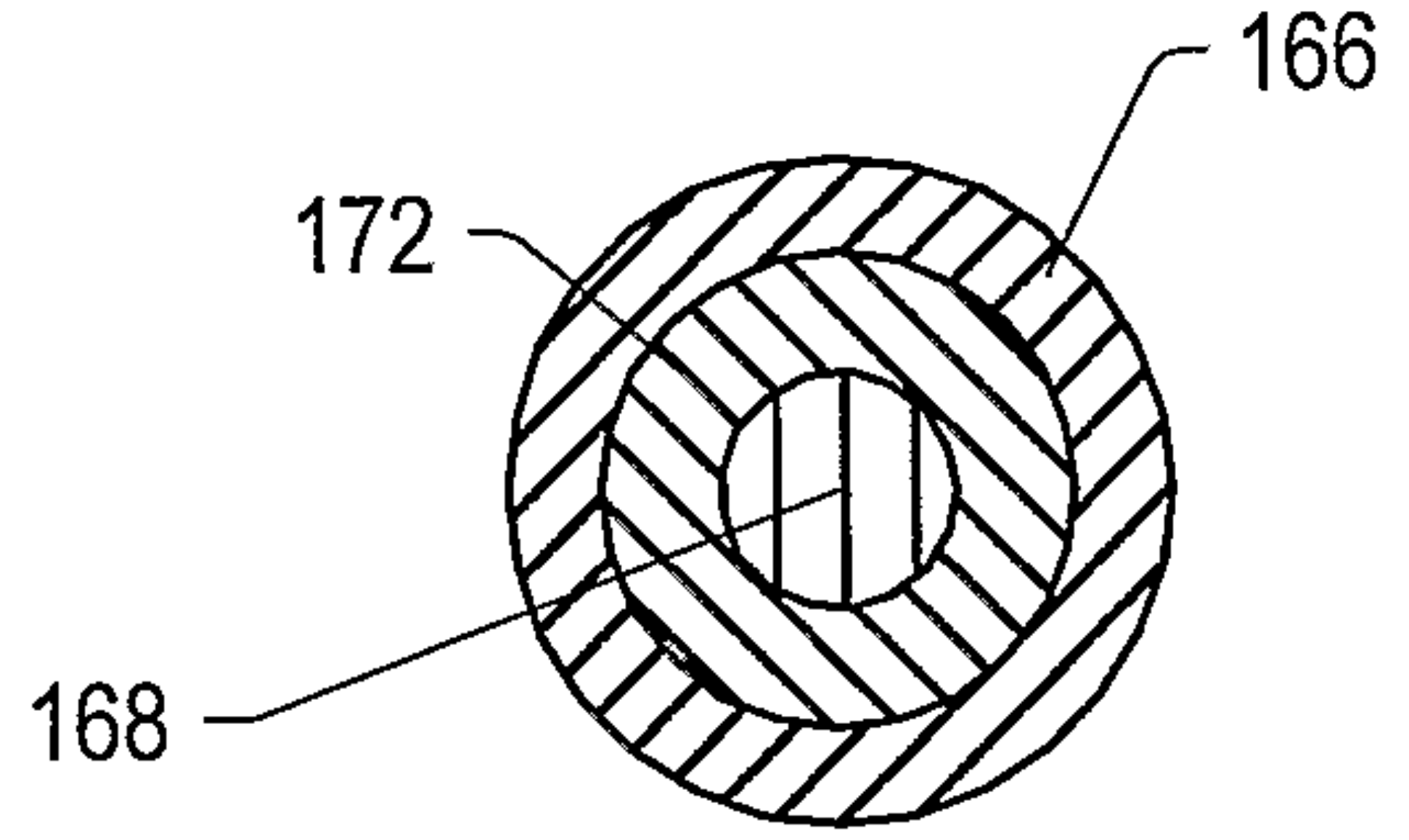


FIG. 22

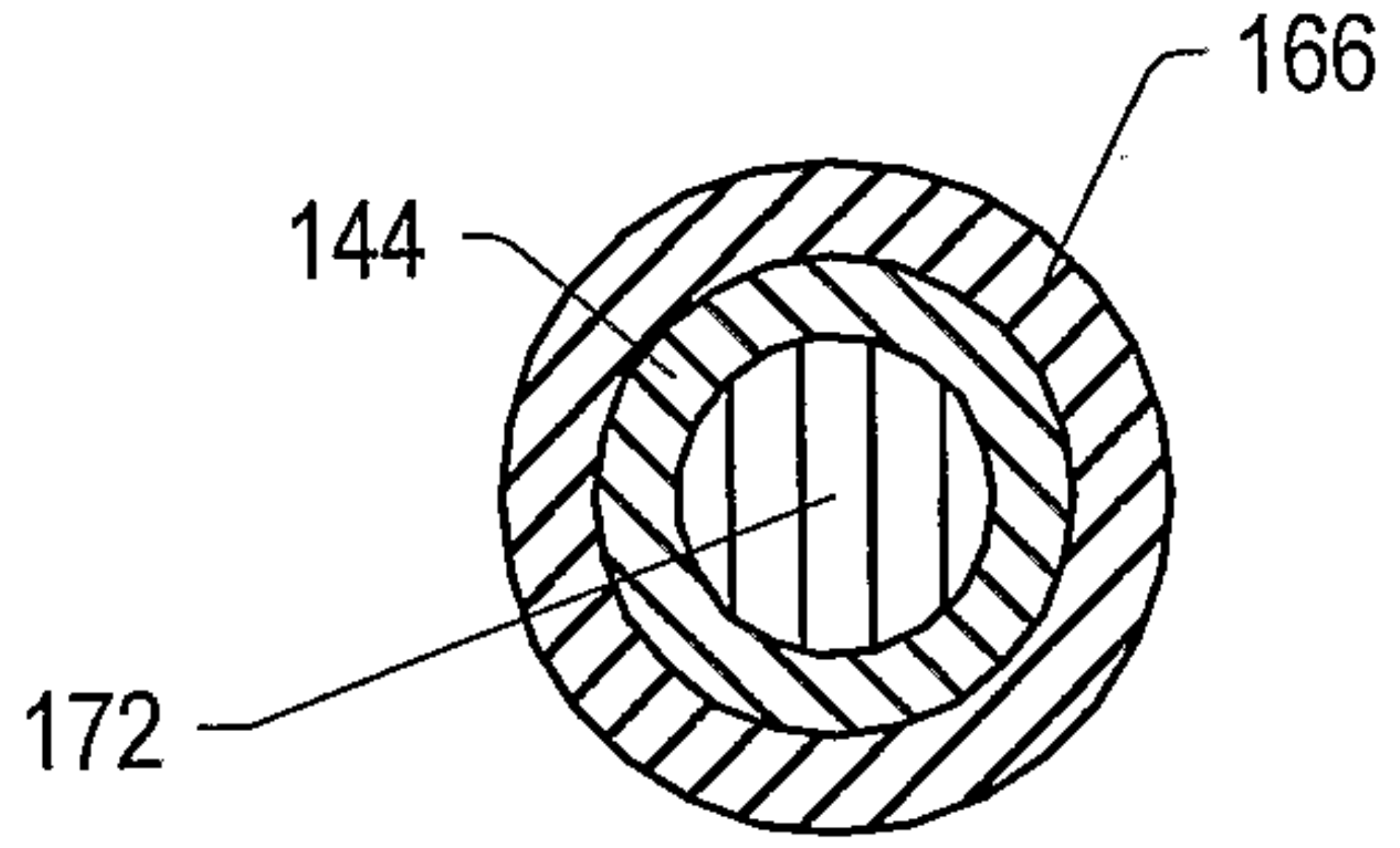


FIG. 23

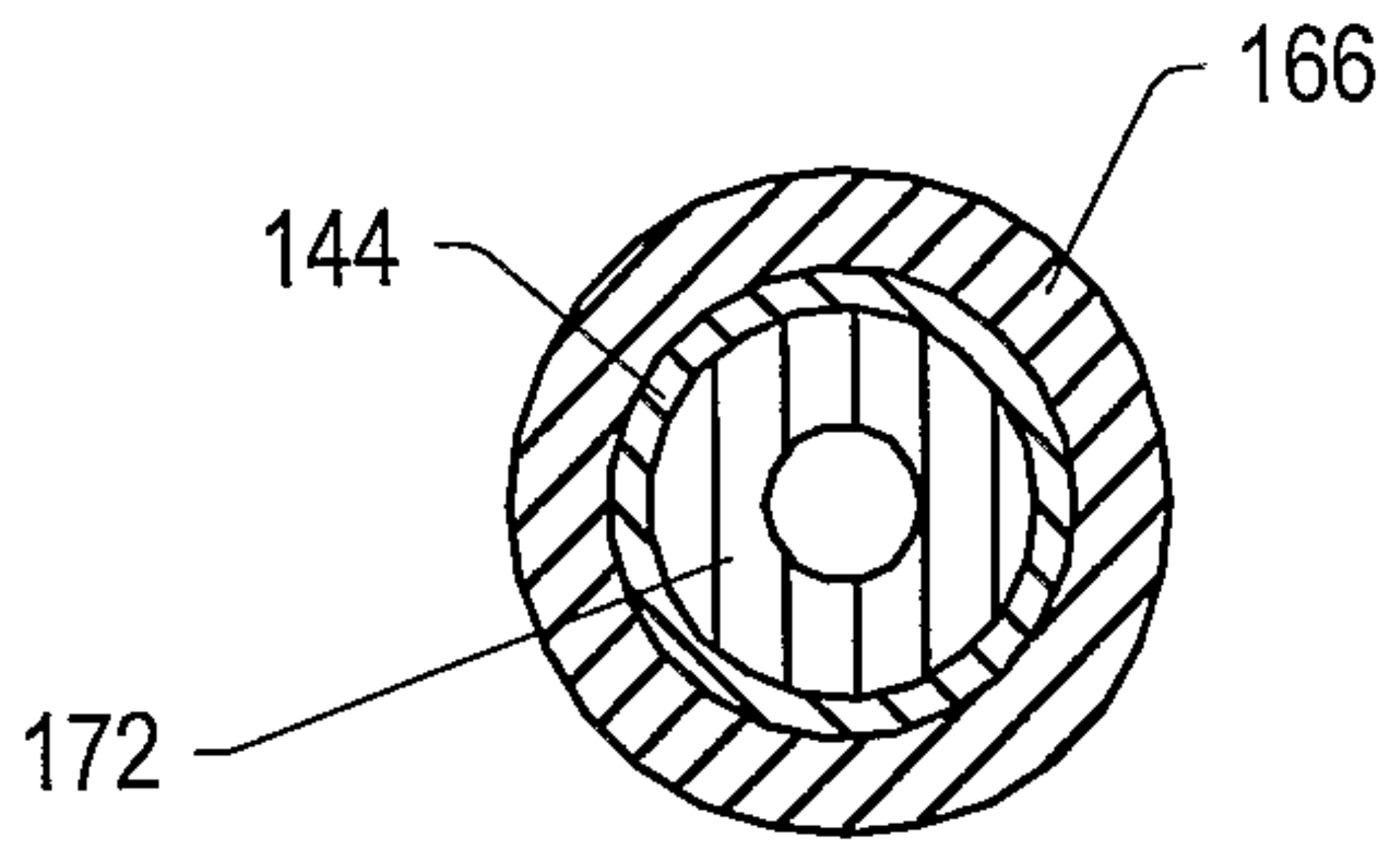


FIG. 24

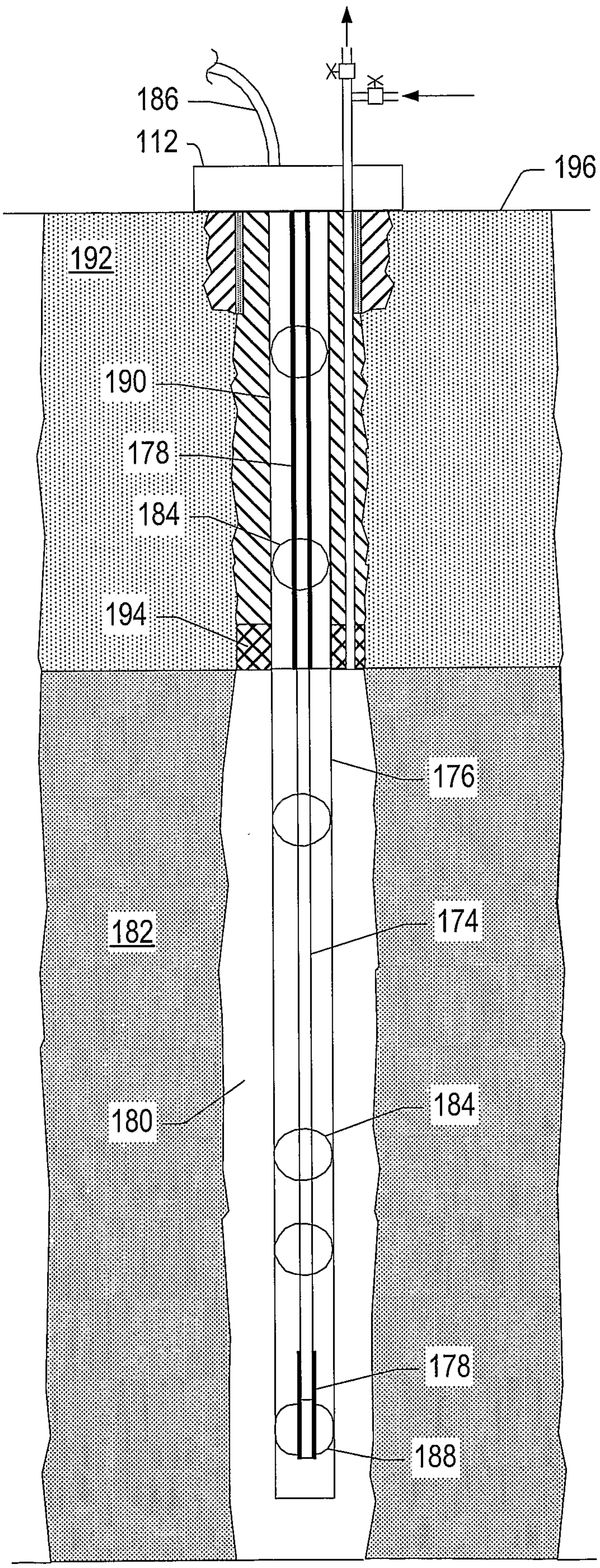


FIG. 25

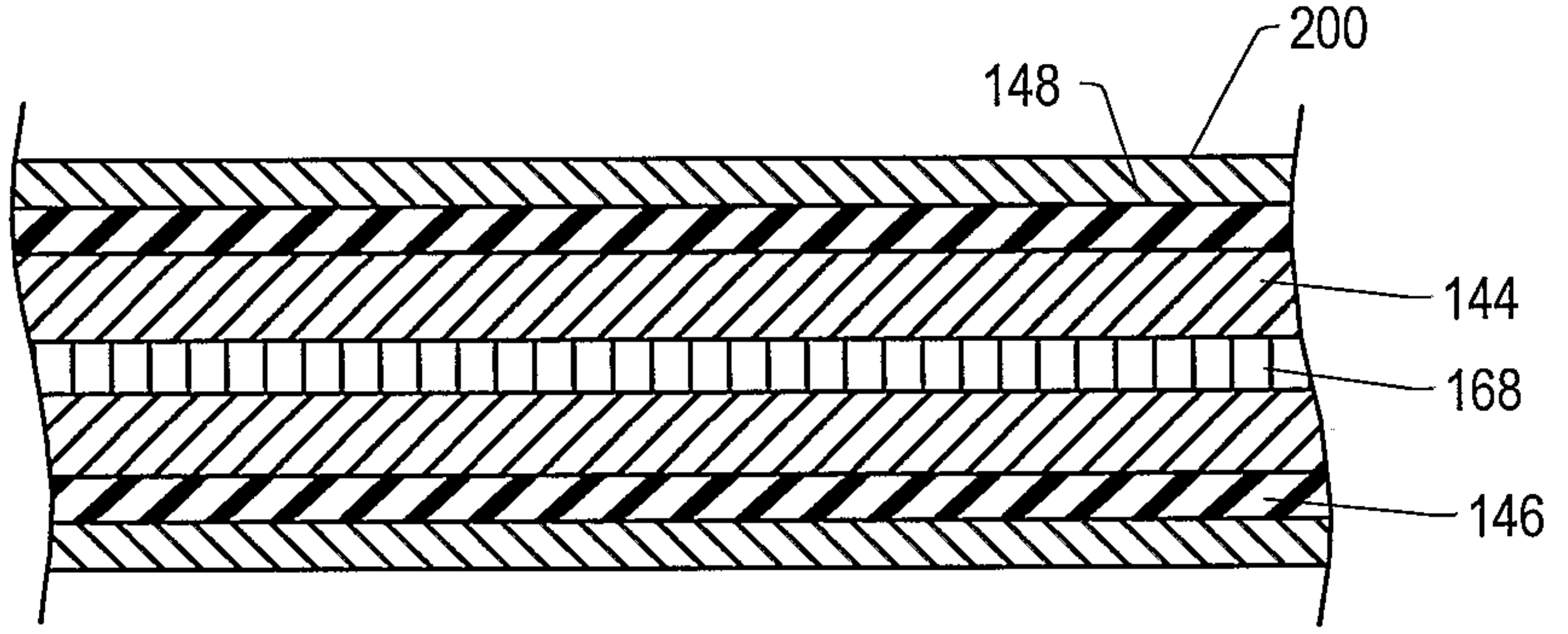


FIG. 26A

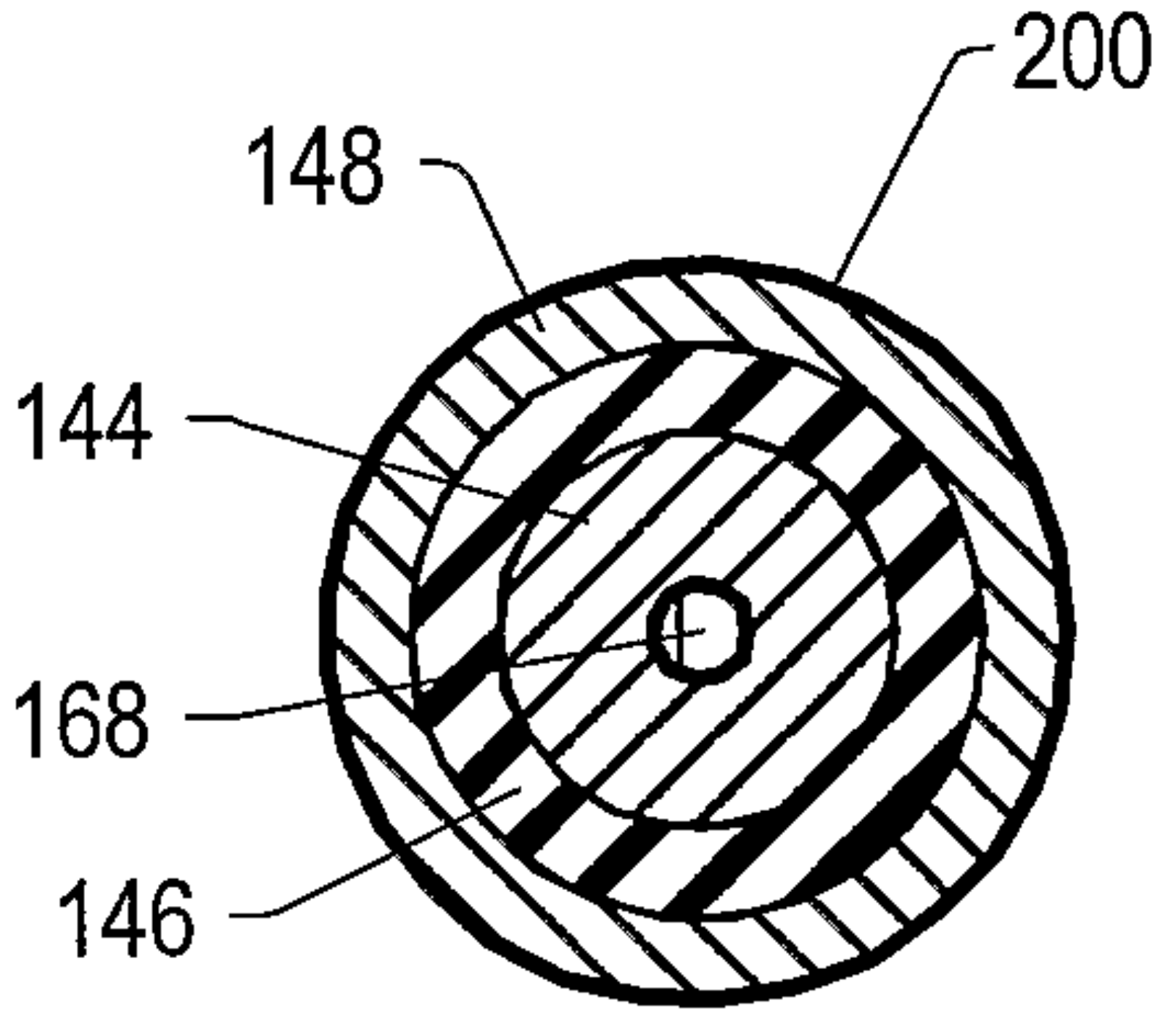


FIG. 26B

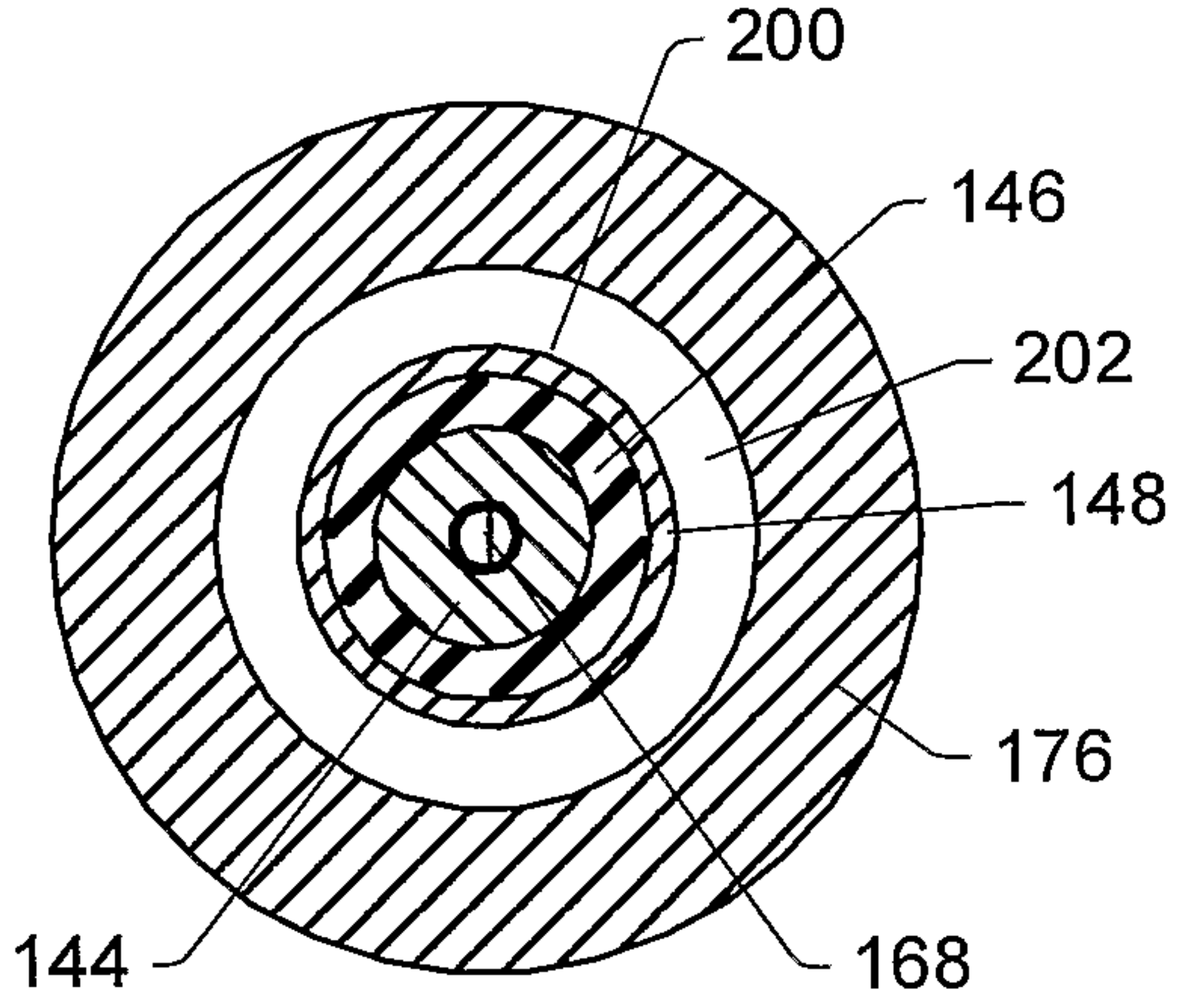


FIG. 28

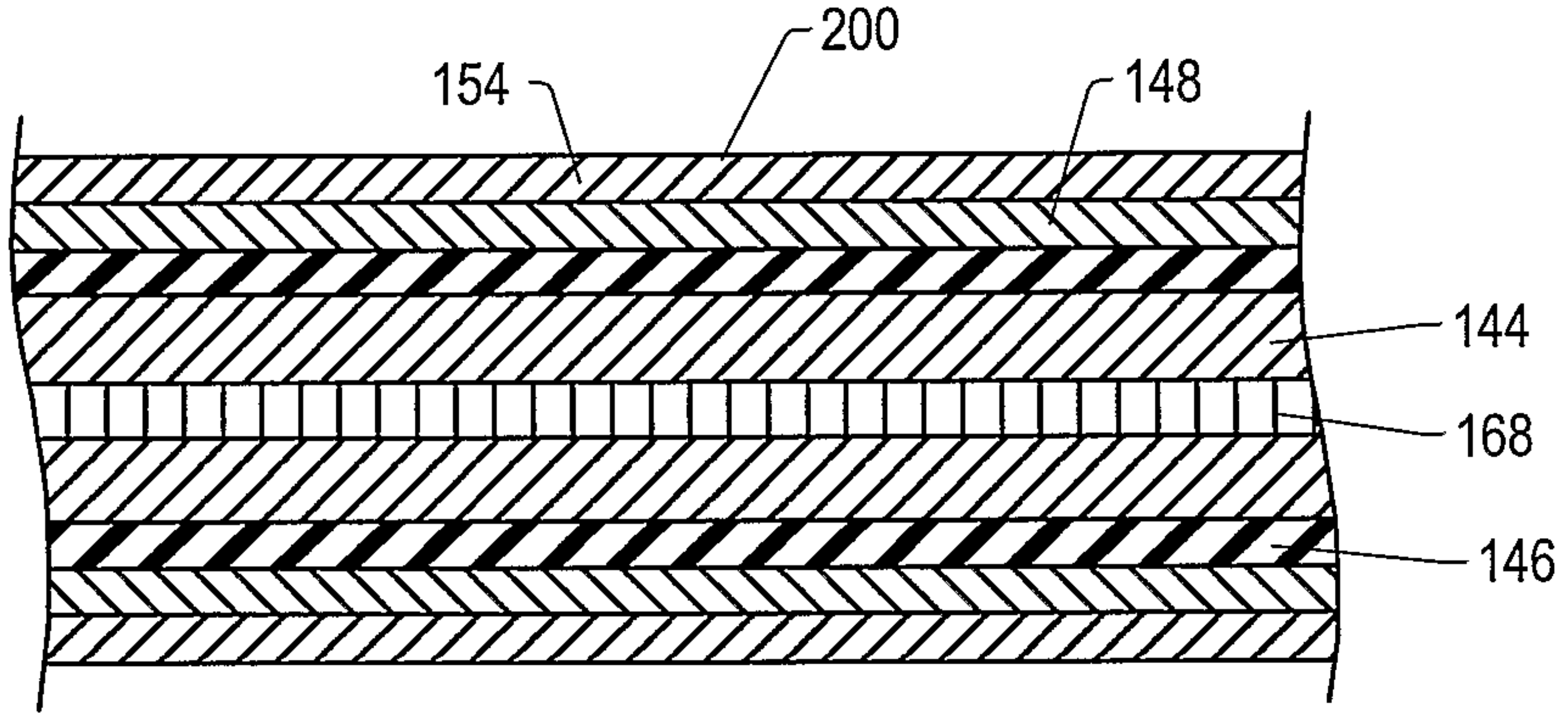


FIG. 27A

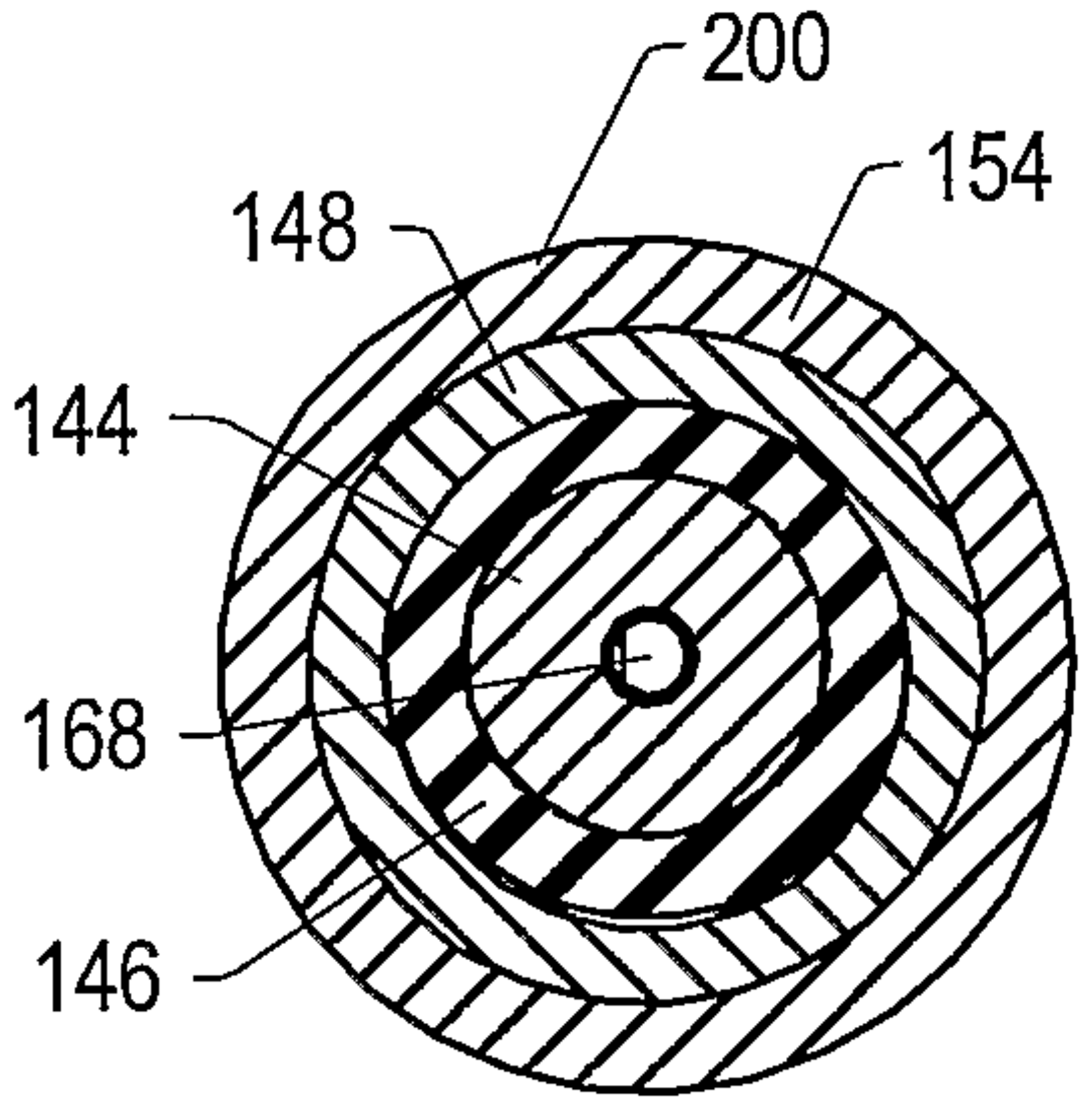


FIG. 27B

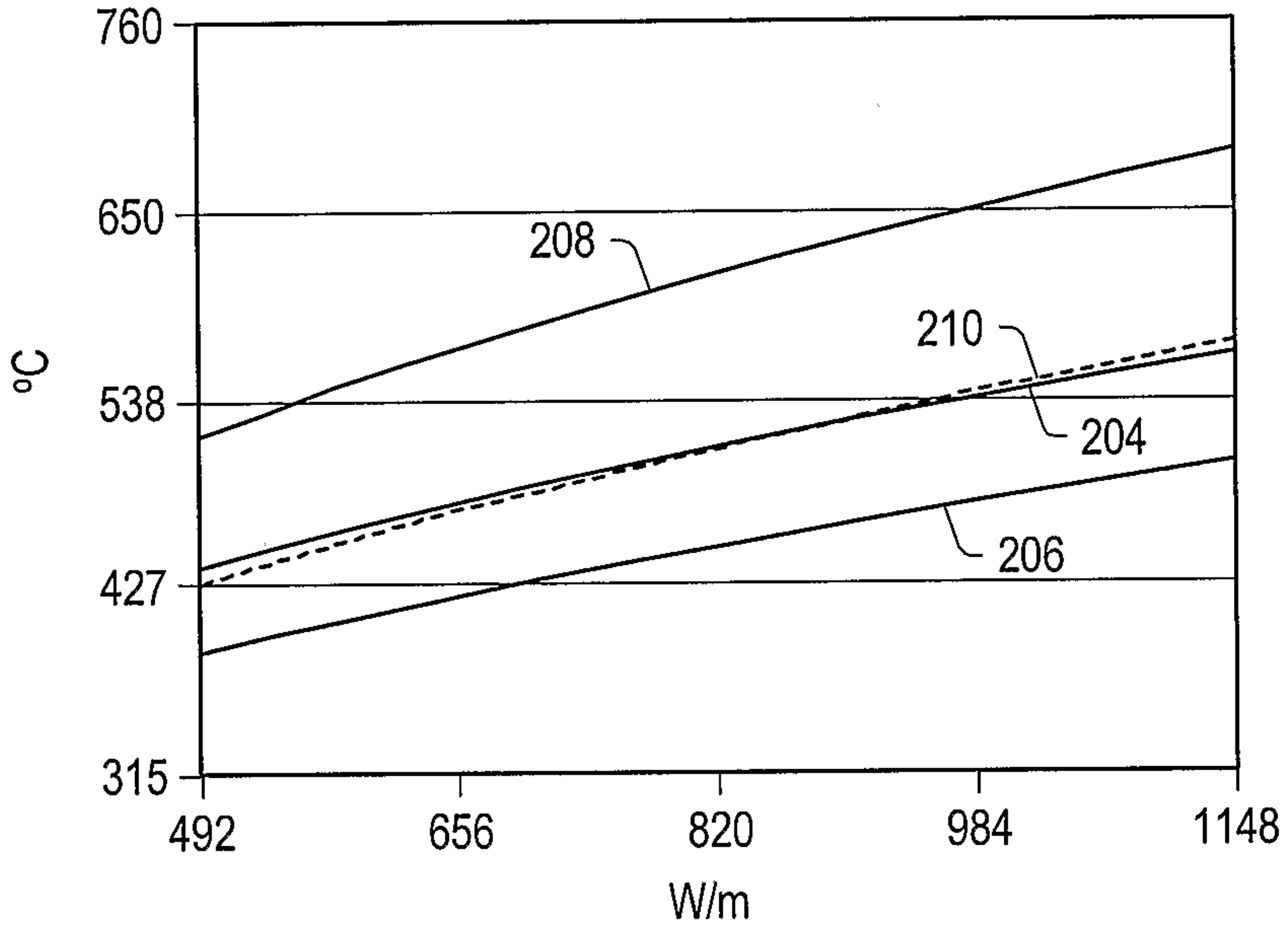

760
650
538
427
315
°C
492
656
820
984
1148
W/m
208
210
204
206

FIG. 29

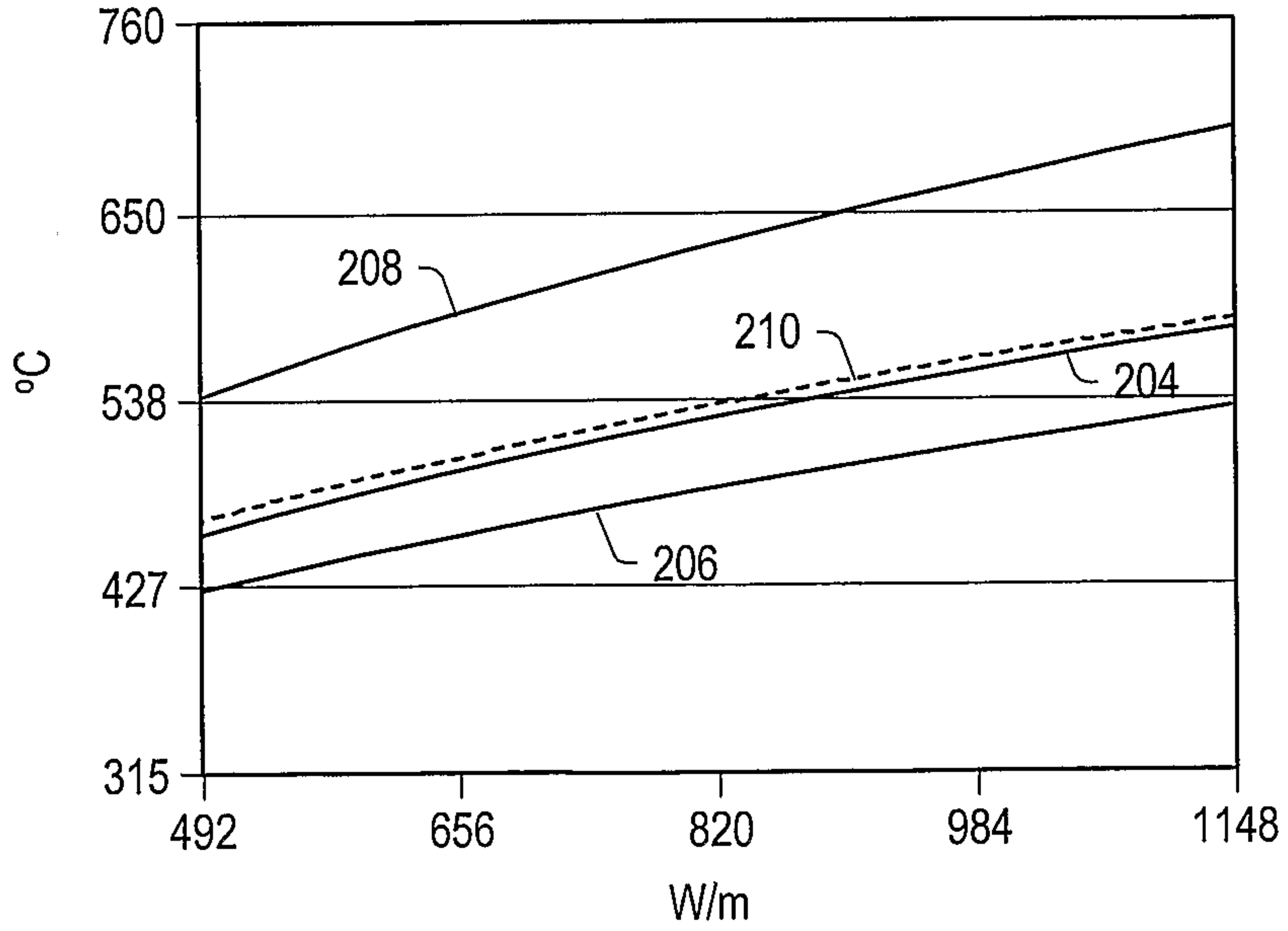

760
650
538
427
315
°C
492
656
820
984
1148
W/m
208
210
204
206

FIG. 30

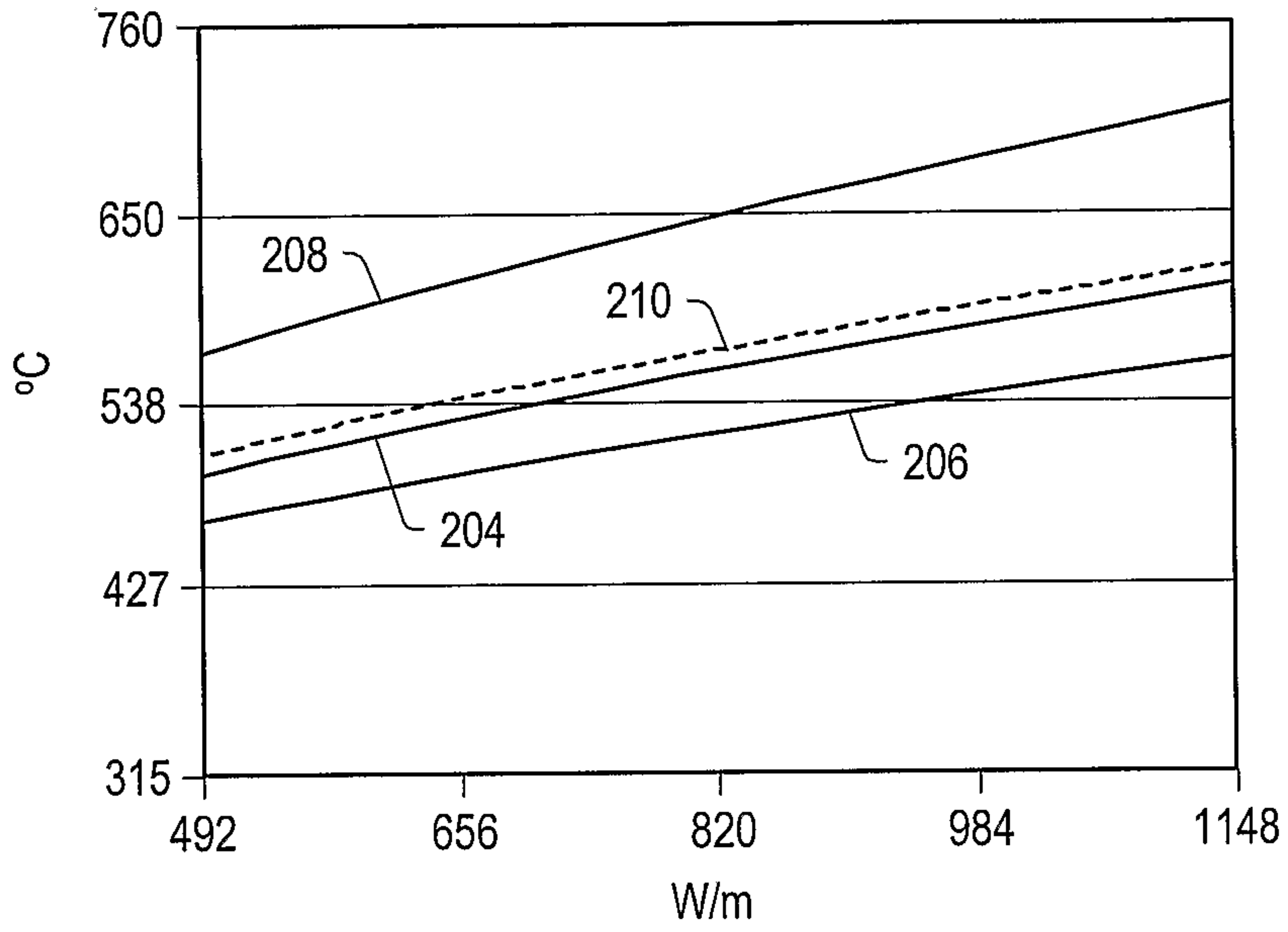

760
650
538
427
315
°C
208
210
204
206
492
656
820
984
1148
W/m

FIG. 31

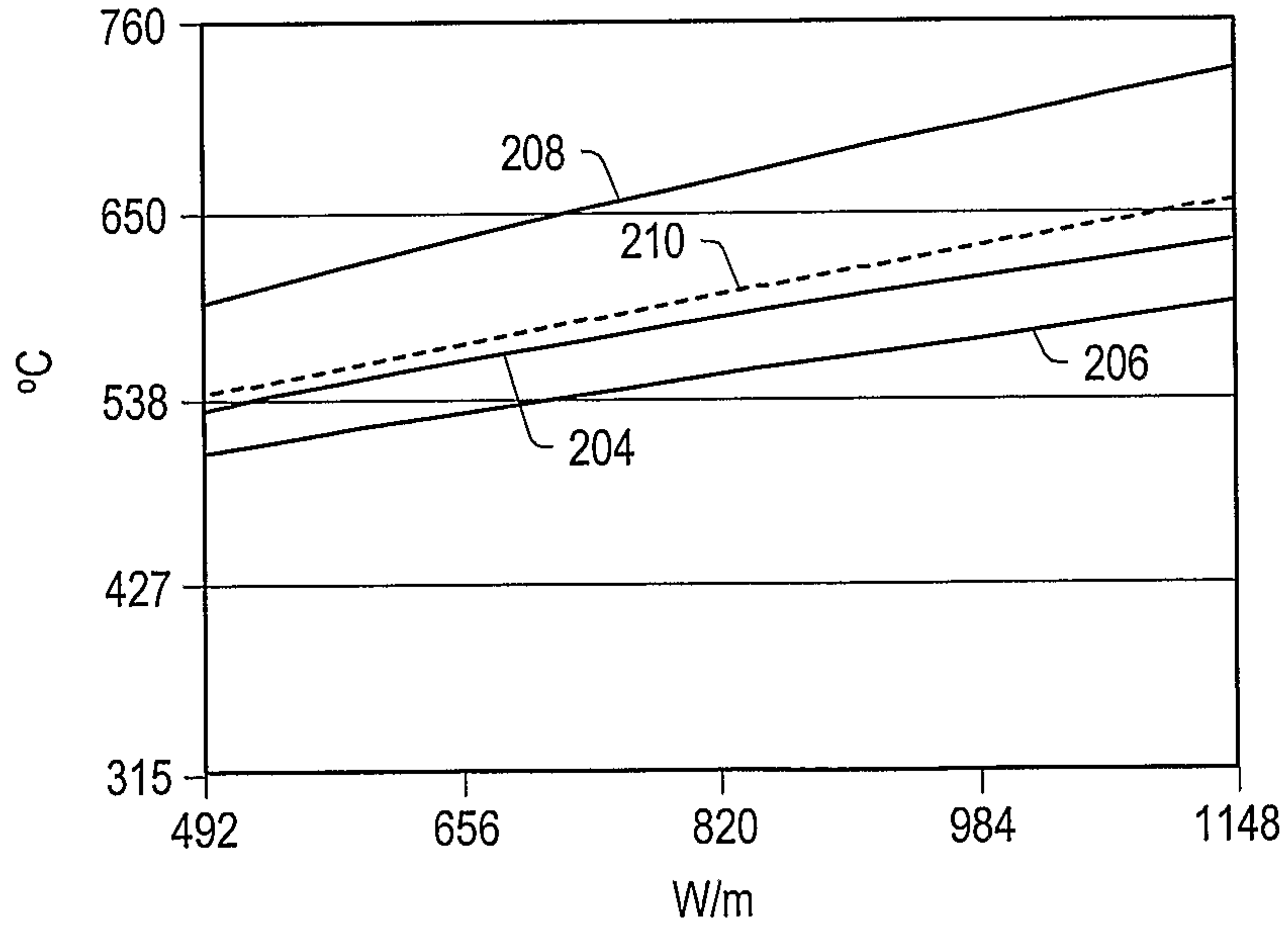

760
650
538
427
315
°C
208
210
204
206
492
656
820
984
1148
W/m

FIG. 32

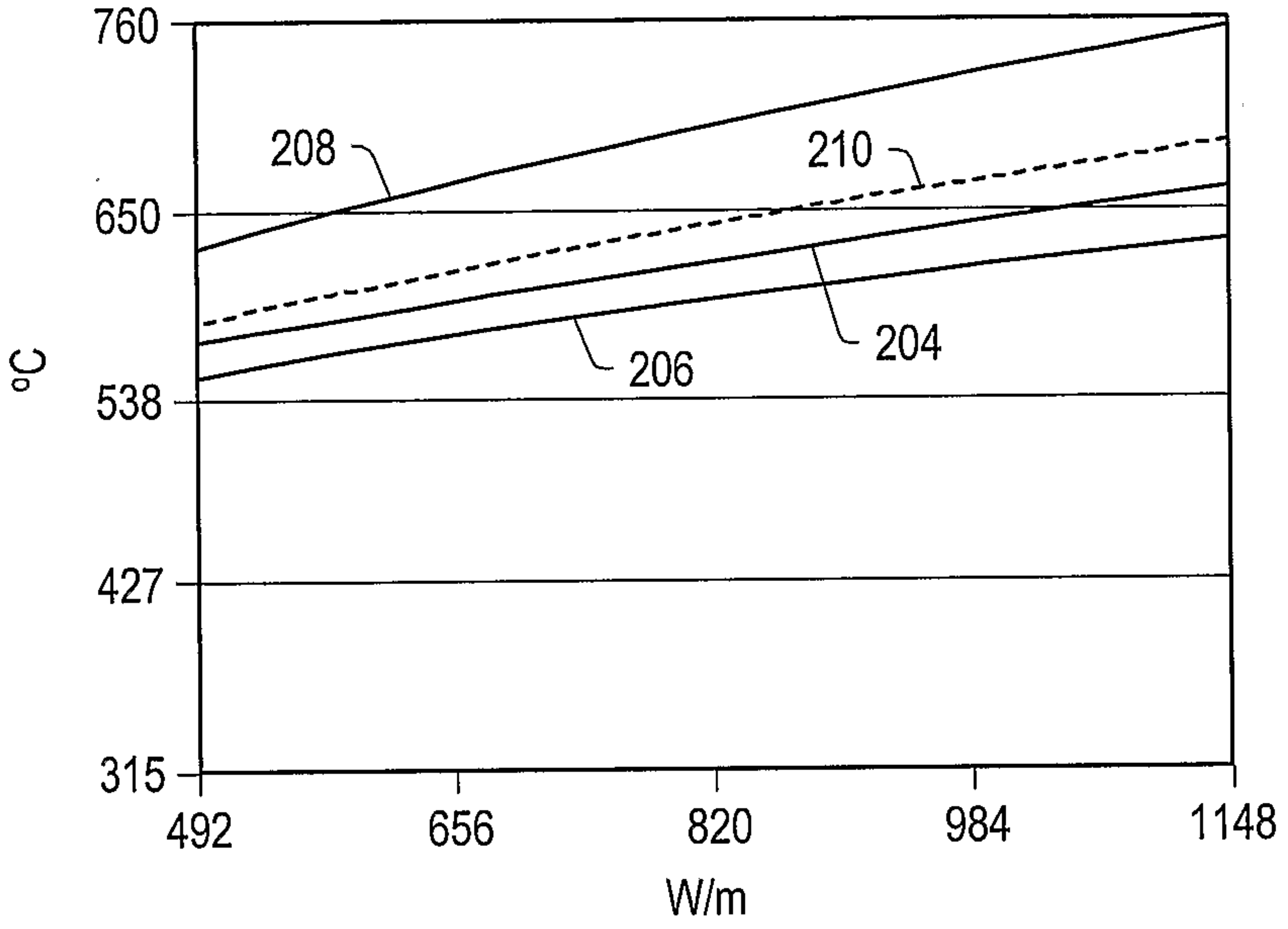

760
650
538
427
315
°C
208
210
204
206
492
656
820
984
1148
W/m

FIG. 33

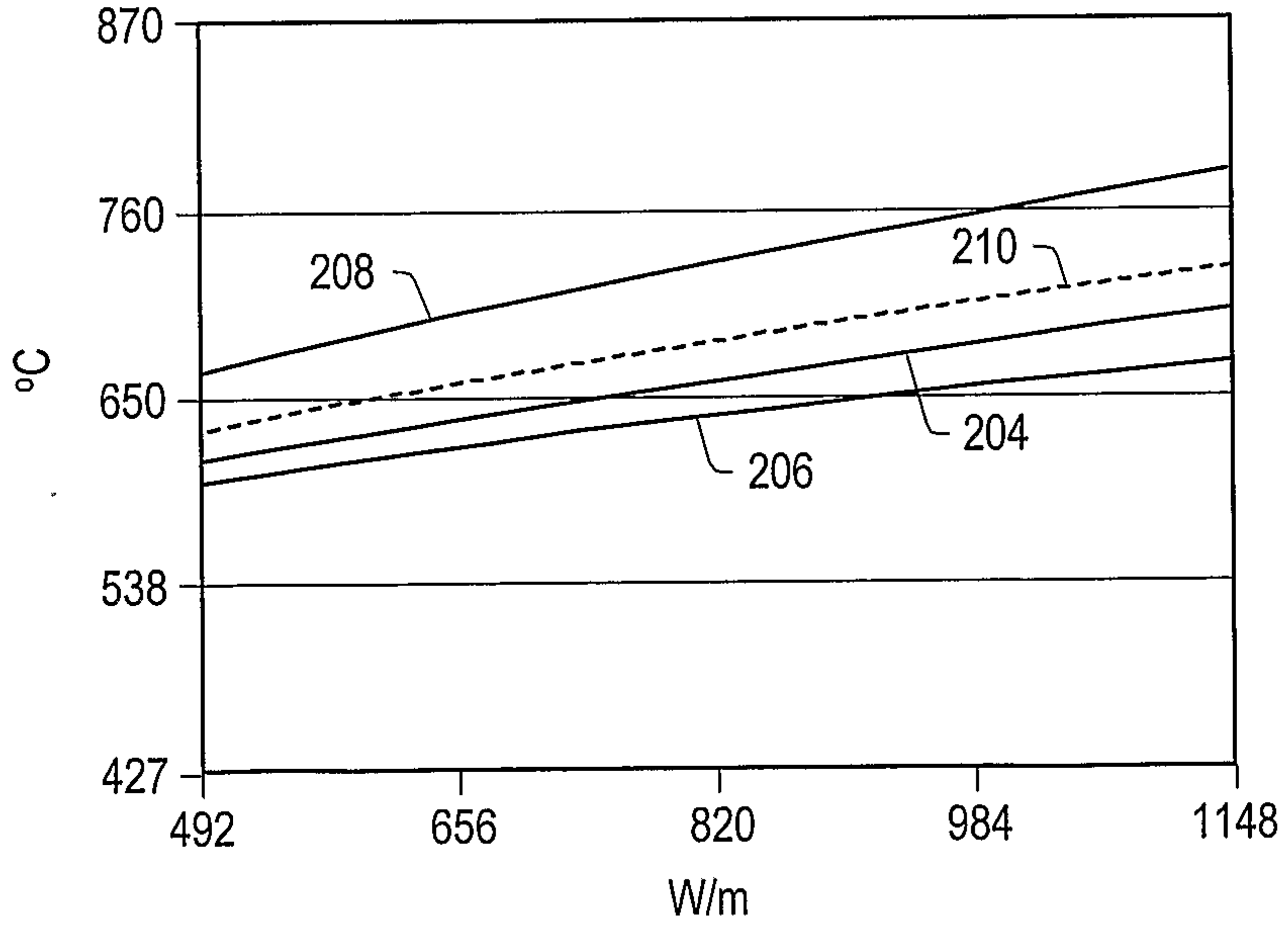

870
760
650
538
427
°C
208
210
204
206
492
656
820
984
1148
W/m

FIG. 34

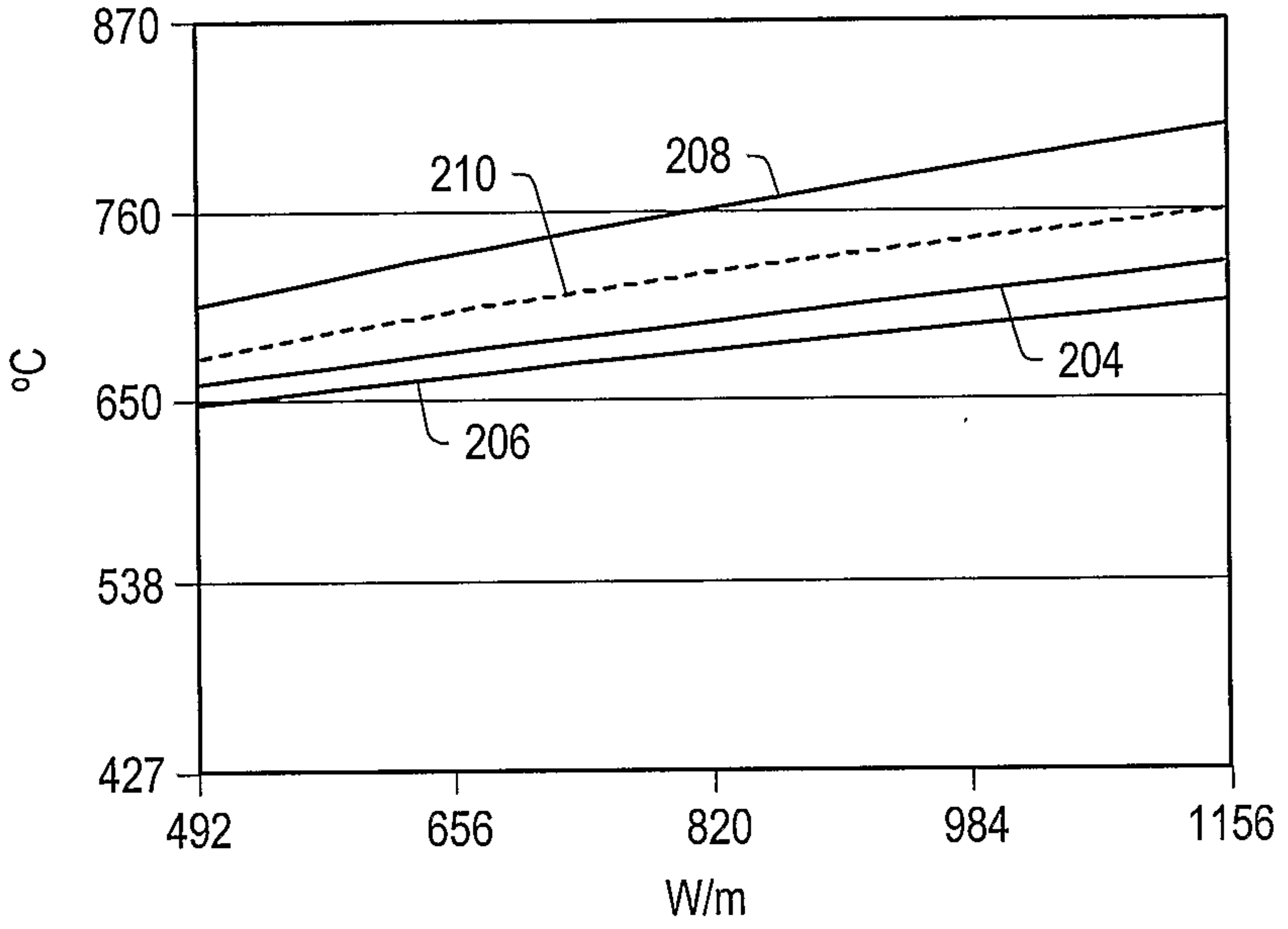

870
760
650
538
427
°C
492
656
820
984
1156
W/m
210
208
204
206

FIG. 35

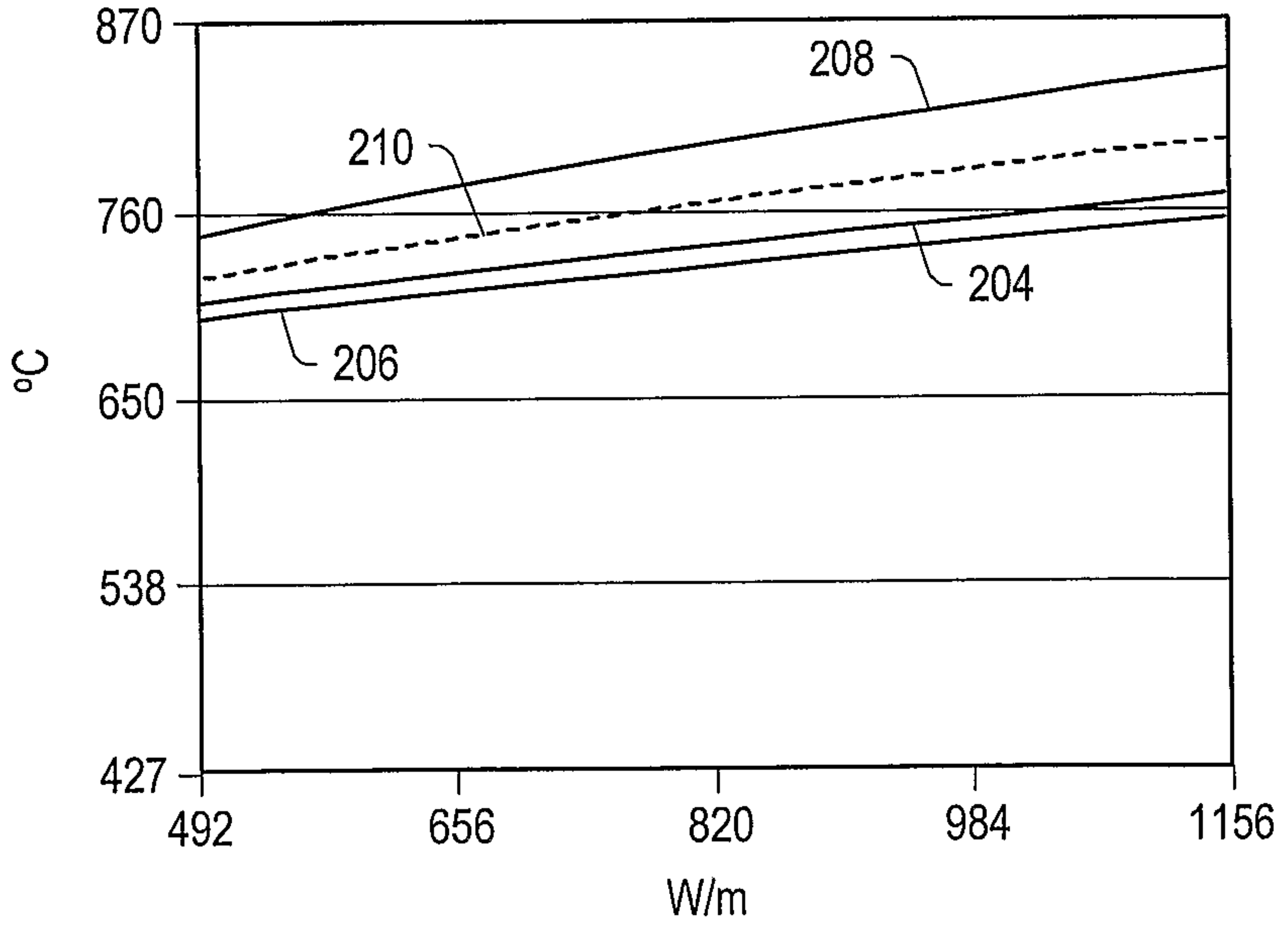

870
760
650
538
427
°C
492
656
820
984
1156
W/m
208
210
204
206

FIG. 36

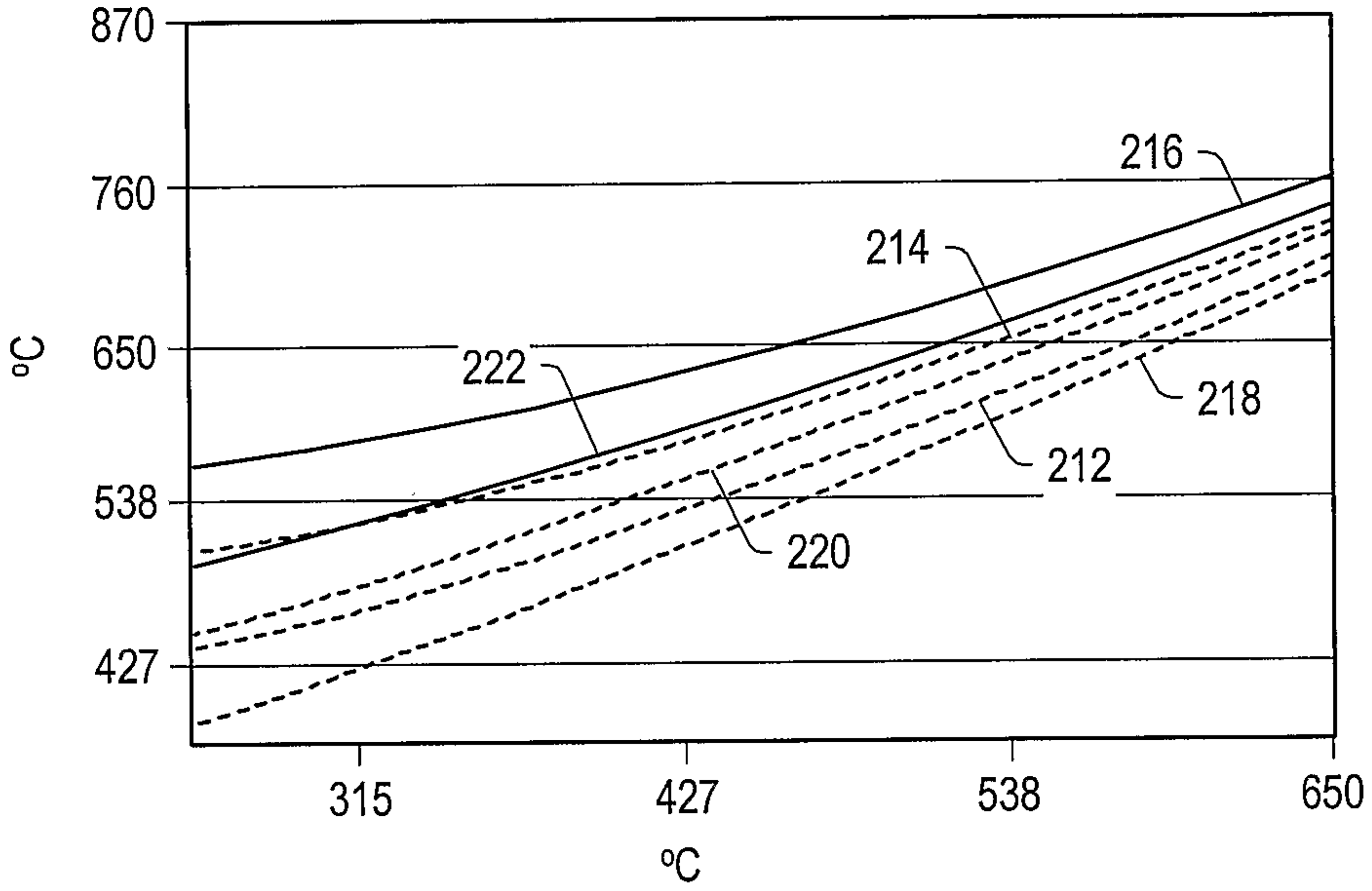

870
760
650
538
427
°C
315
427
538
650
°C
216
214
222
218
212
220

FIG. 37

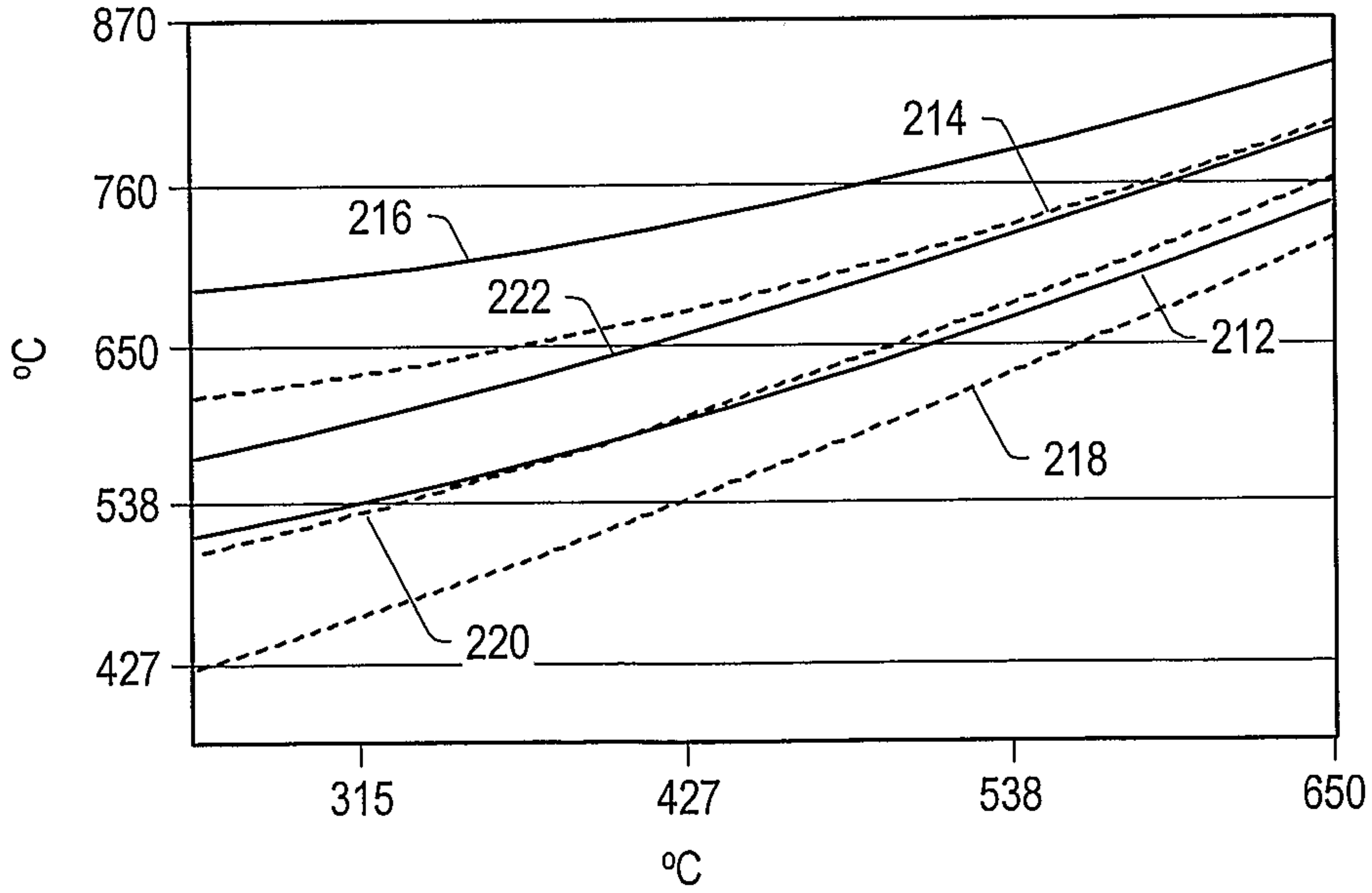

870
760
650
538
427
°C
315
427
538
650
°C
214
216
222
212
218
220

FIG. 38

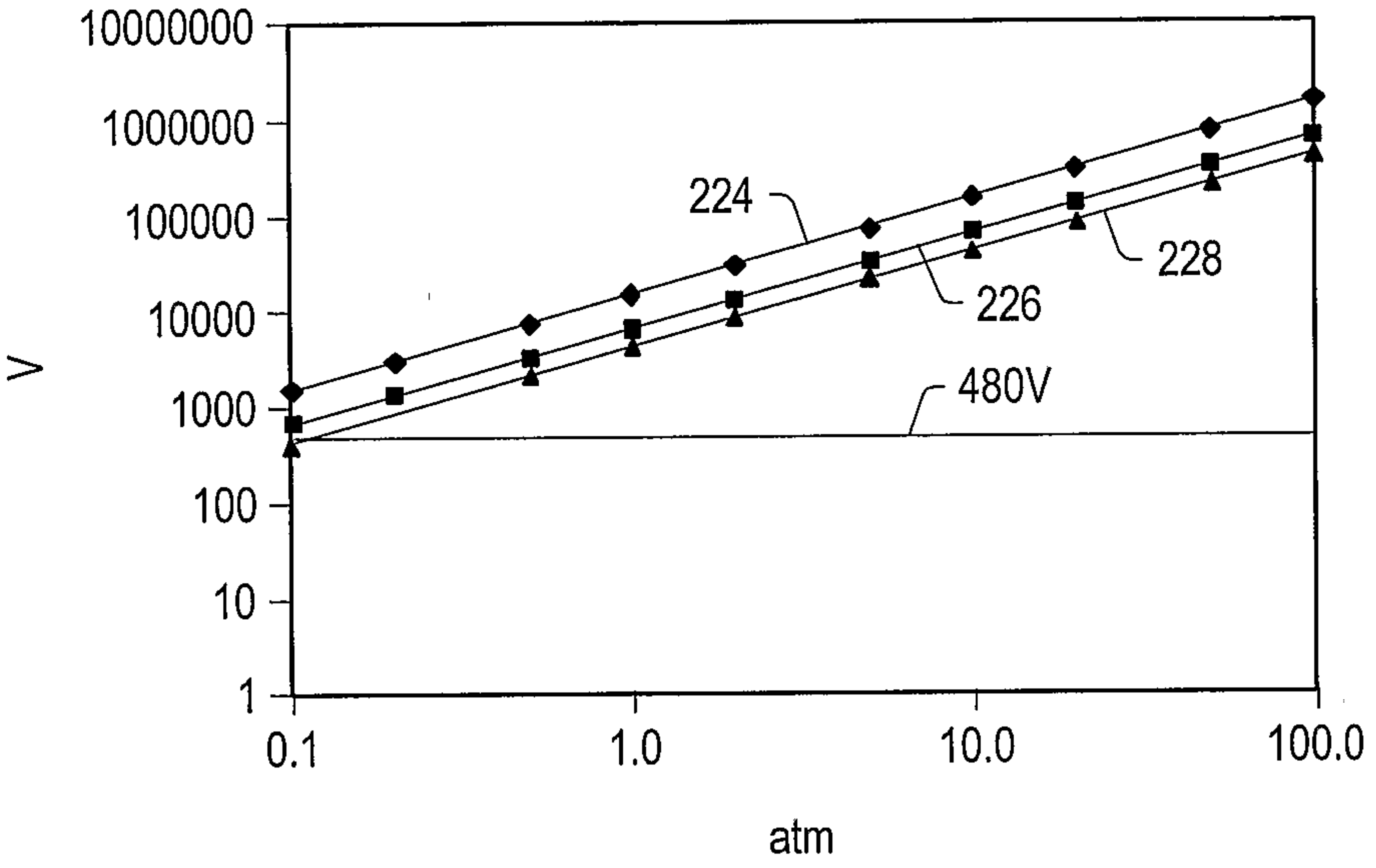

10000000
1000000
100000
10000
1000
100
10
1
V
224
226
228
480V
0.1
1.0
10.0
100.0
atm

FIG. 39

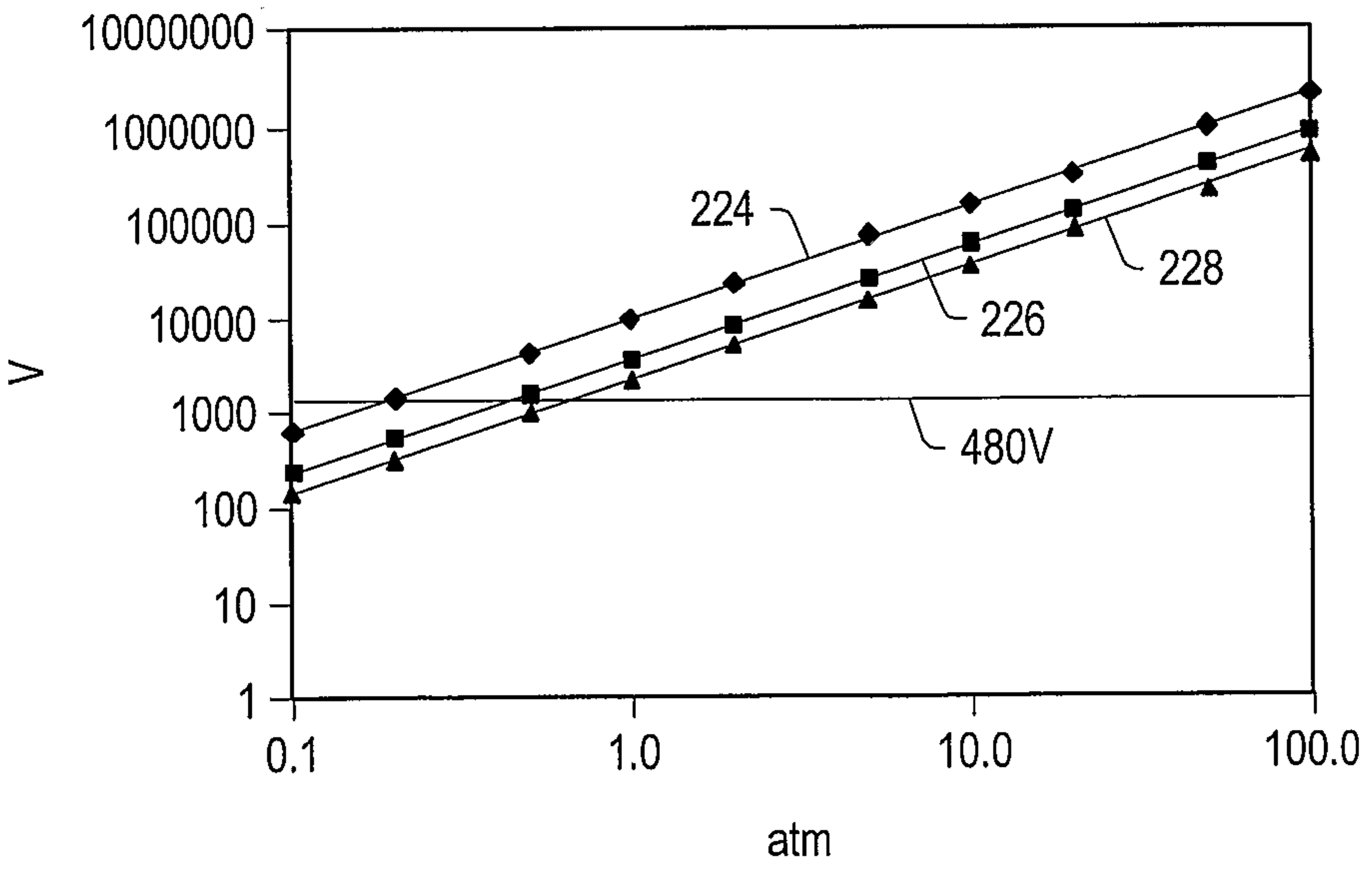

10000000
1000000
100000
10000
1000
100
10
1
V
224
226
228
480V
0.1
1.0
10.0
100.0
atm

FIG. 40

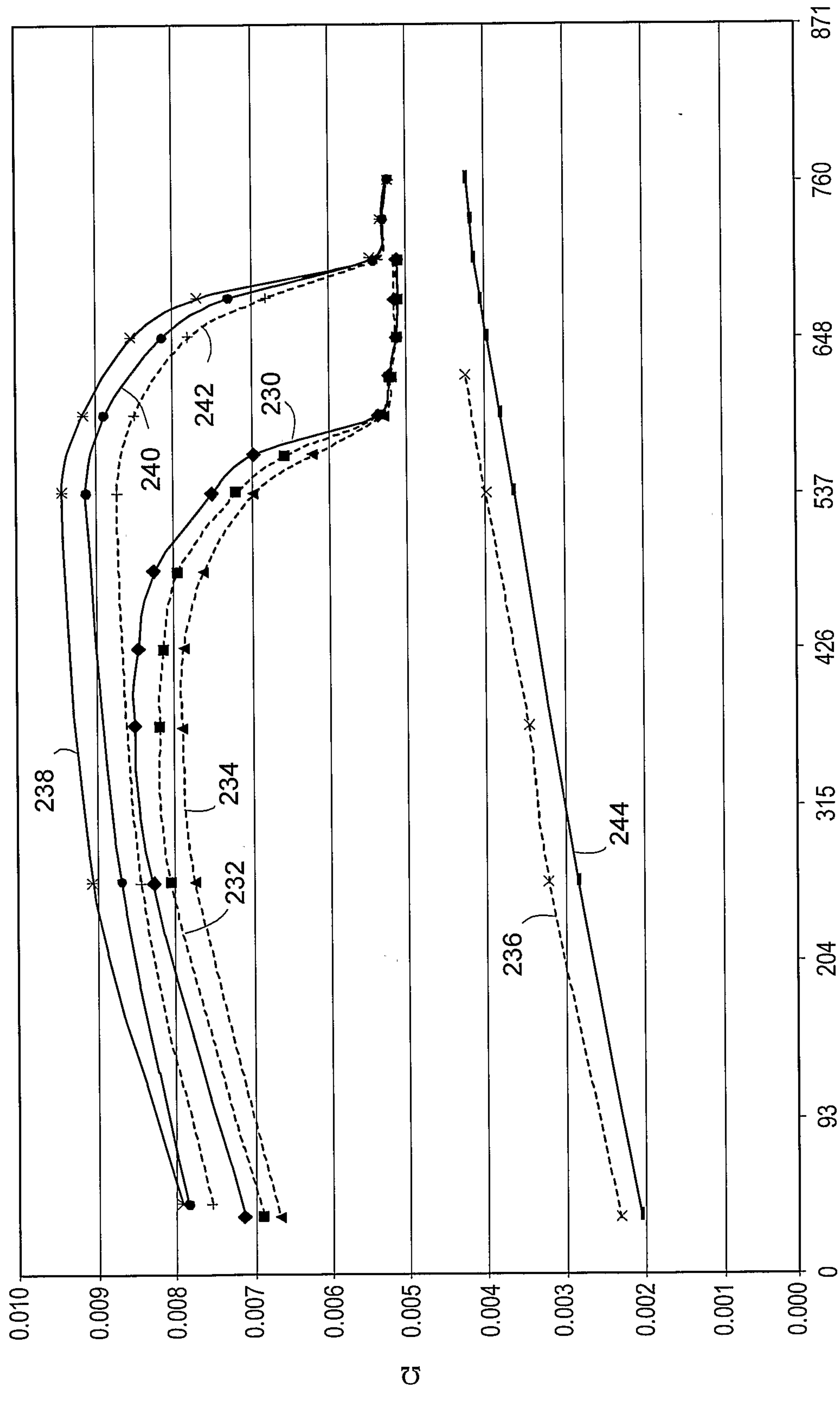

0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Ω
0
93
204
315
426
537
648
760
871
°C
238
234
232
240
242
230
236
244

FIG. 41

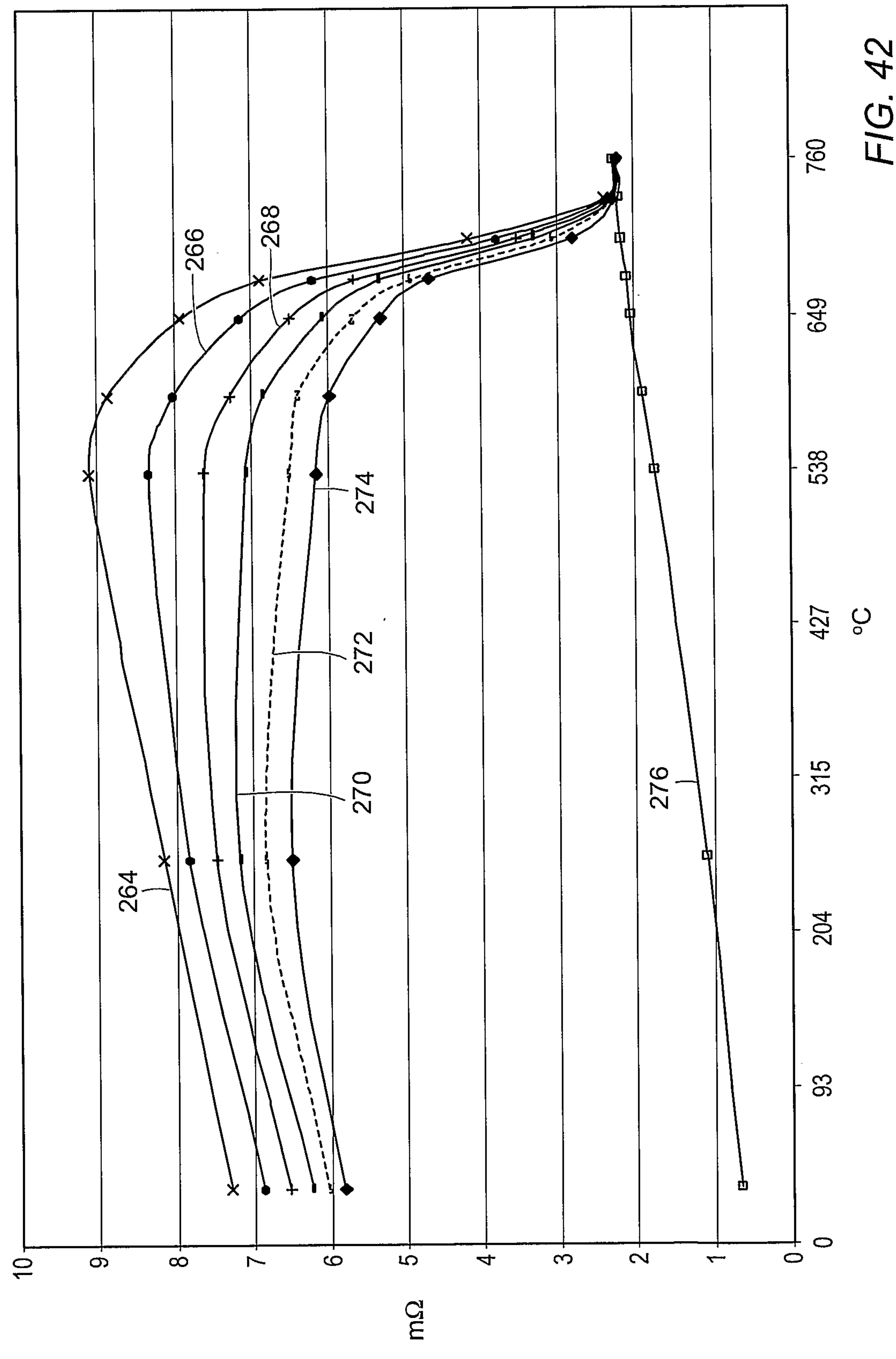

mΩ
10
9
8
7
6
5
4
3
2
1
0
°C
0
93
204
315
427
538
649
760
264
266
268
270
272
274
276

FIG. 42

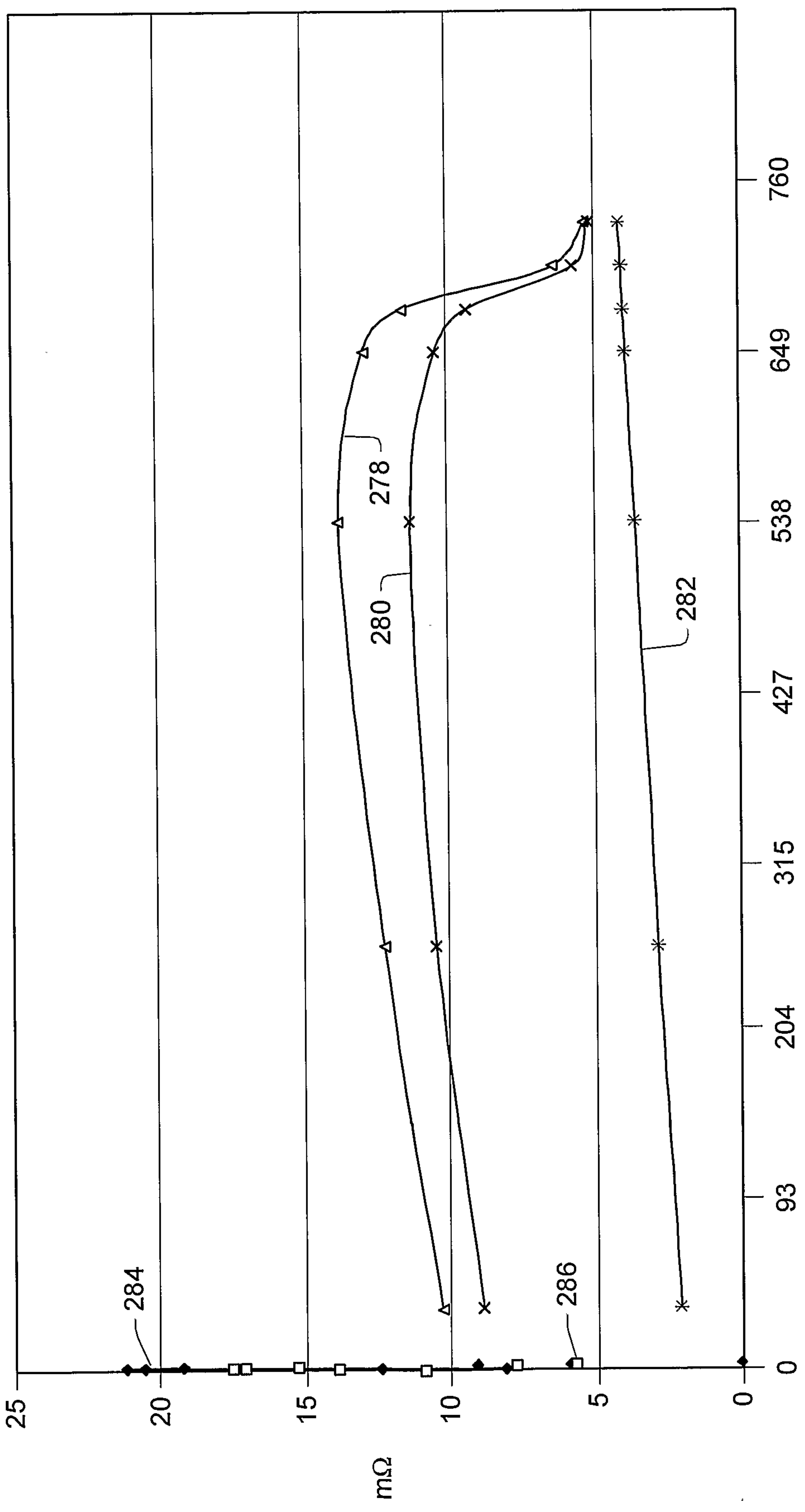


FIG. 43

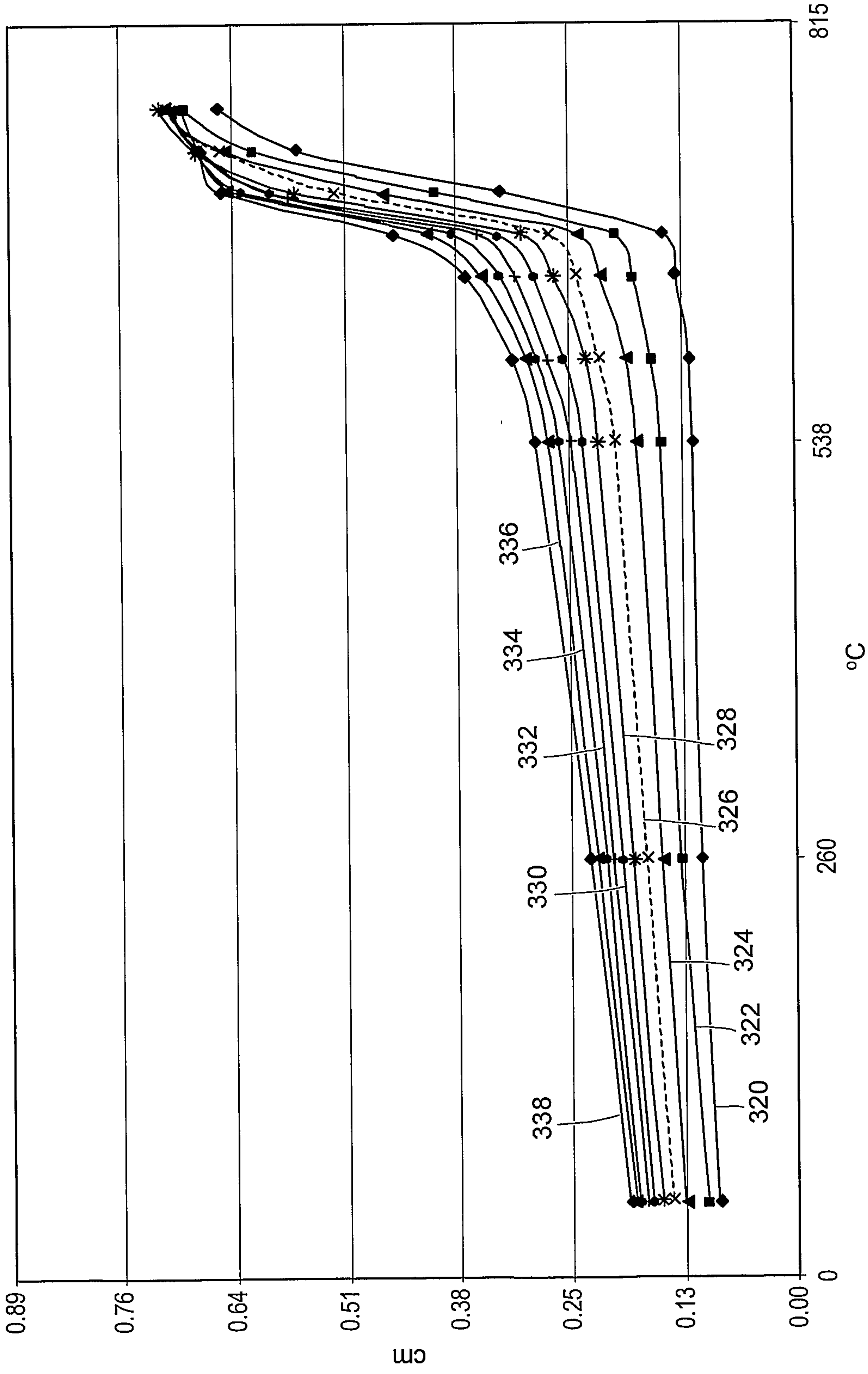

0.89
0.76
0.64
0.51
0.38
0.25
0.13
0.00
cm
0
260
538
815
°C
320
322
324
326
328
330
332
334
336
338

*FIG. 44*

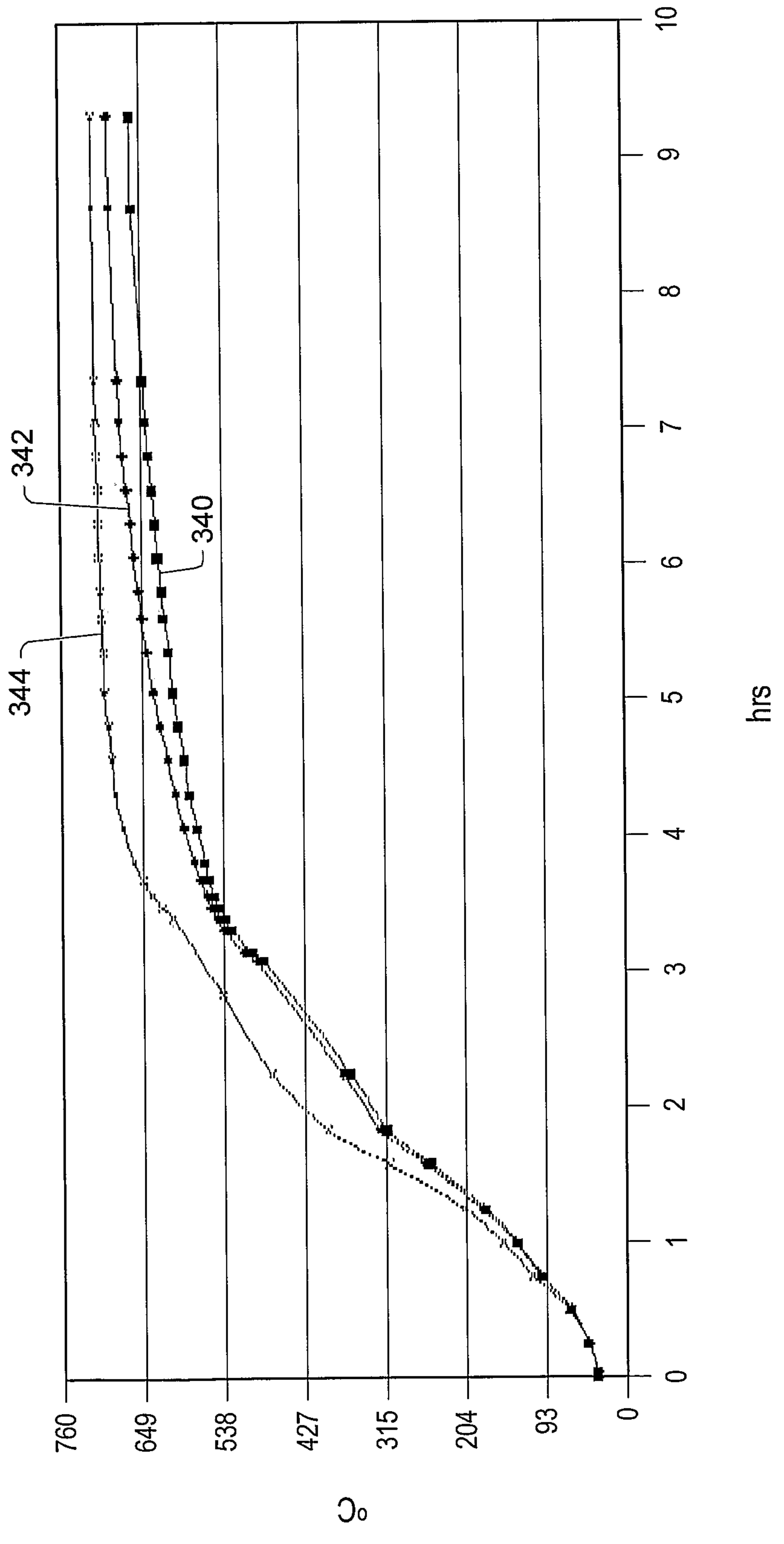


FIG. 45

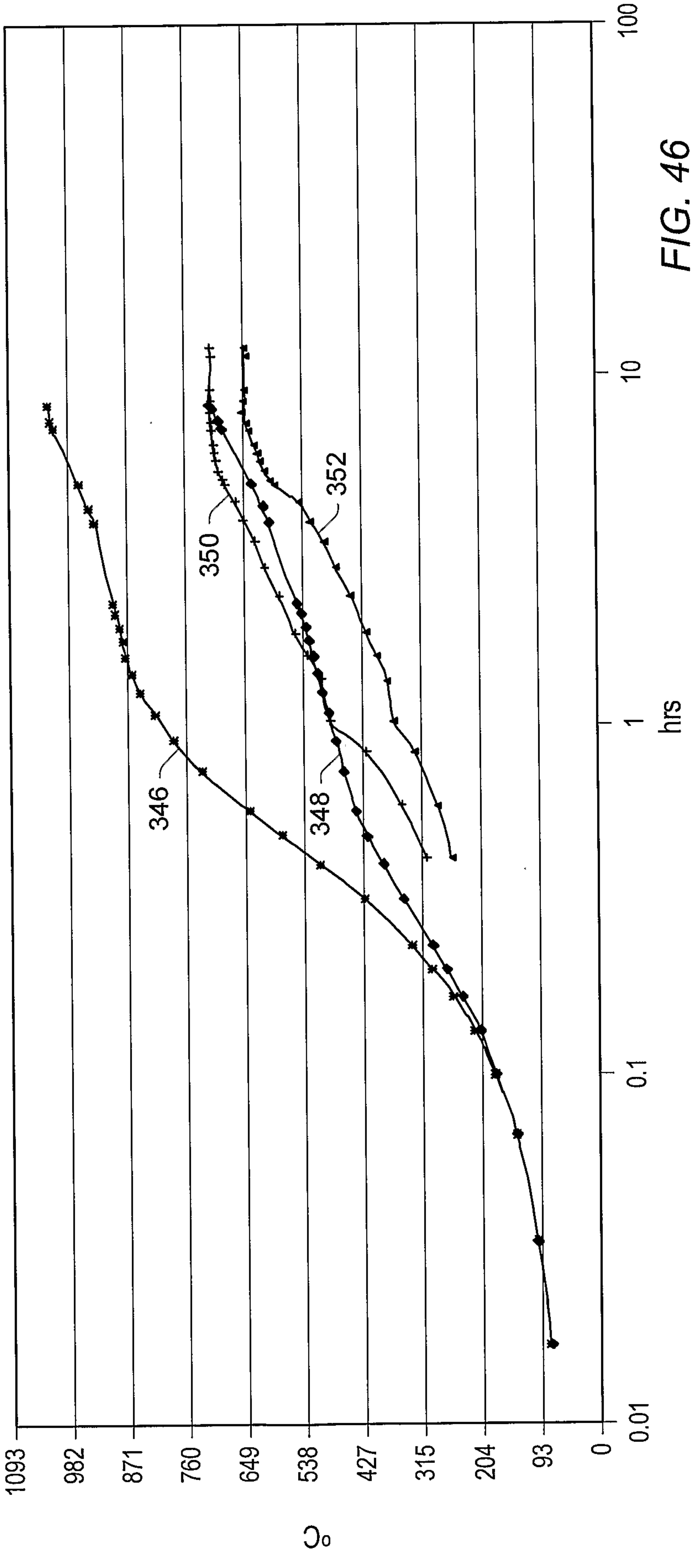

1093
982
871
760
649
538
427
315
204
93
0
°C
0.01
0.1
1
10
100
hrs
346
348
350
352

FIG. 46

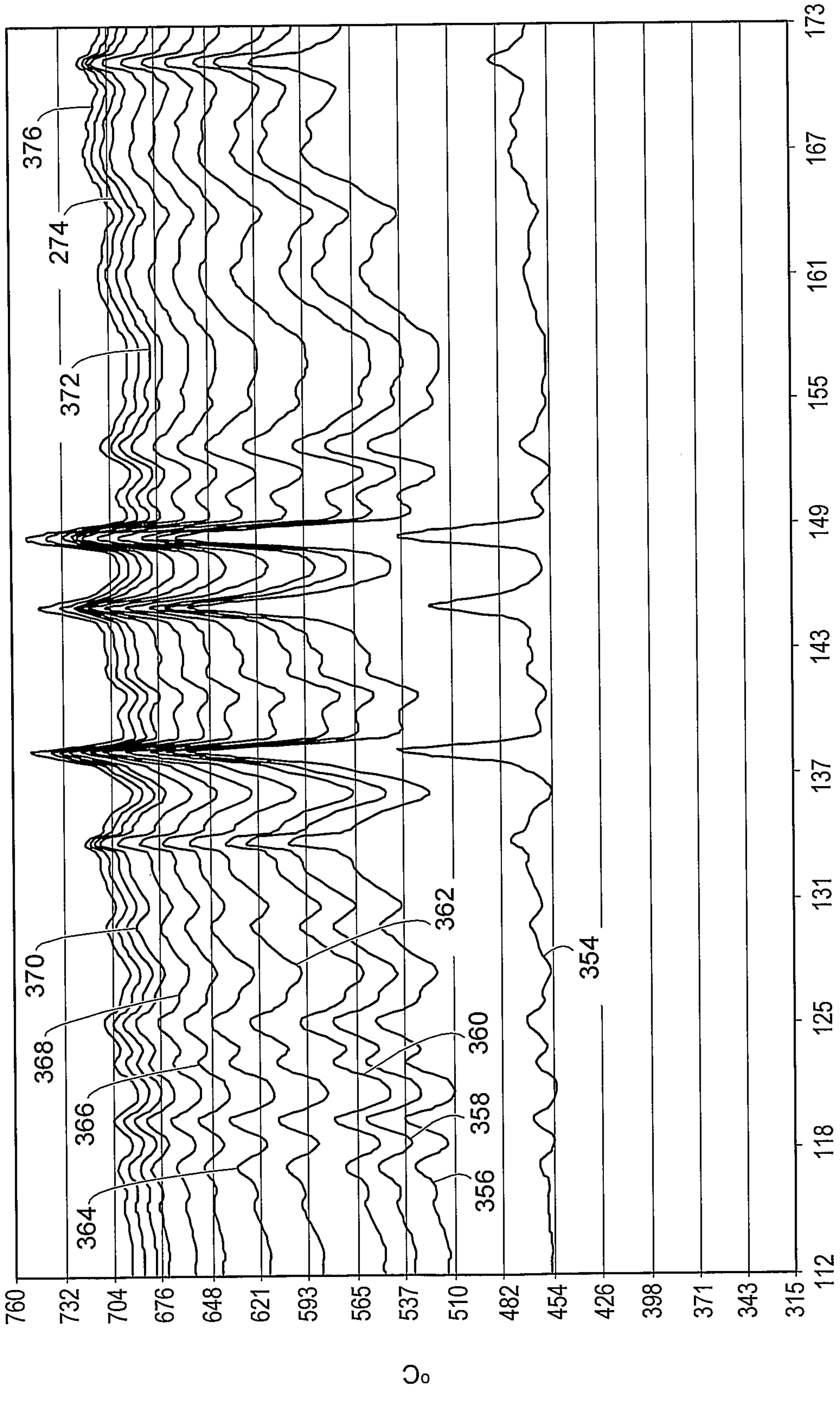

760
732
704
676
648
621
593
565
537
510
482
454
426
398
371
343
315
°C
112
118
125
131
137
143
149
155
161
167
173
m
376
274
372
370
368
366
364
362
360
358
356
354

FIG. 47

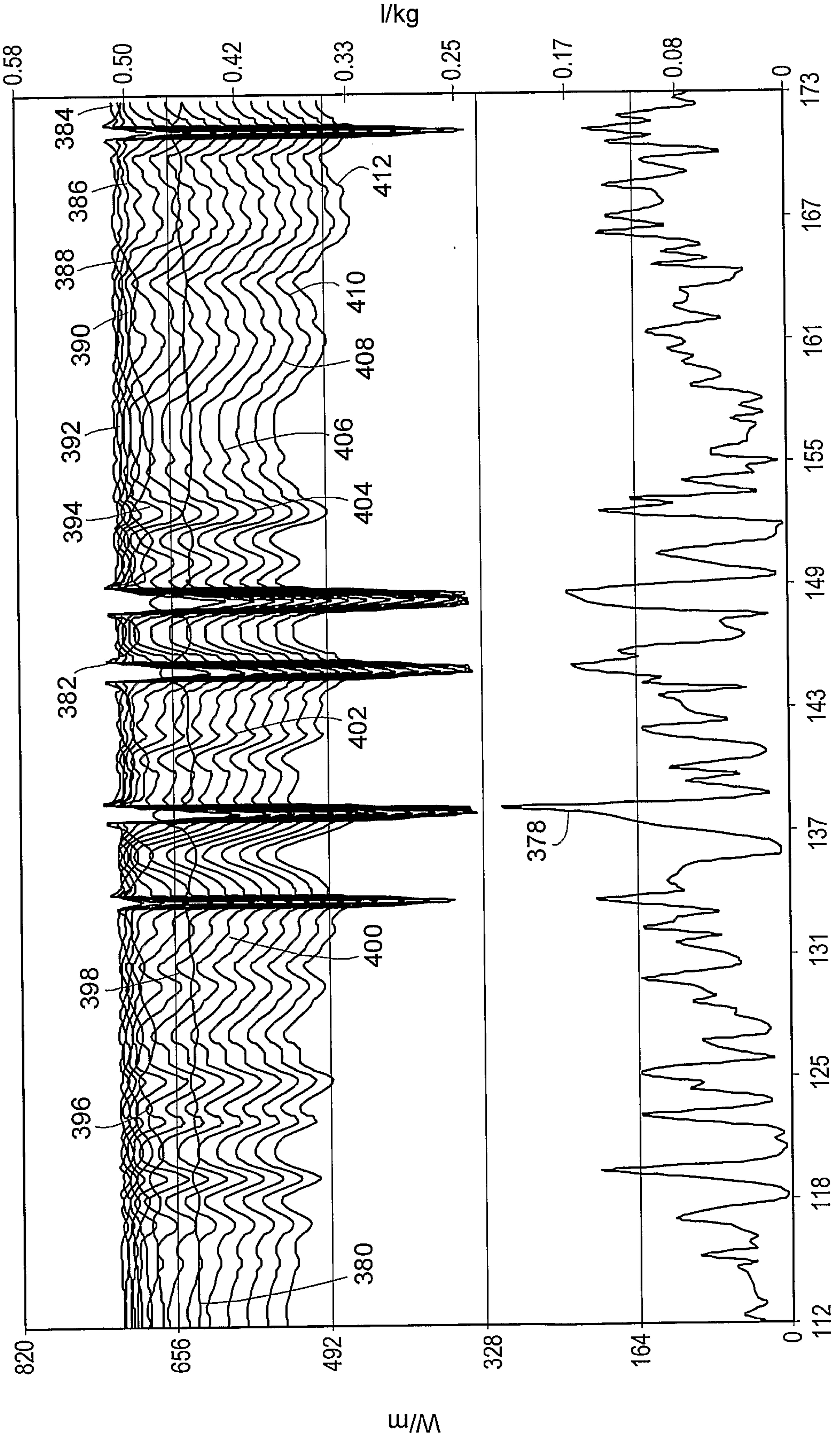

l/kg
0.58
0.50
0.42
0.33
0.25
0.17
0.08
0
W/m
820
656
492
328
164
0
m
112
118
125
131
137
143
149
155
161
167
173
378
380
382
384
386
388
390
392
394
396
398
400
402
404
406
408
410
412

FIG. 48

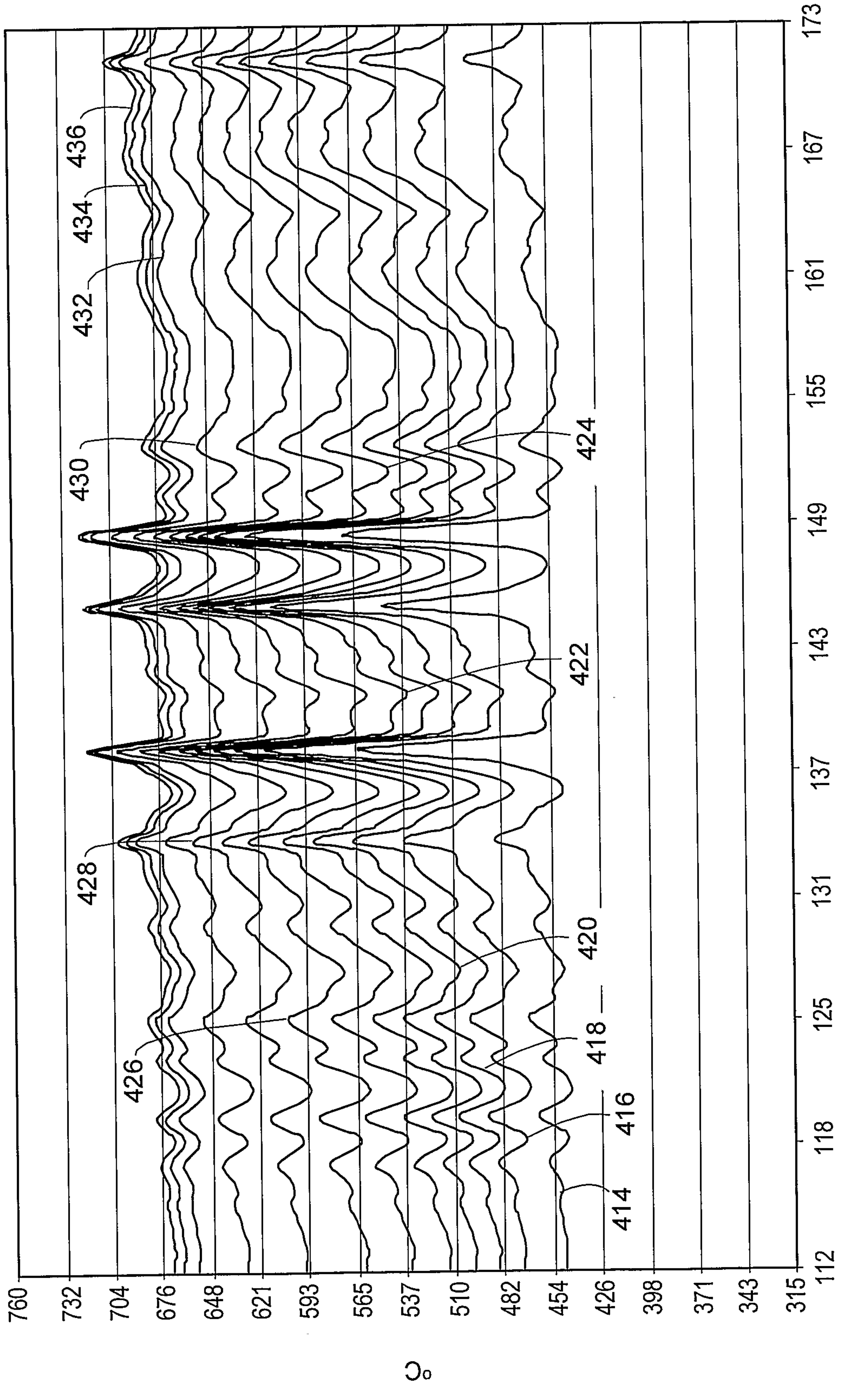

760
732
704
676
648
621
593
565
537
510
482
454
426
398
371
343
315
°C
112
118
125
131
137
143
149
155
161
167
173
m
414
416
418
420
422
424
426
428
430
432
434
436

FIG. 49

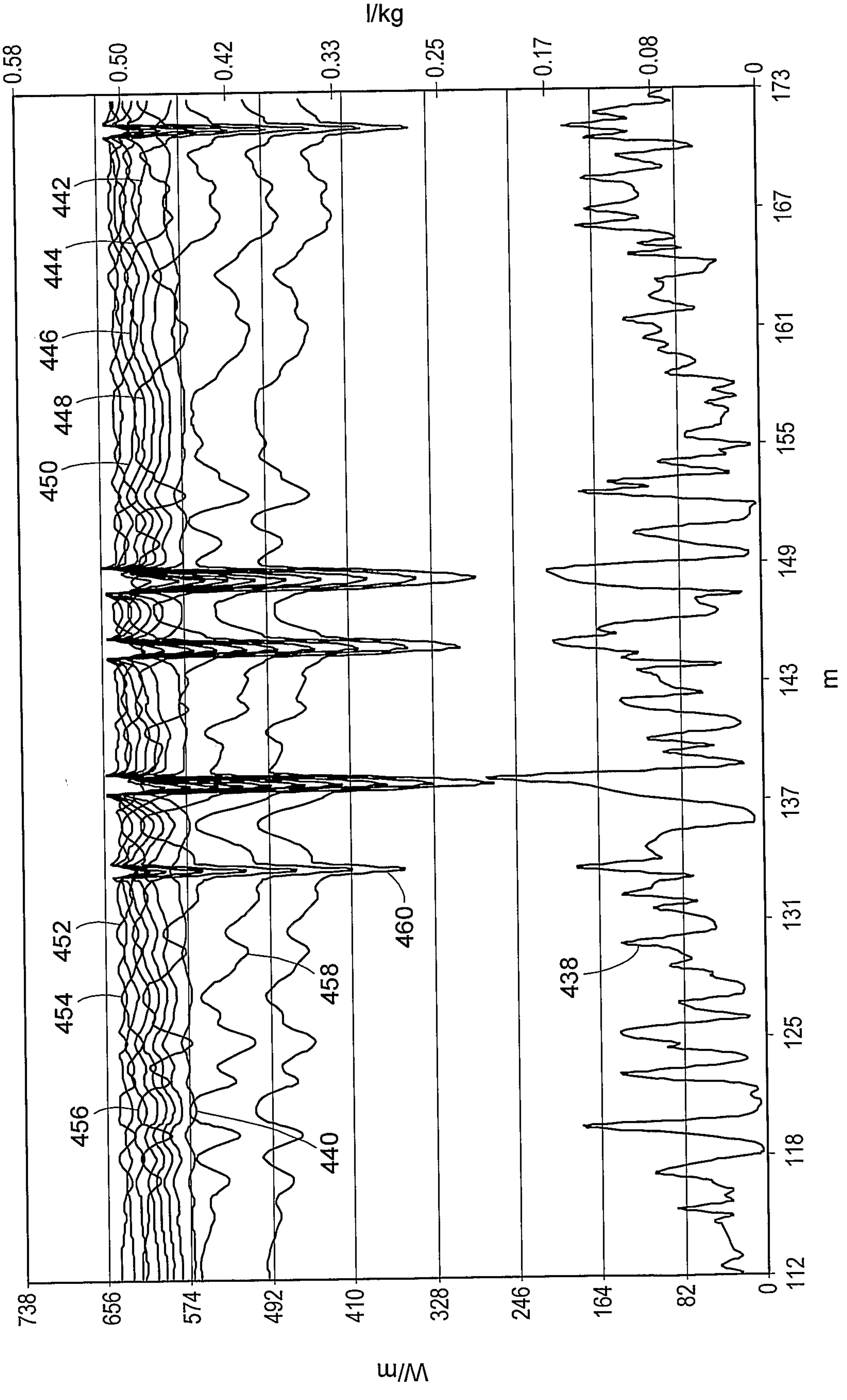

l/kg
0.58
0.50
0.42
0.33
0.25
0.17
0.08
0
W/m
738
656
574
492
410
328
246
164
82
0
m
112
118
125
131
137
143
149
155
161
167
173
442
444
446
448
450
452
454
456
440
458
460
438

FIG. 50

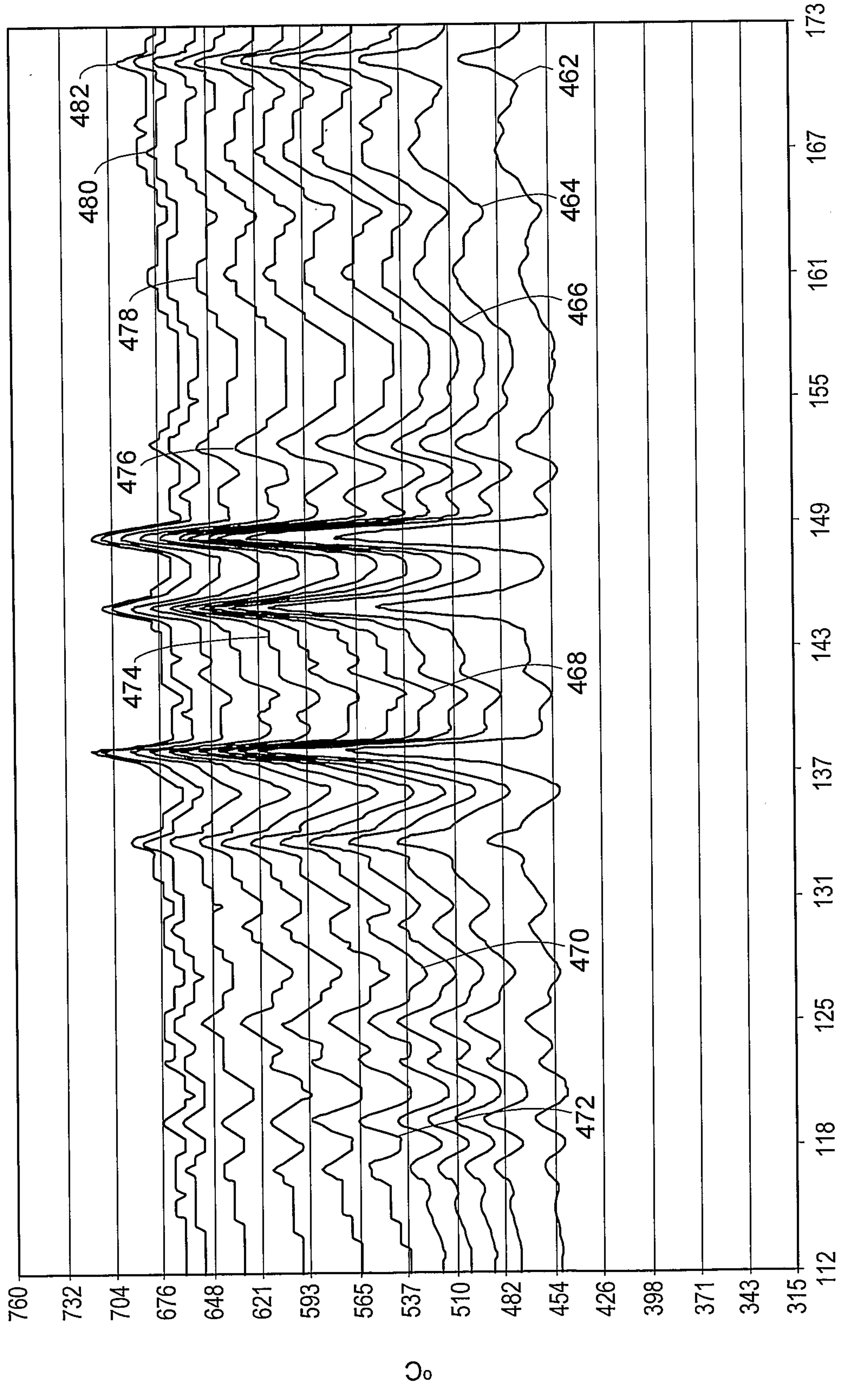

760
732
704
676
648
621
593
565
537
510
482
454
426
398
371
343
315
°C
112
118
125
131
137
143
149
155
161
167
173
m
462
464
466
468
470
472
474
476
478
480
482

FIG. 51

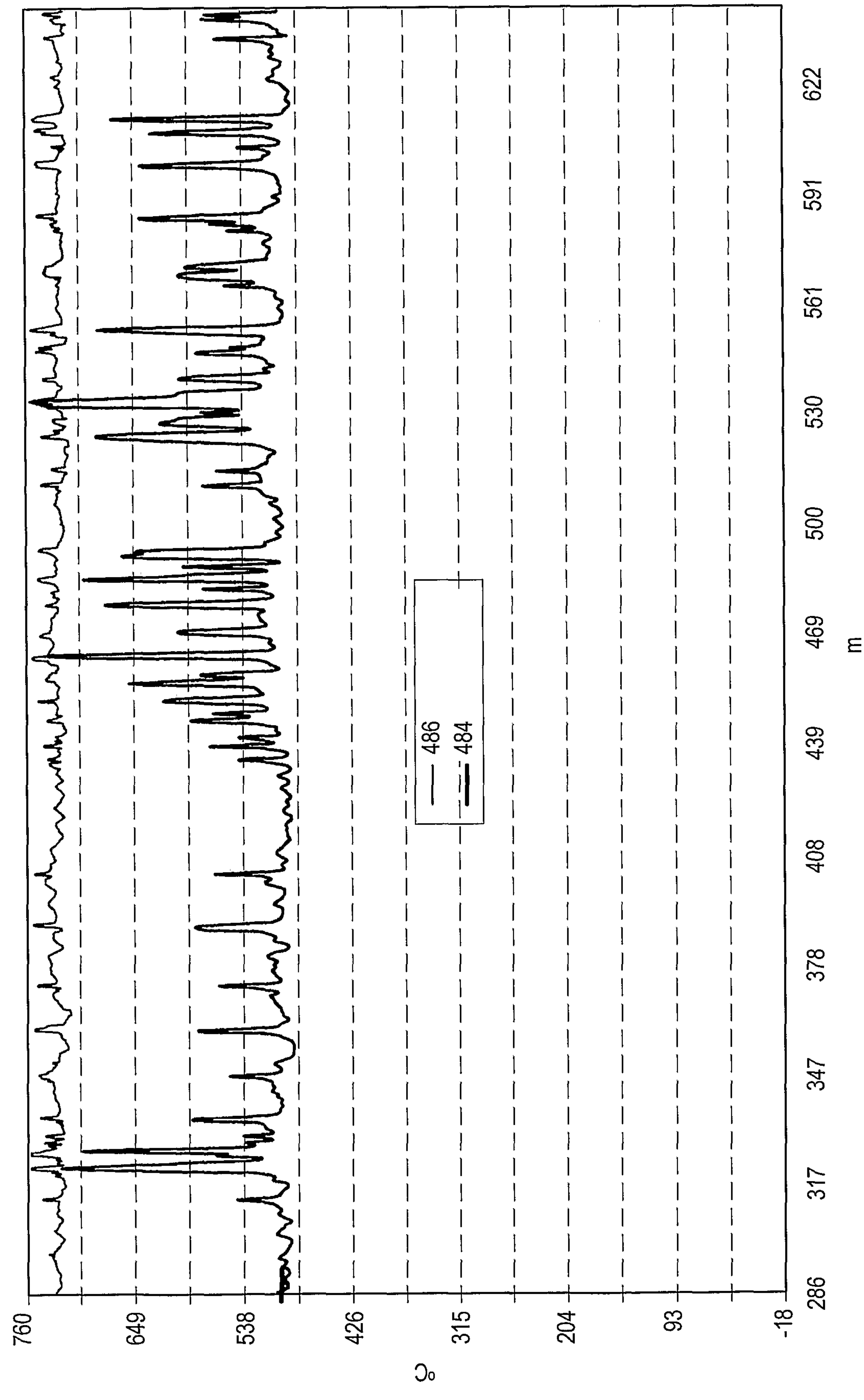

760
649
538
426
315
204
93
-18
°C
286
317
347
378
408
439
469
500
530
561
591
622
m
486
484

*FIG. 52*

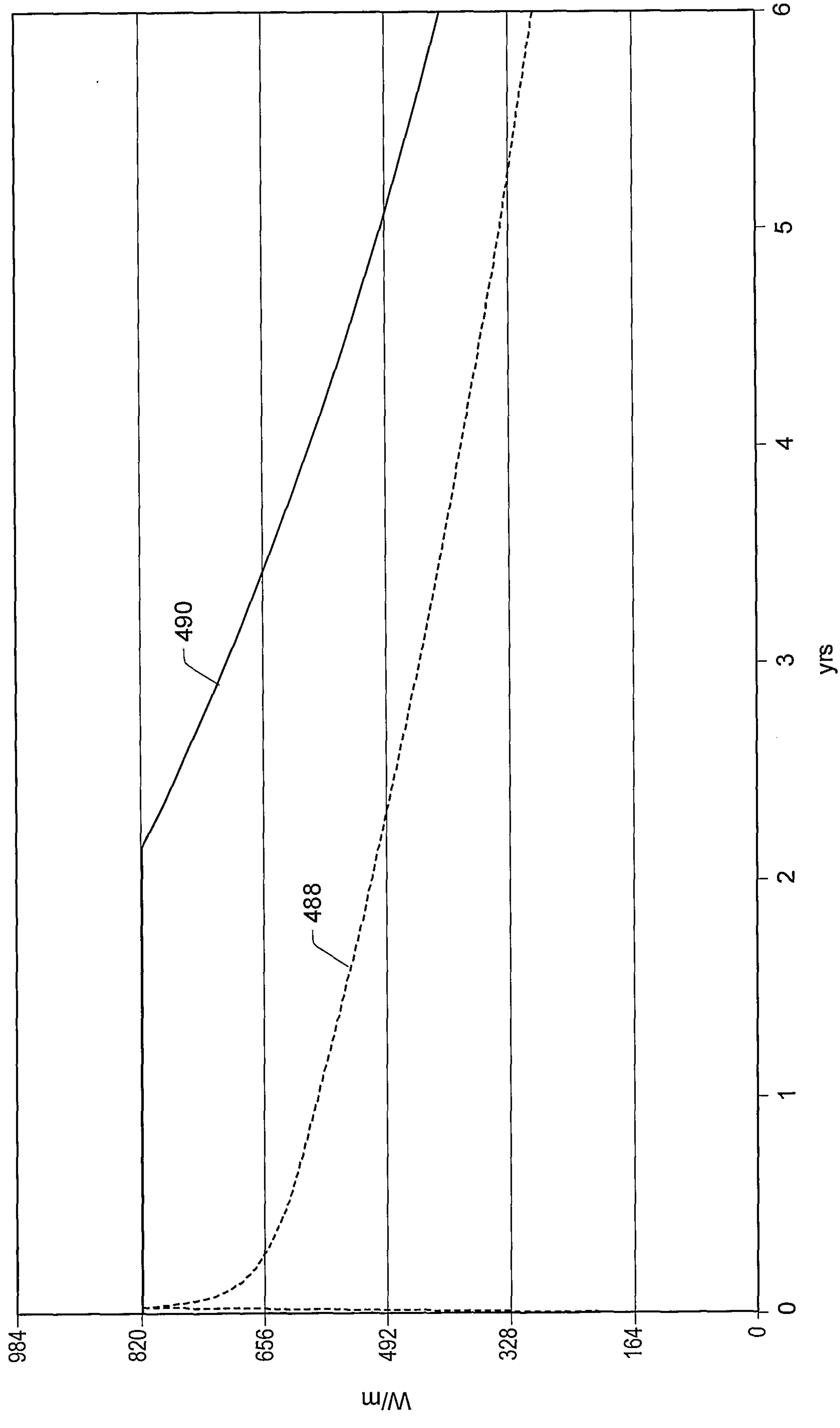


FIG. 53

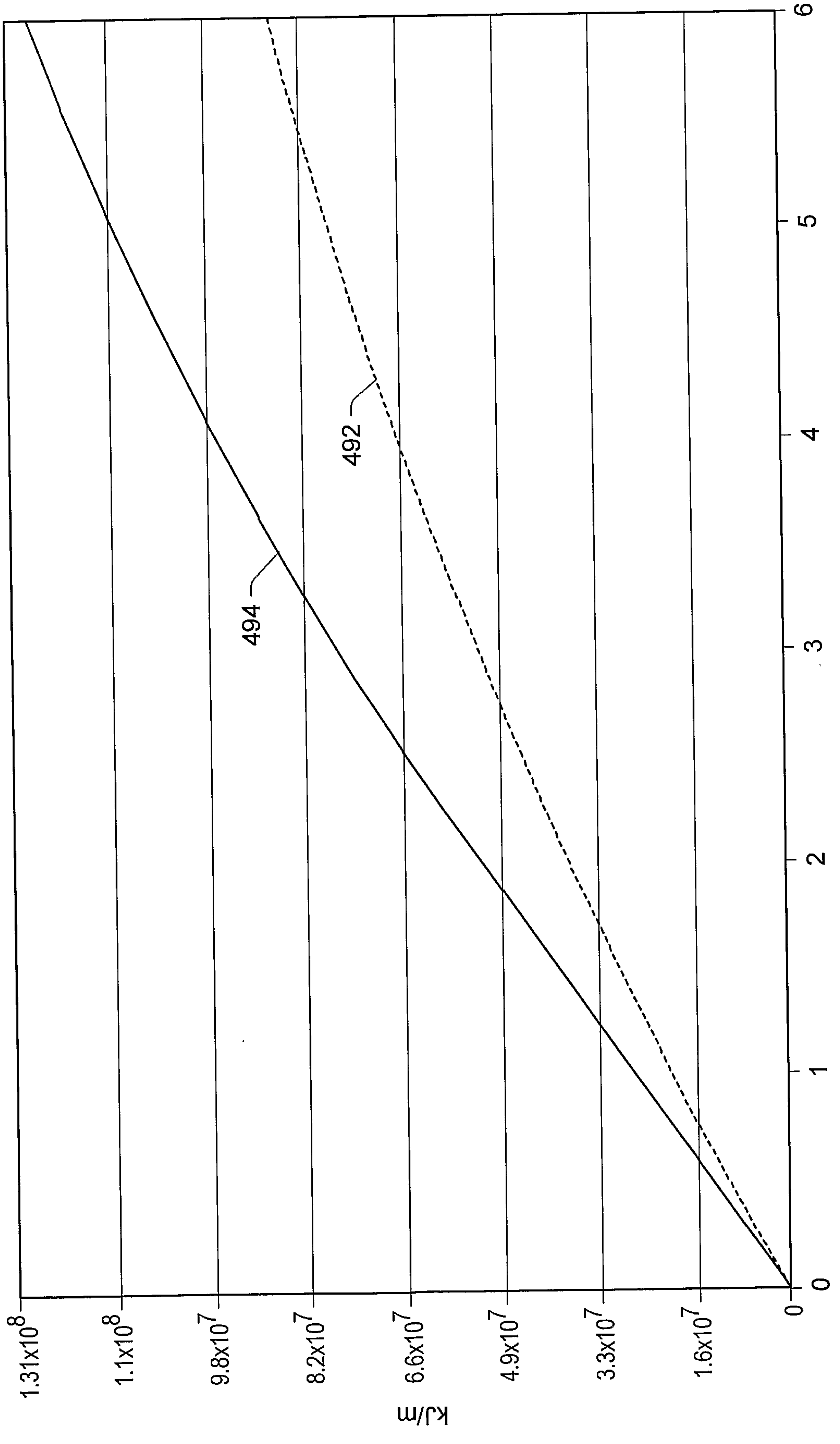
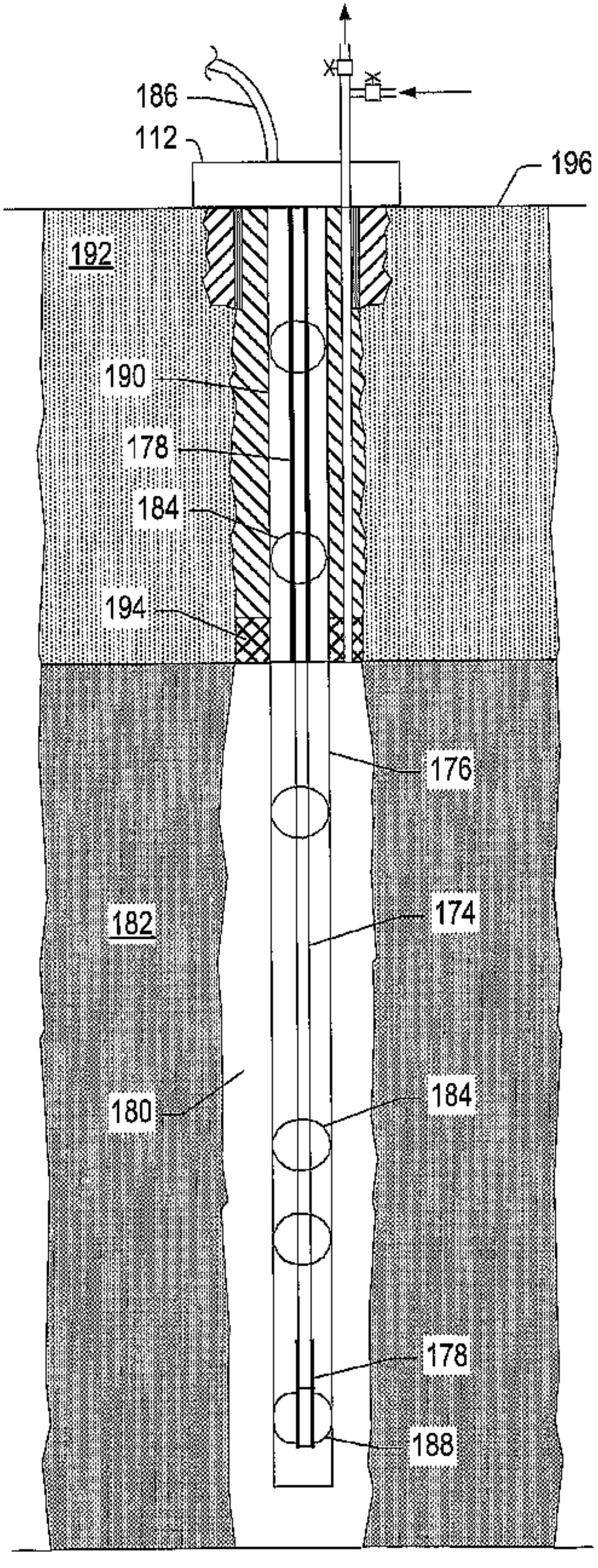

kJ/m
1.31x10$^8$
1.1x10$^8$
9.8x10$^7$
8.2x10$^7$
6.6x10$^7$
4.9x10$^7$
3.3x10$^7$
1.6x10$^7$
0
0
1
2
3
4
5
6
yrs
494
492

FIG. 54


186
112
196
192
190
178
184
194
176
182
174
180
184
178
188