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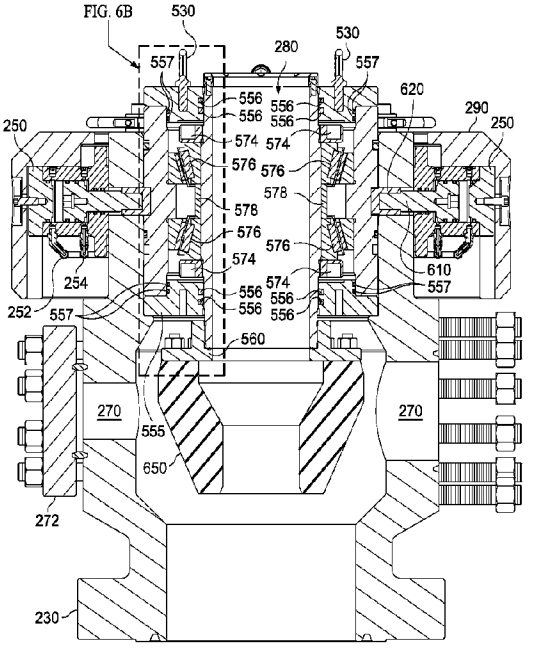


FIG. 6A

(57) Abrégé/Abstract:
A rotating control device includes a bowl housing with an inner aperture to receive a seal and bearing assembly. A plurality of hydraulically-actuated fail-last-position latching assemblies are disposed about an outer surface of the bowl housing to controllably extend a plurality of piston-driven dogs radially into a groove of the seal and bearing assembly. The seal and bearing assembly includes a housing, a mandrel disposed within an inner aperture of the housing, a first interference-fit sealing element attached to a bottom distal end of the mandrel, a plurality of tapered-thrust bearings indirectly mounted to the housing, a preload spacer disposed between top and bottom tapered-thrust bearings, a plurality of jam nuts to adjust a preload of the tapered-thrust bearings and a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel.

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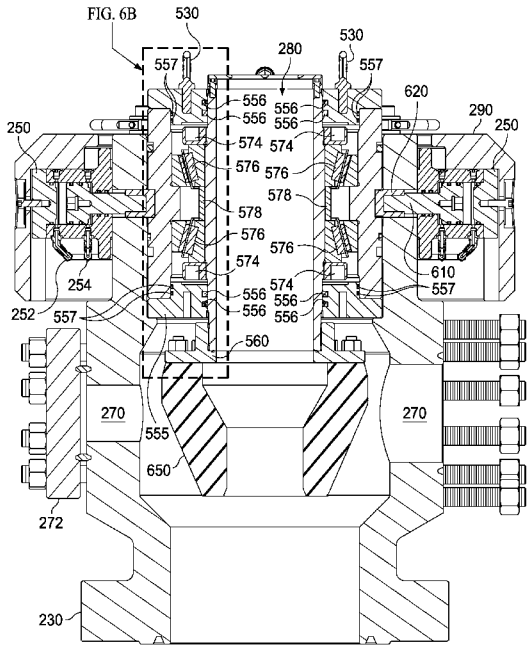


FIG. 6A

(57) Abstract: A rotating control device includes a bowl housing with an inner aperture to receive a seal and bearing assembly. A plurality of hydraulically-actuated fail-last-position latching assemblies are disposed about an outer surface of the bowl housing to controllably extend a plurality of piston-driven dogs radially into a groove of the seal and bearing assembly. The seal and bearing assembly includes a housing, a mandrel disposed within an inner aperture of the housing, a first interference-fit sealing element attached to a bottom distal end of the mandrel, a plurality of tapered-thrust bearings indirectly mounted to the housing, a preload spacer disposed between top and bottom tapered-thrust bearings, a plurality of jam nuts to adjust a preload of the tapered-thrust bearings and a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel.

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IMPROVED ROTATING CONTROL DEVICE FOR LAND RIGS

BACKGROUND OF THE INVENTION

[0001] In conventional drilling operations, a wellhead disposed over a wellbore includes an annular blowout preventer that is fluidly connected to a rotating control device that, with other pressure control equipment, are used to manage wellbore pressure. The drill string extends through an interior passageway of the rotating control device and the annular blowout preventer and extends into the wellbore, which may extend several thousands of feet below the Earth's surface.

[0002] In applications where wellbore pressure is managed, including, for example, managed pressure drilling, pressurized mud cap drilling, underbalanced drilling, extended reach wells, and other drilling operations, the annulus surrounding the drill string is sealed by the rotating control device and the wellbore pressure is managed through manipulation of a surface-backpressure choke manifold disposed on the rig floor. Specifically, wellbore pressure is managed by controlling the choke aperture of the surface-backpressure choke manifold fed by one or more fluid flow lines that divert returning fluids to the surface. Each choke valve of the surface-backpressure choke manifold is capable of a fully opened state where flow is unimpeded, a fully closed state where flow is stopped, and intermediate states where the valve is partially opened, thereby restricting flow and applying surface backpressure commensurate with the flow restriction. If the driller wishes to increase annular pressure, the choke aperture may be closed to the extent necessary to increase the annular pressure the desired amount. Similarly, if the driller wishes to reduce annular pressure, the choke aperture may be opened to the extent necessary to decrease the annular pressure the desired amount. In this way, wellbore pressure may be managed by controlling the surface backpressure from the platform of the drilling rig.

BRIEF SUMMARY OF THE INVENTION

[0003] According to one aspect of one or more embodiments of the present invention, an improved rotating control device includes a bowl housing having a plurality of fluid flow ports and an inner aperture to receive a removably disposed seal and bearing assembly. A plurality of hydraulically-actuated fail-last-position latching assemblies are disposed about an outer surface of the bowl housing to controllably

extend a plurality of piston-driven dogs radially into a groove of the seal and bearing assembly to controllably secure the seal and bearing assembly to the bowl housing. The seal and bearing assembly includes a seal and bearing housing, a mandrel disposed within an inner aperture of the seal and bearing housing, a first interference-fit sealing element attached to a bottom distal end of the mandrel, a plurality of tapered-thrust bearings indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel, a preload spacer disposed between top and bottom tapered-thrust bearings, a plurality of jam nuts to adjust a preload of the tapered-thrust bearings, and a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

[0004] According to one aspect of one or more embodiments of the present invention, a circulating lubricant seal and bearing assembly includes a seal and bearing housing having a groove to receive a plurality of hydraulically-actuated fail-last-position piston-driven dogs. A mandrel having a mandrel lumen is disposed within an inner aperture of the seal and bearing housing. A first interference-fit sealing element is attached to a bottom distal end of the mandrel. A plurality of tapered-thrust bearings are indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel. A preload spacer is disposed between top and bottom tapered-thrust bearings. A plurality of jam nuts are used to adjust a preload of the tapered-thrust bearings. A lower seal carrier is attached to the seal and bearing housing having a plurality of dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

[0005] According to one aspect of one or more embodiments of the present invention, a sealed seal and bearing assembly includes a seal and bearing housing having a groove to receive a plurality of hydraulically-actuated fail-last-position piston-driven dogs. A mandrel having a mandrel lumen is disposed within an inner aperture of the seal and bearing housing. A first interference-fit sealing element is attached to a bottom distal end of the mandrel. A plurality of tapered-thrust bearings are indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel. A preload spacer is disposed between top and bottom tapered-thrust bearings. A plurality of jam nuts to adjust a preload of the tapered-thrust bearings. A lower seal carrier is attached to the seal and bearing housing having a plurality of

dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

[0006] Other aspects of the present invention will be apparent from the following description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure **1** shows a wellhead for a land rig that includes an improved rotating control device in accordance with one or more embodiments of the present invention.

[0008] Figure **2A** shows a first perspective view of an improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0009] Figure **2B** shows a second perspective view of the improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0010] Figure **2C** shows the first perspective view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0011] Figure **2D** shows the second perspective view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0012] Figure **3A** shows a front elevation view of an improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0013] Figure **3B** shows a front elevation view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0014] Figure **3C** shows a rear elevation view of the improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0015] Figure **3D** shows a rear elevation view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0016] Figure **3E** shows a left-side elevation view of the improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0017] Figure **3F** shows a left-side elevation view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0018] Figure **3G** shows a right-side elevation view of the improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0019] Figure **3H** shows a right-side elevation view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0020] Figure **4A** shows a top plan view of an improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0021] Figure **4B** shows a top plan view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0022] Figure **4C** shows a bottom plan view of the improved rotating control device without shroud in accordance with one or more embodiments of the present invention.

[0023] Figure **4D** shows a bottom plan view of the improved rotating control device with shroud in accordance with one or more embodiments of the present invention.

[0024] Figure **5A** shows a perspective view of a sealed seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0025] Figure **5B** shows a top plan view of the sealed seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0026] Figure **5C** shows a bottom plan view of the sealed seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0027] Figure **5D** shows a longitudinal cross section of the sealed seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0028] Figure **5E** shows a perspective view of a circulating lubricant bearing assembly in accordance with one or more embodiments of the present invention.

[0029] Figure **5F** shows a top plan view of the circulating lubricant bearing assembly in accordance with one or more embodiments of the present invention.

[0030] Figure **5G** shows a bottom plan view of the circulating lubricant bearing assembly in accordance with one or more embodiments of the present invention.

[0031] Figure **5H** shows a longitudinal cross section of the circulating lubricant bearing assembly in accordance with one or more embodiments of the present invention.

[0032] Figure **6A** shows a longitudinal cross section of the improved rotating control device with shroud showing engagement of the plurality of hydraulically-actuated piston-driven dogs in accordance with one or more embodiments of the present invention.

[0033] Figure **6B** shows a detailed cross-sectional view of a portion of the improved rotating control device with shroud showing engagement of the plurality of hydraulically-actuated piston-driven dogs, tapered-thrust bearings, preload spacer, and jam nuts in accordance with one or more embodiments of the present invention.

[0034] Figure **7A** shows a longitudinal cross section of an improved rotating control device with shroud showing seal engagement with drill pipe in accordance with one or more embodiments of the present invention.

[0035] Figure **7B** shows a longitudinal cross section of the improved rotating control device with shroud showing seal engagement with drill pipe having a tool joint in accordance with one or more embodiments of the present invention.

[0036] Figure **8A** shows a cross-sectional view of a lower seal carrier of a seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0037] Figure **8B** shows an exploded bottom-facing perspective view of the lower seal carrier of the seal and bearing assembly in accordance with one or more embodiments of the present invention.

[0038] Figure **8C** shows a bottom-facing perspective view of the lower seal carrier of the seal and bearing assembly in accordance with one or more embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0039] One or more embodiments of the present invention are described in detail with reference to the accompanying figures. For consistency, like elements in the various figures are denoted by like reference numerals. In the following detailed description of the present invention, specific details are set forth in order to provide

a thorough understanding of the present invention. In other instances, well-known features to one of ordinary skill in the art are not described to avoid obscuring the description of the present invention.

[0040] In applications where wellbore pressure is managed, an annular closing, or pressure containment, device is used to seal the annulus surrounding the drill string. Pressure containment devices include rotating control devices, non-rotating control devices, and other annular closing devices. Rotating control devices typically include one or more sealing elements that rotate with the drill string, whereas non-rotating control devices typically include one or more sealing elements that do not rotate with the drill string. The one or more sealing elements are either active or passive. Active sealing elements typically use active seals such as, for example, hydraulically actuated sealing elements, whereas passive sealing elements typically use passive seals. Rotating control devices using passive sealing elements are the most commonly used type of pressure containment device in use today due to their comparatively lower upfront costs and proven track record.

[0041] However, conventional rotating control devices suffer from a number of issues that complicate their use, reduce productive uptime, and increase the total cost of ownership. Conventional rotating control devices include one or more sealing elements that perform the sealing function and one or more bearing assemblies that facilitate rotation of the sealing elements with the drill string. The bearing assemblies are prone to failure due to, for example, mechanical wear out, lack of lubrication, reciprocation on the drill pipe, and the like, requiring their removal and replacement, resulting in expensive non-productive downtime. In some circumstances, the drill string must be tripped out to remove and replace the bearing assembly of the rotating control device at substantial expense. As such, a significant contributor to the total cost of ownership of conventional rotating control devices is the cost associated with installing, monitoring, servicing, removing, and replacing the bearing assembly and the related non-productive downtime. In addition, conventional rotating control devices typically use mechanical clamping mechanisms to secure the seal and bearing assembly to a housing. The clamping mechanisms are prone to mechanical wear out and damage from rig operations and reciprocation of the drill string and, when they fail, control of wellbore pressure is lost posing a significant danger to the safety of rig personnel and increasing the risk

of fouling the environment, and the rotating control device itself must be pulled and replaced.

[0042] Accordingly, in one or more embodiments of the present invention, an improved rotating control device for land rigs has a simplified design that includes fewer parts, costs less to manufacture, and reduces upfront costs as well as total cost of ownership. The improved rotating control device includes a plurality of clamp-less, hydraulically-actuated, and fail-last-position latching assemblies that controllably extend a plurality of piston-driven dogs radially into a groove of a seal and bearing assembly. Advantageously, the seal and bearing assembly can be more easily and quickly installed, removed, and replaced with a substantial reduction in the non-productive time typically associated with such tasks. If hydraulic power is lost, the latching assemblies fail in their last position, ensuring that the seal and bearing assembly remains stable within the rotating control device. In addition, the seal and bearing assembly includes a plurality of indirectly mounted tapered-thrust bearings that increase radial stability that reduces or eliminates wear out caused by reciprocation of the drill string, thereby extending the productive life of the seal and bearing assembly. Advantageously, a unique seal carrier design provides highly accurate bearing preload that further extends the productive life of the seal and bearing assembly without the use of springs or shims. The unique seal carrier design includes discrete and removable seal carrier trays that facilitate the efficient removal and replacement of seals without damaging the seal carrier housing. Other advantageous aspects of one or more embodiments of the present invention will be readily apparent to one of ordinary skill in the art based on the following disclosure.

[0043] Figure **1** shows a wellhead system **105** for a land rig (not independently illustrated) that includes an improved rotating control device **100** in accordance with one or more embodiments of the present invention. A wellhead structure **120** may be disposed over a wellbore (not independently illustrated) that is drilled into the Earth's surface **107**. Wellhead **120** may fluidly communicate with a blowout preventer **110** that may fluidly communicate with an annular **115**. Annular **115** may fluidly communicate with rotating control device **100**. Specifically, a bottom flange **230** of rotating control device **100** may connect, directly or indirectly, to annular **115** disposed below rotating control device **100**.

[0044] A drill string (not shown) may be disposed through a common lumen that extends from platform **135** through rotating control device **100**, annular **115**,

blowout preventer **110**, wellhead **120**, and into the wellbore (not independently illustrated). As used herein, lumen means an interior passageway of a tubular or structure that may vary in diameter along the passageway. Drilling fluids (not shown) may be pumped downhole through the interior passageway of the drill string (not shown). Rotating control device **100** may include at least one sealing element (not shown) that seals the annulus (not shown) that surrounds the drill pipe (not shown). A fluid flow line (not shown) may divert returning annular fluids from a fluid flow port of the rotating control device **100** to platform **135** for recycling and reuse. The annular pressure may be managed from the surface by manipulating a surface-backpressure choke manifold (not shown) disposed on the platform **135**.

[0045] Figure **2A** shows a first perspective view of an improved rotating control device **100** without a shroud in accordance with one or more embodiments of the present invention. Rotating control device **100** may include a bowl housing **220**, a bottom flange **230**, and a plurality of hydraulically-actuated fail-last-position latching assemblies **250**.

[0046] Bowl housing **220** may include an inner aperture (not independently illustrated) to receive a removably disposed seal and bearing assembly (*e.g.*, **500** of Figure **5**) and one or more fluid flow ports **270**. A first interference-fit sealing element (not shown) may provide an interference-fit with a drill pipe (not shown) disposed therethrough and seal the cavity (not shown) surrounding the first interference-fit sealing element (not shown) where fluids may be directed to or from the one or more fluid flow ports **270**. In one or more embodiments of the present invention, one or more of fluid flow ports **270** may be a flow diversion port, an injection port, or a surface-backpressure management port. One of ordinary skill in the art will recognize that the number, size, and configuration of fluid flow ports **270** may vary based on an application or design in accordance with one or more embodiments of the present invention. Bottom flange **230** may include a bottom flange lumen that extends centrally therethrough and may be attached to a bottom distal end of bowl housing **220**. Bottom flange **230** may be used to connect rotating control device **100**, directly or indirectly, to an annular (not shown) or blowout preventer (not shown) disposed below rotating control device **100**.

[0047] A plurality of hydraulically-actuated fail-last-position latching assemblies **250** may be disposed about an outer surface of a recessed area **260** of bowl housing **220**. The plurality of hydraulically-actuated fail-last-position latching assemblies **250**

may be clamp-less and hydraulically powered to controllably extend a plurality of piston-driven dogs (not shown) radially into a groove (not shown) of seal and bearing assembly (*e.g.*, **500** of Figure **5**). In this way, the latching assemblies **250** may be used to controllably secure seal and bearing assembly (*e.g.*, **500** of Figure **5**) to bowl housing **220** in a manner that allows for the quick and easy installation, service, removal, and replacement of assembly (*e.g.*, **500** of Figure **5**). Because of the design of the piston-driven dogs (not shown) of latching assemblies **250** and the mating groove (not shown) of seal and bearing housing **240**, in the event hydraulic power is lost, latching assemblies **250** maintain their last position, thus they are said to fail in their last position, thereby improving the safety of rotating control device **100** and operations in progress. As such, hydraulic power is required to activate the piston-driven dog, but not to maintain its position. Hydraulic power is then required again to deactivate the piston-drive dog. In the embodiment depicted, six (6) hydraulically-actuated fail-last-position latching assemblies **250** are distributed about the outer surface of the recessed area **260** of bowl housing **220**. One of ordinary skill in the art will recognize that the number of latching assemblies **250** required to controllably secure the seal and bearing assembly (*e.g.*, **500** of Figure **5**), and their distribution about the outer surface, may vary based on an application or design in accordance with one or more embodiments of the present invention. Further, one of ordinary skill in the art will also recognize that the number of latching assemblies **250** required to controllably secure the seal and bearing assembly (*e.g.*, **500** of Figure **5**) may vary with the dimensions of rotating control device **100**, seal and bearing assembly (*e.g.*, **500** of Figure **5**), the piston-driven dogs (not shown), and the mating groove (not shown) of seal and bearing housing **240** in accordance with one or more embodiments of the present invention. Seal and bearing assembly (*e.g.*, **500** of Figure **5**) may be a sealed (*e.g.*, **500A**) or circulating lubricant (*e.g.*, **500B**) seal and bearing assembly. In the circulating lubricant bearing assembly depicted, lubricant injection line **520** and lubricant removal line **510** may be used to circulate a lubricant through the bearing portion (not shown) of seal and bearing assembly (*e.g.*, **500** of Figure **5**).

[0048] Continuing, Figure **2B** shows a second perspective view of the improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. Hydraulic ports **252** and **254** may be used to provide hydraulic power to the hydraulically-actuated fail-last-position latching

assemblies **250**. Hydraulic fluid may be driven in one of ports **252** or **254**, daisy chained by hydraulic lines **256** to the latching assemblies **250** disposed about bowl housing **220**, and removed from the other port **254** or **252**. Hydraulic lines **256** may be used to daisy chain the hydraulic power to the latching assemblies **250**.

[0049] Continuing, Figure **2C** shows the first perspective view of the improved rotating control device with shroud **290** in accordance with one or more embodiments of the present invention. A protective shroud **290** may be disposed around the plurality of hydraulically-actuated fail-last-position latching assemblies **250** that are distributed about the outer surface of the recessed area **260** of bowl housing **220**. The shroud **290** may be protect the protruding portions of the hydraulically-actuated fail-last-position latching assemblies **250** during installation, operation, service, and removal. Continuing, Figure **2D** shows the second perspective view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention.

[0050] Figure **3A** shows a front elevation view of an improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. A plurality of hydraulically-actuated fail-last-position latching assemblies **250** may be disposed about an outer surface of a recessed portion **260** of bowl housing **220**. Each latching assembly **250** may be oriented such that a piston-driven dog (not shown) may be radially deployed through an opening (not shown) of bowl housing **220** and into a mating groove (not shown) of seal and bearing housing **240** to controllably secure seal and bearing assembly **500** to bowl housing **220**. Continuing, Figure **3B** shows a front elevation view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention. Shroud **290** may be protect the protruding portions of the hydraulically-actuated fail-last-position latching assemblies **250**. Protective shroud **290** may include a cutout where one or more hydraulic ports **252** and **254** may be connected to a latching assembly **250**. The remaining latching assemblies **250** may receive hydraulic power from a daisy-chain of hydraulic fluid lines (not shown) emanating from hydraulic ports **252** and **254**.

[0051] Continuing, Figure **3C** shows a rear elevation view of the improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. The plurality of hydraulically-actuated fail-last-position latching assemblies **250** may include one or more hydraulic ports **252** and **254** that

may be used to hydraulically deploy or retract their piston-driven dogs (not shown). The hydraulic fluid lines **256** may be daisy-chained such that the plurality of latching assemblies **250** deploy or retrain their piston-driven dogs (not shown) at substantially the same time. Continuing, Figure **3D** shows a rear elevation view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention.

[0052] Continuing, Figure **3E** shows a left-side elevation view of the improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. Continuing, Figure **3F** shows a left-side elevation view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention. Continuing, Figure **3G** shows a right-side elevation view of the improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. Continuing, Figure **3H** shows a right-side elevation view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention. One of ordinary skill in the art will recognize that the size, shape, and orientation of one or more fluid flow ports **270** may vary based on an application or design in accordance with one or more embodiments of the present invention.

[0053] Figure **4A** shows a top plan view of an improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. In the top plan view depicted, the distribution of the plurality of hydraulically-actuated fail-last-position latching assemblies **250** about an outer surface of bowl housing **220** is shown. As noted above, the number, size, and distribution of latching assemblies **250** may vary based on an application or design in accordance with one or more embodiments of the present invention. A plurality of hoisting connectors **105** may be distributed about a top portion of bowl housing **220** to facilitate movement of rotating control device **100**. A common lumen **280** may extend from distal end to distal end of rotating control device **100**.

[0054] Continuing, Figure **4B** shows a top plan view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention. In addition to hoisting connectors **105**, seal and bearing assembly **500** may include a plurality of shop hooks **530** that may be used to remove and replace seal and bearing assembly **500**. Continuing, Figure **4C** shows a bottom plan

view of the improved rotating control device **100** without shroud in accordance with one or more embodiments of the present invention. Continuing, Figure **4D** shows a bottom plan view of the improved rotating control device **100** with shroud **290** in accordance with one or more embodiments of the present invention. Common lumen **280** extends through seal and bearing assembly **500** and bottom flange **230** and may vary in diameter along the passageway. The drill pipe (not shown) may be removably disposed therethrough and the first interference-fit sealing element (not shown) may create an annular seal within rotating control device **100**.

[0055] Figure **5A** shows a perspective view of a sealed seal and bearing assembly **500A** in accordance with one or more embodiments of the present invention. Sealed seal and bearing assembly **500A** may include a seal and bearing housing **240**, a mandrel (not independently illustrated) disposed within an inner aperture of seal and bearing housing **240**, a first interference-fit sealing element (not shown) attached to a bottom distal end of the mandrel (not independently illustrated) to perform a sealing function, a plurality of tapered-thrust bearings (not shown) indirectly mounted to seal and bearing housing **240** to facilitate rotation of the mandrel (not independently illustrated) and the first interference-fit sealing element (not shown), a preload spacer (not shown) disposed between top and bottom tapered-thrust bearings (not shown), and a plurality of jam nuts (not shown) to adjust a preload of the tapered-thrust bearings (not shown). Seal and bearing assembly **500A** may include a top plate **550**, also referred to as an upper seal carrier, attached to the top side of seal and bearing housing **240**. A lower seal carrier **555** may be attached to the bottom side of seal and bearing housing **240** and a seal adapter **560** may be attached to a bottom distal end of mandrel **275** for attachment of the first interference-fit sealing element (not shown). A substantially rectangular groove **540** may be disposed about an outer surface of seal and bearing housing **240** to receive a plurality of substantially rectangular piston-driven dogs (not shown) when actuated by the plurality of hydraulically-actuated fail-last-position latching assemblies (not shown). One or more static seals **542** may be disposed about an outer surface of seal and bearing housing **240** to provide a static and non-rotating seal between seal and bearing housing **240** and the bowl housing (*e.g.*, **220**). A plurality of shop hooks **530** may be included to facilitate insertion and removal of seal and bearing assembly **500A** into and out of rotating control device **100**.

[0056] Continuing, Figure **5B** shows a top plan view of the sealed seal and bearing assembly **500A** in accordance with one or more embodiments of the present invention. A common lumen **280** may extend through seal and bearing assembly **500A**. While the first interference-fit sealing element (not shown) may have an inner aperture slightly smaller than the drill pipe (not shown) anticipated to be disposed therethrough, the lumen **280** extends from distal end to distal end of seal and bearing assembly **500A**. Continuing, Figure **5C** shows a bottom plan view of the sealed seal and bearing assembly **500A** in accordance with one or more embodiments of the present invention. Seal and bearing assembly **500A** may include a seal adapter **560** disposed on a bottom of seal and bearing housing **240** of seal and bearing assembly **500A**. Seal adapter **560** may attach to the bottom distal end of the mandrel (not shown) of seal and bearing assembly **500A** and be used to attach a first interference-fit sealing element (not shown).

[0057] Continuing, Figure **5D** shows a longitudinal cross section of the sealed seal and bearing assembly **500A** in accordance with one or more embodiments of the present invention. Seal and bearing assembly **500A** may include seal and bearing housing **240**, a rotating mandrel **275** disposed within an inner aperture of seal and bearing housing **240**, a first interference-fit sealing element (not shown) attached to a seal adapter **560** attached to the bottom distal end of mandrel **275**, a plurality of tapered thrust-bearings **576** indirectly mounted to seal and bearing housing **240** to facilitate rotation of mandrel **275**, a preload spacer **578** disposed between top and bottom tapered-thrust bearings **576**, and a plurality of jam nuts **574** to adjust a preload of the tapered-thrust bearings **576**. The plurality of tapered-thrust bearings **576** may be indirectly mounted to seal and bearing housing **240** at an offset angle to increase radial stability and prevent wear out from reciprocation of the drill pipe (not shown) disposed therethrough. A common lumen **280** extends from distal end to distal end of seal and bearing assembly **500A**. The plurality of jam nuts **574** and seal adapter **560** may be threaded such that they maintain preload with rotation of the drill pipe (not shown).

[0058] Seal and bearing housing **240** may include a groove **540** that is substantially rectangular and non-tapered to receive a plurality of substantially rectangular piston-driven dogs (not shown) to controllably secure seal and bearing assembly **500A** to rotating control device **100**. One of ordinary skill in the art will recognize that the shape of the piston-driven dogs (not shown) and mating groove **540** may

vary in shape and size in accordance with one or more embodiments of the present invention. One or more static sealing elements **542** may be disposed about an outer surface of seal and bearing housing **240** to provide a static seal between seal and bearing housing **240** and the bowl housing (*e.g.*, **220**). Lower seal carrier **555** may include a plurality of dynamic sealing elements **556** that contact rotating mandrel **275** and a plurality of static sealing elements **557** that contact seal and bearing housing **240**. Upper seal carrier **550** may also include a plurality of dynamic sealing elements **556** and a plurality of static sealing elements **557**. A lubricating grease (not independently illustrated) may be disposed within the seal and bearing housing **240** to lubricate the tapered-thrust bearings **576**.

[0059] Figure **5E** shows a perspective view of a circulating lubricant seal and bearing assembly **500B** in accordance with one or more embodiments of the present invention. Circulating lubricant seal and bearing assembly **500B** may include a seal and bearing housing **240**, a mandrel (not independently illustrated) disposed within an inner aperture of seal and bearing housing **240**, a first interference-fit sealing element (not shown) attached to a bottom distal end of the mandrel (not independently illustrated) to perform a sealing function, a plurality of tapered-thrust bearings (not shown) indirectly mounted to seal and bearing housing **240** to facilitate rotation of the mandrel (not independently illustrated) and the first interference-fit sealing element (not shown), a preload spacer (not shown) disposed between top and bottom tapered-thrust bearings (not shown), and a plurality of jam nuts (not shown) to adjust a preload of the tapered-thrust bearings (not shown). Seal and bearing assembly **500B** may include a top plate **550**, also referred to as an upper seal carrier, disposed on top of seal and bearing housing **240** and a seal adapter **560** disposed on bottom of seal and bearing housing **240**. A lower seal carrier **555** may be attached to the bottom side of seal and bearing housing **240** and a seal adapter **560** may be attached to a bottom distal end of mandrel **275** for attachment of the first interference-fit sealing element (not shown). A substantially rectangular groove **540** may be disposed about an outer surface of seal and bearing housing **240** to receive a plurality of substantially rectangular piston-driven dogs (not shown) when actuated by the plurality of hydraulically-actuated fail-last-position latching assemblies (not shown). One or more static seals **542** may be disposed about an outer surface of seal and bearing housing **240** to provide a static and non-rotating seal between seal and bearing housing **240** and the bowl housing (*e.g.*, **220**). A

plurality of shop hooks **530** may be included to facilitate insertion and removal of seal and bearing assembly **500B** into and out of rotating control device **100**. A circulating lubricant may be injected via a lubricant injection port **520** and removed from a lubricant removal port **510**. The injected lubricant may circulate within the bearing assembly of seal and bearing assembly **500B**.

[0060] Continuing, Figure **5F** shows a top plan view of the circulating lubricant seal and bearing assembly **500B** in accordance with one or more embodiments of the present invention. A common lumen **280** may extend through seal and bearing assembly **500B**. While the first interference-fit sealing element (not shown) may have an inner aperture slightly smaller than the drill pipe (not shown) anticipated to be disposed therethrough, the lumen **280** extends from distal end to distal end of seal and bearing assembly **500B**. Continuing, Figure **5G** shows a bottom plan view of the circulating lubricant seal and bearing assembly **500B** in accordance with one or more embodiments of the present invention. Seal and bearing assembly **500B** may include a seal adapter **560** disposed on a bottom of seal and bearing housing **240** of seal and bearing assembly **500B**. Seal adapter **560** may attach to the bottom distal end of the mandrel (not shown) of seal and bearing assembly **500B** and be used to attach a first interference-fit sealing element (not shown).

[0061] Continuing, Figure **5H** shows a longitudinal cross section of the circulating lubricant seal and bearing assembly **500B** in accordance with one or more embodiments of the present invention. Seal and bearing assembly **500B** may include seal and bearing housing **240**, a mandrel **275** disposed within an inner aperture of seal and bearing housing **240**, a first interference-fit sealing element (not shown) attached to a seal adapter **560** attached to the bottom distal end of mandrel **275**, a plurality of tapered thrust-bearings **576** indirectly mounted to seal and bearing housing **240** to facilitate rotation of mandrel **275**, a preload spacer **578** disposed between top and bottom tapered-thrust bearings **576**, and a plurality of jam nuts **574** to adjust a preload of the tapered-thrust bearings **576**. The plurality of tapered-thrust bearings **576** may be indirectly mounted to seal and bearing housing **240** at an offset angle to increase radial stability and prevent wear out from reciprocation of the drill pipe (not shown) disposed therethrough. A common lumen **280** extends from distal end to distal end of seal and bearing assembly **500B**. The plurality of jam nuts **574** may be threaded such that they maintain preload with rotation of the drill pipe (not shown). Seal and bearing housing **240** may include a

groove **540** that is substantially rectangular and non-tapered to receive a plurality of substantially rectangular piston-driven dogs (not shown) to controllably secure seal and bearing assembly **500B** to rotating control device **100**. One of ordinary skill in the art will recognize that the shape of the piston-driven dogs (not shown) and mating groove **540** may vary in shape and size in accordance with one or more embodiments of the present invention. One or more static sealing elements **542** may be disposed about an outer surface of seal and bearing housing **240** to provide a static seal between seal and bearing housing **240** and the bowl housing (*e.g.*, **220**). Lower seal carrier **555** may include a plurality of dynamic sealing elements **556** that contact rotating mandrel **275** and a plurality of static sealing elements **557** that contact seal and bearing housing **240**. Upper seal carrier **550** may also include a plurality of dynamic sealing elements **556** and a plurality of static sealing elements **557**. A circulating lubricant (not independently illustrated) may be injected via lubricant injection port **520**, circulated within the bearing assembly **500**, and removed via lubricant removal port **510**.

[0062] Figure **6A** shows a longitudinal cross section of the improved rotating control device **100** with shroud **290** showing engagement of the plurality of hydraulically-actuated piston-driven dogs **540** in accordance with one or more embodiments of the present invention. A seal adapter **560** may be attached to a bottom distal end of mandrel **275**. A first interference-fit sealing element **650** may be attached to seal adapter **560**. For example, sealing element **650** may be bolted to seal adapter **560**. Each of a plurality of hydraulically-actuated fail-last-position latching assemblies **250** may include a piston-driven **610** dog **620** that fits within groove **540** of seal and bearing housing **240**, thereby providing retention. Sealing elements **542**, **556**, **557** and first interference-fit sealing element **650** may seal an annulus between the drill pipe (not shown) and bowl housing **220**. During drilling operations, the returning annular fluids may be directed from rotating control device **100** to the rig floor by way of one or more of the fluid flow ports (*e.g.*, **270** of Figure 7**A**).

[0063] The first interference-fit sealing element **650** and mandrel **275** may rotate with the drill pipe (not shown). The first interference-fit sealing element **650** may be composed of natural rubber, nitrile butadiene rubber, hydrogenated nitrile butadiene rubber, polyurethane, elastomeric material, or combinations thereof. The first interference-fit sealing element **650** may include a first seal lumen having a first seal inner aperture slightly smaller than an outer diameter of the drill pipe (not shown).

The mandrel lumen, the first seal lumen, and the bottom flange lumen may form a common lumen **280** that extends from distal end to distal end of rotating control device **100**. One of ordinary skill in the art will recognize that the lumens of each component may have a diameter that varies from component to component. During drilling operations, a drill pipe (not shown) may be disposed through the common lumen **280**, whereby a first seal is established, in part, by the first interference-fit sealing element **650**. The wellbore pressure may be managed by a surface-backpressure choke manifold (not shown) disposed on the rig floor (not shown) that manipulates the fluid flow rate from one or more fluid flow ports **270** to the surface.

[0064] Continuing, Figure **6B** shows a detailed cross-sectional view of a portion of the improved rotating control device **100** with shroud **290** showing engagement of the plurality of hydraulically-actuated piston-driven dogs **620**, tapered-thrust bearings **576**, preload spacer **578**, and jam nuts **574** in accordance with one or more embodiments of the present invention. A plurality of tapered-thrust bearings **576** may be indirectly mounted at an offset angle to increase radial stability.

[0065] In certain embodiments, the top tapered-thrust bearings **576** may be indirectly mounted at an offset angle, θ, in a range between 10 degrees and 40 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. In other embodiments, the top tapered-thrust bearings **576** may be indirectly mounted at an offset angle, θ, in a range between 20 degrees and 30 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. In still other embodiments, the top tapered-thrust bearings **576** may be indirectly mounted at an offset angle, θ, in a range between 0 degrees and 50 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. One of ordinary skill in the art will recognize that the positive offset angle of the top tapered-thrust bearings **576** may vary based on an application or design in accordance with one or more embodiments of the present invention.

[0066] The bottom tapered-thrust bearings **576** may be indirectly mounted at an offset angle, $-\theta$, in a range between -10 degrees and -40 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. In other embodiments, the bottom tapered-thrust bearings **576** may be indirectly mounted at an offset angle, $-\theta$, in a range between -20 degrees and -30 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. In still other embodiments, the top tapered-thrust bearings **576** may be indirectly mounted at an offset angle, $-\theta$, in a

range between 0 degrees and -50 degrees from a perpendicular line to a longitudinal axis of rotating control device **100**. One of ordinary skill in the art will recognize that the negative offset angle of the bottom tapered-thrust bearings **576** may vary based on an application or design in accordance with one or more embodiments of the present invention.

[0067] A plurality of jam nuts **574** may be used to preload the plurality of tapered-thrust bearings **576**, the top and bottom of which, are separated by a preload spacer **578**. The jam nuts **574** may be tightened or loosened to adjust a preload on the tapered-thrust bearings **576** and preload spacer **578**. Upper seal carrier **550**, the plurality of jam nuts **574**, and lower seal carrier **555** may be threaded or otherwise attached such that they maintain the preload during rotation of the drill pipe (not shown).

[0068] Figure **7A** shows a longitudinal cross section of an improved rotating control device **100** with shroud **290** showing seal engagement with drill pipe **710** in accordance with one or more embodiments of the present invention. When the drill string is tripped in, drill pipe **710** may be disposed through the common lumen **280** of rotating control device **100**. The first interference-fit sealing element **650** may form a seal about drill pipe **710**, thereby sealing the annulus between drill pipe **710** and bowl housing **220**. The returning annular fluids (not shown) may be diverted from bowl housing **220** to the surface of the platform (not shown) by way of one or more fluid flow ports **270**.

[0069] Continuing, Figure **7B** shows a longitudinal cross section of the improved rotating control device **100** with shroud **290** showing seal engagement with drill pipe **710** having a tool joint **720** in accordance with one or more embodiments of the present invention. Because the first interference-fit sealing element **650** is composed of flexible material(s), when drill pipe **710** is tripped into or out of the hole, a tool joint **720** may pass through rotating control device **100** while maintaining the annular seal. In this way, pressure may be maintained during tripping in and out of the hole.

[0070] Figure **8A** shows a cross-sectional view of a lower seal carrier **555** of a seal and bearing assembly **500** in accordance with one or more embodiments of the present invention. The proper function of the plurality of sealing elements **556** is critically important to maintain the annular seal surrounding the drill pipe (not shown). In embodiments previously depicted, the plurality of sealing elements **556**

were disposed in grooves formed on an inner circumferential surface of the lower seal carrier **555** itself. Because of their location, it has been discovered that, over time, these sealing elements **556** wear into the carrier **555** and become very difficult to remove and ultimately replace. Typically, a field hand must use a screw driver or other blunt instrument to pry the worn sealing elements **556** off of the lower seal carrier **555**, potentially damaging the seal carrier **555** and impacting its ability to maintain the annular seal. As such, in certain embodiments, lower seal carrier **555** may be modified as shown in Figures **8A** through **8C** to include a plurality of removable seal carrier trays **810** and a seal plate **820** to facilitate the quick and easy removal and replacement of sealing elements **556** in the field.

[0071] Continuing, Figure **8B** shows an exploded bottom-facing perspective view of the lower seal carrier **555** of the seal and bearing assembly **500** in accordance with one or more embodiments of the present invention. A first sealing element **556a** may be disposed in a groove formed in lower seal carrier **555**. Each of a second **556b**, a third **556c**, and a fourth **556d** sealing element may be disposed in their own respective seal carrier trays **810**. Each seal carrier tray **810** includes an inner circumferential surface that receives a sealing element **556** and a plurality of mounting holes (not independently illustrated) to receive a plurality of mounting bolts **830**. As such, when installing the plurality of sealing elements **556**, a first sealing element **556a** may be disposed within the groove formed in lower seal carrier **555**, a second sealing element **556b** may be disposed within a seal carrier tray **810b** and tray **810b** may be disposed within lower seal carrier **555**, a third sealing element **556c** may be disposed within a seal carrier tray **810c** and tray **810c** may be disposed within lower seal carrier **555**, and a fourth sealing element **556d** may be deposed within seal carrier tray **810d** and tray **810d** may be disposed within lower seal carrier **555**. A seal plate **820** may be disposed over the fourth sealing element **556d** and a plurality of bolts **830** may be used to secure seal plate **820**, as well as the plurality of sealing elements **556** disposed within their respective seal trays **810**, to lower seal carrier **555**.

[0072] Continuing, Figure **8C** shows a bottom-facing perspective view of the lower seal carrier **555** of the seal and bearing assembly **500** in accordance with one or more embodiments of the present invention. Once modified lower seal carrier **555** has been assembled, it may be installed as part of seal and bearing assembly **500** in exactly the same manner as other embodiments described herein and functions the

same way. While the modified lower seal carrier **555** includes four (4) sealing elements, one of ordinary skill in the art will recognize that the plurality of sealing elements **556** may vary based on an application or design in accordance with one or more embodiments of the present invention.

[0073] Advantages of one or more embodiments of the present invention may include one or more of the following:

[0074] In one or more embodiments of the present invention, an improved rotating control device has a simplified design that includes fewer parts, costs less to manufacture, reduces cost of ownership, and has a reduced and less expensive maintenance schedule.

[0075] In one or more embodiments of the present invention, an improved rotating control device provides a unique seal carrier design that allows bearing assemblies to be easily serviced or replaced with a significant reduction in non-productive time and associated costs.

[0076] In one or more embodiments of the present invention, an improved rotating control device includes a unique seal carrier design with highly accurate bearing preload that extends the productive life of the rotary seal. The seal carrier can be removed without having to refurbish the internal bearings. The preload of the bearings may be precisely managed without the use of springs or shims.

[0077] In one or more embodiments of the present invention, an improved rotating control device includes indirectly mounted tapered-thrust bearings that increase radial load capacity and stability.

[0078] In one or more embodiments of the present invention, an improved rotating control device includes pilot operated, and hydraulically actuated, latching dogs that fail in their last position to ensure engagement when power is lost.

[0079] In one or more embodiments of the present invention, an improved rotating control device provides improved static ratings from five hundred (500) pounds per square inch ("PSI") to five thousand (5000) PSI.

[0080] In one or more embodiments of the present invention, an improved rotating control device provides improved rotation rate up to at least two hundred and twenty (220) revolutions per minute ("RPM").

[0081] While the present invention has been described with respect to the above-noted embodiments, those skilled in the art, having the benefit of this disclosure, will recognize that other embodiments may be devised that are within the scope of

the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the appended claims.

CLAIMS

What is claimed is:

1. A rotating control device comprising:

a bowl housing comprising a plurality of fluid flow ports and an inner aperture to receive a removably disposed seal and bearing assembly;

a plurality of hydraulically-actuated fail-last-position latching assemblies disposed about an outer surface of the bowl housing to controllably extend a plurality of piston-driven dogs radially into a groove of the seal and bearing assembly to controllably secure the seal and bearing assembly to the bowl housing; and

the seal and bearing assembly comprising:

a seal and bearing housing,

a mandrel disposed within an inner aperture of the seal and bearing housing,

a first interference-fit sealing element attached to a bottom distal end of the mandrel,

a plurality of tapered-thrust bearings indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel,

a preload spacer disposed between top and bottom tapered-thrust bearings,

a plurality of jam nuts to adjust a preload of the tapered-thrust bearings, and

a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

2. The rotating control device of claim 1, further comprising:

a top flange comprising a top flange lumen attached to a top distal end of the bowl housing; and

a bottom flange comprising a bottom flange lumen attached to a bottom distal end of the bowl housing.

3. The rotating control device of claim 1, further comprising a shroud to protect protruding portions of the hydraulically-actuated fail-last-position latching assemblies.

4. The rotating control device of claim 1, wherein the first interference-fit sealing element seals an annulus surrounding the drill pipe.

5. The rotating control device of claim 1, wherein the first interference-fit sealing element and the mandrel rotate with the drill pipe.

6. The rotating control device of claim 1, wherein the first interference-fit sealing element comprises natural rubber, nitrile butadiene rubber, hydrogenated nitrile butadiene rubber, polyurethane, elastomeric material, or combinations thereof.

7. The rotating control device of claim 1, wherein the first interference-fit sealing element comprises a first seal lumen having a first seal inner aperture slightly smaller than an outer diameter of the drill pipe.

8. The rotating control device of claim 1, wherein the plurality of tapered-thrust bearings are indirectly mounted at an offset angle to increase radial stability.

9. The rotating control device of claim 1, wherein top tapered-thrust bearings are indirectly mounted at an offset angle in a range between 10 degrees and 40 degrees from a perpendicular line to a longitudinal axis of the rotating control device.

10. The rotating control device of claim 1, wherein bottom tapered-thrust bearings are indirectly mounted at an offset angle in a range between -10 degrees and -40 degrees from a perpendicular line to a longitudinal axis of the rotating control device.

11. The rotating control device of claim 1, wherein the plurality of jam nuts maintain preload with rotation of the drill pipe.

12. The rotating control device of claim 1, wherein a bottom flange of the bowl housing is attached to an annular or blow-out preventer connection disposed below the rotating control device.

13. The rotating control device of claim 1, wherein the plurality of fluid flow ports comprise one or more of a flow diversion port, an injection port, and a surface-backpressure management port.

14. The rotating control device of claim 2, wherein the top flange lumen, a mandrel lumen, a first seal lumen of the first interference fit-sealing element, and the bottom flange lumen comprise a common lumen through which drill pipe is removably disposed.

15. The rotating control device of claim 1, wherein the groove that receives the plurality of piston-driven dogs is substantially rectangular and non-tapered.

16. The rotating control device of claim 1, wherein the lower seal carrier comprises:

a plurality of removable seal carrier trays; and

a seal plate,

wherein one or more of the dynamic sealing elements are disposed within an inner circumferential surface of one or more removable seal carrier trays.

17. A circulating lubricant seal and bearing assembly comprising:

a seal and bearing housing comprising a groove to receive a plurality of hydraulically-actuated fail-last-position piston-driven dogs;

a mandrel comprising a mandrel lumen disposed within an inner aperture of the seal and bearing housing;

a first interference-fit sealing element attached to a bottom distal end of the mandrel;

a plurality of tapered-thrust bearings indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel;

a preload spacer disposed between top and bottom tapered-thrust bearings;

a plurality of jam nuts to adjust a preload of the tapered-thrust bearings; and

a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

18. The circulating lubricant seal and bearing assembly of claim 17, wherein the lower seal carrier comprises:

a plurality of removable seal carrier trays; and

a seal plate,

wherein one or more of the dynamic sealing elements are disposed within an inner circumferential surface of one or more removable seal carrier trays.

19. The circulating lubricant seal and bearing assembly of claim 17, further comprising:

a fluid injection port to inject lubricating fluid at a higher pressure than a wellbore to lubricate the tapered-thrust bearings.

20. A sealed seal and bearing assembly comprising:

a seal and bearing housing comprising a groove to receive a plurality of hydraulically-actuated fail-last-position piston-driven dogs;

a mandrel comprising a mandrel lumen disposed within an inner aperture of the seal and bearing housing;

a first interference-fit sealing element attached to a bottom distal end of the mandrel;

a plurality of tapered-thrust bearings indirectly mounted to the seal and bearing housing to facilitate rotation of the mandrel;

a preload spacer disposed between top and bottom tapered-thrust bearings;

a plurality of jam nuts to adjust a preload of the tapered-thrust bearings; and

a lower seal carrier attached to the seal and bearing housing comprising a plurality of dynamic sealing elements that contact the mandrel and a plurality of static sealing elements that contact the seal and bearing housing.

21. The sealed seal and bearing assembly of claim 20, wherein the lower seal carrier comprises:

a plurality of removable seal carrier trays; and

a seal plate,

wherein one or more of the dynamic sealing elements are disposed within an inner circumferential surface of one or more removable seal carrier trays.

22. The sealed seal and bearing assembly of claim 20, further comprising:

a lubricating grease disposed within the seal and bearing housing to lubricate the tapered-thrust bearings.

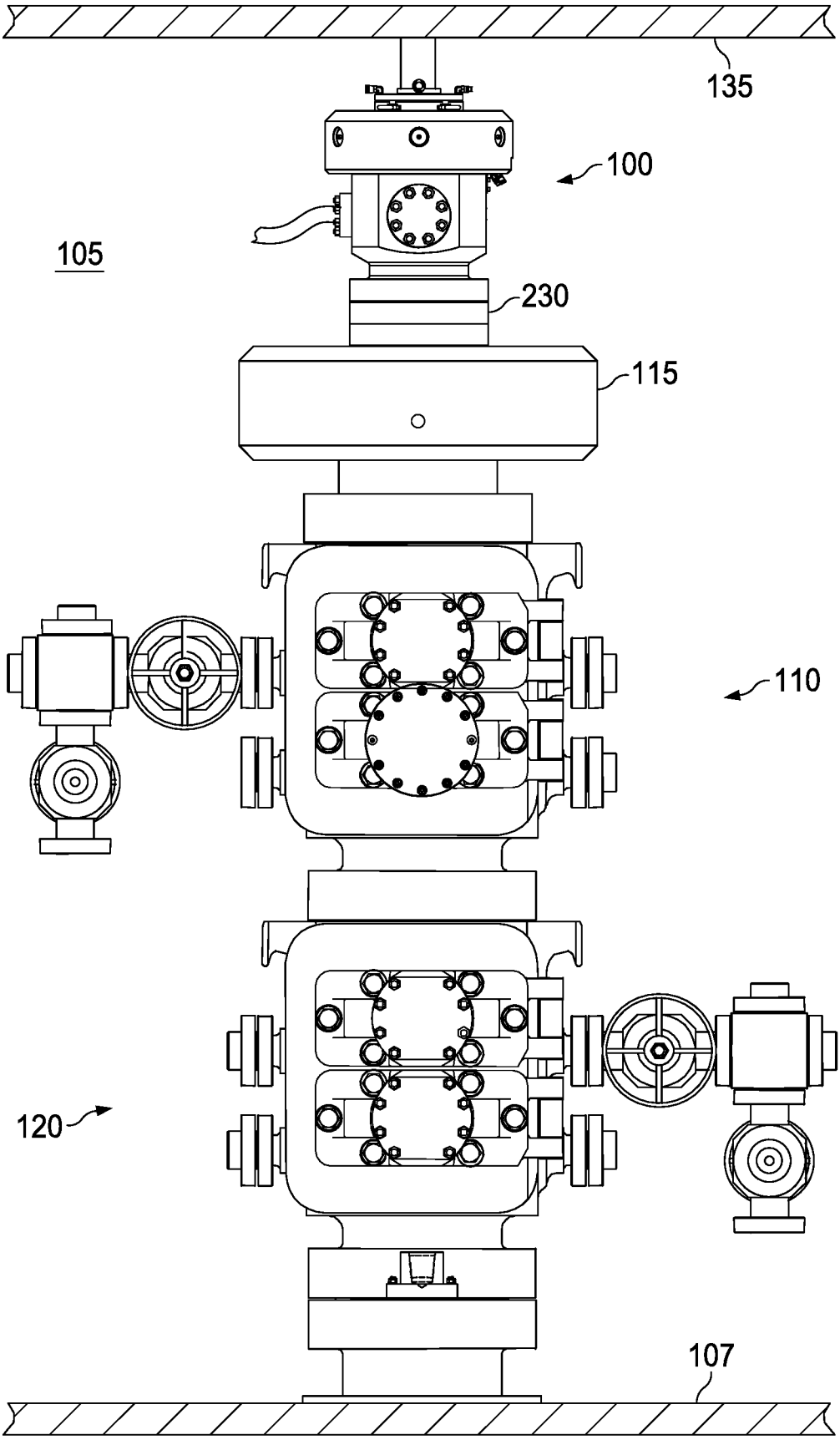


FIG. 1

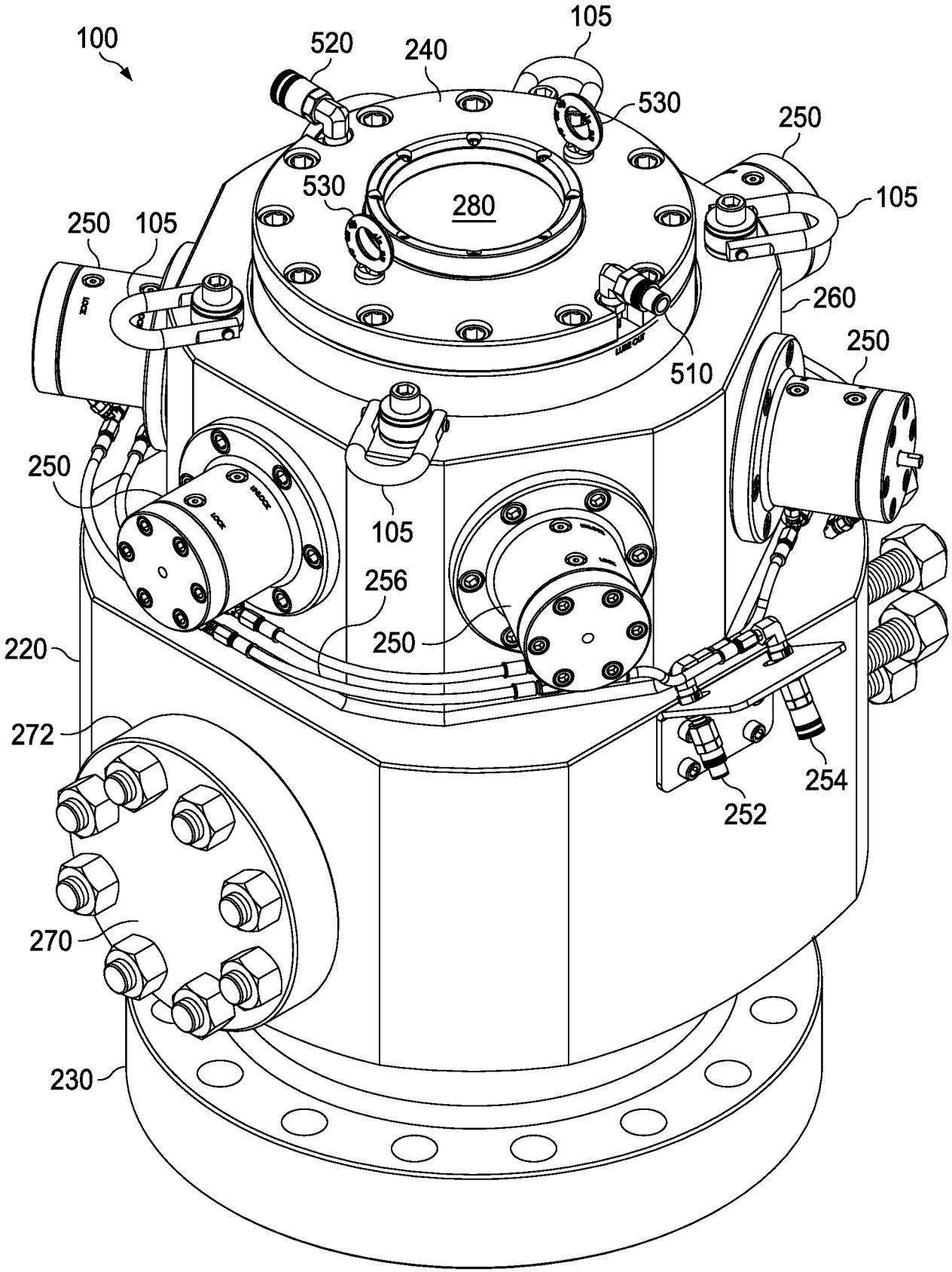

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FIG. 2A

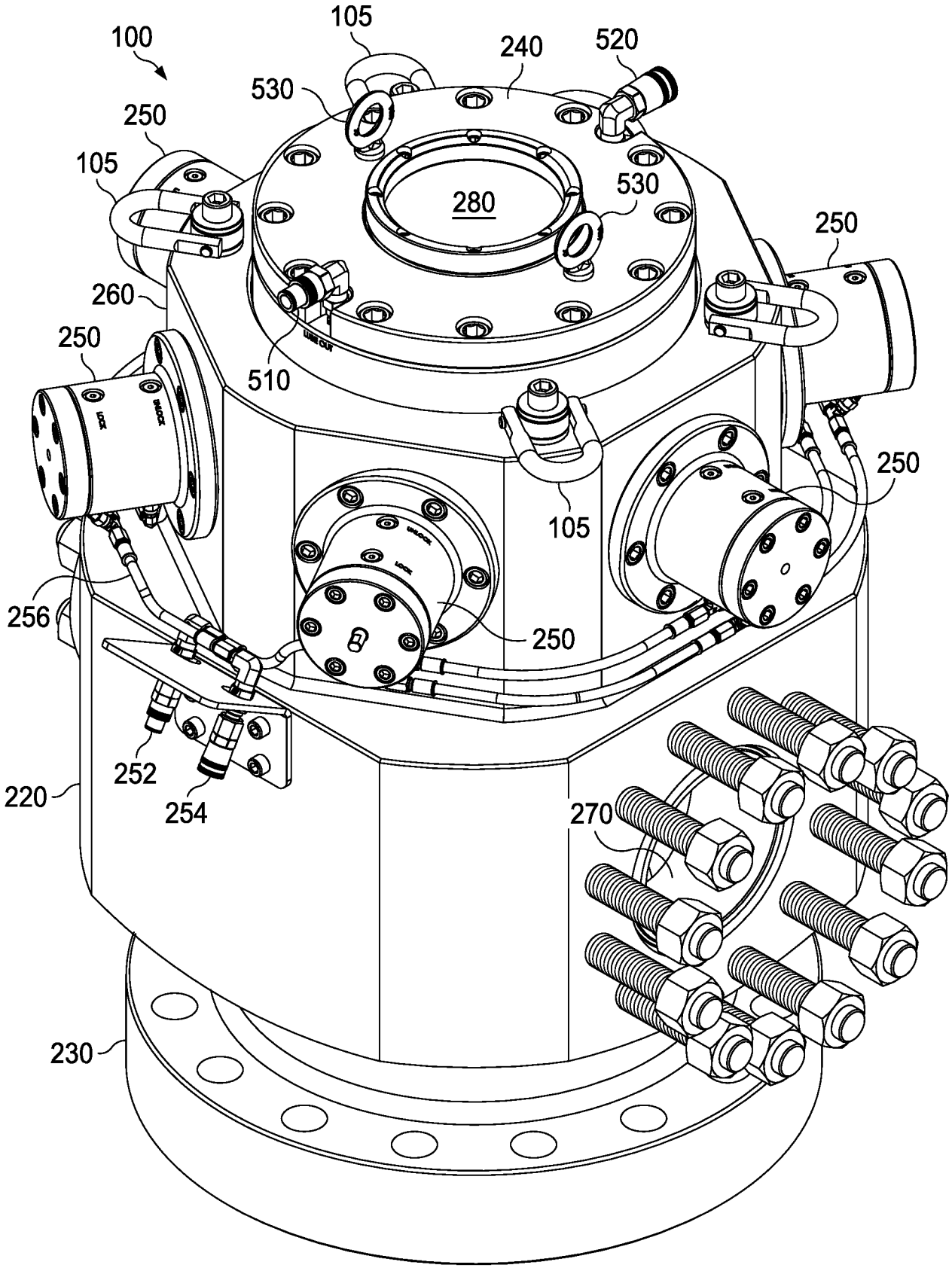

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FIG. 2B

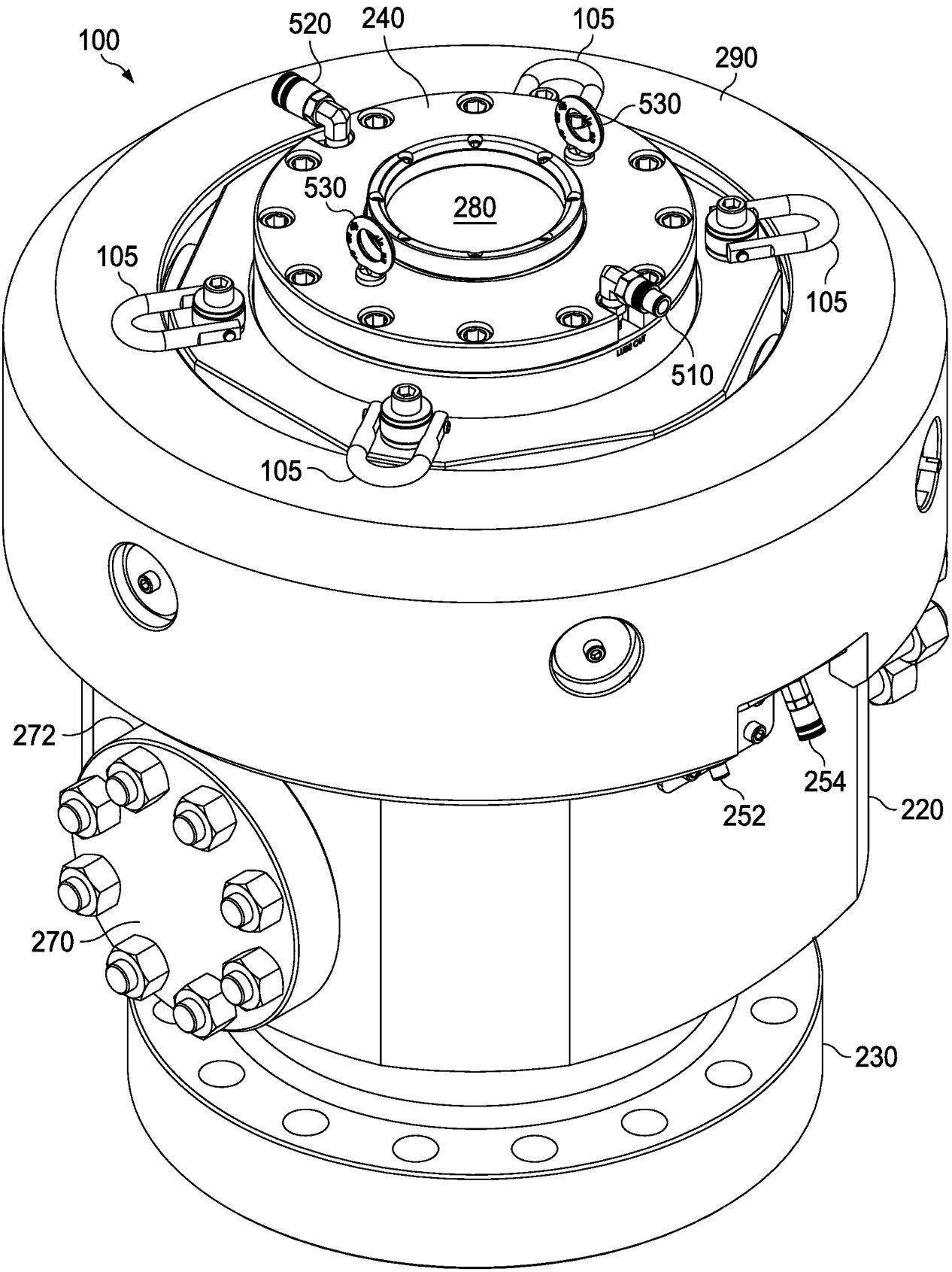

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FIG. 2C

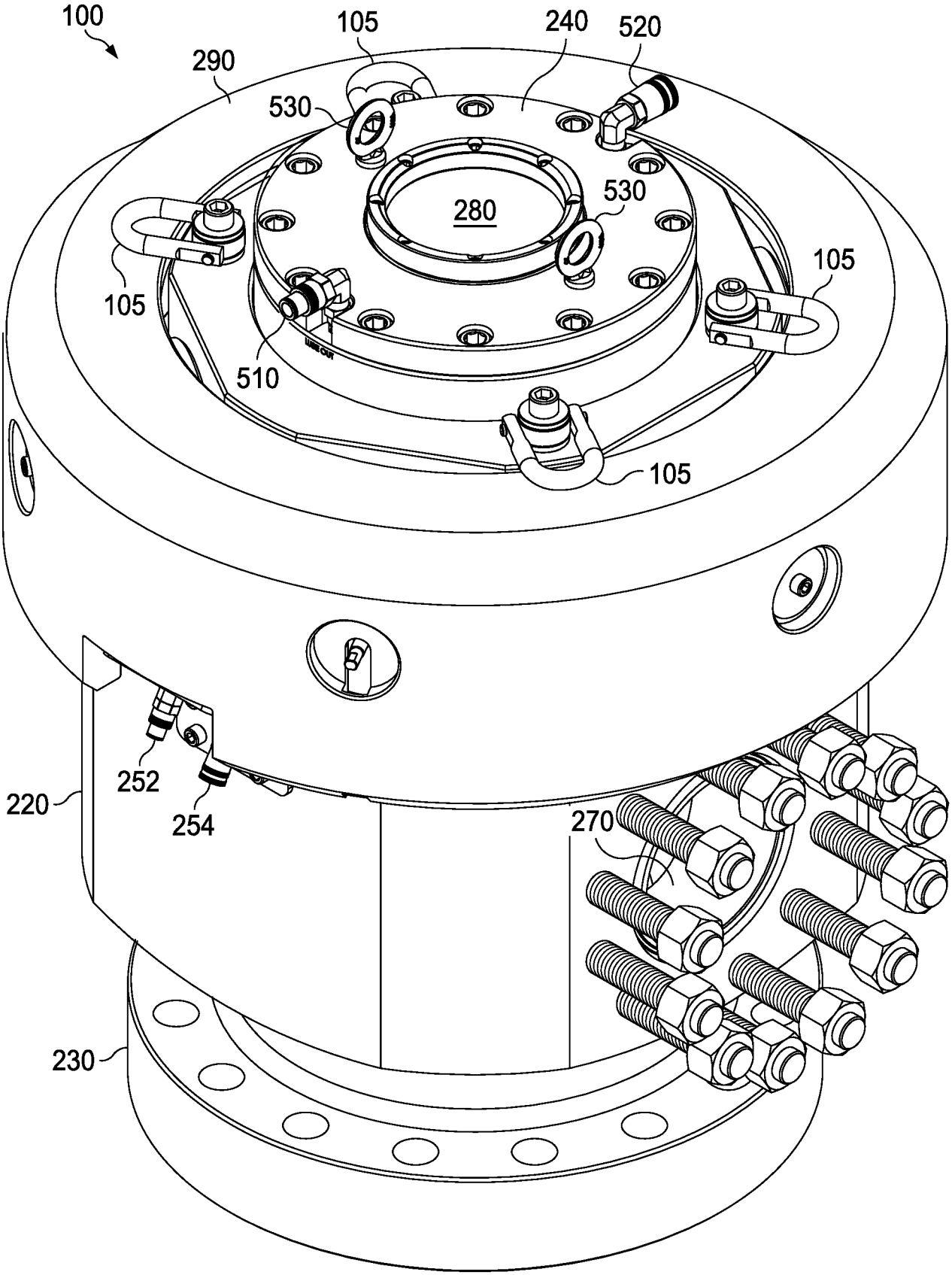

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FIG. 2D

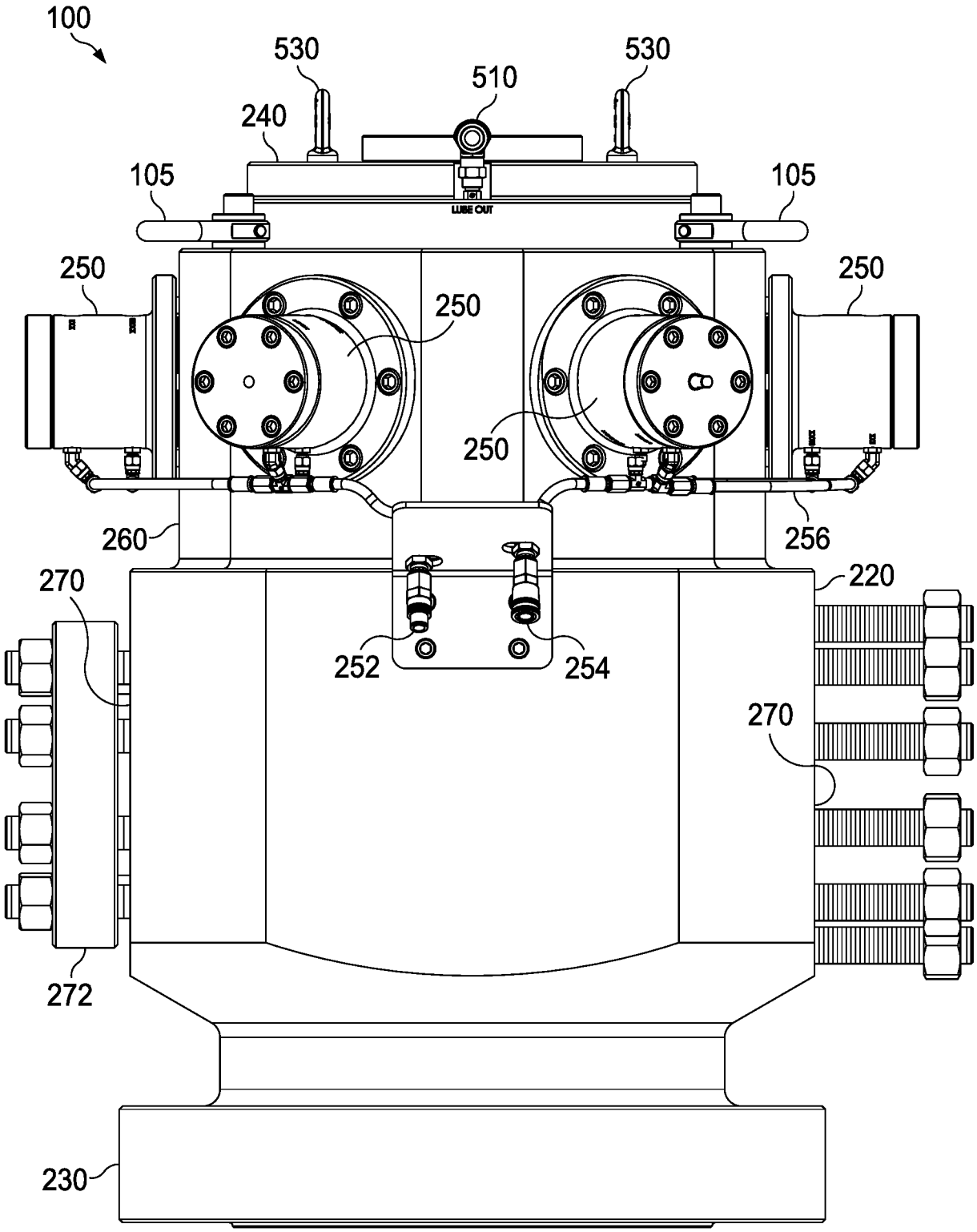

100
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530
510
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LUBE OUT
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254
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272
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FIG. 3A

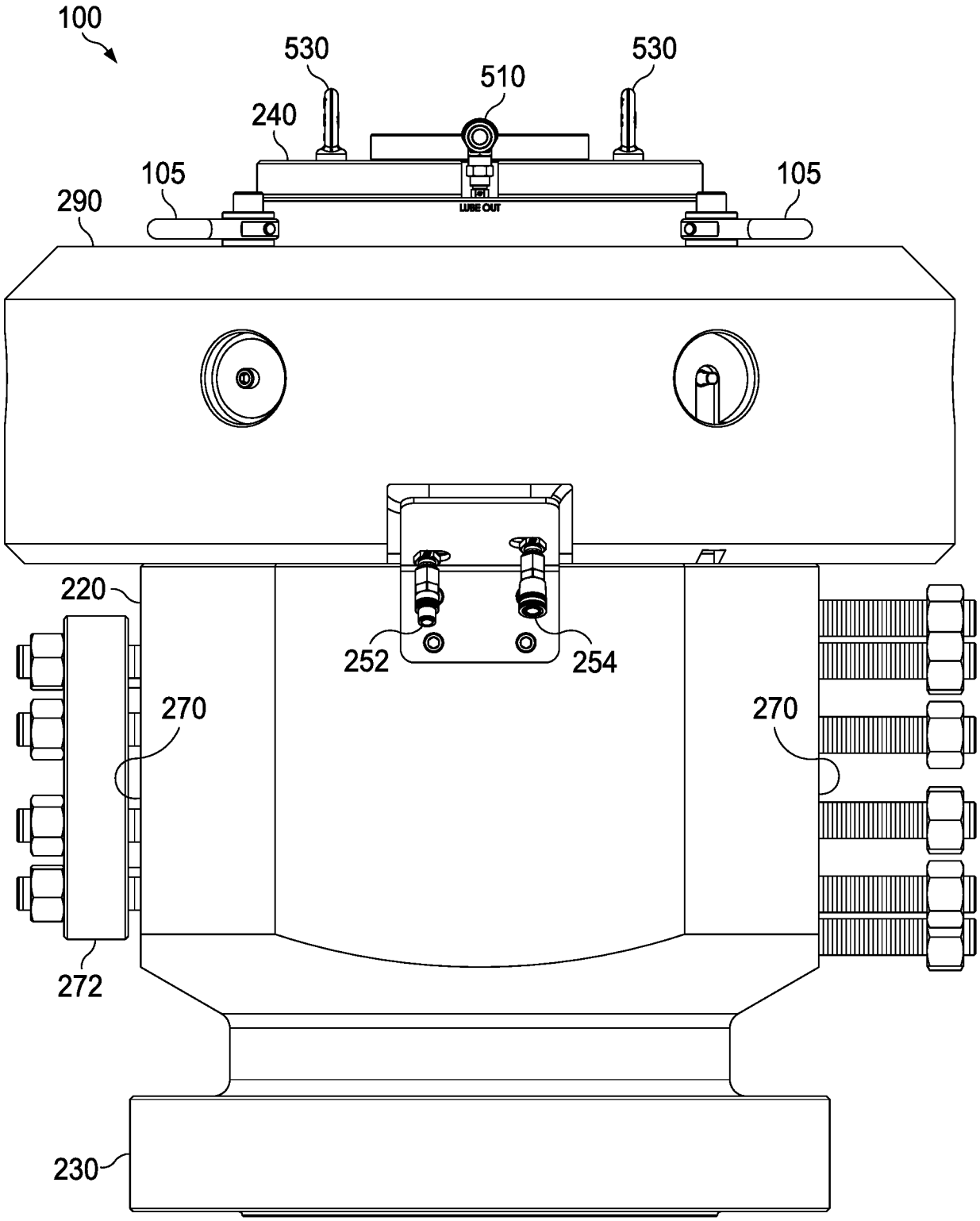

100
530
530
510
240
105
105
290
LINE OUT
220
252
254
270
270
272
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FIG. 3B

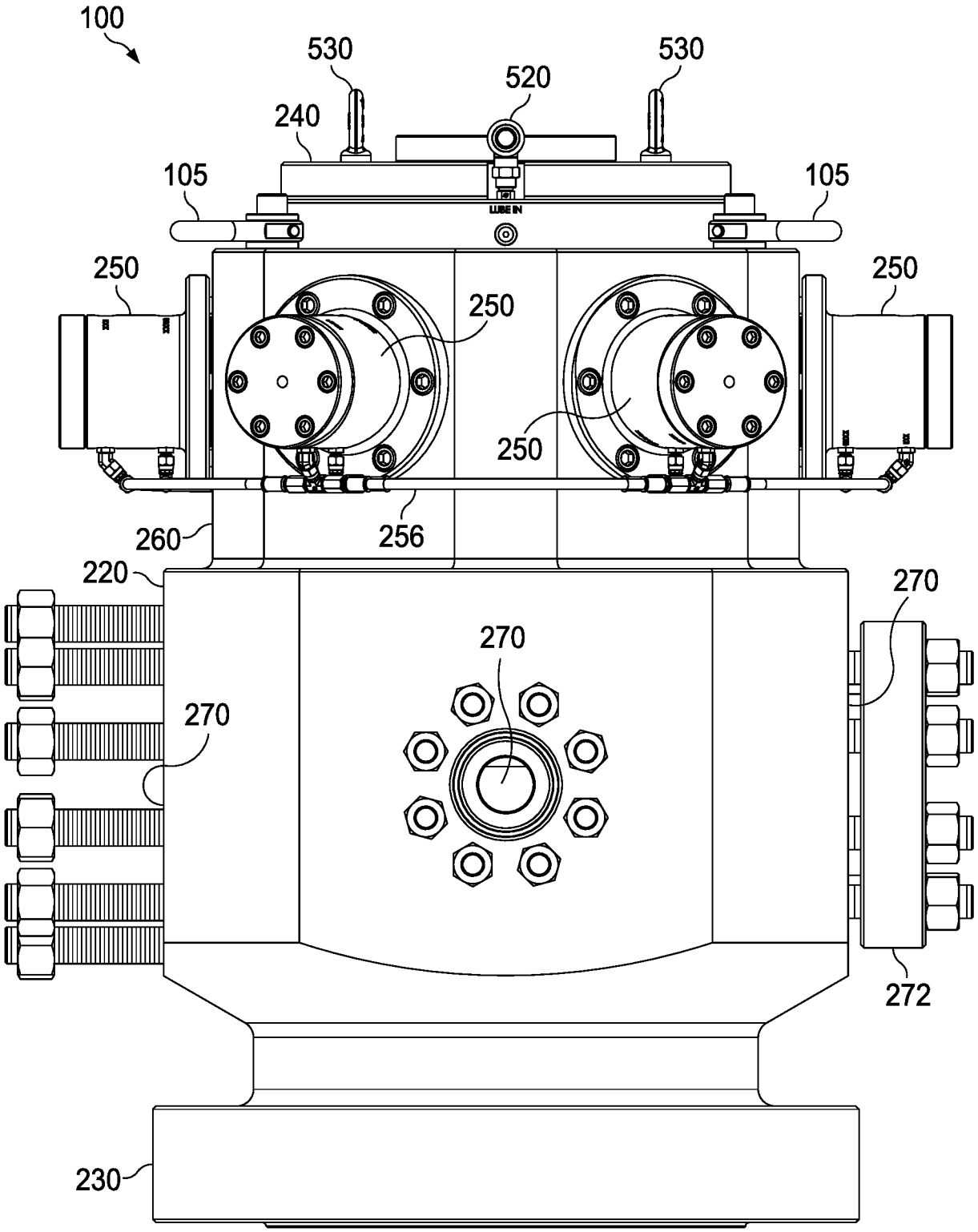

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LUBE IN
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256
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270
270
272
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FIG. 3C

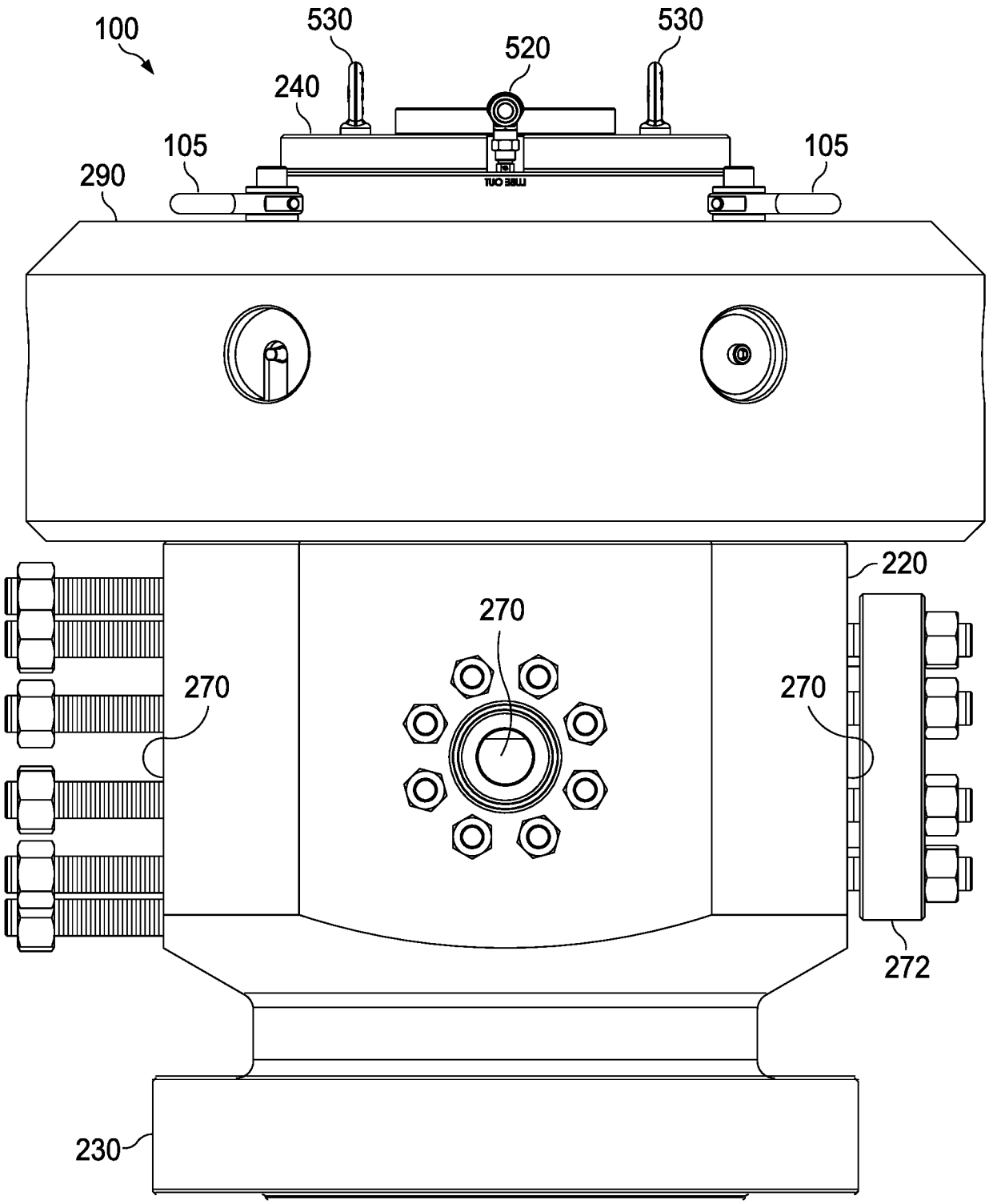


FIG. 3D

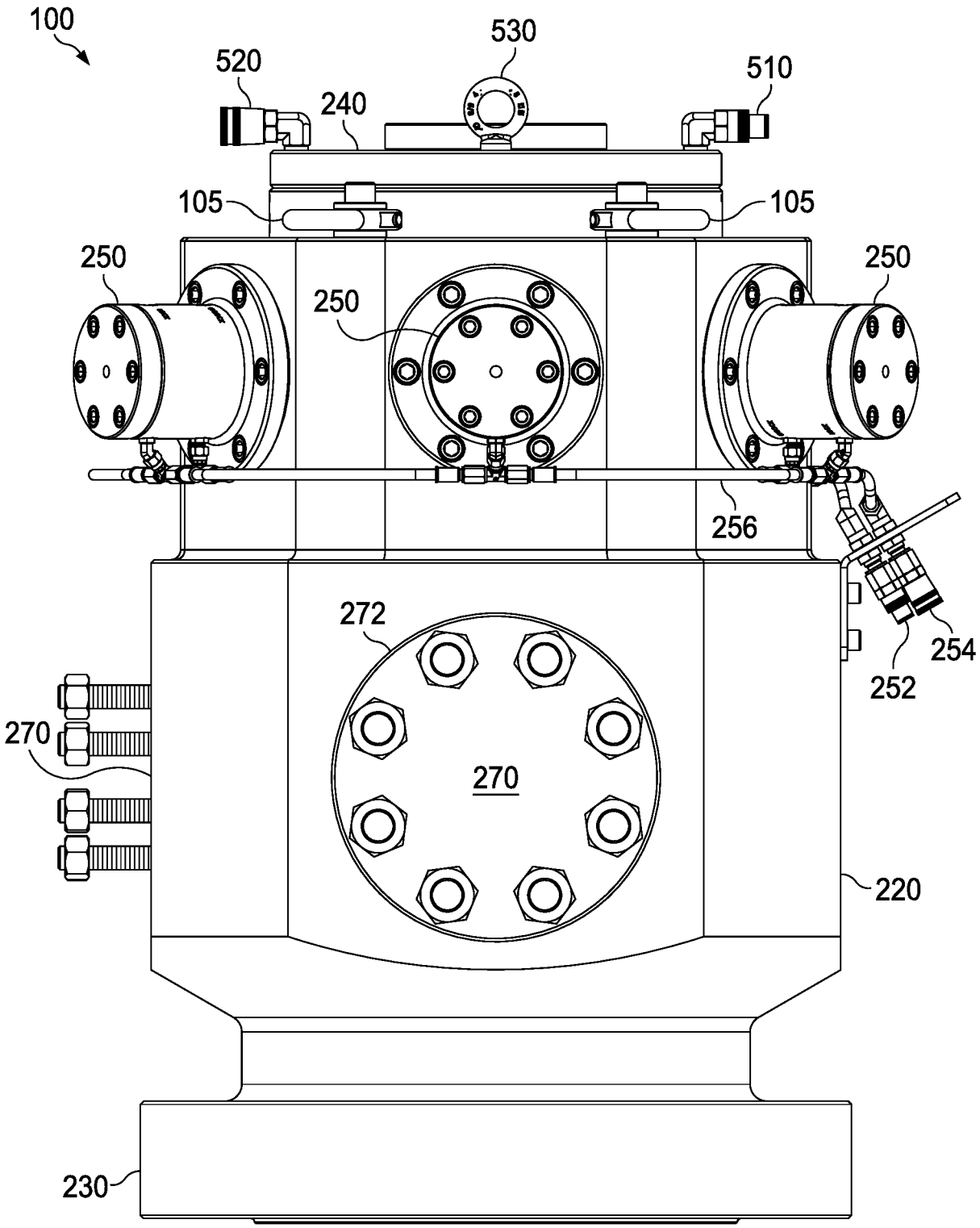

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FIG. 3E

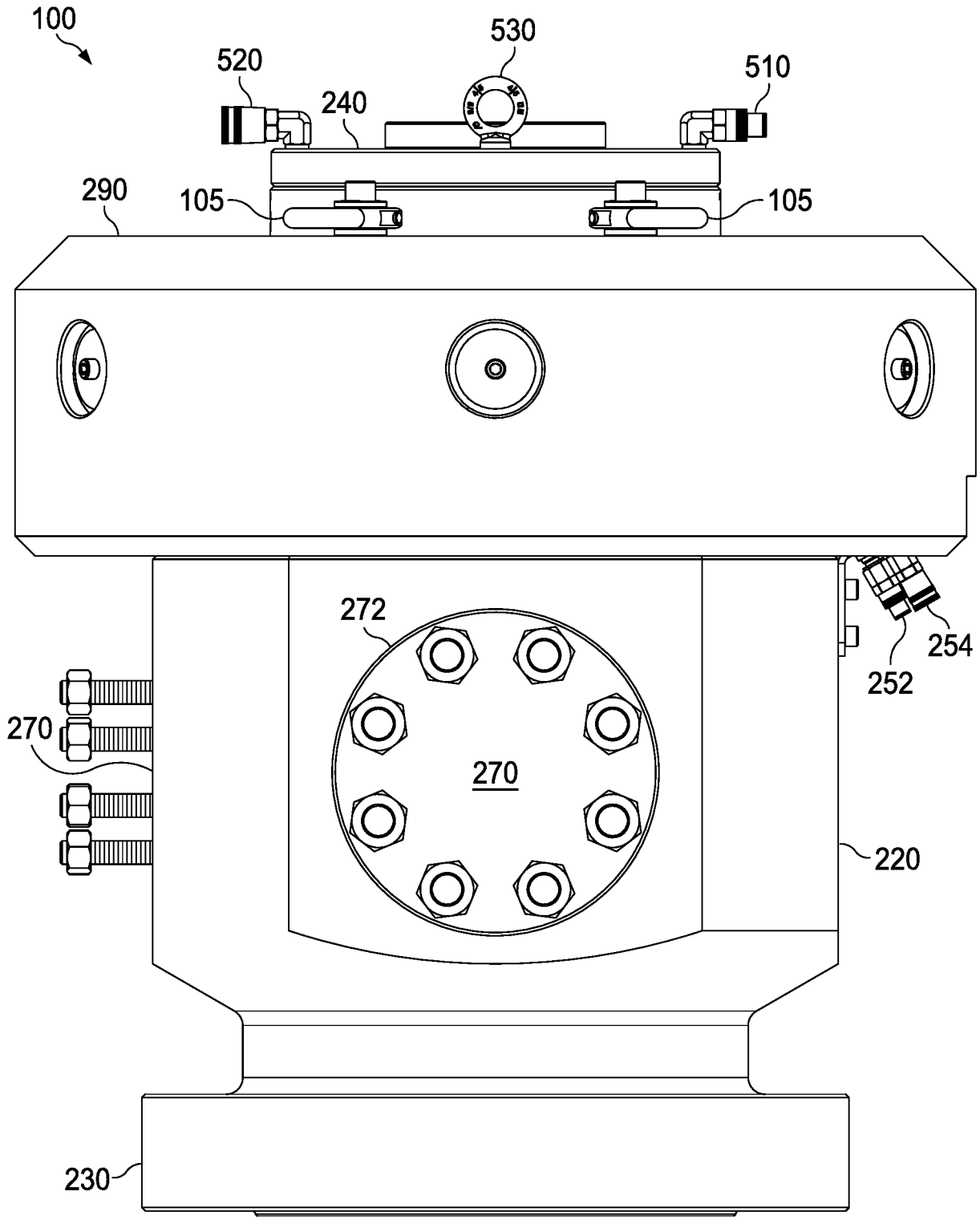


FIG. 3F

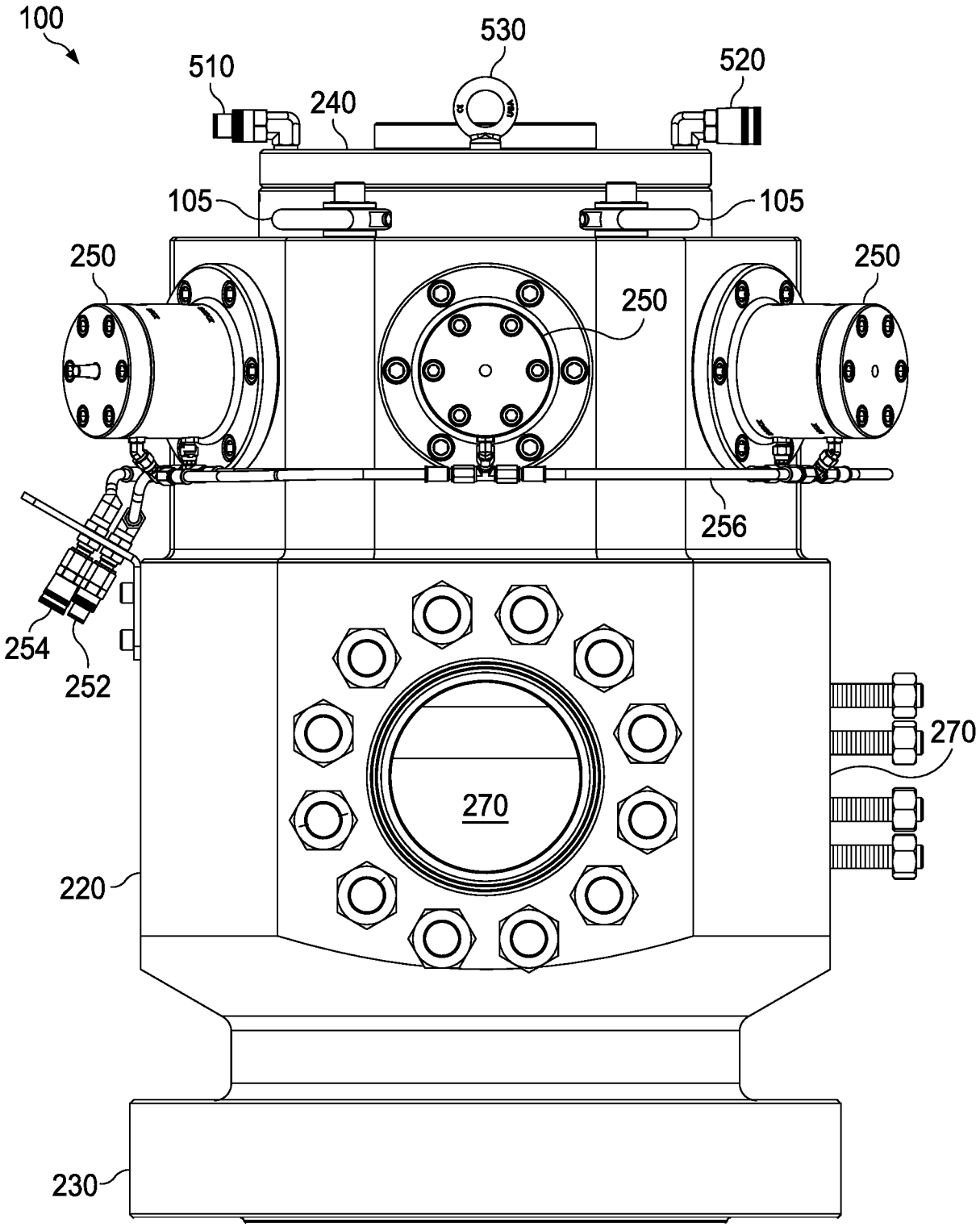

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FIG. 3G

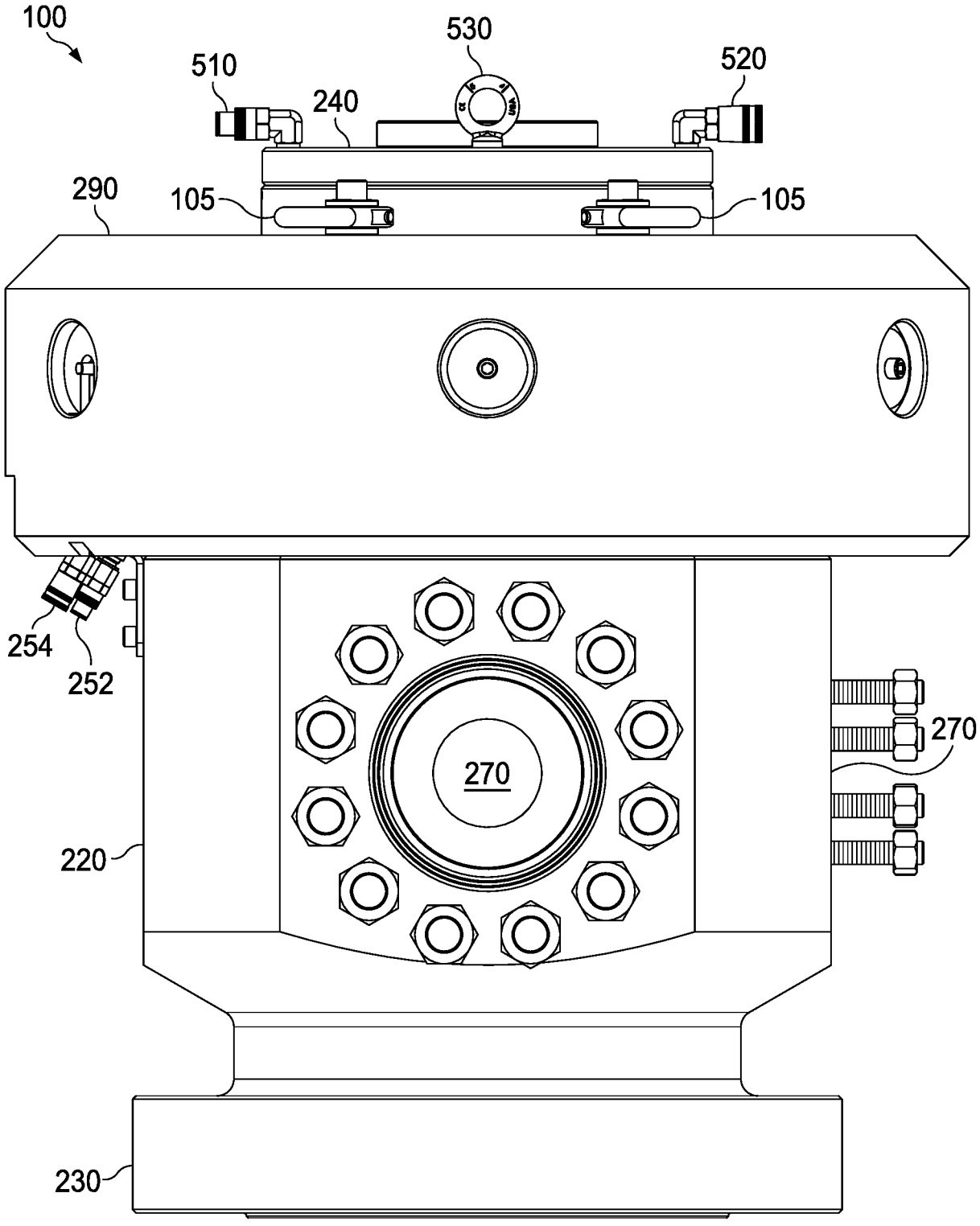


FIG. 3H

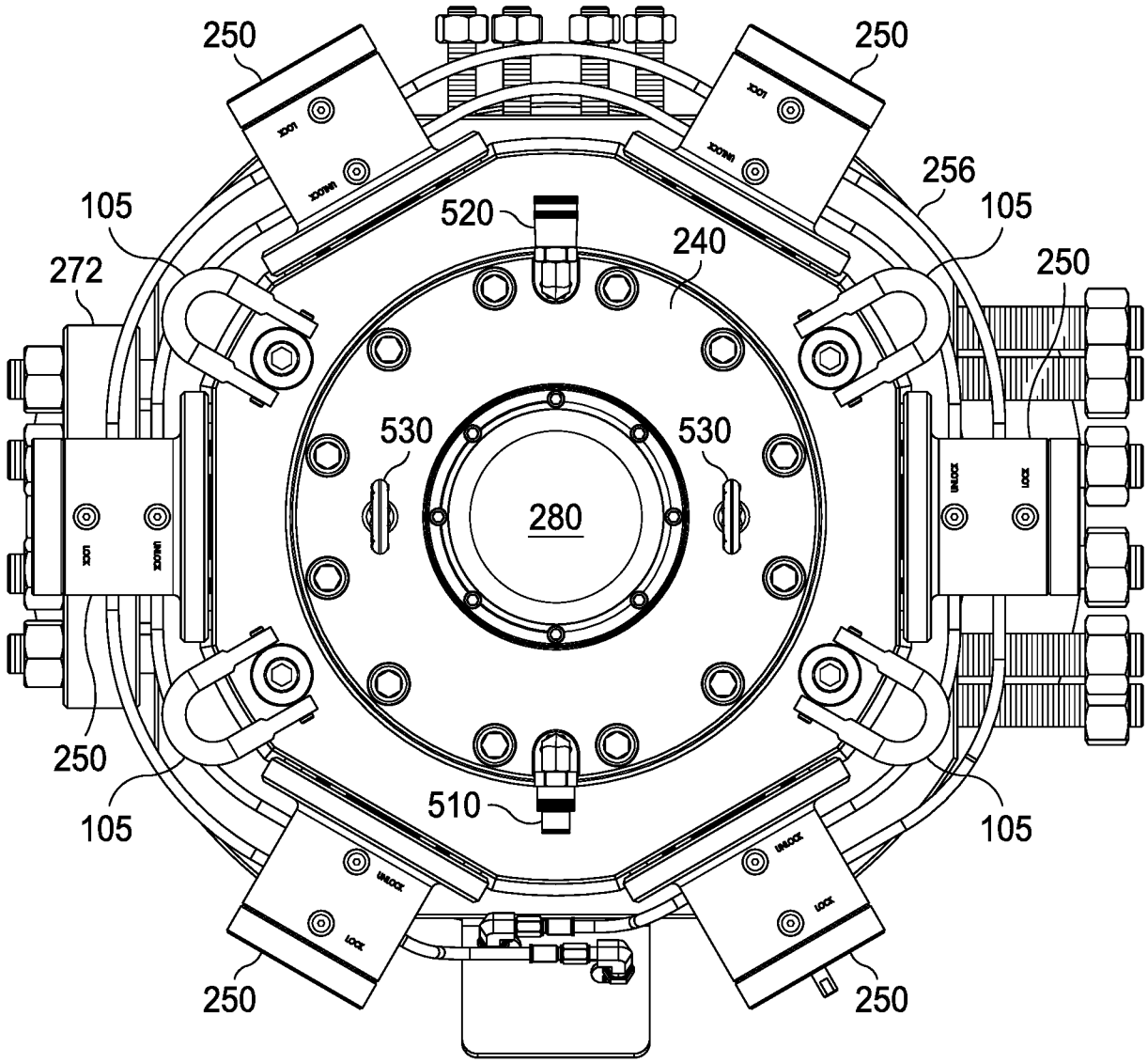

250
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256
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105
520
240
272
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530
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510
105
250
250

FIG. 4A

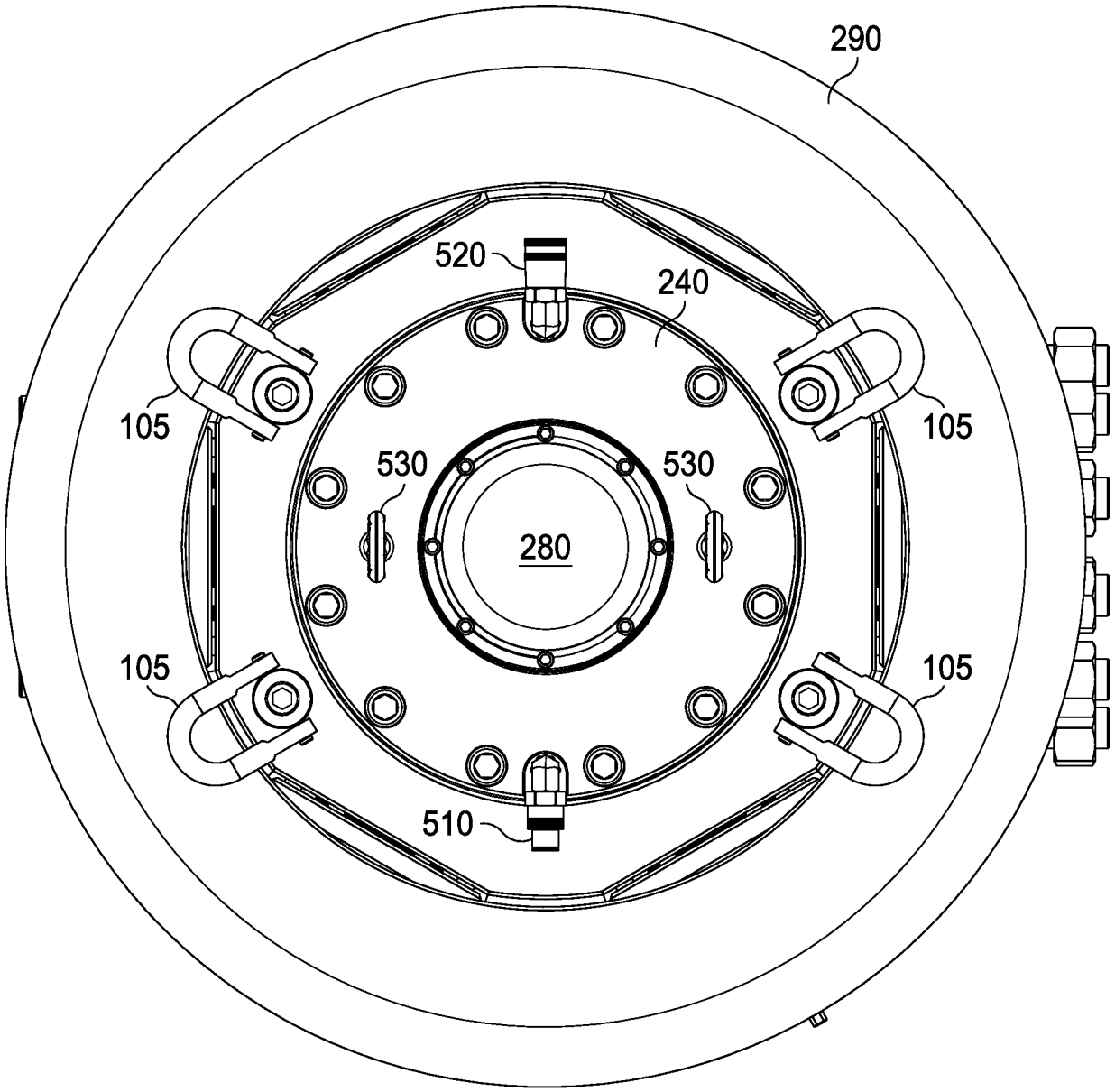


FIG. 4B

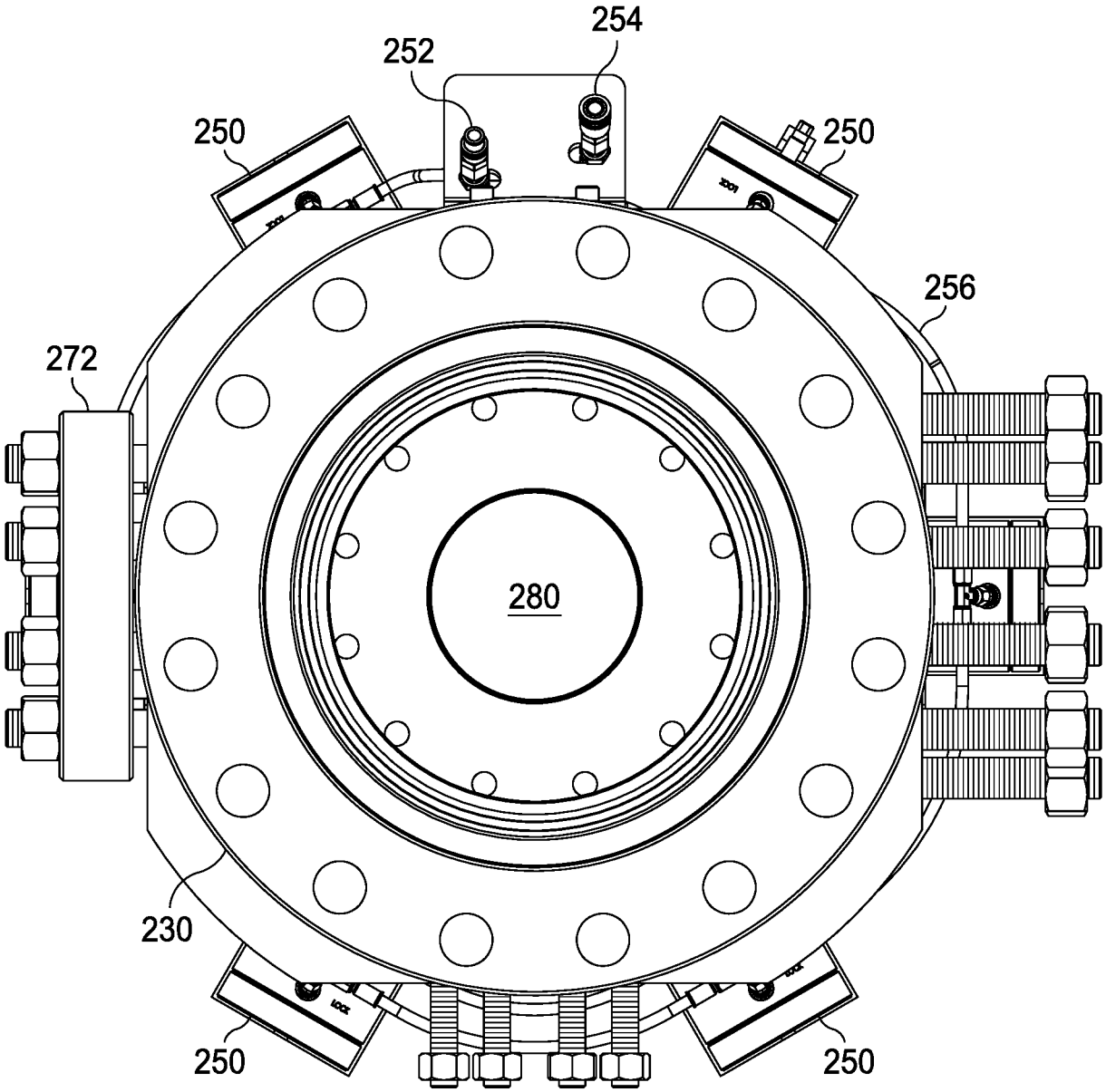


FIG. 4C

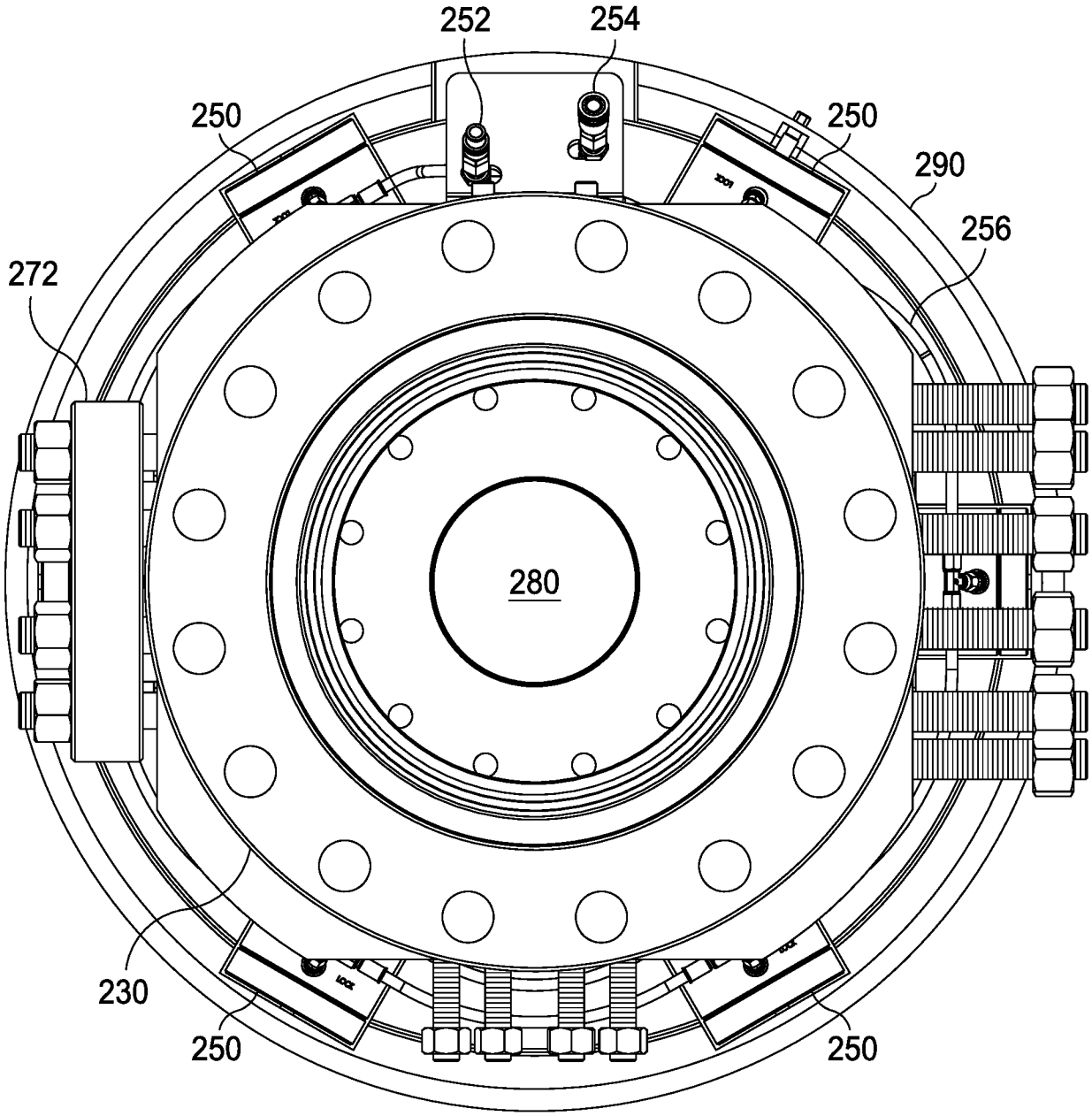


FIG. 4D

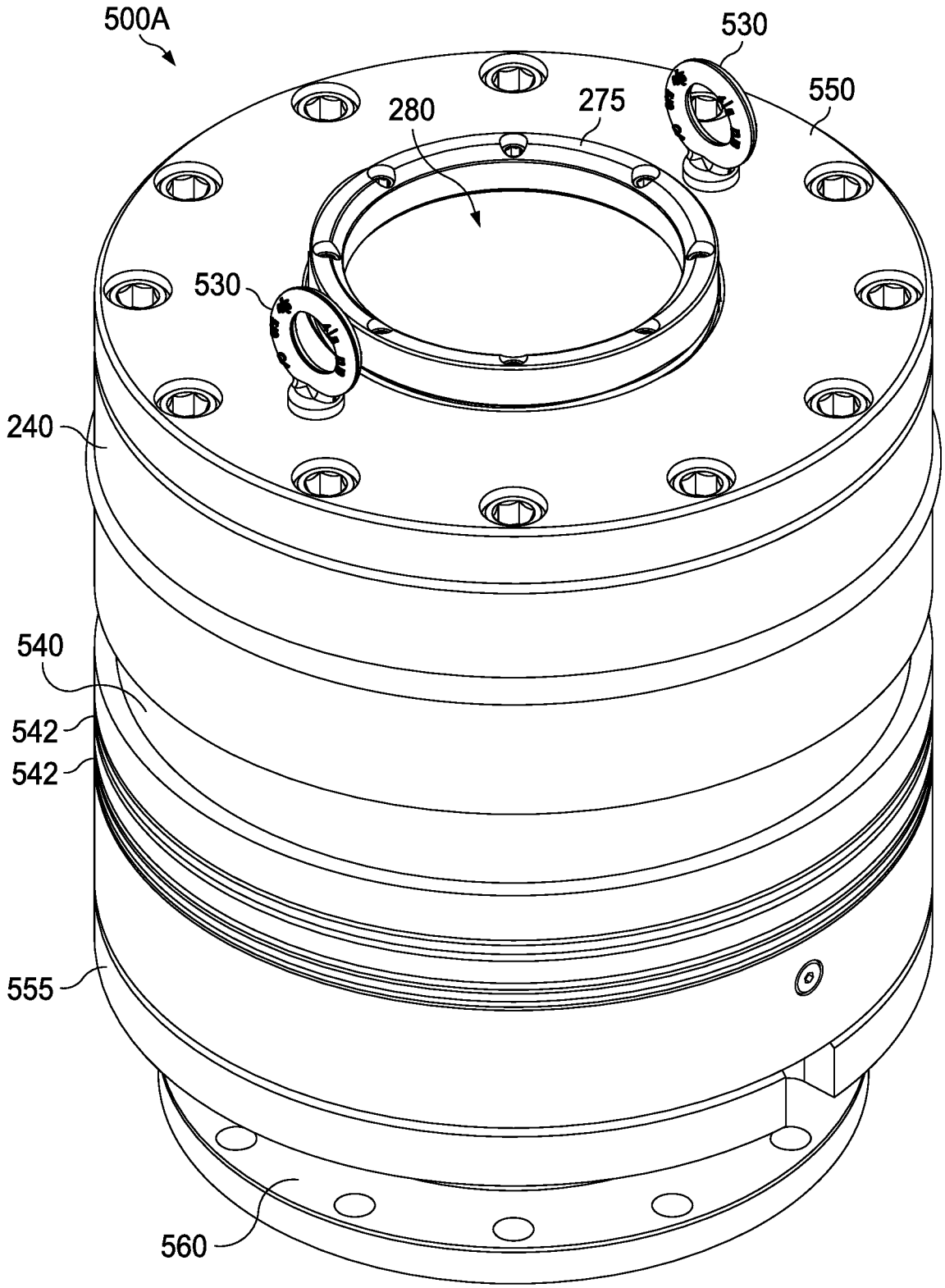


FIG. 5A

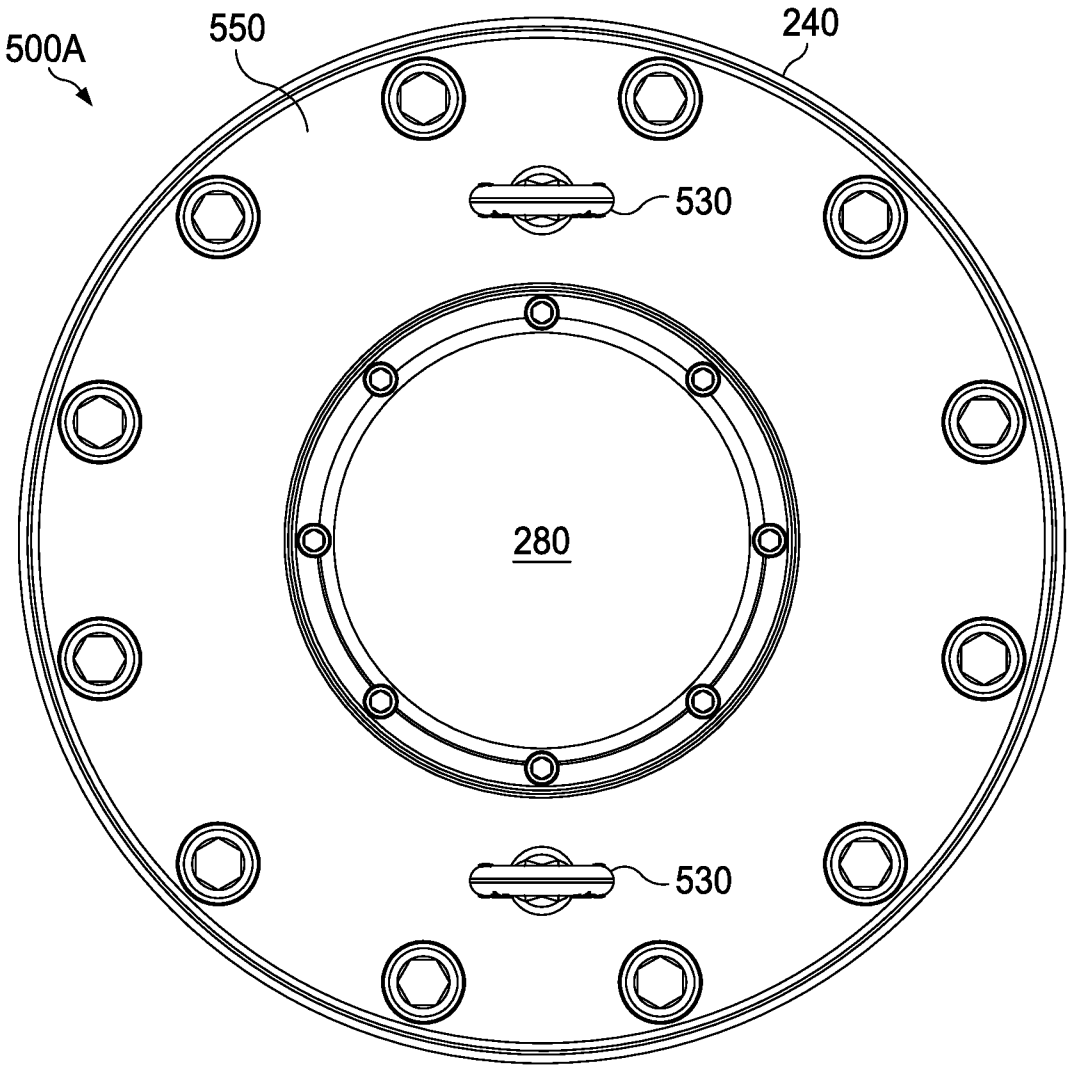


FIG. 5B

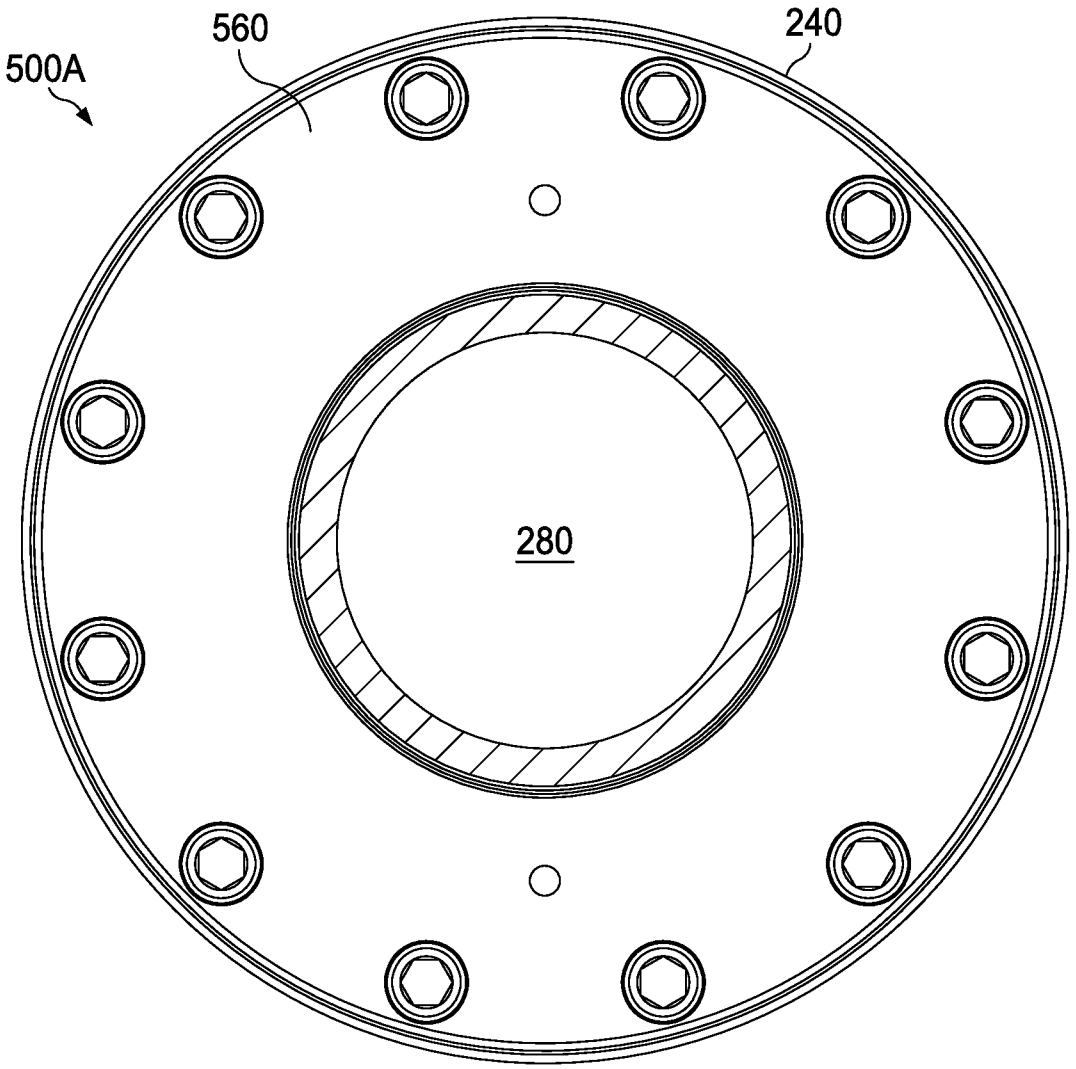


FIG. 5C

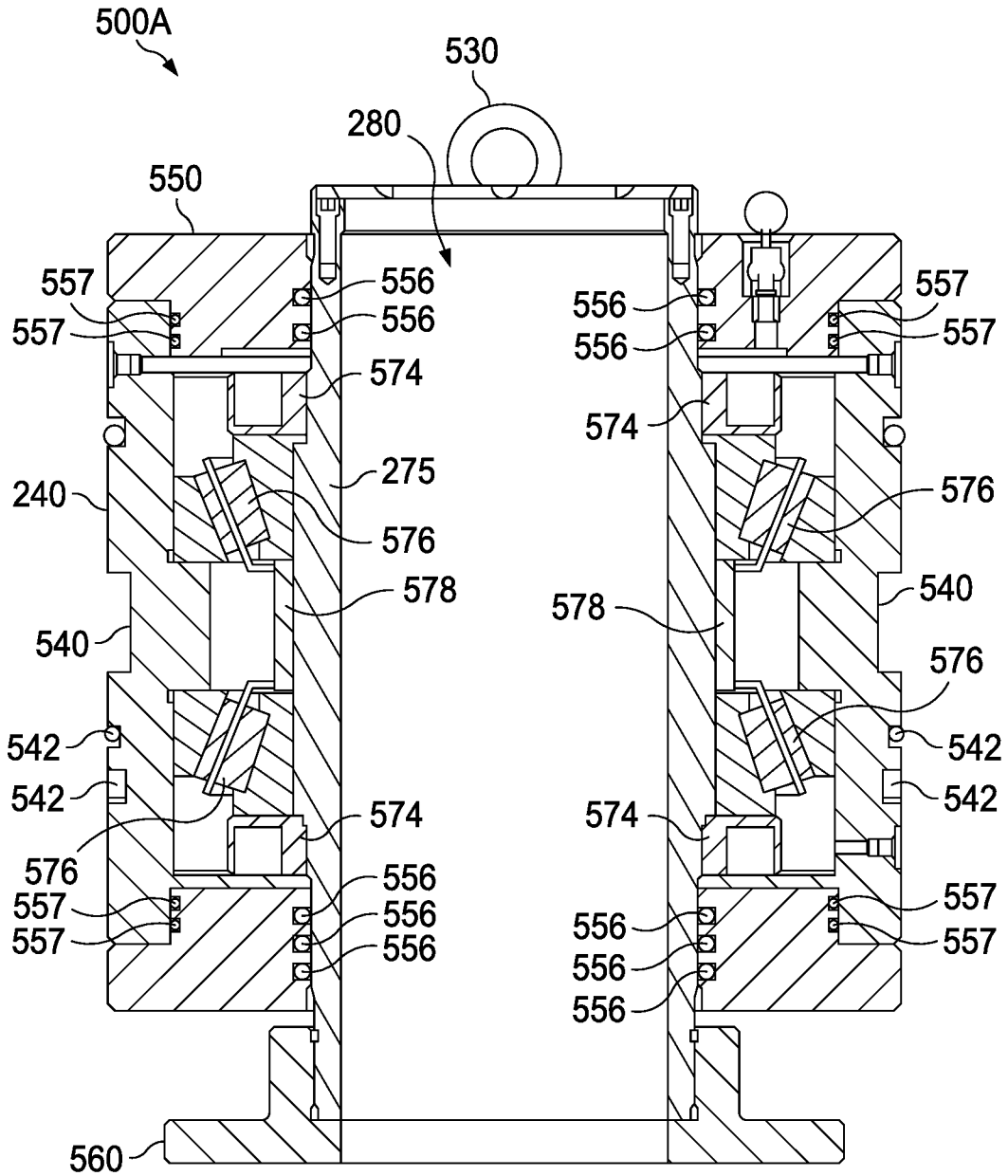

500A
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FIG. 5D

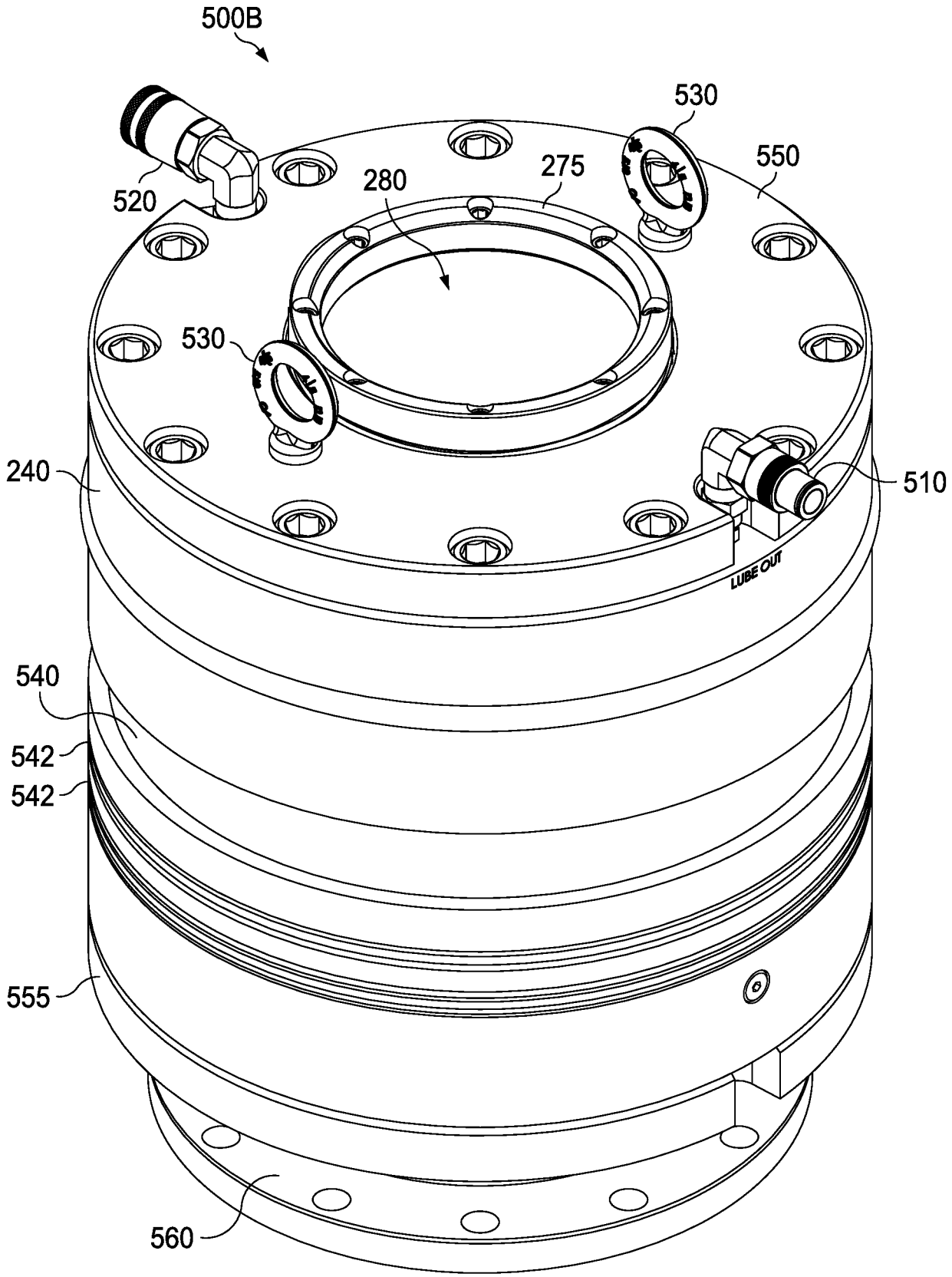

500B
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LUBE OUT
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542
555
560

FIG. 5E

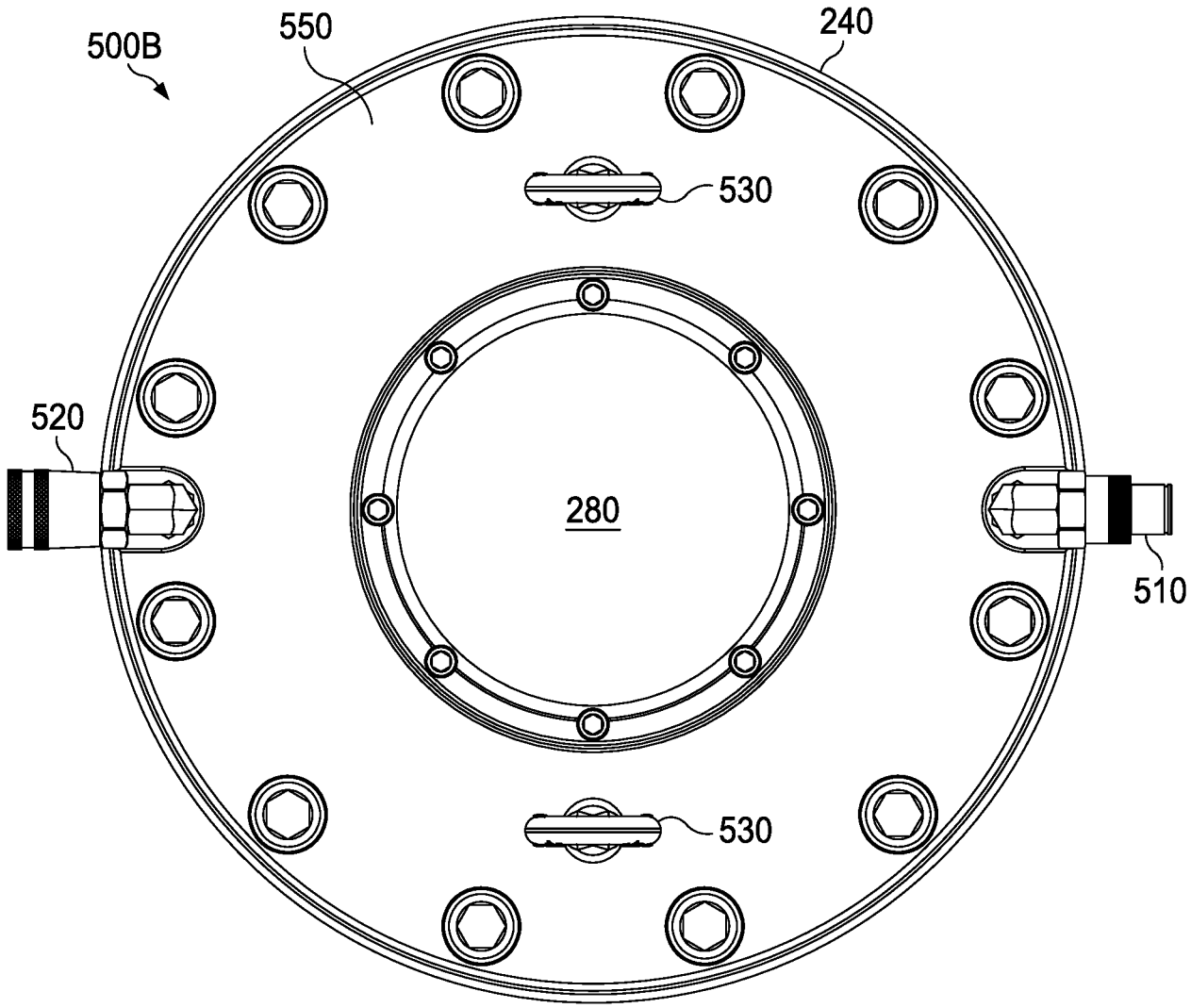


FIG. 5F

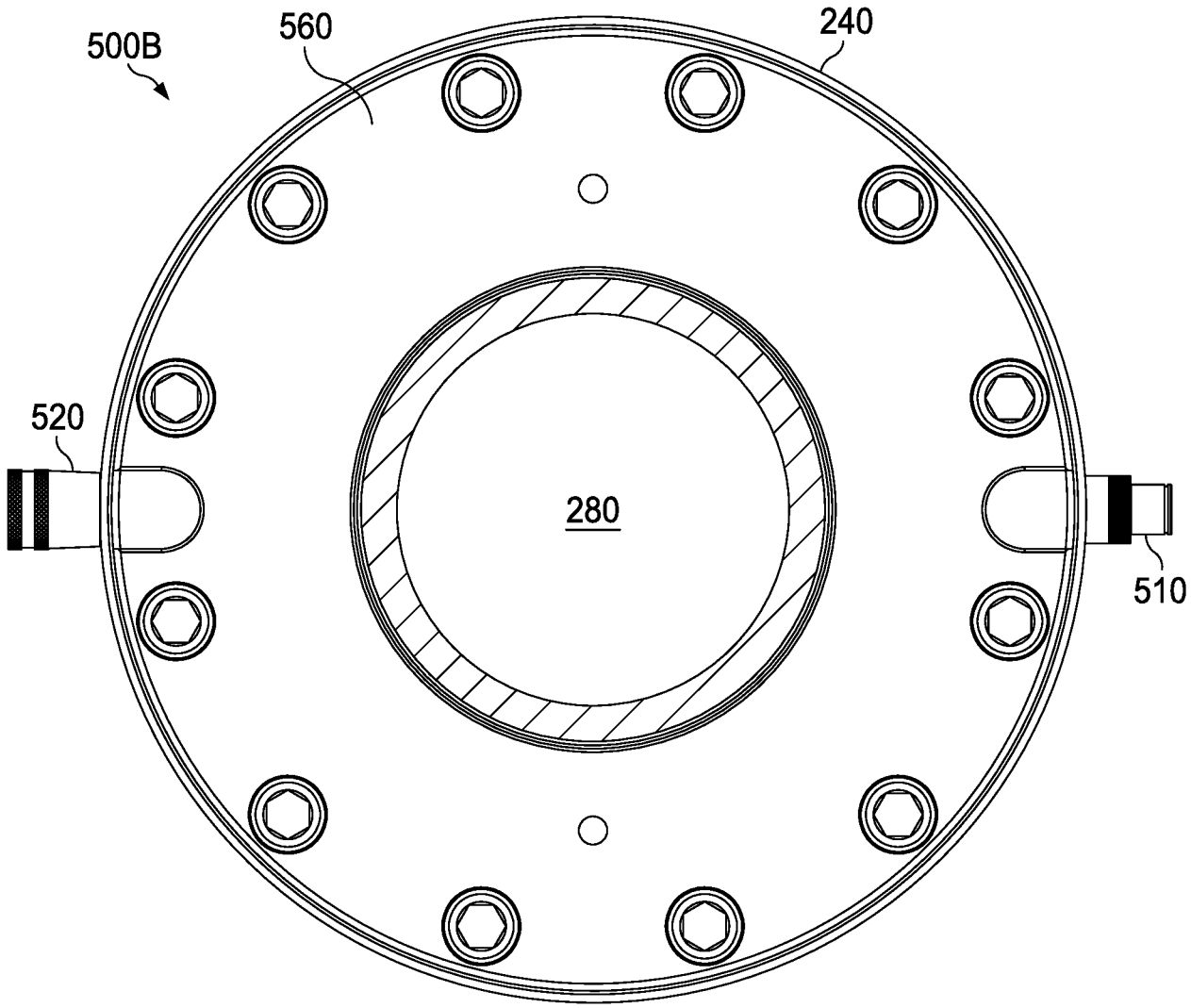


FIG. 5G

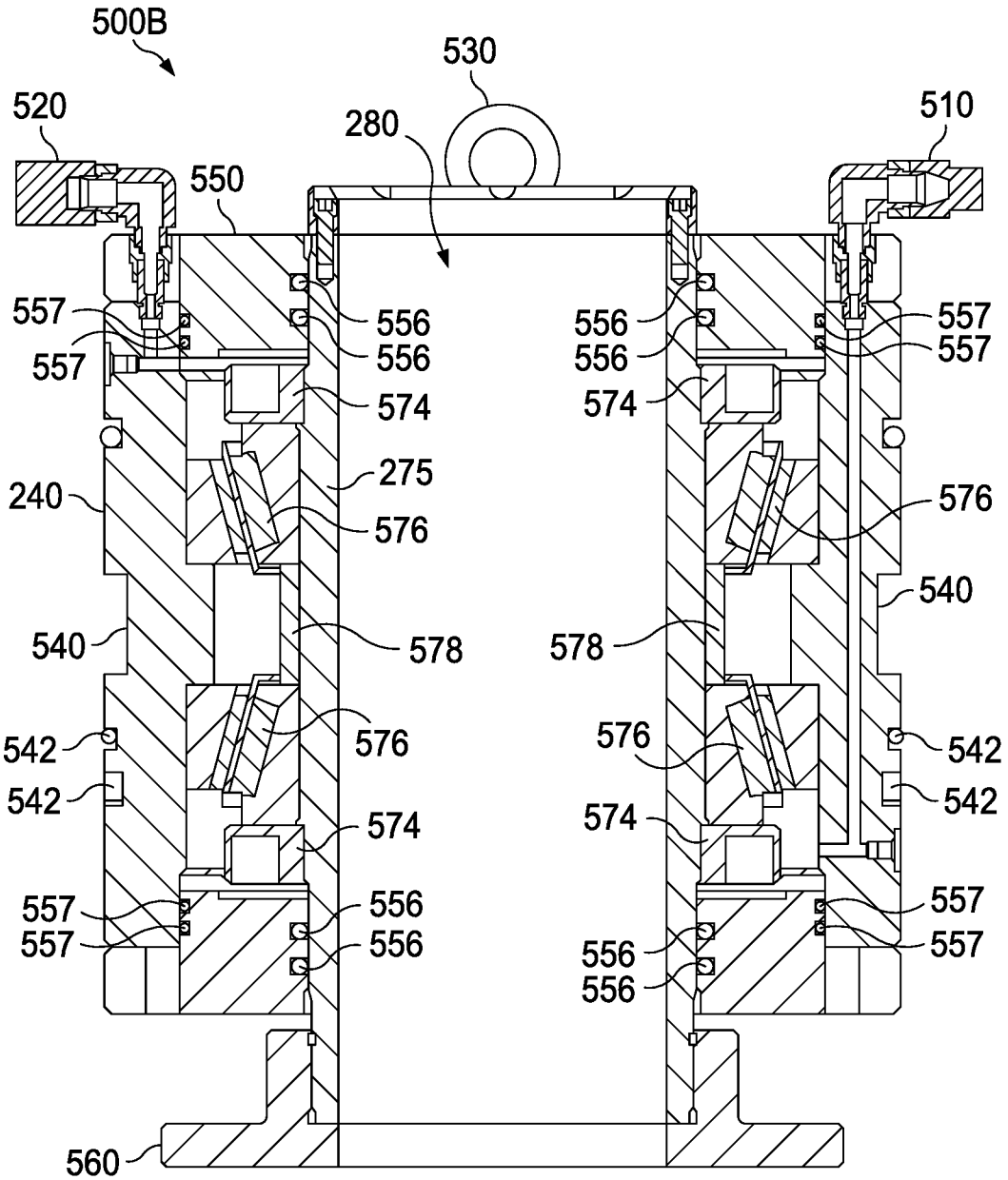

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FIG. 5H

FIG. 6B

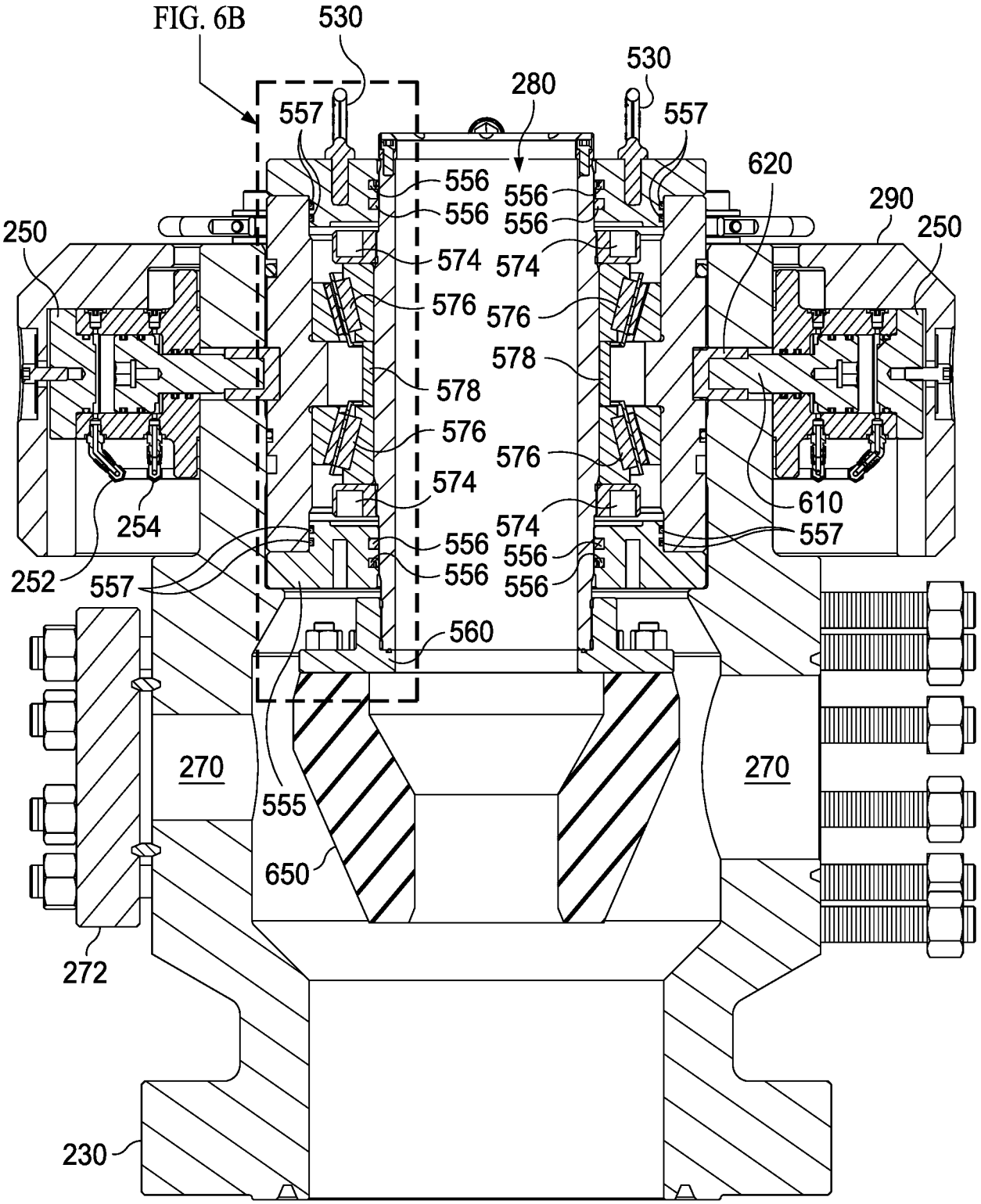

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FIG. 6A

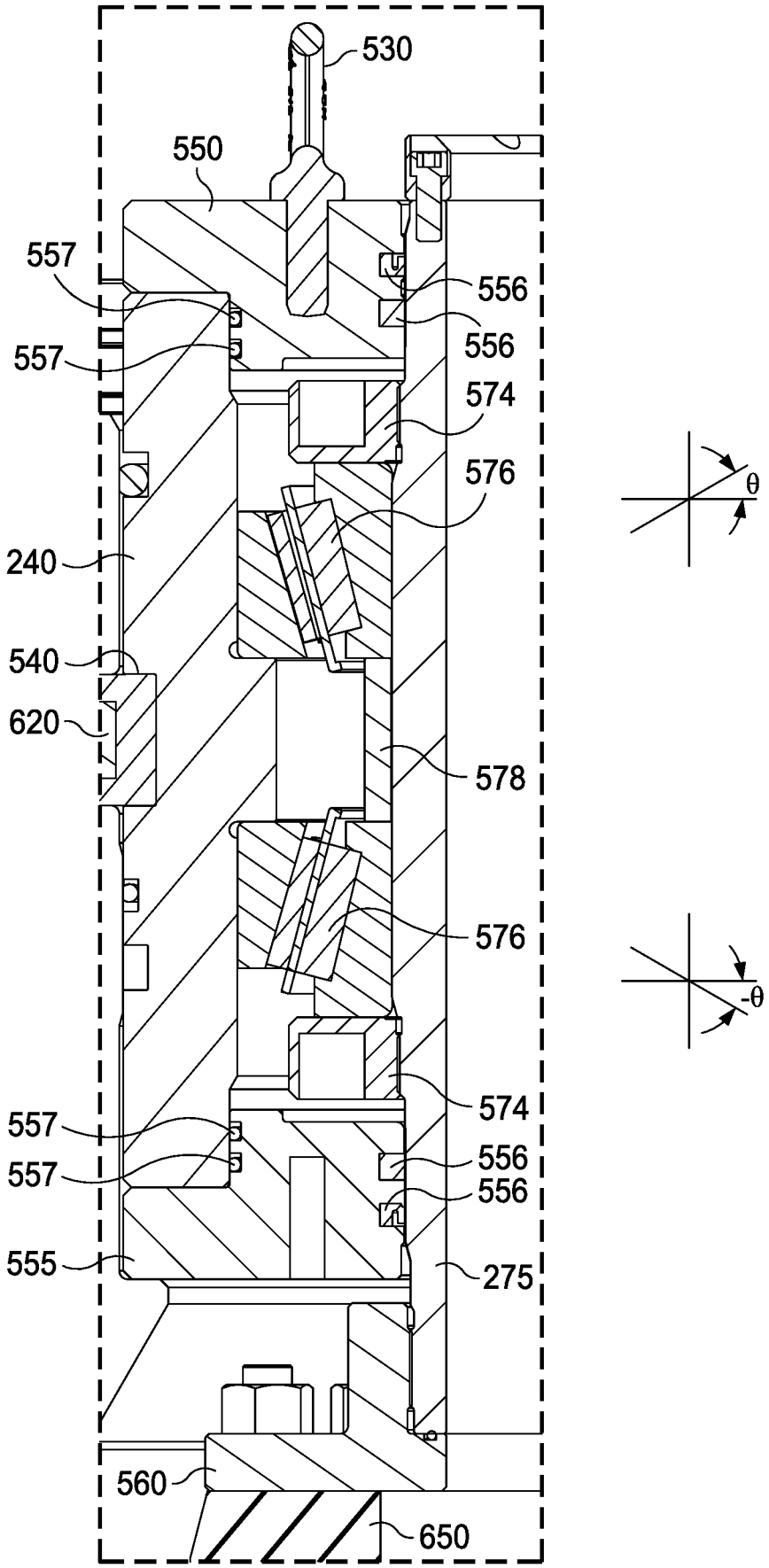

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540
620
578
576
-θ
574
557
557
556
556
555
275
560
650

FIG. 6B

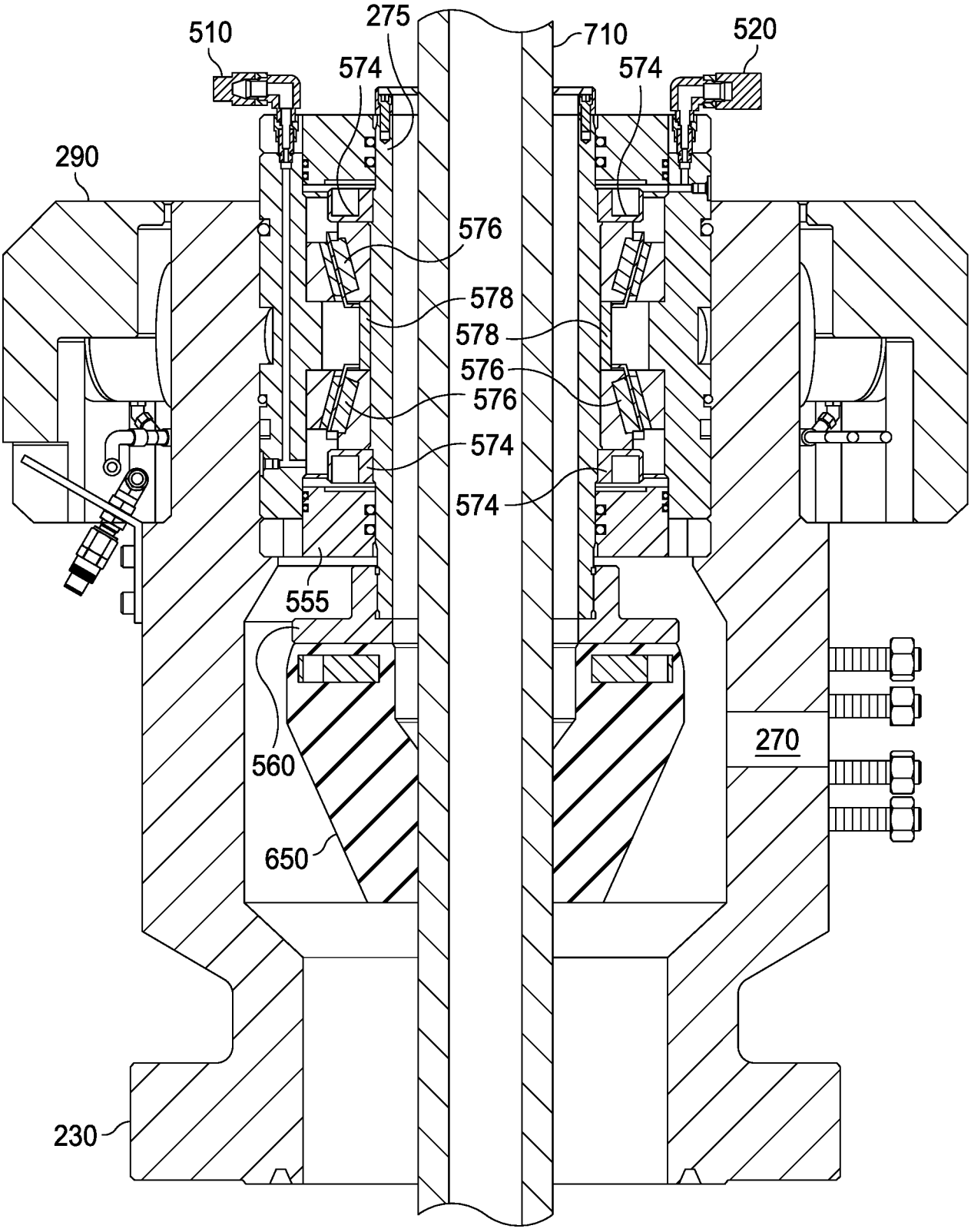

510
275
710
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574
574
290
576
578
578
576
576
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574
555
560
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230

FIG. 7A

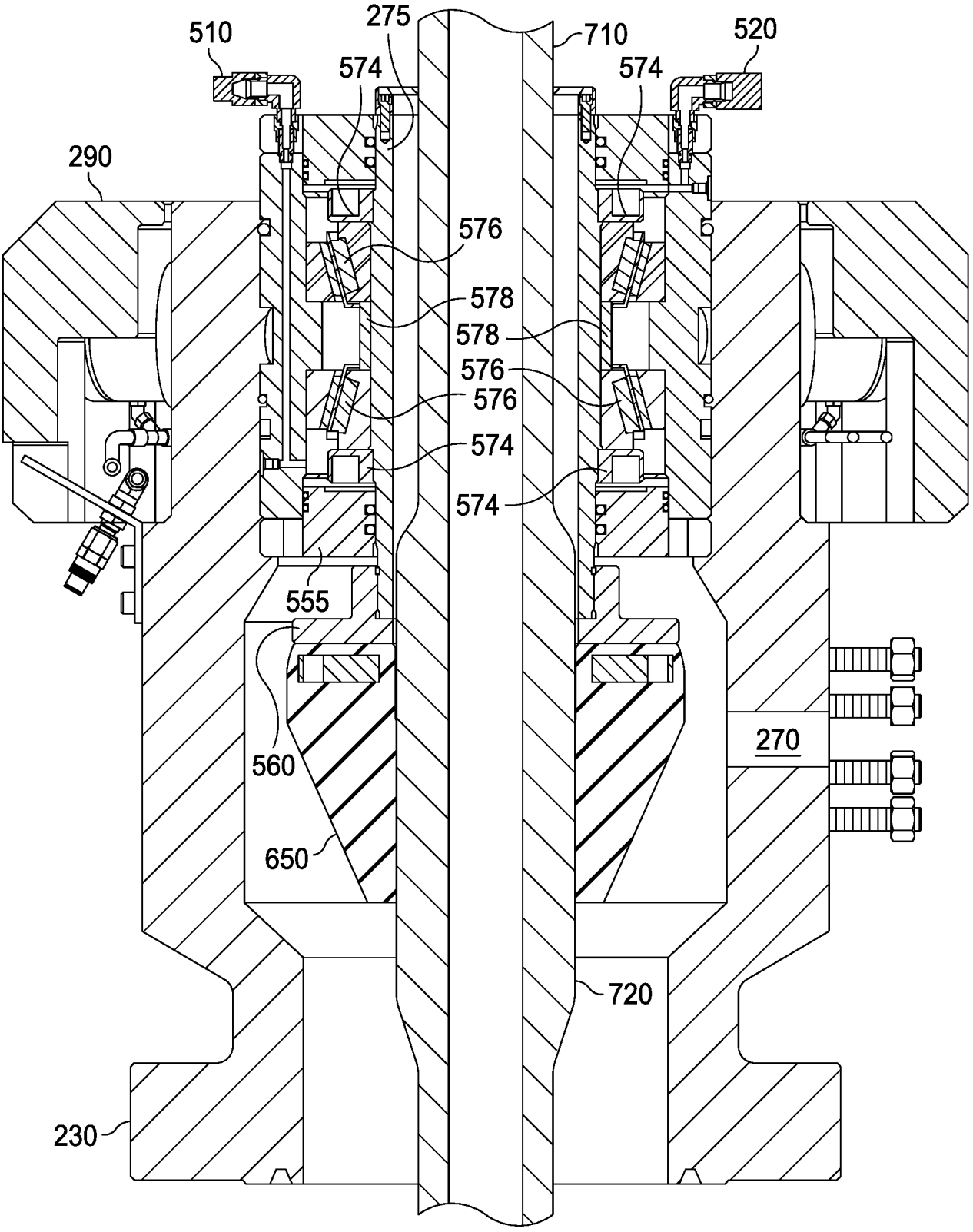

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FIG. 7B

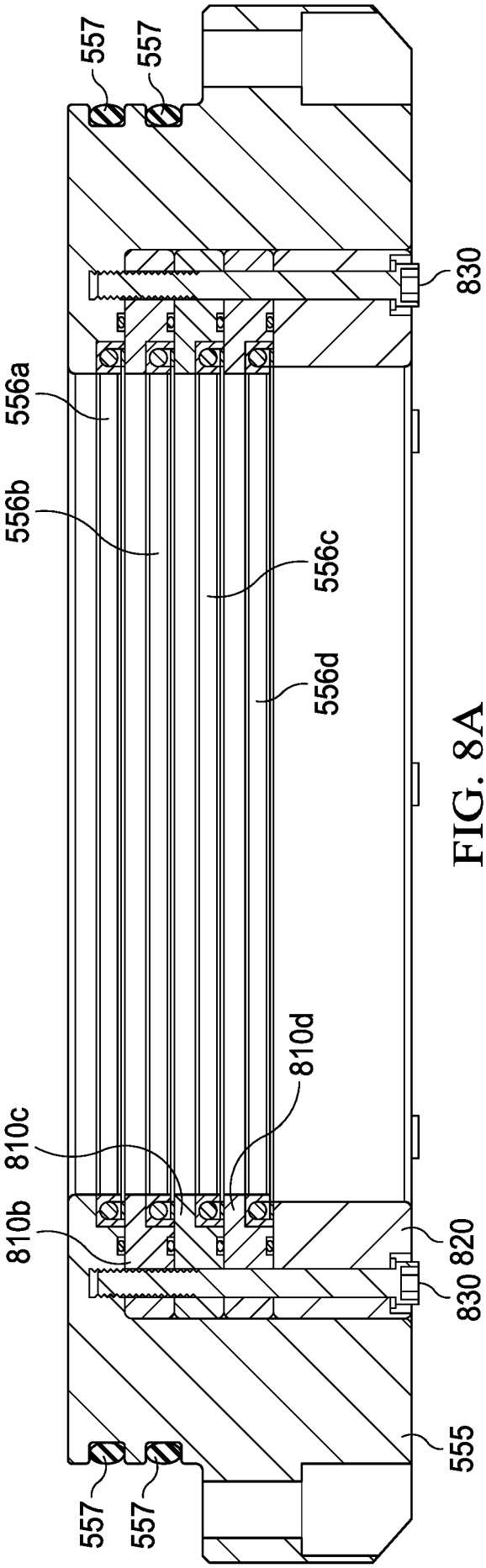

557
557
830
556a
556b
556c
556d
810d
810c
810b
820
830
555
557
557

FIG. 8A

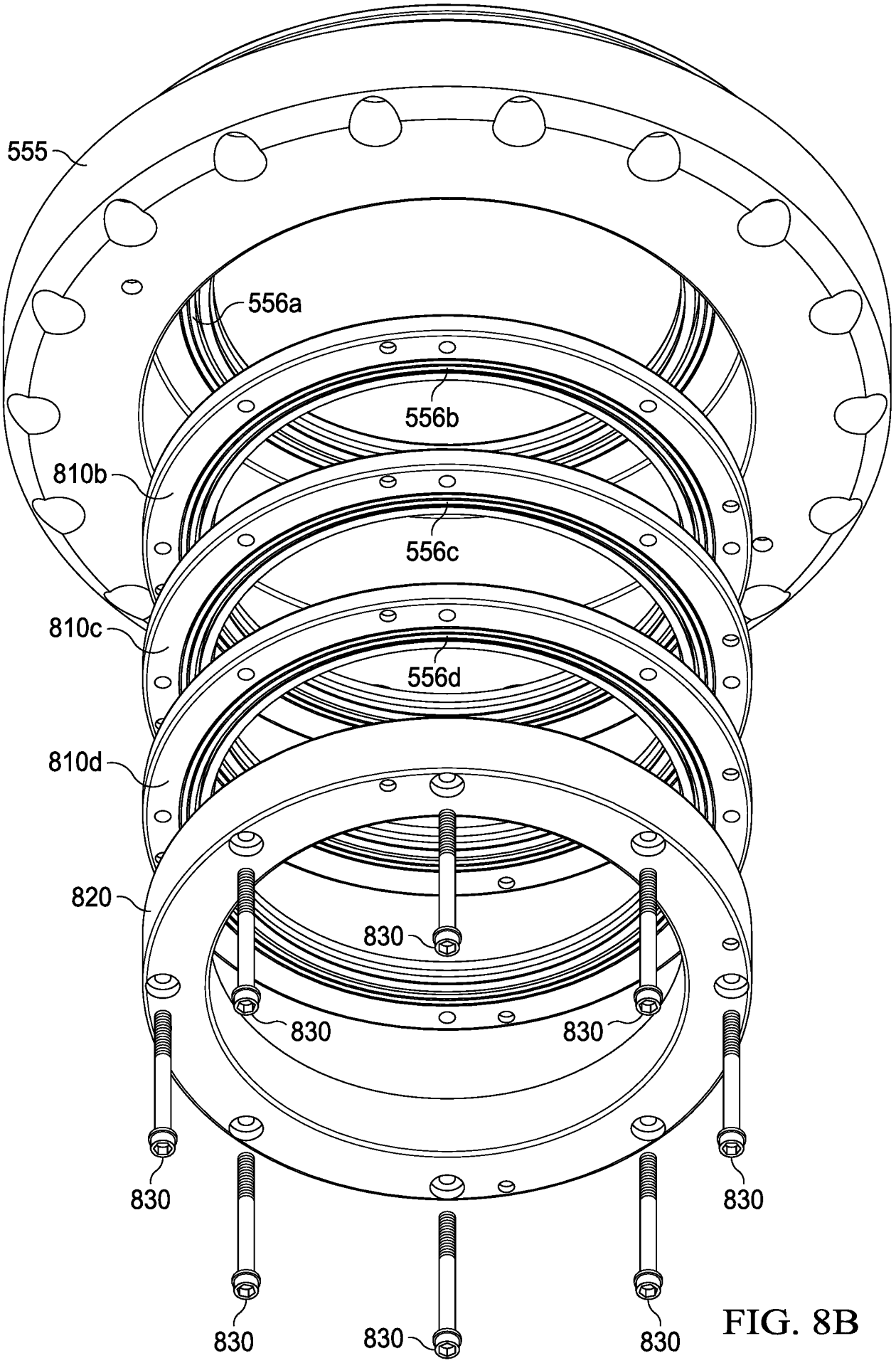

555
556a
556b
810b
556c
810c
556d
810d
820
830
830
830
830
830
830
830

FIG. 8B

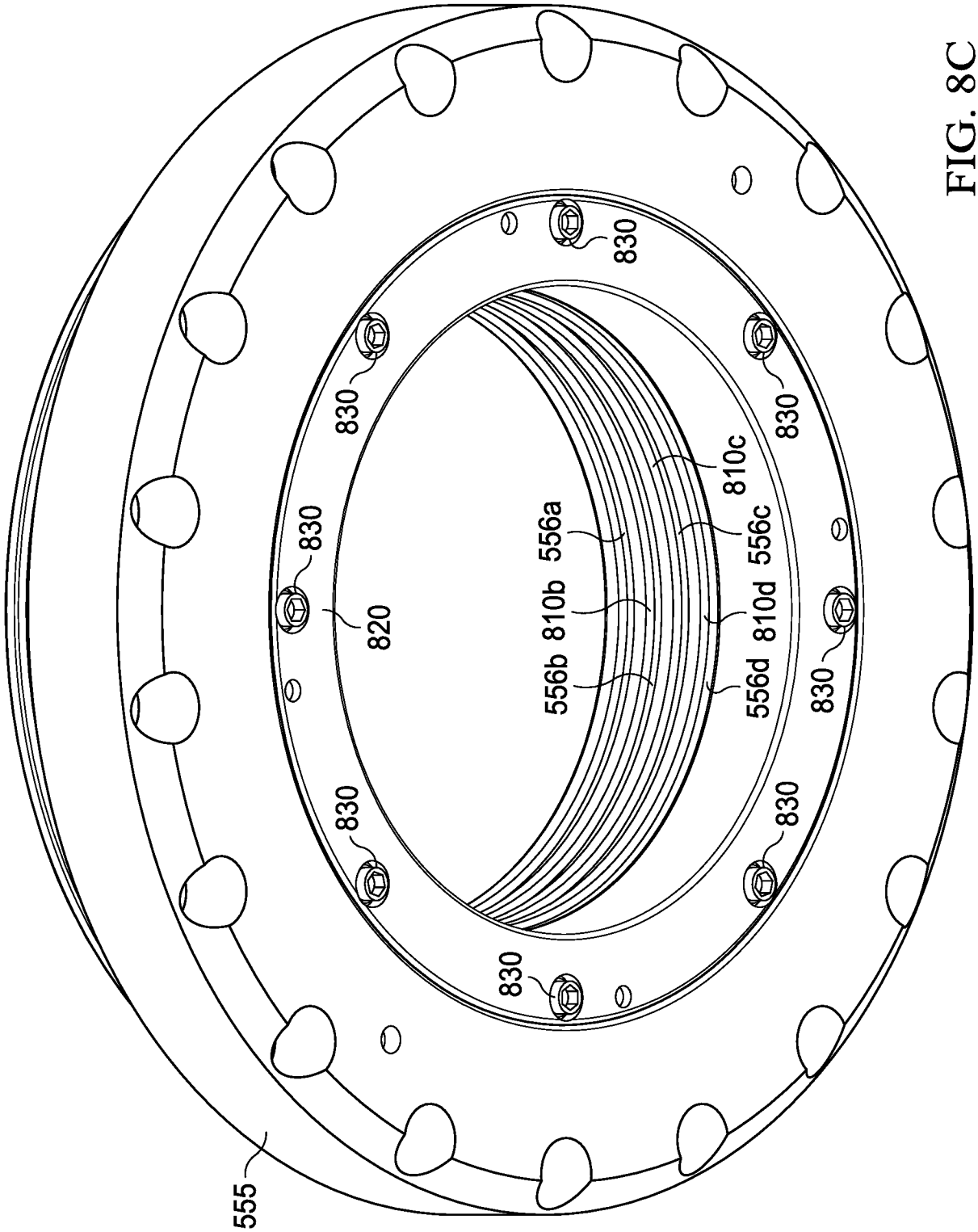


FIG. 8C

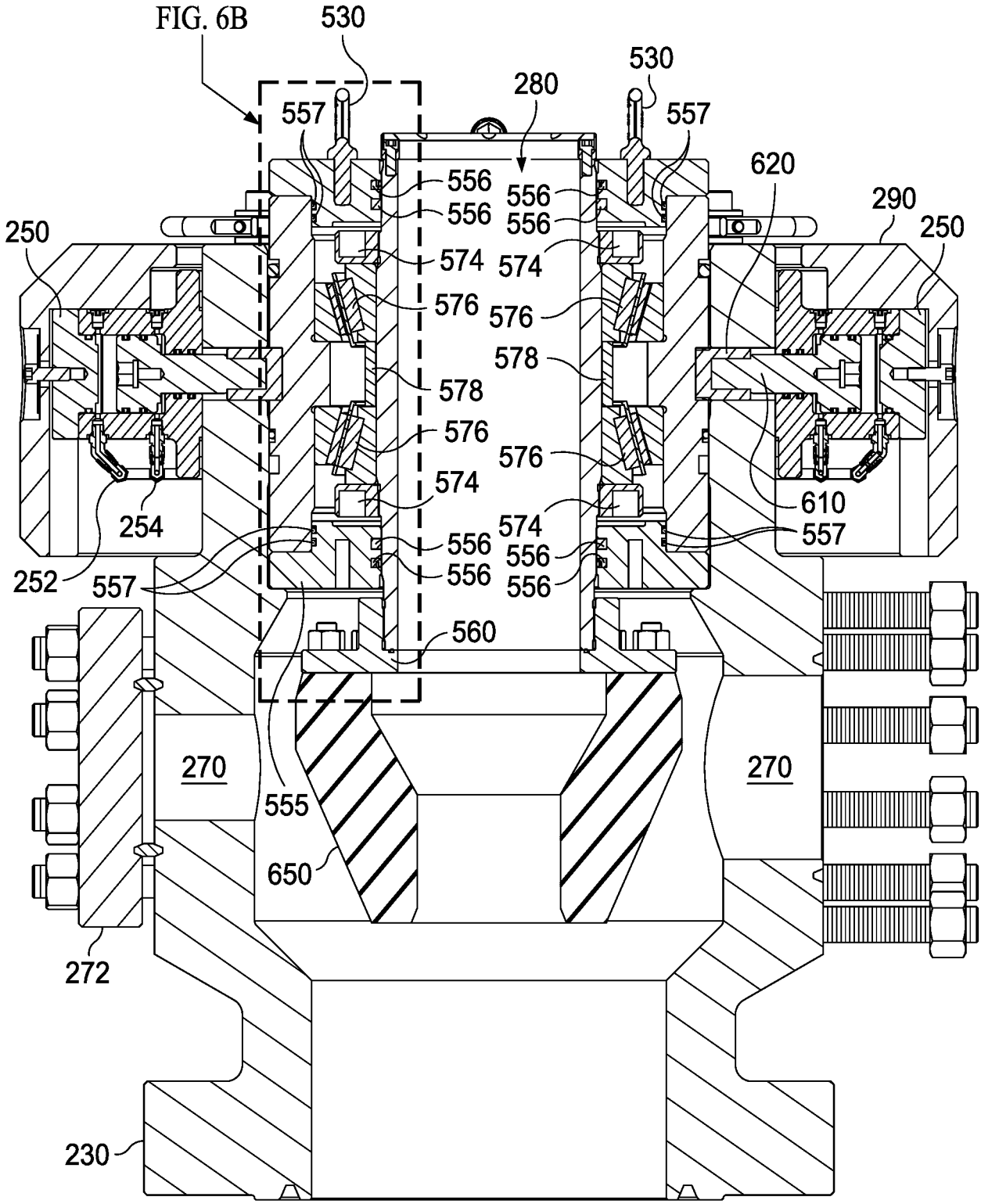

FIG. 6B
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252
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FIG. 6A