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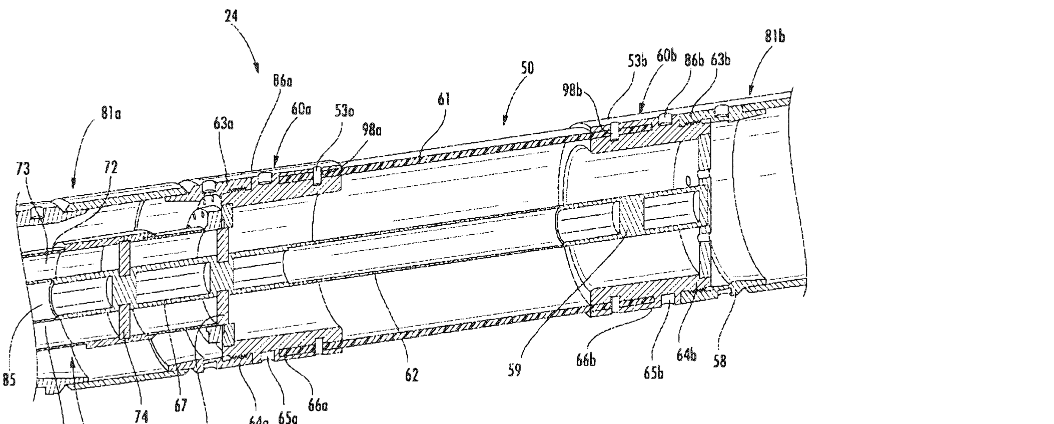

FIG. 4

(57) Abstract: An RF antenna assembly may be positioned within a wellbore in a subterranean formation for hydrocarbon resource recovery. The RF antenna assembly includes first and second tubular conductors and a feed structure therebetween defining a dipole antenna to be positioned within the wellbore, and an RF transmission line extending within one of the tubular conductors. The feed structure includes a dielectric tube, a first connector coupling the RF transmission line to the first tubular conductor, and a second connector coupling the RF transmission line to the second tubular conductor.

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RF ANTENNA ASSEMBLY WITH FEED STRUCTURE HAVING DIELECTRIC TUBE AND RELATED METHODS

Field of the Invention

The present invention relates to the field of hydrocarbon resource processing, and, more particularly, to an antenna assembly isolator and related methods.

Background of the Invention

Energy consumption worldwide is generally increasing, and conventional hydrocarbon resources are being consumed. In an attempt to meet demand, the exploitation of unconventional resources may be desired. For example, highly viscous hydrocarbon resources, such as heavy oils, may be trapped in sands where their viscous nature does not permit conventional oil well production. This category of hydrocarbon resource is generally referred to as oil sands. Estimates are that trillions of barrels of oil reserves may be found in such oil sand formations.

In some instances, these oil sand deposits are currently extracted via open-pit mining. Another approach for in situ extraction for deeper deposits is known as Steam-Assisted Gravity Drainage (SAGD). The heavy oil is immobile at reservoir temperatures, and therefore, the oil is typically heated to reduce its viscosity and mobilize the oil flow. In SAGD, pairs of injector and producer wells are formed to be laterally extending in the ground. Each pair of injector/producer wells includes a lower producer well and an upper injector well. The injector/production wells are typically located in the payzone of the subterranean formation between an underburden layer and an overburden layer.

The upper injector well is used to typically inject steam, and the lower producer well collects the heated crude oil or bitumen that flows out of the formation, along with any water from the condensation of injected steam. The injected steam forms a steam chamber that expands vertically and horizontally in the formation. The heat from the steam reduces the viscosity of the heavy crude oil or bitumen, which allows it to flow down into the lower producer well where it is collected and recovered. The steam and gases rise due to their lower density. Gases, such as methane, carbon dioxide, and hydrogen sulfide, for example, may tend to rise in the steam chamber and fill the void space left by the oil defining an insulating layer above the steam. Oil and water flow is by gravity driven drainage urged into the lower producer well.

Operating the injection and production wells at approximately reservoir pressure may address the instability problems that adversely affect high-pressure steam processes. SAGD may produce a smooth, even production that can be as high as 70% to 80% of the original oil in place (OOIP) in suitable reservoirs. The SAGD process may be relatively sensitive to shale streaks and other vertical barriers since, as the rock is heated, differential thermal expansion causes fractures in it, allowing steam and fluids to flow through. SAGD may be twice as efficient as the older cyclic steam stimulation (CSS) process.

Many countries in the world have large deposits of oil sands, including the United States, Russia, and various countries in the Middle East. Oil sands may represent as much as two-thirds of the world's total petroleum resource, with at least 1.7 trillion barrels in the Canadian Athabasca Oil Sands, for example. At the present time, only Canada has a large-scale commercial oil sands industry, though a small amount of oil from oil sands is also produced in Venezuela. Because of increasing oil sands production, Canada has become the largest single supplier of oil and products to the United States. Oil sands now are the source of almost half of Canada's oil production, while Venezuelan production has been declining in recent years. Oil is not yet produced from oil sands on a significant level in other countries.

U.S. Published Patent Application No. 2010/0078163 to Banerjee et al. discloses a hydrocarbon recovery process whereby three wells are provided: an uppermost well used to inject water, a middle well used to introduce microwaves into the reservoir, and a lowermost well for production. A microwave generator generates microwaves which are directed into a zone above the middle well through a series of waveguides. The frequency of the microwaves is at a frequency substantially equivalent to the resonant frequency of the water so that the water is heated.

Along these lines, U.S. Published Patent Application No. 2010/0294489 to Dreher, Jr. et al. discloses using microwaves to provide heating. An activator is injected below the surface and is heated by the microwaves, and the activator then heats the heavy oil in the production well. U.S. Published Patent Application No. 2010/0294488 to Wheeler et al. discloses a similar approach.

U.S. Patent No. 7,441,597 to Kasevich discloses using a radio frequency generator to apply radio frequency (RF) energy to a horizontal portion of an RF well positioned above a horizontal portion of an oil/gas producing well. The viscosity of the oil is reduced as a result of the RF energy, which causes the oil to drain due to gravity. The oil is recovered through the oil/gas producing well.

U.S. Patent No. 7,891,421, also to Kasevich, discloses a choke assembly coupled to an outer conductor of a coaxial cable in a horizontal portion of a well. The inner conductor of the coaxial cable is coupled to a contact ring. An insulator is between the choke assembly and the contact ring. The coaxial cable is coupled to an RF source to apply RF energy to the horizontal portion of the well.

Unfortunately, long production times, for example, due to a failed start-up, to extract oil using SAGD may lead to significant heat loss to the adjacent soil, excessive consumption of steam, and a high cost for recovery. Significant water resources are also typically used to recover oil using SAGD, which impacts the environment. Limited water resources may also limit oil recovery. SAGD is also not an available process in permafrost regions, for example, or in areas that may lack sufficient cap rock, are considered “thin” payzones, or payzones that have interstitial layers of shale. While RF heating may address some of these shortcomings, further improvements to RF heating may be desirable. For example, it may be relatively difficult to install or integrate RF heating equipment into existing wells.

Summary of the Invention

In view of the foregoing background, it is therefore an object of the present invention to provide a dielectric dipole isolator that is physically robust and reduced in size.

This and other objects, features, and advantages in accordance with the present invention are provided by an RF antenna assembly designed to be positioned within a wellbore in a subterranean formation for hydrocarbon resource recovery. The RF antenna assembly comprises first and second tubular conductors and a feed structure therebetween defining a dipole antenna to be positioned within the wellbore, and an RF transmission line extending within one of the tubular conductors. The feed structure comprises a dielectric tube, a first connector coupling the RF transmission line to the first tubular conductor, and a second connector coupling the RF transmission line to the second tubular conductor. For example, the dielectric tube may comprise a cyanate ester composite material. Advantageously, the feed structure isolates the elements of the dipole antenna in a more compact structure.

More specifically, the RF transmission line may comprise a series of coaxial sections coupled together in end-to-end relation, each coaxial section comprising an inner conductor, an outer conductor surrounding the inner conductor, and a dielectric therebetween. The first connector may couple the outer conductor to the first tubular conductor, and the second connector may couple the inner conductor to the second tubular conductor.

Another aspect is directed to a method of making an RF antenna assembly to be positioned within a wellbore in a subterranean formation for hydrocarbon resource recovery. The method includes providing first and second tubular conductors and a feed structure therebetween to define a dipole antenna to be positioned within the wellbore, positioning an RF transmission line to extend within one of the tubular conductors, and forming the feed structure. The feed structures comprises a dielectric tube, a first connector coupling the RF transmission line to the first tubular conductor, and a second connector coupling the RF transmission line to the second tubular conductor.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of an antenna assembly in a subterranean formation, according to the present invention.

FIG. 2 is a perspective view of adjacent coupled RF coaxial transmission lines in the antenna assembly of FIG. 1.

FIG. 3 is a perspective view of the feed connector (dielectric isolator) from the antenna assembly of FIG. 1 with the first and second tubular conductors and RF transmission line removed.

FIG. 4 is a cross-sectional view along line 4-4 of a portion of the feed connector FIG. 3 with the first and second tubular conductors and RF transmission line added.

FIG. 5A is an enlarged portion of the cross-sectional view of FIG. 4.

FIG. 5B is an enlarged portion of the cross-sectional view of FIG. 4 with the second tubular conductor removed.

FIG. 6 is another enlarged portion of the cross-sectional view of FIG. 4 with the second tubular conductor and second dielectric spacer removed.

FIG. 7 is a schematic diagram of another embodiment of an RF antenna assembly, according to the present invention.

FIG. 8 is a cross-sectional view along line 8-8 of a coupling structure from the first set thereof from the antenna assembly of FIG. 7.

FIG. 9 is a perspective view of the coupling structure of FIG. 8 with the tubular conductor removed.

FIG. 10 is a perspective view of a coupling structure from the second set thereof from the antenna assembly of FIG. 7 with the tubular conductor removed.

FIG. 11 is a cross-sectional view along line 11-11 of the coupling structure of FIG. 10.

FIG. 12 is a cross-sectional view of a portion of the coupling structure of FIG. 10.

FIGS. 13A-13C are perspective views of the coupling structure of FIG. 10 during steps of assembly.

FIGS. 14A-14C are heating pattern diagrams of an example embodiment of the antenna assembly of FIG. 7.

FIGS. 15A-15C are additional heating pattern diagrams of an example embodiment of the antenna assembly of FIG. 7 with varying conductivity and permittivity.

FIGS. 16A-16B are a Smith Chart and a permittivity diagram, respectively, of an example embodiment of the antenna assembly of FIG. 7.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime notation is used to indicate similar elements in alternative embodiments.

Referring initially to FIGS. 1-2, a hydrocarbon recovery system **20** according to the present invention is now described. The hydrocarbon recovery system **20** includes an injector well **22**, and a producer well **23** positioned within respective wellbores in a subterranean formation **27** for hydrocarbon recovery. The injector well **22** includes an antenna assembly **24** at a distal end thereof. The hydrocarbon recovery system **20** includes an RF source **21** for driving the antenna assembly **24** to generate RF heating of the subterranean formation **27** adjacent the injector well **22**.

The antenna assembly **24** comprises a tubular antenna element **28**, for example, a center fed dipole antenna, positioned within one of the wellbores, and a RF coaxial transmission line positioned within the tubular antenna element. The RF coaxial transmission line comprises a series of coaxial sections **31a-31b** coupled together in end-to-end relation. The tubular antenna element **28** also includes a plurality of tool-receiving recesses **27** for utilization of a torque tool in assembly thereof. The coaxial sections **31a-31b** also include a plurality of tool-receiving recesses **42a-42b**.

The antenna assembly **24** includes a dielectric spacer **25** between the tubular antenna element **28** and the RF coaxial transmission line **31a-31b**, and a dielectric spacer **26** for serving as a centering ring for the antenna assembly **24** while in the respective wellbore.

Referring now additionally to FIGS. 3-5B, the RF antenna assembly **24** comprises first and second tubular conductors **81a-81b**, and a feed structure **50** therebetween defining a dipole antenna positioned within the respective wellbore. The RF transmission line **82** extends within one of the tubular conductors **81a**. The feed structure **50** comprises a dielectric tube **61**, a first connector **60a** coupling the RF transmission line **82** to the first tubular conductor **81a**, and a second connector **60b** coupling the RF transmission line to the second tubular conductor **81b**. For example, the dielectric tube **61** may comprise a cyanate ester composite material (e.g. quartz enhanced) or another suitable dielectric composite that has mechanical strength for structural integrity, and absorbs minimal amounts of radiated energy.

More specifically, the RF transmission line **82** may comprise a series of coaxial sections coupled together in end-to-end relation, each coaxial section comprising an inner conductor **71**, an outer conductor **72** surrounding the inner conductor, and a dielectric **73** therebetween. The first connector **60a** couples the outer conductor **72** to the first tubular conductor **81a**, and the second connector **60b** couples the inner conductor **71** to the second tubular conductor **81b**. In the illustrated embodiment, the first and second connectors **60a-60b** include a plurality of tool-receiving recesses **65a-65d** on an outer surface thereof. The tool-receiving recesses **65a-65d** are illustratively circular in shape, but in other embodiments, may comprise other shapes, such as a hexagon shape. The tool-receiving recesses **65a-65d** are provided to aid in using torque wrenches in assembling the antenna assembly **24**. As perhaps best seen in FIG. 4, the RF transmission line **82** is affixed to the first connector **60a** with a plurality of bolts. Of course, other fasteners may be used.

In the illustrated embodiment, the inner conductor **71** comprises a tube defining a first fluid passageway **85** therein (e.g. for the flow of cooling fluid/gas in). The outer conductor **72** is illustratively spaced from the inner conductor **71** to define a second fluid passageway **73** (e.g. for cooling/gas out fluid). The passageways **85, 73** permit the flow of selective gases and fluids that aid in the hydrocarbon recovery process.

The feed structure **50** includes an intermediate conductor **62** extending within the dielectric tube **61** and coupling the inner conductor **71** to the second connector **60b**. For example, the intermediate conductor **62** illustratively comprises a conductive tube (of a material comprising, e.g., copper, aluminum). Moreover, the RF transmission line **82** includes an inner conductor coupler **67** for coupling the inner conductor **71** to the intermediate conductor **62**, and first and second dielectric spacers **74-75**, each comprising a bore therein for receiving the inner conductor coupler. The first and second dielectric spacers **74-75** are shown without fluid openings, but in other embodiments (FIG. 6), they may include them, thereby permitting the flow of fluids within the dielectric tube **61**. Advantageously, the inner conductor coupler **67** accommodates differential thermal expansion. Additionally, the first and second tubular conductors **81a-81b** each comprises a threaded end **63a-63b**, and the first and second connectors **60a-60b** each comprises a threaded end **86a-86b** engaging a respective threaded end of the first and second tubular conductors for defining overlapping mechanical threaded joints **64a-64b**. The threaded ends **63a-63b** of the first and second tubular conductors **81a-81b** each comprises a mating face adjacent the first and second connectors **60a-60b**. The mating face includes a threading relief recess to provide good contact at the outer extreme of the first and second connectors **60a-60b.** The overlapping mechanical threaded joints **64a-64b** provide for a hydraulic seal that seals in fluid and gases within the antenna assembly **24**.

The second connector **60b** illustratively includes an interface plate **58** mechanically coupled thereto, via fasteners, and another inner conductor coupler **59**. The interface plate **58** illustratively includes openings (slits) therein for permitting the controlled flow of coolant. In some embodiments, the coolant would flow from the inner conductor coupler **59** through the dielectric tube **61** and return to the second fluid passageway **73**. In these embodiments, the first and second dielectric spacers **74-75** each include openings therein for providing the flow (FIG. 6).

As perhaps best seen in FIGS. 5A and 5B, each of the first and second connectors **60a-60b** comprises a recess **66a-66b** for receiving adjacent portions of the dielectric tube **61**. In the illustrated embodiment, each recess comprises a circular slot that is circumferential with regards to the first and second connectors **60a-60b**. Moreover, all edges in the illustrated embodiment are rounded, which helps to reduce arching in high voltage (HV) applications.

In one embodiment, the dielectric tube **61** is affixed to each of the first and second connectors **60a-60b** with a multi-step process. First, the recesses **66a-66b** are primed for bonding, and then an adhesive material **99b**, such as an epoxy (e.g. EA9494 (Hysol EA 9394 high temperature epoxy adhesive, other similar high temperature adhesives can be used. This provides stability and strength in the bonded joint.)), is placed therein. Thereafter, the first and second connectors **60a-60b** and the dielectric tube **61** are drilled to create a plurality of spaced apart blind passageways **53a-53b**, i.e. the drill hole does not completely penetrate the first and second connectors. The passageways **53a-53b** are then reamed, and for each passageway, a pin **78** is placed therein. The passageways **53a-53b** are then filled with an epoxy adhesive **77**, such as Sylgard 186, as available from the Dow Corning Corporation of Midland, Michigan, and then the surface is fly cut to provide a smooth surface. The epoxy adhesive **77** forces out and air pockets and insures structural integrity. A high-temp adhesive, such as Loctite 609 (for cylindrical assemblies), is applied just prior to assembly of the pin **78** in the passageway **53a-53b**, the axial hole **76** in the pin allowing gasses to escape on assembly.

Advantageously, the feed structure **50** isolates the first and second tubular conductors **81a-81b** of the dipole antenna, thereby preventing arching for high voltage applications in a variety of environmental conditions. Moreover, the feed structure **50** is mechanically robust and readily supports the antenna assembly **24**. The dielectric tube **61** has a low power factor (i.e. the product of the dielectric constant and the dissipation factor), which inhibits dielectric heating of the feed structure **50**. Moreover, the materials of the feed structure **50** have long term resistance to typical oil field chemicals, providing for reliability and robustness, and have high temperature survivability without significant degradation of the desirable properties.

In another embodiment, the feed structure **50** may include a ferromagnetic tubular balun extending through the RF transmission line **82** and to the dielectric tube **61**, terminating at the balun isolator. The balun surrounds the inner conductor **71** and aids in isolating the inner conductor and reducing common mode current.

Another aspect is directed to a method of making an RF antenna assembly **24** to be positioned within a respective wellbore in a subterranean formation **27** for hydrocarbon resource recovery. The method includes providing first and second tubular conductors **81a-81b** and a feed structure **50** therebetween to define a dipole antenna to be positioned within the respective wellbore, positioning an RF transmission line **82** to extend within one of the tubular conductors **81a**, and forming the feed structure. The feed structure **50** comprises a dielectric tube **61**, a first connector **60a** coupling the RF transmission line **82** to the first tubular conductor **81a**, and a second connector **60b** coupling the RF transmission line to the second tubular conductor **81b**.

Referring again to FIGS. 1-4, an RF antenna assembly **24** according to the present invention is now described. The RF antenna assembly **24** is configured to be positioned within a wellbore in a subterranean formation **27** for hydrocarbon resource recovery. The RF antenna assembly **24** comprises first and second tubular conductors **81a-81b** and a dielectric isolator **50** therebetween. The dielectric isolator **50** comprises a dielectric tube **61** having opposing first and second open ends, a first tubular connector **60a** comprising a first slotted recess **66a** receiving therein the first open end of the dielectric tube, and a second tubular connector **60b** comprising a second slotted recess **66b** receiving therein the second open end of the dielectric tube.

More specifically, the dielectric tube includes a first plurality of passageways **98a** therein adjacent the first open end and through the first slotted recess **66a**, and a second plurality of passageways **98b** therein adjacent the second open end and through the second slotted recess **66b**. The first tubular connector **60a** includes a first plurality of blind **53a-53b** openings therein aligned with the first plurality of passageways **98a**, and the second tubular connector **60b** includes a second plurality of blind openings **53c-53d** therein aligned with the second plurality of passageways **98b**.

The RF antenna assembly **24** includes a first plurality of pins extending through the first pluralities of passageways and blind openings **98a, 53a-53b**, and a second plurality of pins **78** extending through the second pluralities of passageways **98b** and blind openings **53c-53d**. Although the first plurality of pins is not depicted, the skilled person would appreciate they are formed similarly to the second pins **78**. The RF antenna assembly **24** further comprises adhesive **99b** securing the first and second tubular connectors **60a-60b** to the respective first and second open ends.

Additionally, the first tubular connector **60a** includes a first threaded surface **86a** for engaging an opposing threaded end **63a** of the first tubular conductor, and the second tubular connector **60b** includes a second threaded surface **86b** for engaging an opposing threaded end **63b** of the second tubular conductor. The first tubular connector **60a** illustratively includes a first plurality of tool-receiving recesses **65a-65b** on a first outer surface thereof, and the second tubular connector **60b** illustratively includes a second plurality of tool-receiving recesses **65c-65d** on a second outer surface thereof. The dielectric isolator **50** illustratively includes an inner conductor **62** extending within the dielectric tube.

Referring additionally to FIG. 6, the first tubular connector **60a** illustratively includes an inner interface plate **92** (outer conductor plate), an outer interface plate **91**, and an O-ring **94** between the interface plates for providing a tight seal. The first tubular connector **60a** illustratively includes a pair of O-rings **93a-93b** between the outer interface plate **91** and the first threaded surface **86a**. The outer interface plate **91** illustratively includes a plurality of circumferential openings **96a-96b**, which each receives fasteners therethrough, such as screws or pins. The pair of O-rings **93a-93b** provides a good seal to control the fluid paths for the cooling oil, and gas paths (as discussed above).

The fasteners physically couple the outer interface plate **91** to the first tubular connector **60a**. The electrical coupling between the outer interface plate **91** and the first tubular connector **60a** is at a contact point **89**. The coupling also includes a relief recess **95** to generate high force on a defined rim to ensure "metal to metal" contact at a certain pressure, and to guarantee the electrical path. The inner interface plate **92** illustratively includes a plurality of openings **87a-87b** for similarly receiving fasteners to mechanically couple the inner and outer interface plates **91-92** together.

The large number of small fasteners in the inner and outer interface plates **91-92** decreases the radial space for connection, and increases HV standoff distances inside the dielectric isolator **50**. Also, the inner and outer interface plates **91-92** have rounded surfaces to increase HV breakdown.

Another aspect is directed to a method of assembling an RF antenna assembly **24** to be positioned within a wellbore in a subterranean formation **27** for hydrocarbon resource recovery. The method comprises coupling first and second tubular conductors **81a-81b** and a dielectric isolator **50** therebetween, the dielectric isolator comprising a dielectric tube **61** having opposing first and second open ends, a first tubular connector **60a** comprising a first slotted recess **66a** receiving therein the first open end of the dielectric tube, and a second tubular connector **60b** comprising a second slotted recess **66b** receiving therein the second open end of the dielectric tube.

In the illustrated embodiment, the dielectric isolator **50** couples together two dipole element tubular conductors **81a-81b**, but in other embodiments. The tubular connectors **60a-60b** of the dielectric isolator **50** may omit the electrical couplings to the inner conductor **71** and outer conductor **72** of the RF transmission line **82**. In these embodiments, the RF transmission line **82** passes through the dielectric isolator **50** for connection further down the borehole, i.e. a power transmission node.

Referring now additionally to FIG. 7, another embodiment of the RF antenna assembly **24'** is now described. In this embodiment of the RF antenna assembly **24'**, those elements already discussed above with respect to FIGS. 1-6 are given prime notation and most require no further discussion herein. This embodiment differs from the previous embodiment in that this RF antenna assembly **24'** includes a series of tubular dipole antennas **102a'-102c', 103a'-103b'** to be positioned within the wellbore, each tubular dipole antenna comprising a pair of dipole elements **102a'-103a', 103a'-102b', 103b'-102c'**. The RF antenna assembly **24'** includes an RF transmission line **82'** extending within the series of tubular dipole antennas **102a'-102c', 103a'-103b'**, and a respective coupling structure **104'-107', 111'** between each pair of dipole elements and between the series of tubular dipole antennas. Each coupling structure **104'-107', 111'** comprises a dielectric tube **61'** mechanically coupling adjacent dipole elements **102a'-103a', 103a'-102b', 103b'-102c'**, and a pair of tap connectors **60a'-60b'** carried by the dielectric tube and electrically coupling the RF transmission line **82'** to a corresponding dipole element. Additionally, the RF antenna assembly **24'** includes $\lambda/2$ dipoles elements **102a'-103a', 103a'-102b', 103b'-102c'**, and a balun element **101'** coupled to the first coupling structure **111'**.

More specifically, the RF transmission line **82'** comprises an inner conductor **71'**, an outer conductor **72'** surrounding the inner conductor, and a dielectric (e.g. air or cooling fluid) therebetween. The respective coupling structures comprise first **105'-106'** and second **104', 107', 111'** sets thereof. The tap connectors **60a'-60b'** of the first set of coupling structures **105'-106'** electrically couple the outer conductor **72'** to the corresponding dipole elements **103a'-103b'**. The tap connectors of the second set of coupling structures **104', 107', 111'** electrically couple the inner conductor **71'** to the corresponding dipole elements **102a'-102c'**.

Referring now additionally to FIGS. 8-9, in the illustrated embodiment, each first set coupling structure **105'-106'** comprises an electrically conductive support ring **110'** surrounding the outer conductor **72'** and being in the tap connector **60b'** for coupling the outer conductor to the corresponding dipole element **103a'-103b'**. Each first set coupling structure **105'-106'** illustratively includes a circular finger stock **185'** (e.g. beryllium copper (BeCu)) surrounding the electrically conductive support ring **110'** and for providing a solid electrical coupling. As perhaps best seen in FIG. 9, the electrically conductive support ring **110'** includes a plurality of passageways for permitting the flow of fluid therethrough.

Referring now additionally to FIGS. 10-12, in the illustrated embodiment, each second set coupling structure **104', 107', 111'** comprises a dielectric support ring **120'** surrounding the outer conductor **72'** and in the tap connector **60b'**, and an electrically conductive radial member **125'** extending through the dielectric support ring and the outer conductor, and coupling the inner conductor **71'** to the corresponding dipole element **102a'-102c'**. Each second set coupling structure **104', 107', 111'** illustratively includes a first circular conductive coupler **123'** surrounding the inner conductor **71'**, and a second circular conductive coupler **127'** surrounding the outer conductor **72'**.

Each second set coupling structure **104', 107', 111'** illustratively includes an insulating tubular member **122'** surrounding the electrically conductive radial member **125'** and insulating it from the outer conductor **72'**. The insulating tubular member **122'** is within the dielectric support ring **120'**. Additionally, each second set coupling structure **104', 107', 111'** illustratively includes a cap portion **126'** having a finger stock **121'** (e.g. beryllium copper (BeCu)) for providing a good electrical connection to the corresponding dipole element **102a'-102c'**, and a radial pin **186'** extending therethrough for coupling the cap portion to the electrically conductive radial member **125'** (also mechanically coupling the dielectric support ring **120'** and the insulating tubular member **122'** to the outer conductor). As shown, the path of the electrical current from the inner conductor **71'** to the tap connector **60b'** is noted with arrows.

Referring now additionally to FIGS. 13A-13C, the steps for assembling the second set coupling structure **104', 107', 111'** includes coupling the second circular conductive coupler **127'** to surround the outer conductor **72'**, and coupling the tubular member **122'** to the outer conductor with the cap portion **126'**. The dielectric support ring **120'** comprises half portions that are assembled one at a time, and coupled together with fasteners. Also, the cap portion **126'** allows the outer isolator to slide and thread into place while maintaining electrical contact.

Advantageously, the second set coupling structure **104’, 107’, 111’** may allow for current and voltage transfer to the transducer element while maintaining coaxial transmission line **82’** geometry, inner and outer conductor fluid paths **73’, 85’**, coefficient of thermal expansion (CTE) growth of components, installation concept of operations (CONOPS) (i.e. torque/ twisting), and fluid/gas path on exterior of transmission line. Also, the power tap size can be customized to limit current and voltage. In particular, the size and number of electrical “taps” result in a current dividing technique that supplies each antenna segment with the desired power. Also, the RF antenna assembly **24’** provides flexibility in designing the number and radiation power of the antenna elements **102a’-102c’, 103a’-103b’**.

Also, the RF antenna assembly **24’** allows for the formation of as many antenna segments as desired, driven from a single RF coaxial transmission line **82’**. This makes for a selection of frequency independent of overall transducer length. Also, the RF antenna assembly **24’** allows “power splitting” and tuning, by selection of the size and number of center conductor taps, and maintains coaxial transmission line **82’** geometry, allowing the method for sequential building of the coax/antenna sections to be maintained. The RF antenna assembly **24’** can be field assembled and does not require specific “clocking” of the antenna exterior with respect to the inner conductor “tap” points, assembly uses simple tools.

Furthermore, the RF antenna assembly **24’** may permit sealing fluid flow to allow cooling fluid/gas and to allow for pressure balancing of the power node and antenna. The RF antenna assembly **24’** accommodates differential thermal expansion for high temperature use, and utilizes several mechanical techniques to maintain high RF standoff distances. Also, RF antenna assembly **24’** has multiple element sizes that can be arrayed together, allowing for the transducer to be driven at more than one frequency to account different subterranean environments along the length of the wellbore.

Additionally, the inner conductor **71’** comprises a tube defining a first fluid passageway **85’** therein, and the outer conductor **72’** is spaced from the inner conductor to define a second fluid passageway **73’**. Each dielectric tube **61’** includes opposing open ends, and with opposing tap connectors **60a’-60b’.** Each opposing tap connector **60a’-60b’** is tubular and comprises a slotted recess **66a’-66b’** receiving therein the respective opposing open end of the dielectric tube **61’**. Also, each tubular opposing tap connector **60a’-60b’** includes a threaded surface **86a'-86b'** for engaging an opposing threaded end **63a'-63b'** of the corresponding dipole element **102a'-102c', 103a'-103b'**, and a first plurality of tool-receiving recesses **65a-65d** on a first outer surface thereof.

Another aspect is directed to a method of making a RF antenna assembly **24'** operable to be positioned within a wellbore in a subterranean formation **27'** for hydrocarbon resource recovery. The method comprises positioning a series of tubular dipole antennas **102a'-102c', 103a'-103b'** within the wellbore, each tubular dipole antenna comprising a pair of dipole elements, positioning an RF transmission line **82'** to extend within the series of tubular dipole antennas, and positioning a respective coupling structure **105'-107', 111'** between each pair of dipole elements and between the series of tubular dipole antennas. Each coupling structure **105'-107', 111'** comprises a dielectric tube **61'** mechanically coupling adjacent dipole elements **102a'-102c', 103a'-103b'**, and at least one tap connector **60a'-60b'** carried by the dielectric tube and electrically coupling the RF transmission line **82'** to a corresponding dipole element.

Referring now to FIGS. 14A-15C, the heating pattern of the RF antenna assembly **24'** is shown. Diagrams **140-142** show the heating pattern with ε_r=14, σ=0.003 S/m, and diagrams **150-152** show the heating pattern with ε_r=30, σ=0.05 S/m. Advantageously, the RF antenna assembly **24'** collinear array configuration provides a uniform heating pattern along the axis of the array. Also, the football shaped desiccation region is based on heating patterns of a dipole antenna. For the sake of maximum uniformity between models, this desiccation shape was used for alternate antenna designs also. The actual shape of the desiccation region may be different.

[0001] Referring now additionally to FIGS. 16A-16B, a Smith Chart **160** (Frequency Sweep: 5.2– 5.4 MHz) and another associate diagram **165** illustrate performance of the RF antenna assembly **24'**. Sensitivity: 1) Impedance is comparable to a dipole as the pay zone moves from saturation (solid with X mark, plain dashed line) to desiccation (solid line with circle, and dashed line with square mark). 2) Impedance is managed over the pay zone corner cases for low and high ε_r and σ.

Name	Freq	Ang	Mag	RX
m1	5.8791	-154.5753	0.0892	0.8485 - 0.0655i
m2	6.1761	1.1308	0.1360	1.3148 + 0.0072i
m3	5.8667	-151.6645	0.0715	0.8797 - 0.0600i
m4	6.1885	3.0302	0.0062	1.0124 + 0.0007i
m5	5.8667	-159.9952	0.0345	0.9369 - 0.0222i
m6	6.1390	173.9086	0.0559	0.8947 + 0.0106i

Table 1: Data Points for Smith Chart (FIG. 16A)

Other features relating to RF antenna assemblies are disclosed in co-pending applications: titled “RF ANTENNA ASSEMBLY WITH DIELECTRIC ISOLATOR AND RELATED METHODS,” Attorney Docket No. GCSD-2557 (61897); and titled “RF ANTENNA ASSEMBLY WITH SERIES DIPOLE ANTENNAS AND COUPLING STRUCTURE AND RELATED METHODS,” Attorney Docket No. GCSD-2630 H8904 (61898), all incorporated herein by reference in their entirety.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

CLAIMS

1. A radio frequency (RF) antenna assembly configured to be positioned within a wellbore in a subterranean formation for hydrocarbon resource recovery, the RF antenna assembly comprising:

first and second tubular conductors and a feed structure therebetween defining a dipole antenna to be positioned within the wellbore; and

an RF transmission line extending within one of said tubular conductors;

said feed structure comprising

a dielectric tube,

a first connector coupling said RF transmission line to said first tubular conductor, and

a second connector coupling said RF transmission line to said second tubular conductor.

2. The RF antenna assembly of claim 1 wherein said RF transmission line comprises a series of coaxial sections coupled together in end-to-end relation, each coaxial section comprising an inner conductor, an outer conductor surrounding said inner conductor, and a dielectric therebetween.

3. The RF antenna assembly of claim 2 wherein said first connector couples said outer conductor to said first tubular conductor; and wherein said second connector couples said inner conductor to said second tubular conductor.

4. The RF antenna assembly of claim 2 wherein said inner conductor comprises a tube defining a first fluid passageway therein; and wherein said outer conductor is spaced from said inner conductor to define a second fluid passageway.

5. The RF antenna assembly of claim 2 wherein said feed structure comprises an intermediate conductor extending within said dielectric tube and coupling said inner conductor to said second connector.

6. The RF antenna assembly of claim 5 wherein said intermediate conductor comprises a conductive tube.

7. The RF antenna assembly of claim 1 wherein said first and second tubular conductors each comprises a threaded end; and wherein said first and second connectors each comprises a threaded end engaging a respective threaded end of said first and second tubular conductors for defining overlapping mechanical threaded joints.

8. A method of making a radio frequency (RF) antenna assembly to be positioned within a wellbore in a subterranean formation for hydrocarbon resource recovery, the method comprising:

providing first and second tubular conductors and a feed structure therebetween to define a dipole antenna to be positioned within the wellbore;

positioning an RF transmission line to extend within one of the tubular conductors; and

forming the feed structure to comprise

a dielectric tube,

a first connector coupling the RF transmission line to the first tubular conductor, and

a second connector coupling the RF transmission line to the second tubular conductor.

9. The method of claim 8 further comprising forming the RF transmission line to comprise a series of coaxial sections coupled together in end-to-end relation, each coaxial section comprising an inner conductor, an outer conductor surrounding the inner conductor, and a dielectric therebetween.

10. The method of claim 9 wherein forming the feed structure comprises forming the first connector to couple the outer conductor to the first tubular conductor, and forming the second connector to couple the inner conductor to the second tubular conductor.

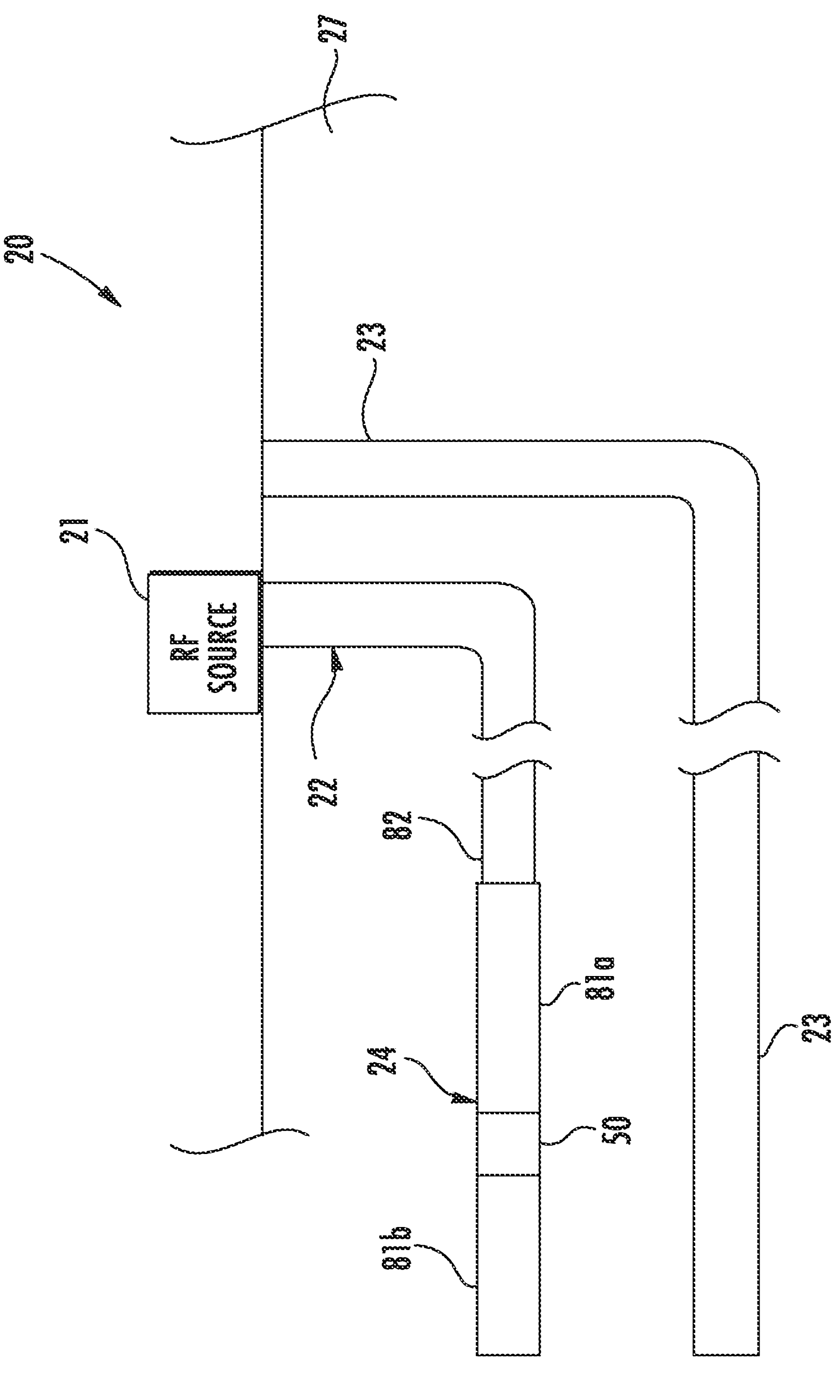


FIG. 1

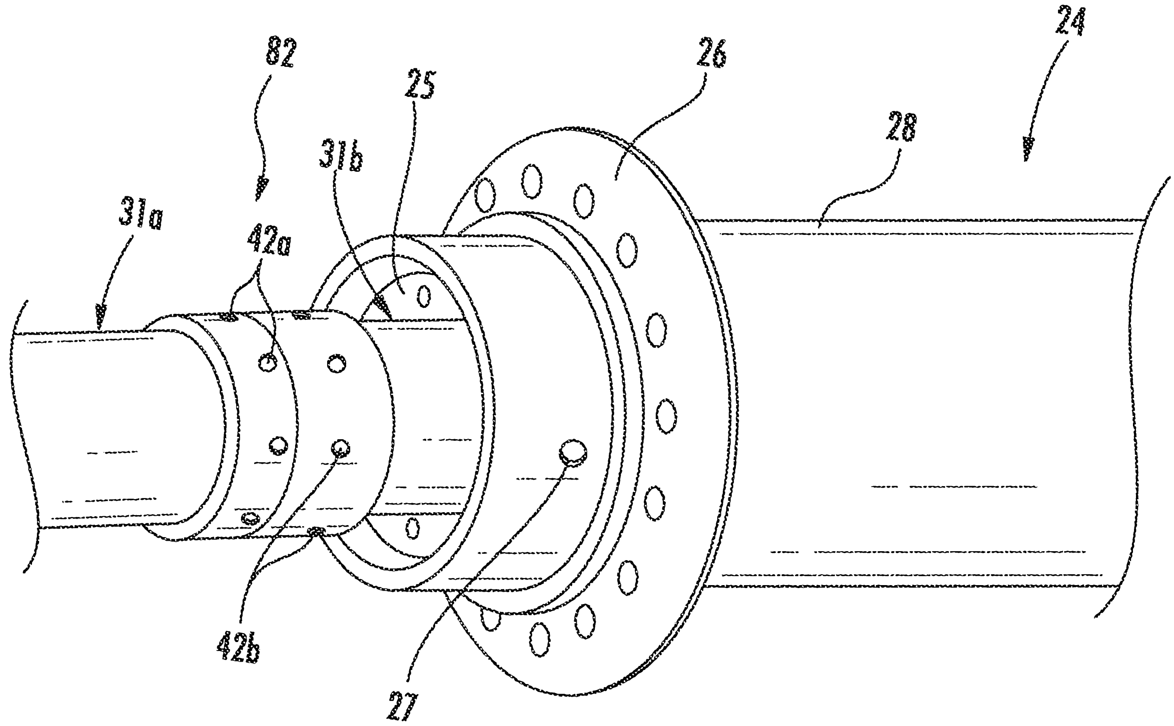


FIG. 2

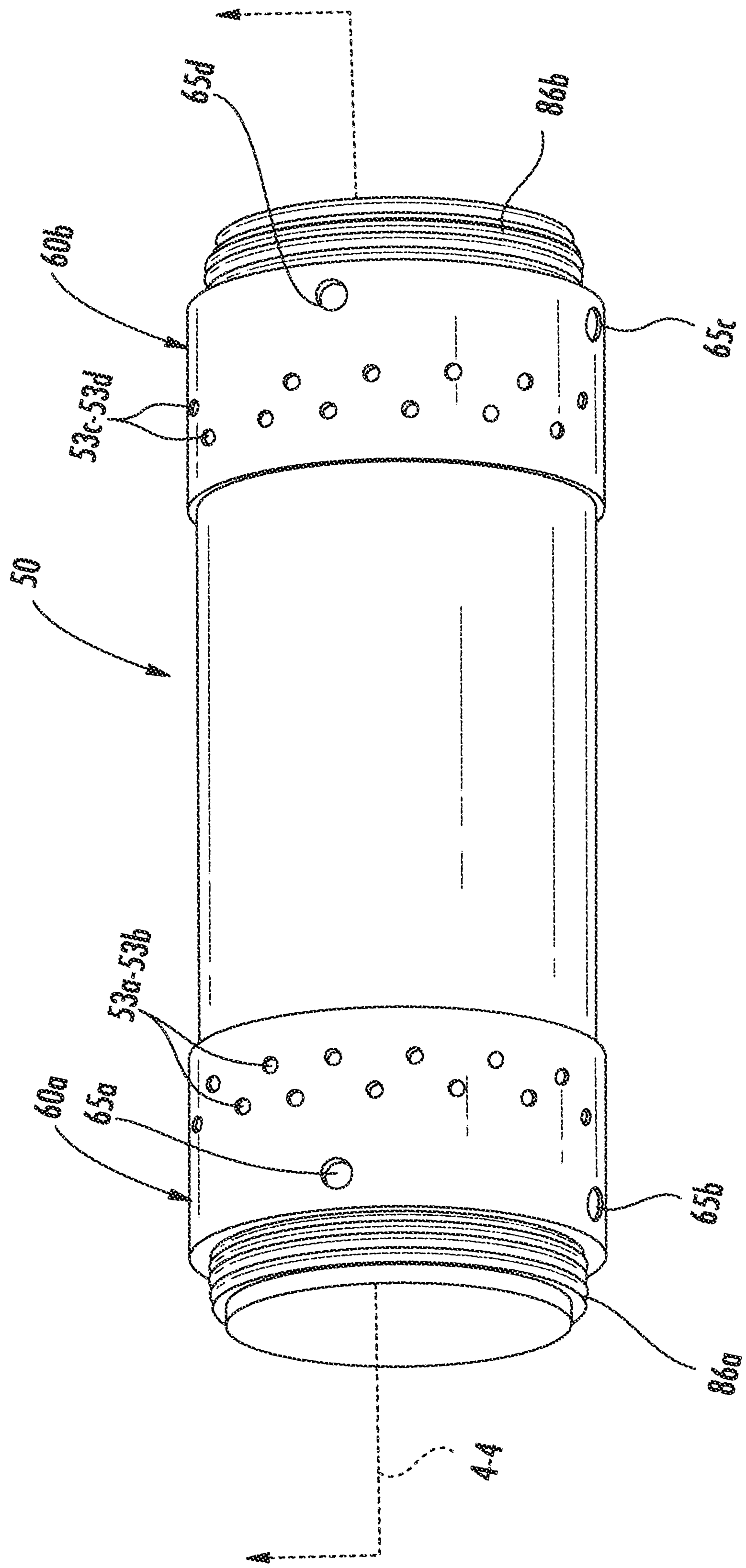


FIG. 3

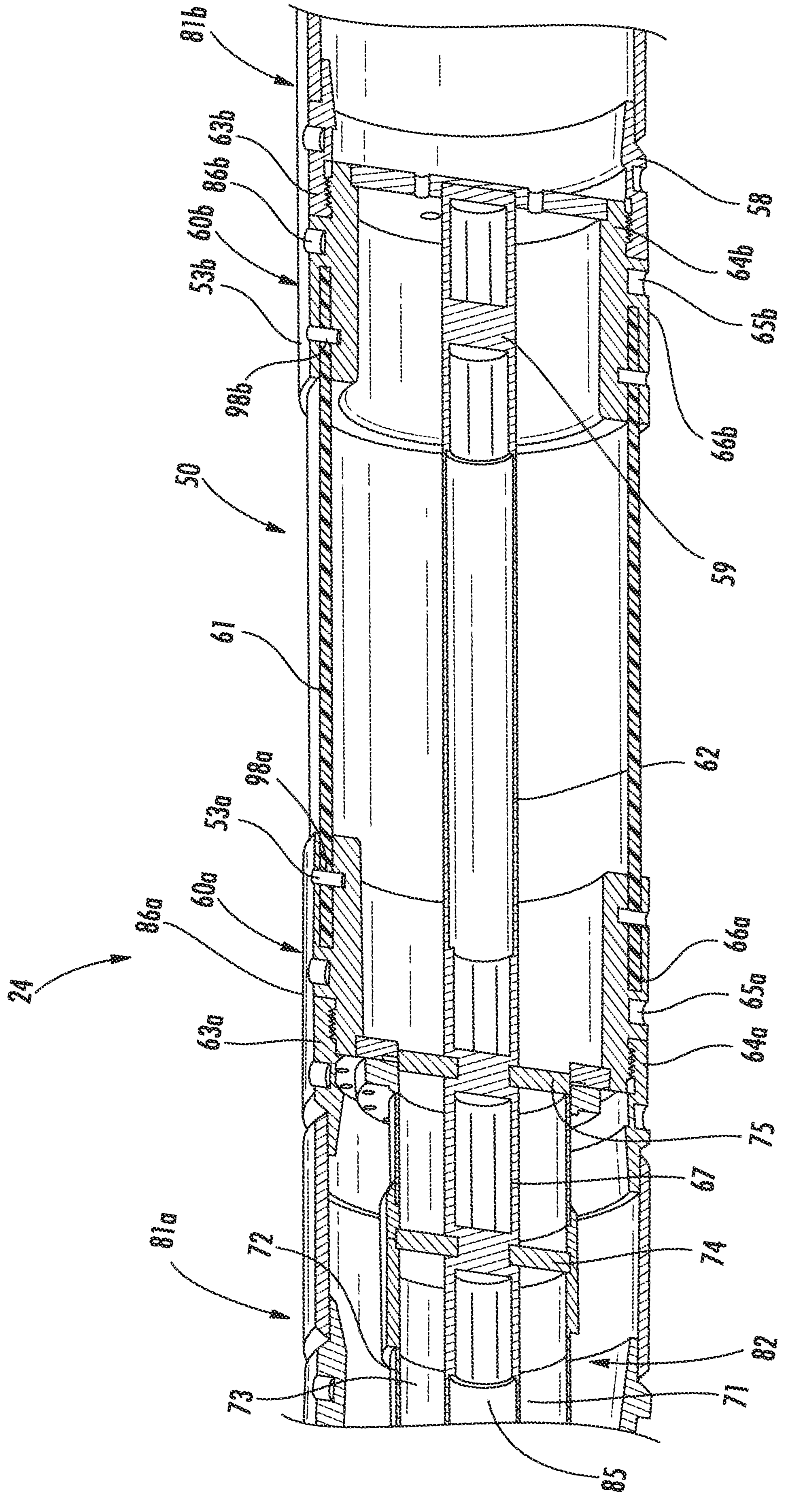

81b
63b
86b
60b
53b
98b
58
64b
65b
66b
50
59
61
62
98a
53a
60a
86a
24
63a
66a
65a
64a
75
67
81a
72
74
82
73
71
85

FIG. 4

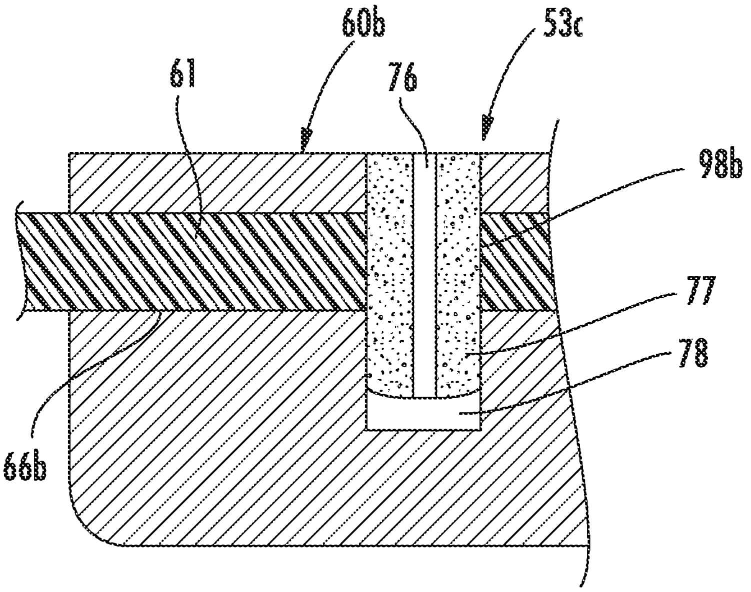


FIG. 5A

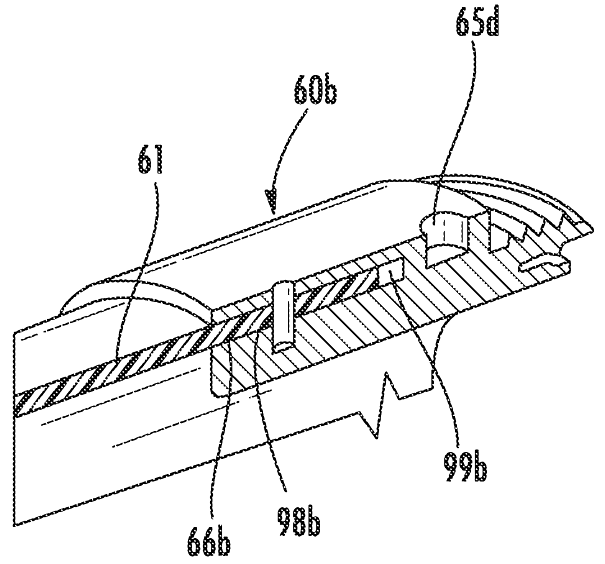


FIG. 5B

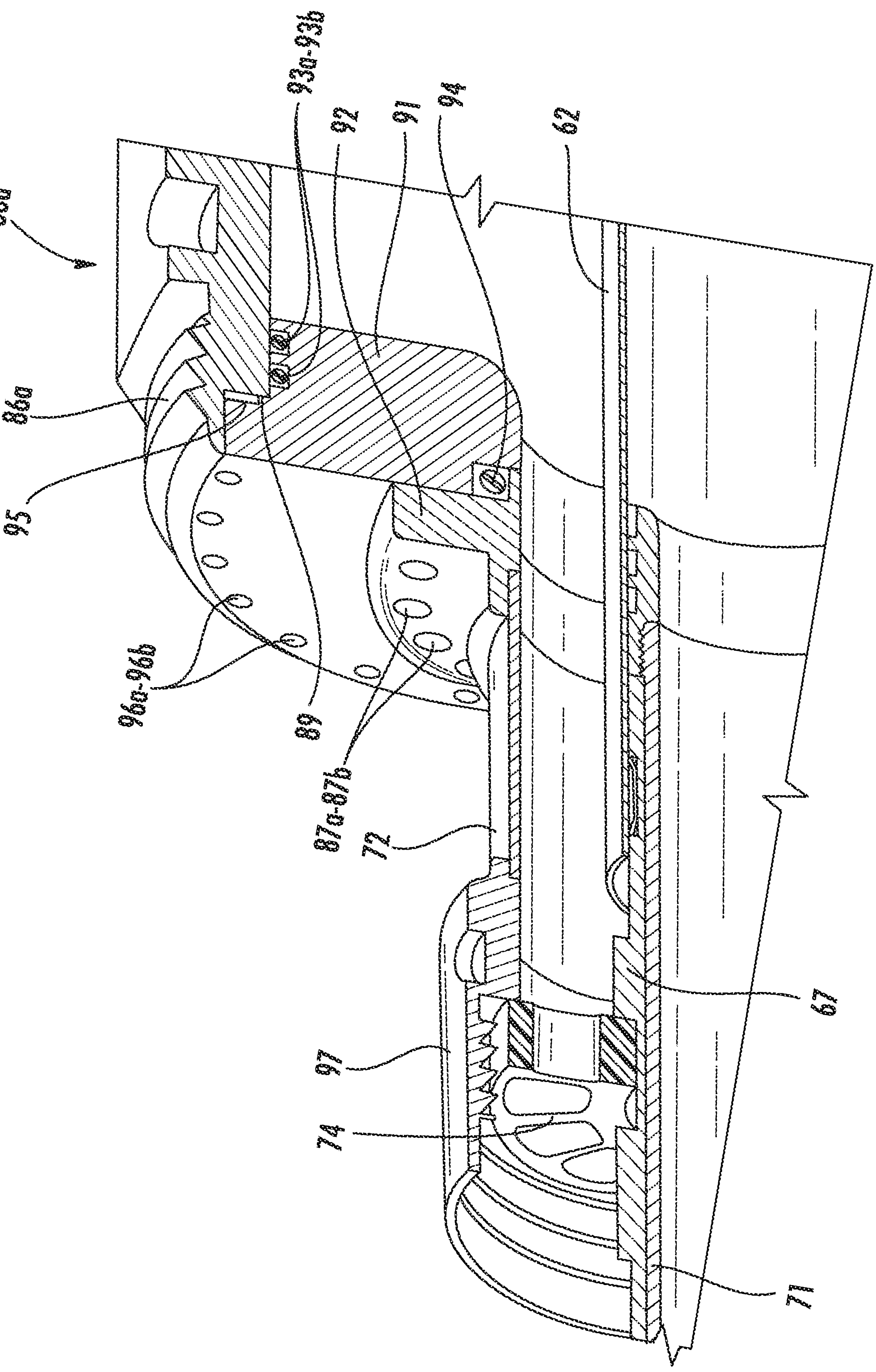


FIG. 6

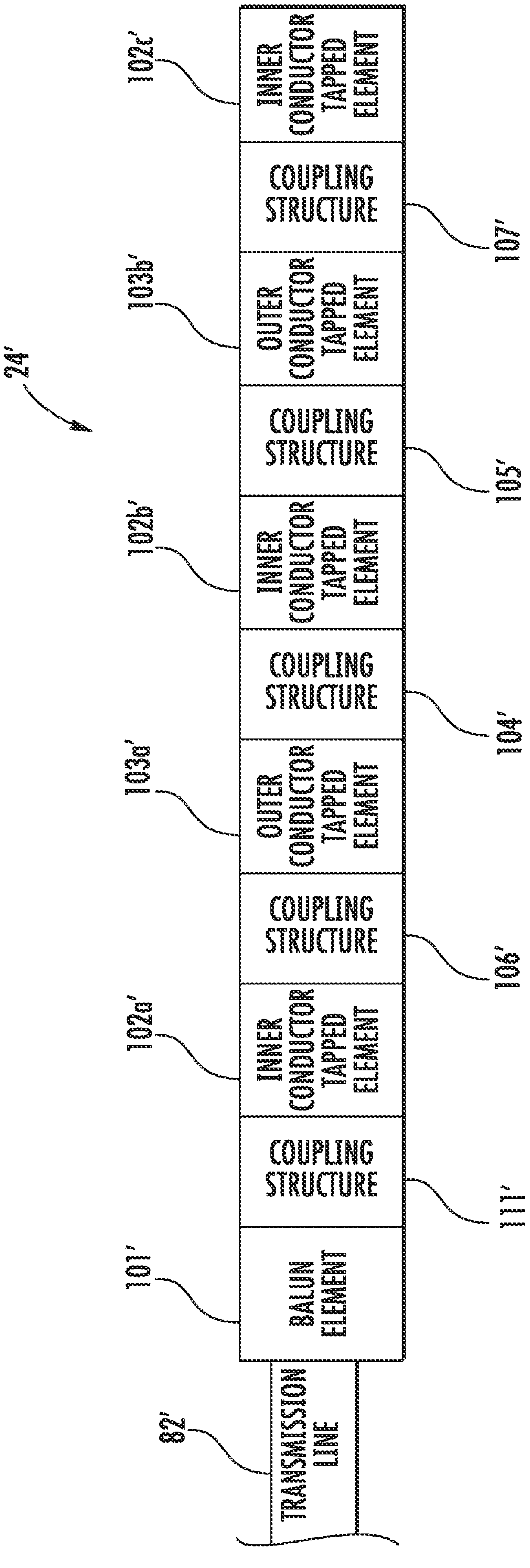

24'
82'
TRANSMISSION LINE
101'
BALUN ELEMENT
111'
COUPLING STRUCTURE
102a'
INNER CONDUCTOR TAPPED ELEMENT
106'
COUPLING STRUCTURE
103a'
OUTER CONDUCTOR TAPPED ELEMENT
104'
COUPLING STRUCTURE
102b'
INNER CONDUCTOR TAPPED ELEMENT
105'
COUPLING STRUCTURE
103b'
OUTER CONDUCTOR TAPPED ELEMENT
107'
COUPLING STRUCTURE
102c'
INNER CONDUCTOR TAPPED ELEMENT

FIG. 7

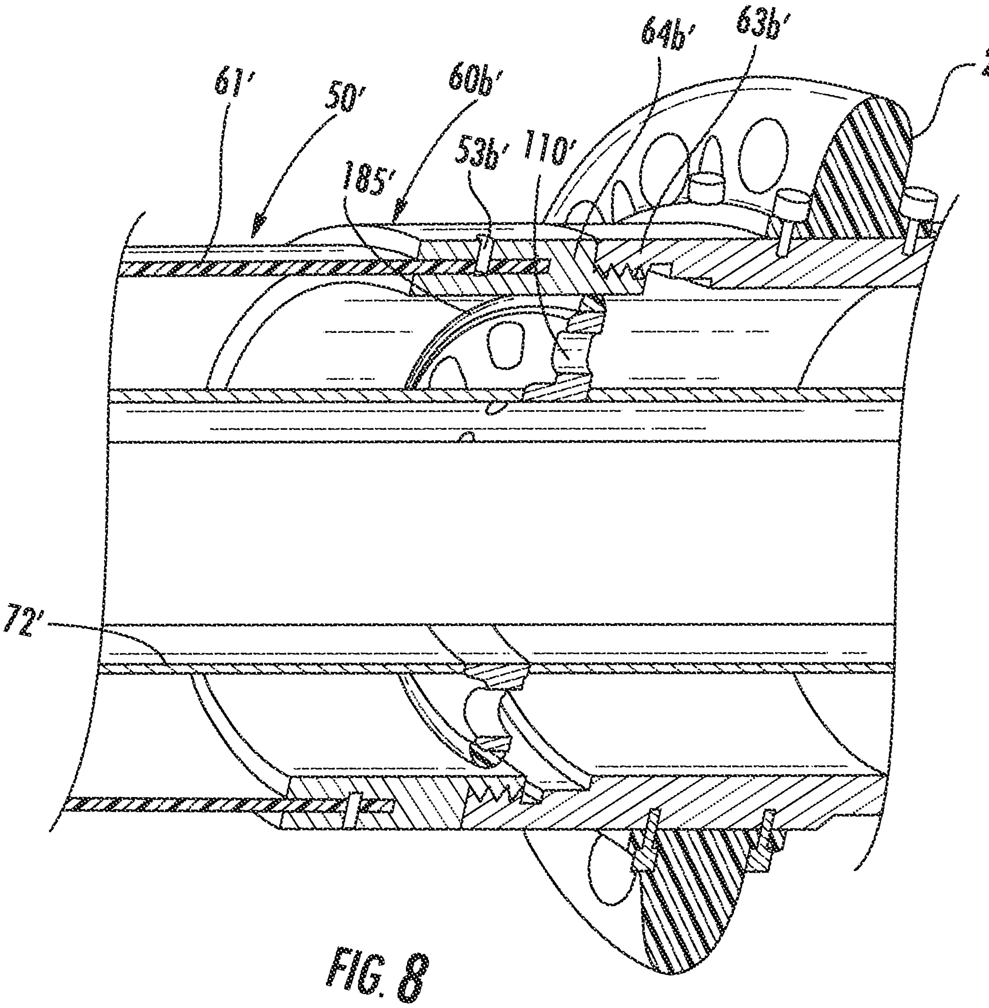


FIG. 8

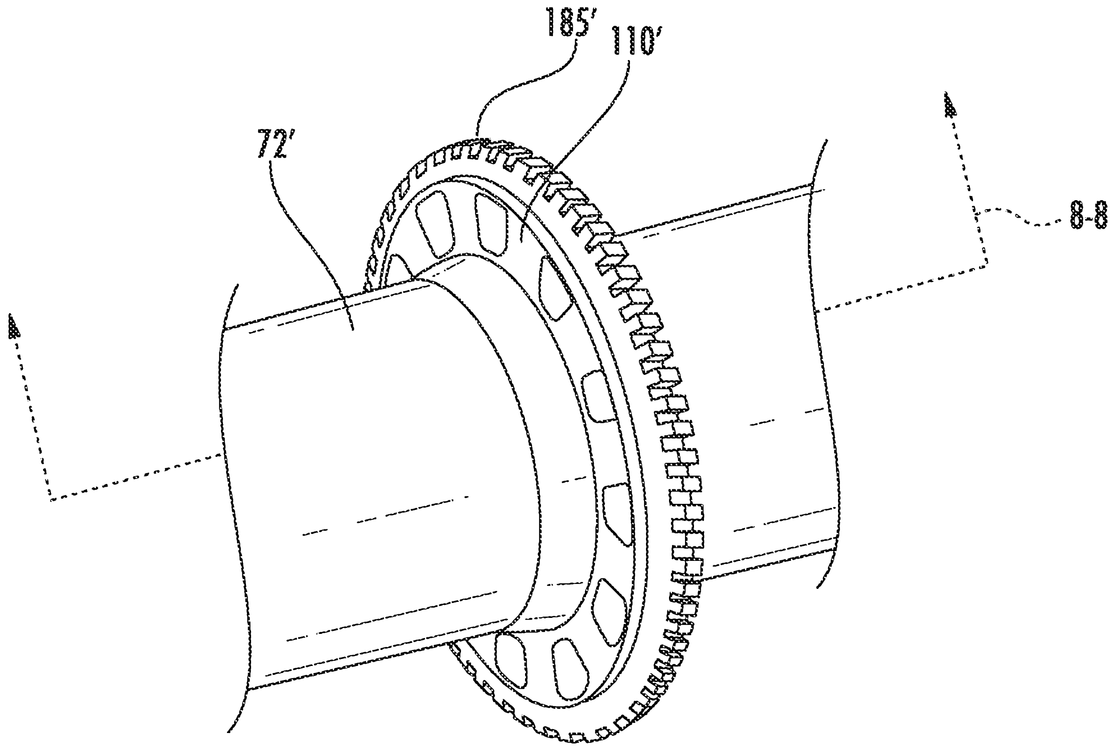


FIG. 9

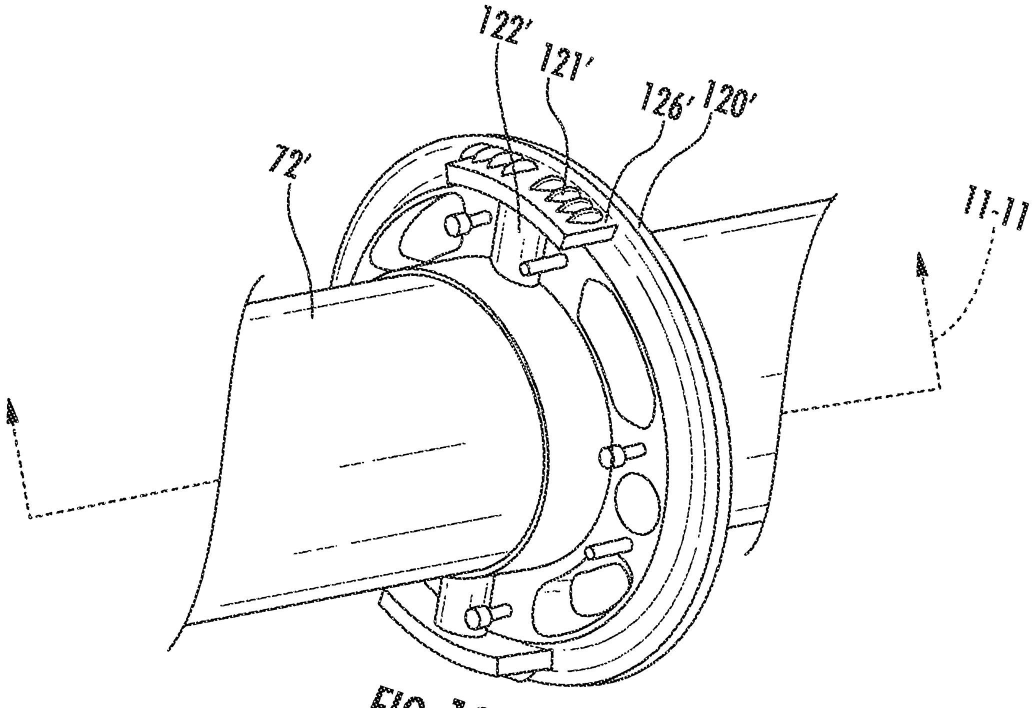


FIG. 10

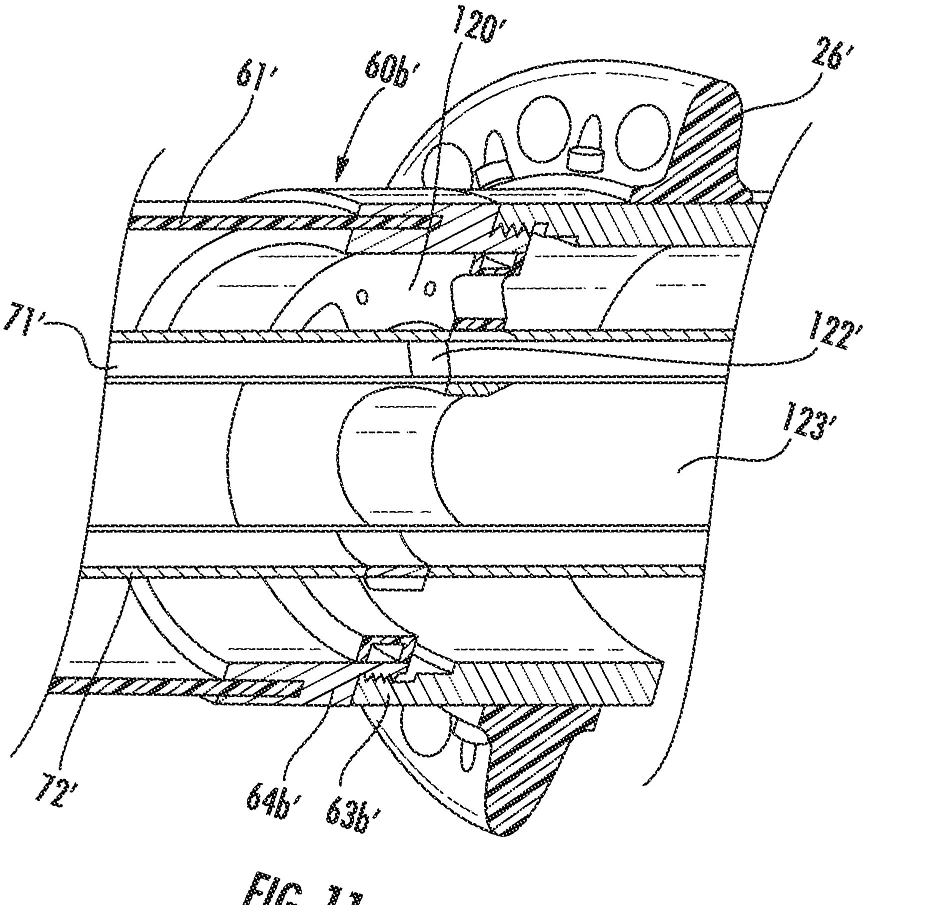


FIG. 11

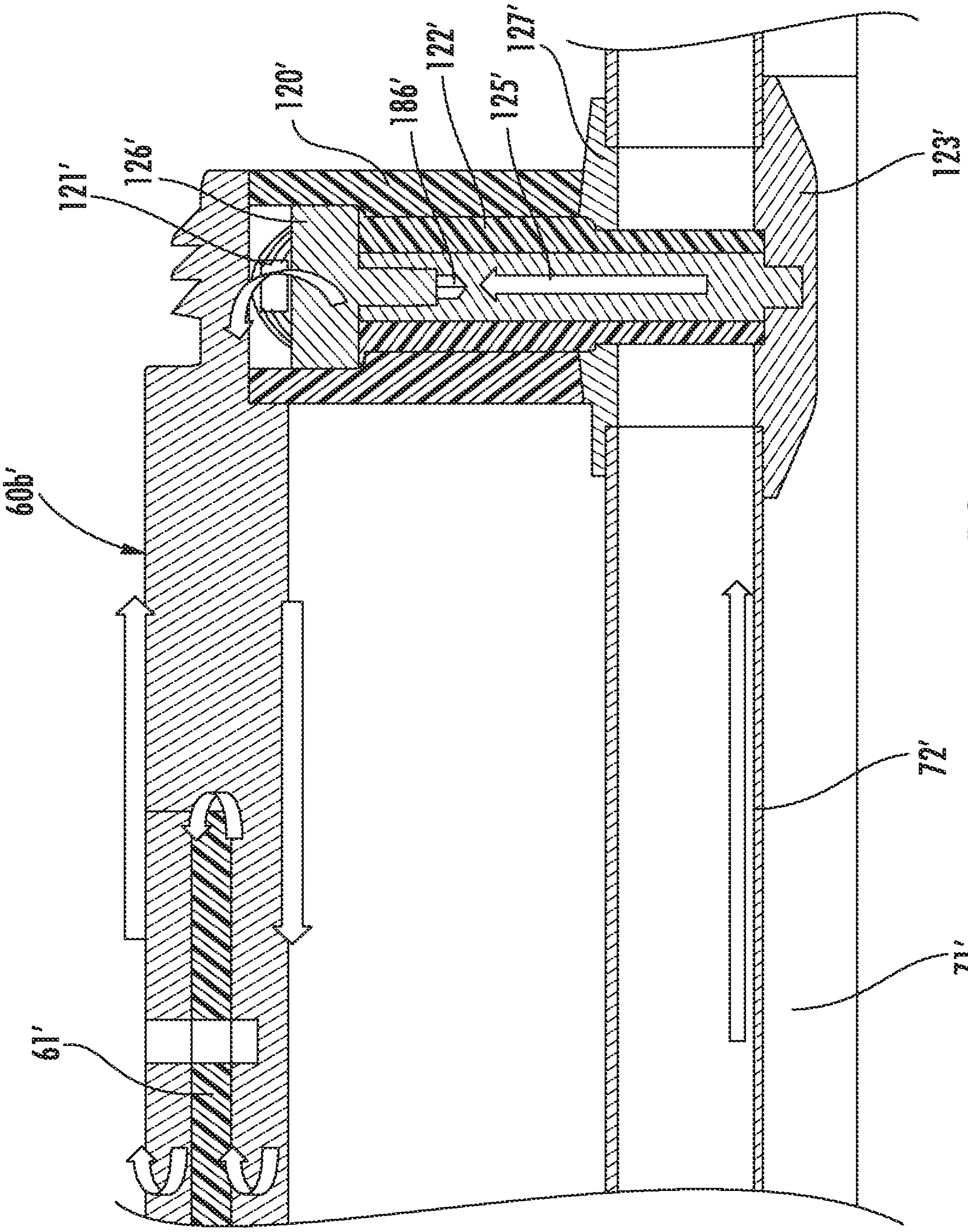


FIG. 12

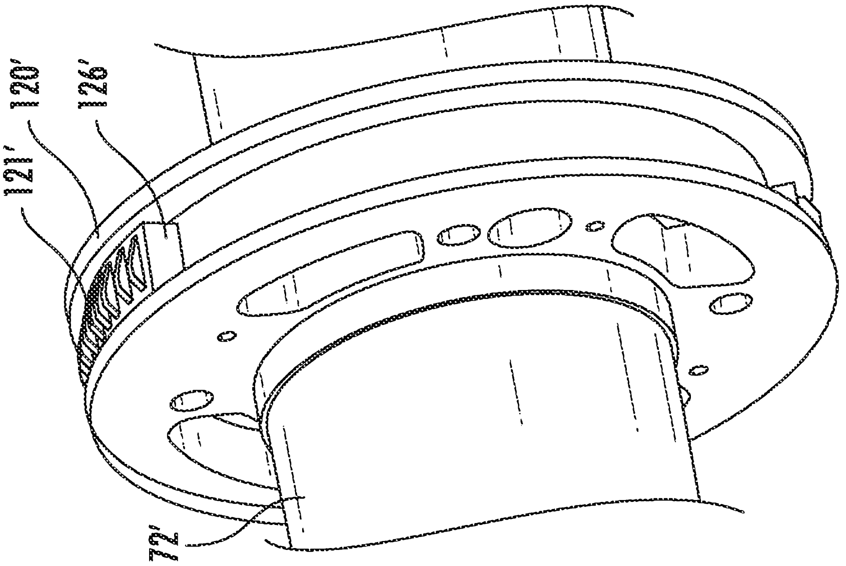


FIG. 13C

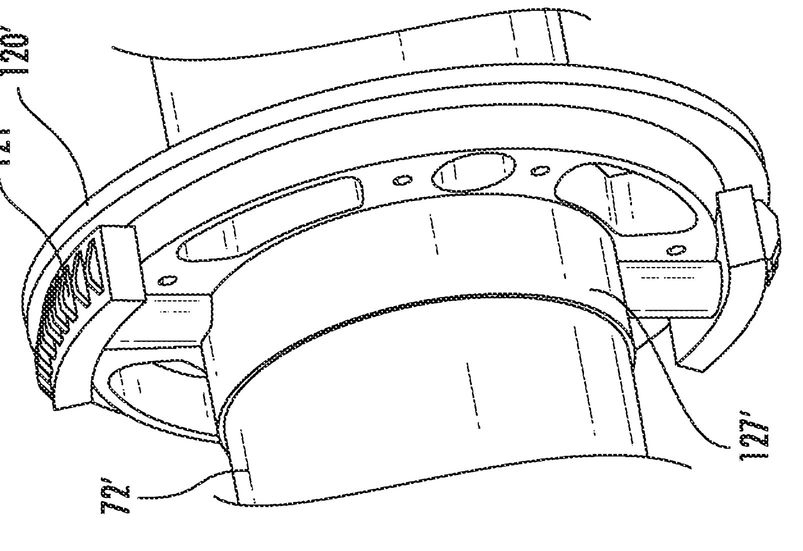


FIG. 13B

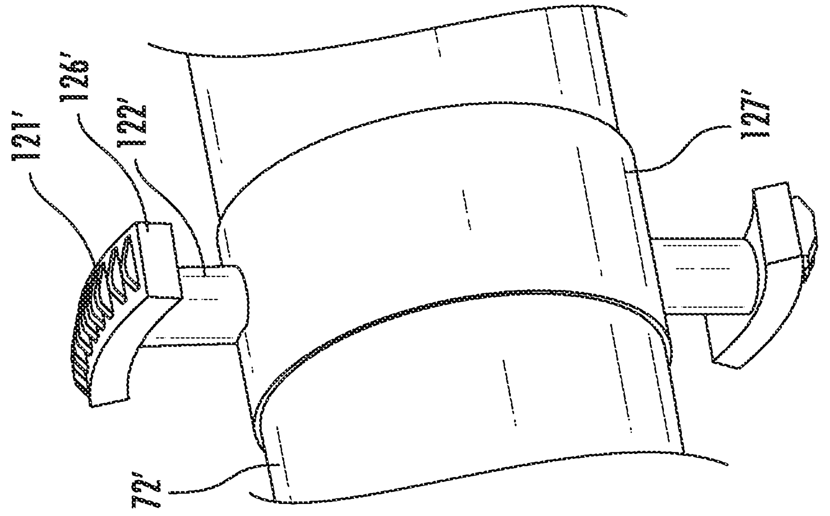


FIG. 13A

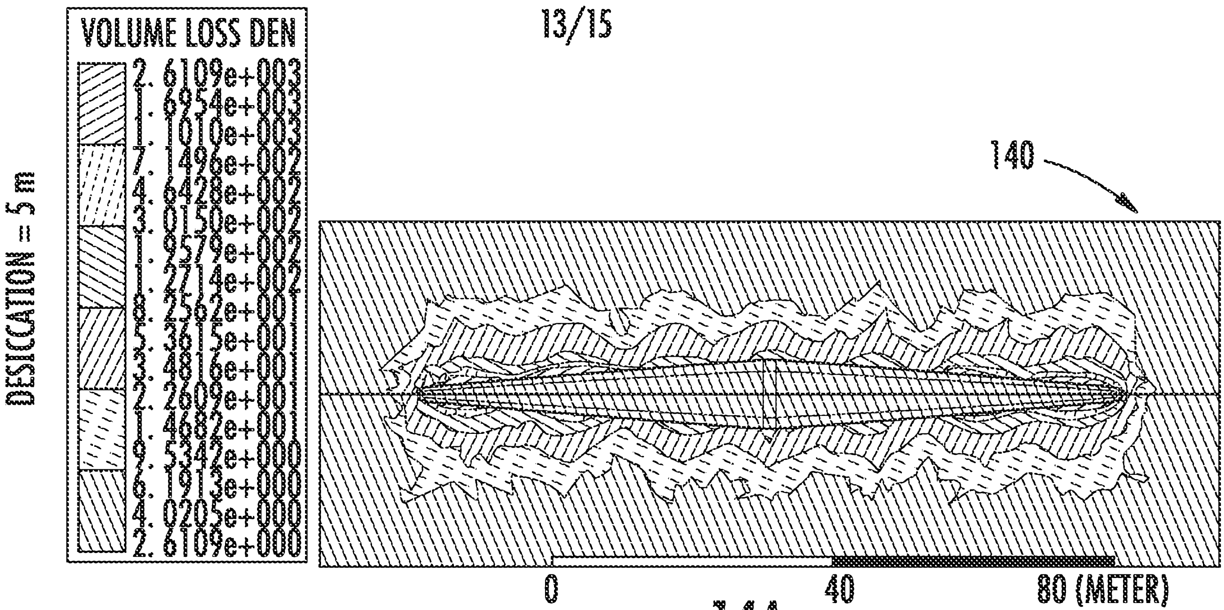


FIG. 14A

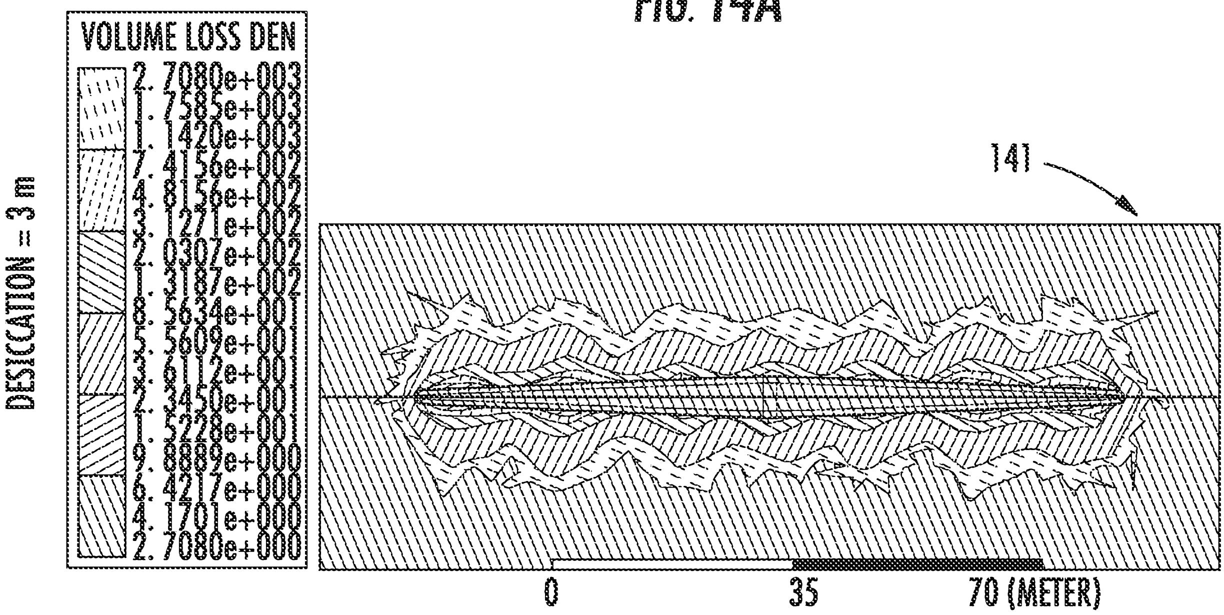


FIG. 14B

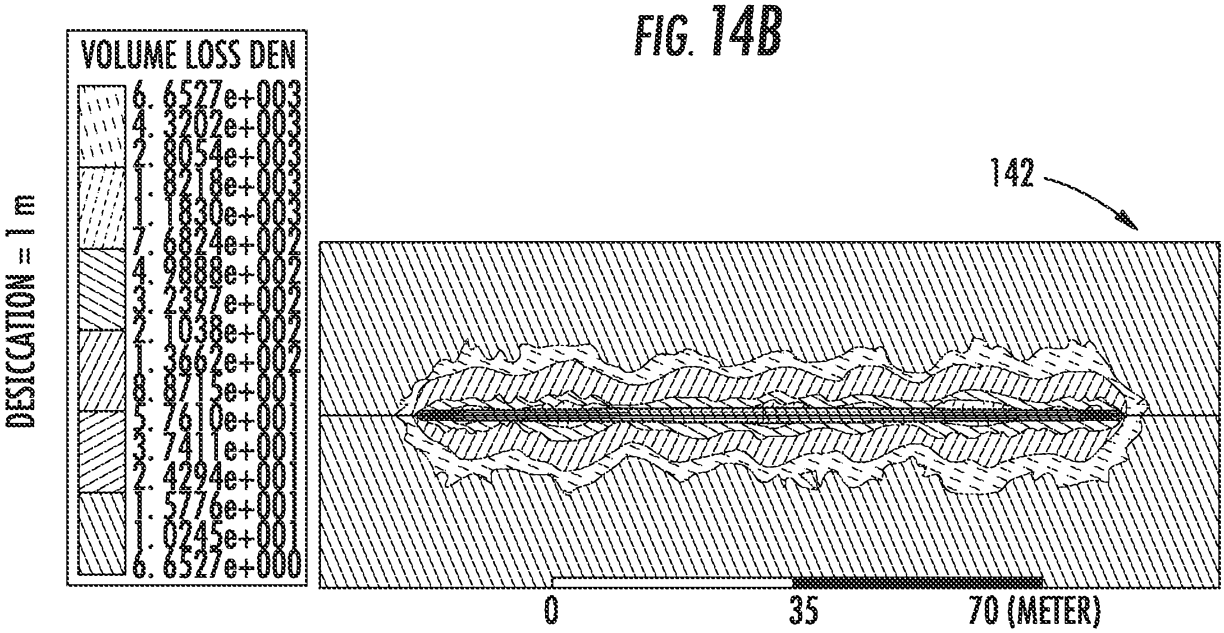


FIG. 14C

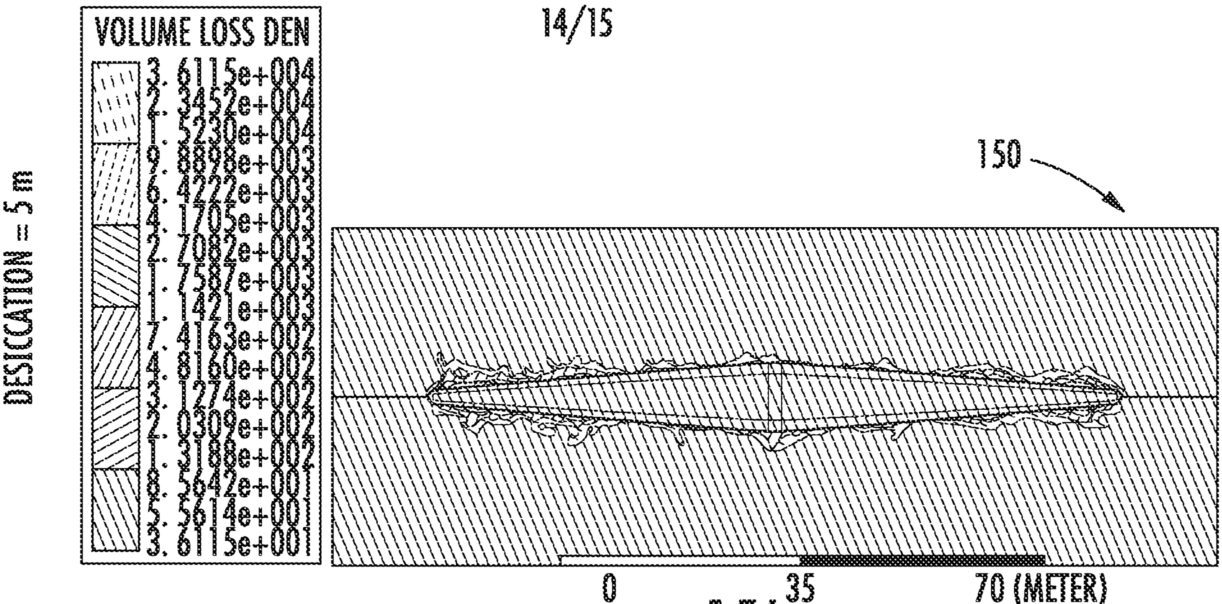


FIG. 15A

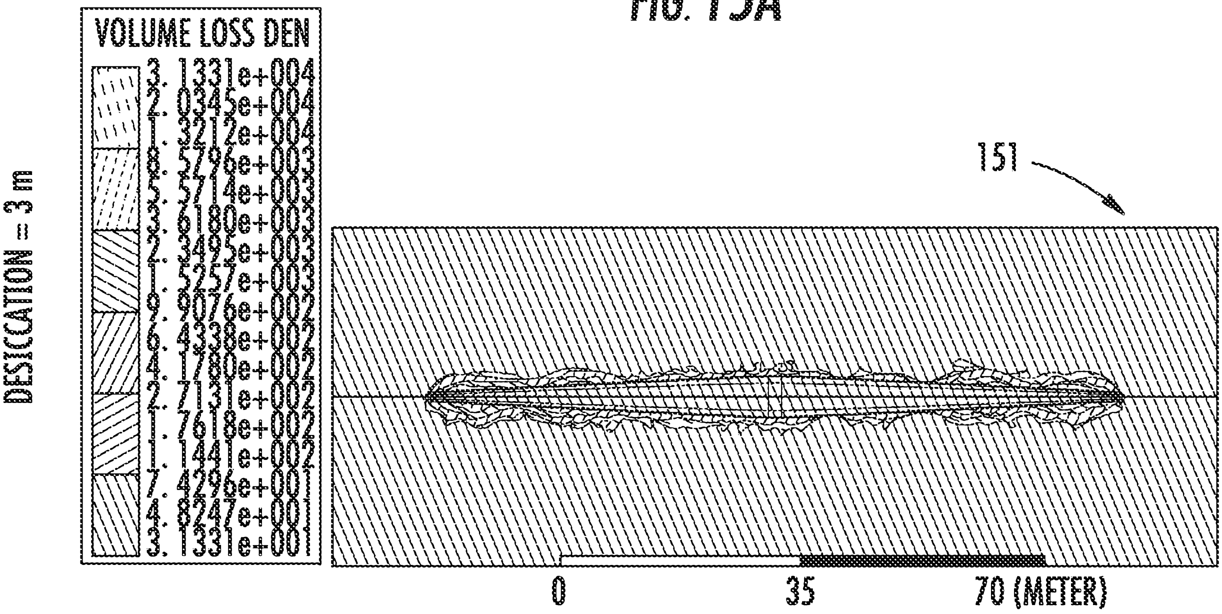


FIG. 15B

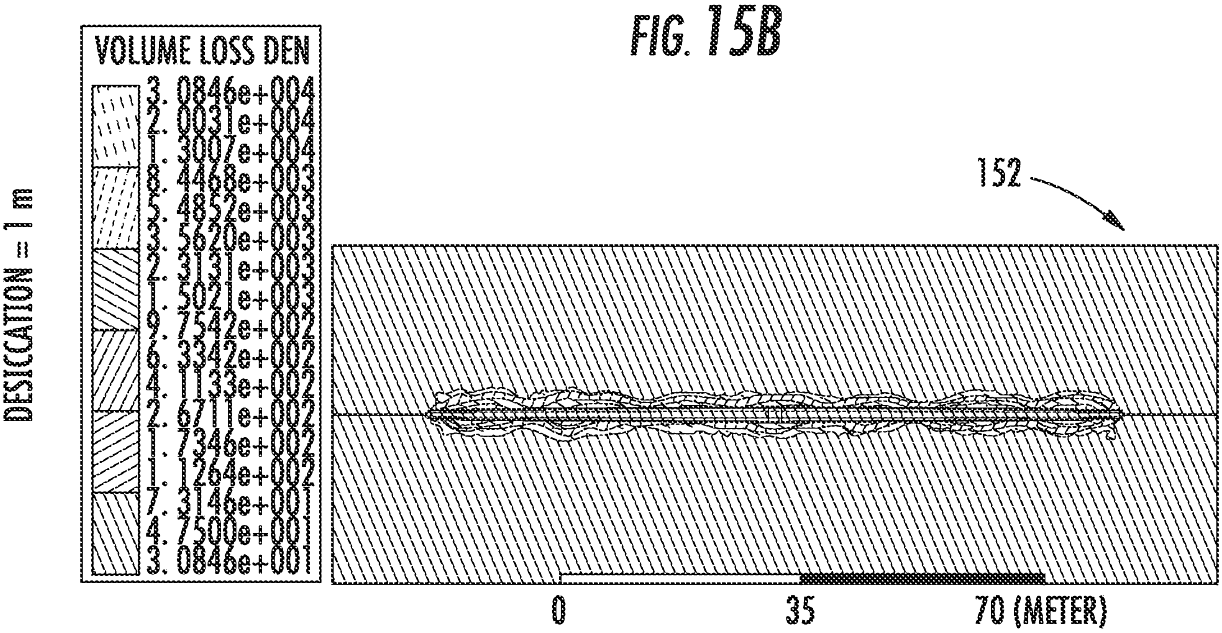


FIG. 15C

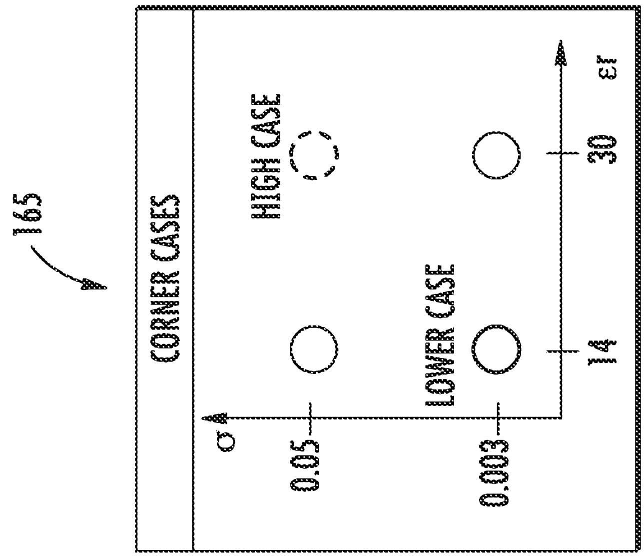
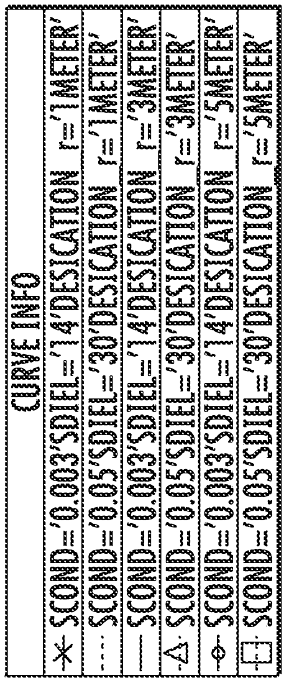


FIG. 16B



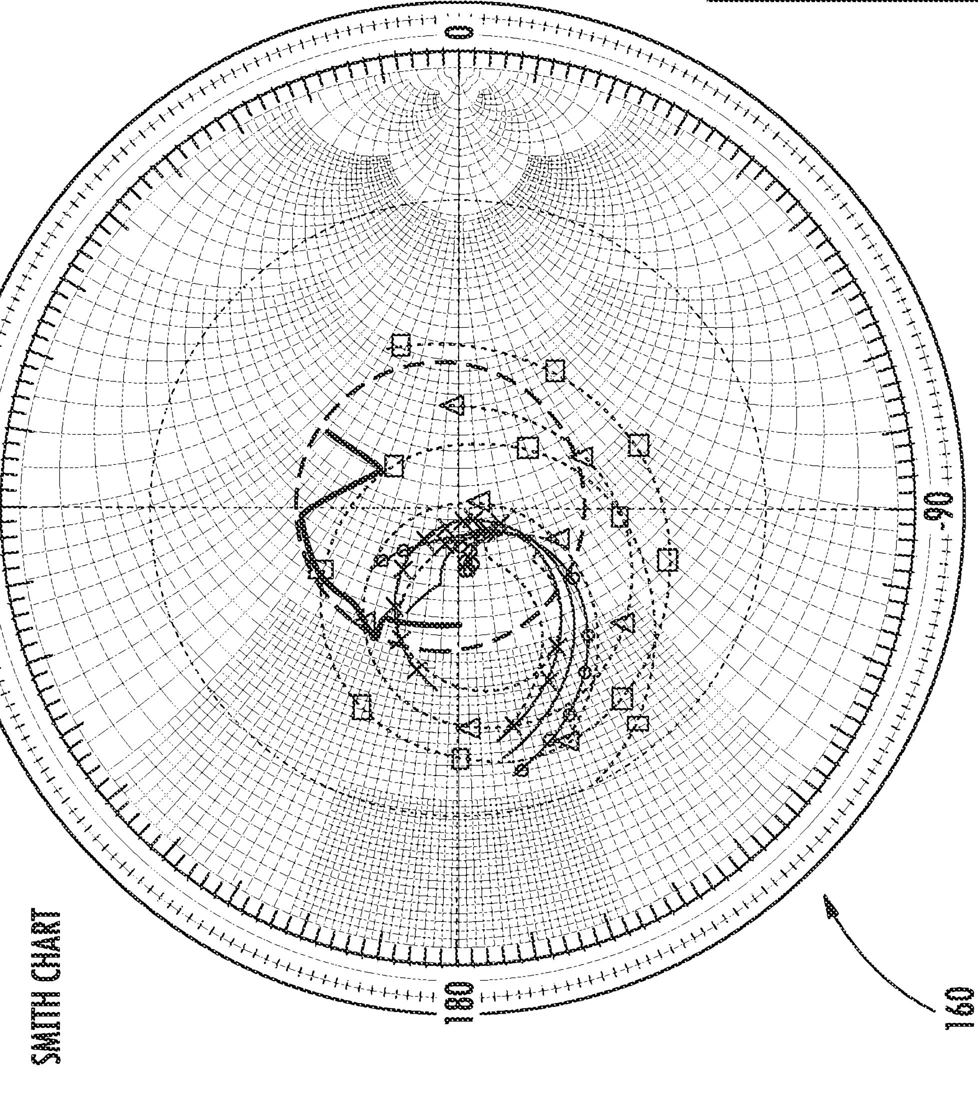


FIG. 16A