(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 September 2011 (15.09.2011)

PCT

(10) International Publication Number
WO 2011/112595 A1

(51) International Patent Classification:
G21C 7/10 (2006.01)

(21) International Application Number:
PCT/US2011/027570

(22) International Filing Date:
8 March 2011 (08.03.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
12/722,696 12 March 2010 (12.03.2010) US

(71) Applicant *(for all designated States except US)*: **BABCOCK & WILCOX NUCLEAR OPERATIONS GROUP, INC.** [US/US]; 24703 Euclid Avenue, Euclid, OH 44117 (US).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **DESANTIS, Paul, K.** [US/US]; 36060 Cannon Road, Bentleyville, OH 44022 (US).

(74) Agent: **SEYMOUR, Michael, J.**; Babcock & Wilcox Power Generation Group, Inc., Patent Dept., 20 S. Van Buren Avenue, Barberton, OH 44203 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: CONTROL ROD DRIVE MECHANISM FOR NUCLEAR REACTOR

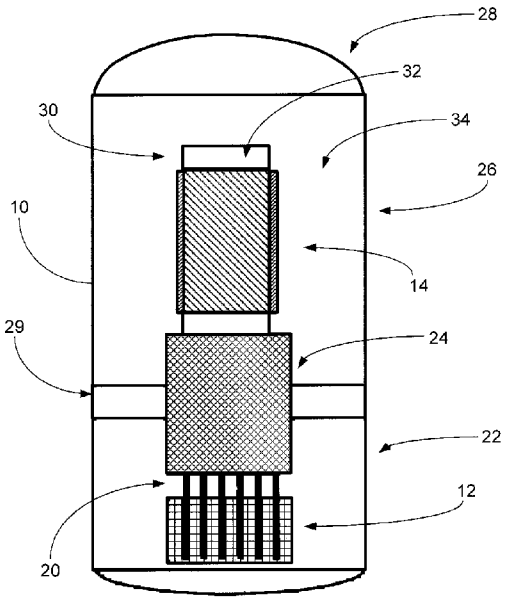


FIG. 1

(57) Abstract: A control rod drive mechanism (CRDM) comprises a lead screw, a motor threadedly coupled with the lead screw to linearly drive the lead screw in an insertion direction or an opposite withdrawal direction, a latch assembly secured with the lead screw and configured to (i) latch to a connecting rod and to (ii) unlatch from the connecting rod, the connecting rod being free to move in the insertion direction when unlatched, and a release mechanism configured to selectively unlatch the latch assembly from the connecting rod.

WO 2011/112595 A1

CONTROL ROD DRIVE MECHANISM FOR NUCLEAR REACTOR

BACKGROUND

[0001] In a pressurized water reactor (PWR) or other type of nuclear reactor, movable control rods are used to control the nuclear reaction. The control rods include a neutron absorbing material, and are arranged to be inserted into the reactor core. In general, the further the control rods are inserted into the core, the more neutrons are absorbed and the more the nuclear reaction rate is slowed. Precise control of the amount of insertion, and accurate measurement of same, is useful in order to precisely control the reactivity. The control rods drive mechanism (CRDM) provides this control.

[0002] In an emergency, the control rods can be fully inserted in order to quickly quench the nuclear reaction. In such a "scram", it is useful to have an alternative fast mechanism for inserting the control rods. Additionally or alternatively, it is known to have dedicated control rods that are either fully inserted (thus turning the nuclear reaction "off") or fully withdrawn (thus making the reactor operational). In such systems, the "on/off" rods are sometimes referred to as "shutdown rods" while the continuously adjustable control rods are sometimes referred to as "gray rods".

[0003] Given these considerations, it is known to construct a CRDM employing a lead screw that is engaged by a separable roller-nut assembly. During normal operation, the roller-nut assembly is clamped onto the lead screw by an affirmative magnetic force acting against biasing springs. By turning the roller nut the lead screw, and hence the attached control rods, are moved in precisely controllable fashion toward or away from the reactor core. In a scram, the electrical current is cut thus cutting the magnetic force, the biasing springs open the separable roller nut, and the gray rod including the lead screw scrams. An example of such a configuration is disclosed, for example, in Domingo Ricardo Giorsetti, "Analysis of the Technological Differences Between Stationary & Maritime Nuclear Power Plants", M.S.N.E.

Thesis, Massachusetts Institute of Technology (MIT) Department of Nuclear Engineering (1977) which is incorporated herein by reference in its entirety.

[0004] For an integral pressurized water reactor (integral PWR), it is known to mount the CRDM externally and to couple with the control rods inside the pressure vessel by suitable feedthroughs. To reduce the extent of feedthroughs, it has also been proposed to integrate the CRDM within the pressure vessel. See, for example, Ishizaka et al., "Development of a Built-In Type Control Rod Drive Mechanism (CRDM) For Advanced Marine Reactor X (MRX)", Proceedings of the International Conference on Design and Safety of Advanced Nuclear Power Reactors (ANP '92), October 25-29, 1992 (Tokyo Japan) published by the Atomic Energy Society of Japan in October 1992, which is incorporated herein by reference in its entirety.

[0005] Existing CRDM designs have certain disadvantages. These disadvantages are enhanced when an internal CRDM design is chosen in which the complex electro-mechanical CDRM is internal to the high pressure and high temperature environment within the pressure vessel. Placement of the CRDM internally within the pressure vessel also imposes difficult structural challenges.

[0006] The separable roller-nut creates a complex linkage with the lead screw that can adversely impact gray rod insertion precision during normal operation. Reattachment of the roller-nut to the lead screw can be complex, and it may not be immediately apparent when contact is reestablished, thus introducing a positional offset after recovery from the scram event. Scramming the lead screw also has the potential to cause irrecoverable damage to the threading or structural integrity of the lead screw. Still further, wear over time can be a problem for the complex separable roller-nut.

[0007] Another consideration is reliability. Because rod scramming is a safety-critical feature, it must operate reliably, even in a loss of coolant

accident (LOCA) or other failure mode that may include interruption of electrical power, large pressure changes, or so forth.

[0008] The control rod position detector is also typically a complex device. In some systems, an external position detector is employed, which requires feedthroughs across the pressure vessel wall. For the internal CRDM of the MRX reactor, a complex position detector was designed in which a transducer generates a torsional strain pulse that passes through a magnetoresistive waveguide, and magnetic field interactions are measured to adduce the rod position. In general, an internal position detector operating on an electrical resistance basis is prone to error due to temperature-induced changes in material resistivity.

BRIEF SUMMARY

[0009] In one aspect of the disclosure, a control rod mechanism for use in a nuclear reactor comprises: at least one control rod configured for insertion in a reactor core to absorb neutrons; a hollow lead screw; a motor operatively coupled with the hollow lead screw to drive the hollow lead screw linearly toward or away from the reactor core; a connecting rod connected with the aforementioned at least one control rod and disposed partially inside the hollow lead screw; a latch assembly having latches that when closed operatively connect the connecting rod and the lead screw so that when the latches are closed the connecting rod and the aforementioned at least one control rod move together with the lead screw when the lead screw is driven by the motor; and a release mechanism configured to cause the latches of the latch assembly to open responsive to a scram condition to detach the connecting rod from the lead screw such that the connecting rod and the aforementioned at least one control rod scram but the lead screw remains operatively coupled with the motor and does not scram.

[0010] In another aspect of the disclosure, a control rod drive mechanism (CRDM) comprises: a lead screw; a motor threadedly coupled with the lead

screw to linearly drive the lead screw in an insertion direction or an opposite withdrawal direction; a latch assembly secured with the lead screw and configured to (i) latch to a connecting rod and to (ii) unlatch from the connecting rod, the connecting rod being free to move in the insertion direction when unlatched; and a release mechanism configured to selectively unlatch the latch assembly from the connecting rod.

[0011] In another aspect of the disclosure, a control rod drive mechanism (CRDM) comprises: a plurality of CRDM units each comprising a lead screw and a motor configured to drive the lead screw; and a support mounting the plurality of CRDM units in a nuclear reactor vessel with the motors of adjacent CRDM units arranged at different heights respective to a reactor core of the nuclear reactor vessel. Each CRDM unit is connected with one or more control rods such that the motor driving the lead screw moves the connected one or more control rods toward, away from, or within the reactor core.

[0012] In another aspect of the disclosure, a control rod drive mechanism (CRDM) comprises: a lead screw; a drive assembly configured to linearly drive the lead screw in an insertion or opposite withdrawal direction, the drive assembly including a motor and at least one non-separable ball nut coupling with the lead screw; and a latch assembly connected with the lead screw and having (i) a latched state in which the latch assembly is latched to a connecting rod and (ii) an unlatch state in which the latch assembly is not latched to the connecting rod.

[0013] In another aspect of the disclosure, a control rod mechanism for use in a nuclear reactor comprises: at least one control rod; a connecting rod connected with the aforementioned at least one control rod at a lower end of the connecting rod; and a control rod drive mechanism (CRDM) including a latch assembly having (i) a latched state in which the latch assembly is latched to an upper end of the connecting rod and (ii) an unlatched state in which the latch assembly is not latched to the upper end of the connecting

rod, and a linear drive mechanism configured to drive the latch assembly linearly toward or away from a nuclear reactor core.

[0014] In another aspect of the disclosure, in a control rod mechanism as set forth in the immediately preceding paragraph the CRDM is configured to allow the connecting rod to be removed by placing the latch assembly in the unlatched state and drawing the connecting rod away from the nuclear reactor core through the CRDM.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for purposes of illustrating preferred embodiments and are not to be construed as limiting the invention.

[0016] FIGURE 1 diagrammatically shows an illustrative nuclear reactor vessel of the pressurized water reactor (PWR) type.

[0017] FIGURE 2 diagrammatically shows the upper internals section of the illustrative nuclear reactor vessel of FIGURE 1.

[0018] FIGURES 3-5 diagrammatically show aspects of a shutdown control rod system employing hydraulic lift.

[0019] FIGURES 6-15 diagrammatically show aspects of a control rod system with electromagnetic gray rod functionality and a magnetic latch system for scram functionality.

[0020] FIGURES 16-21 diagrammatically show aspects of a control rod system with electromagnetic gray rod functionality and a latch system driven by a hydraulic lift for scram functionality.

[0021] FIGURES 22 and 23 show perspective and perspective partial sectional views, respectively, of a suitable array of CDRM employing a staggered vertical motor arrangement.

[0022] FIGURES 24 and 25 show perspective and exploded perspective views, respectively, of a "J"-groove coupling between the lower end of a connecting rod and a rod cluster assembly.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0023] With reference to FIGURE 1, an illustrative nuclear reactor vessel of the pressurized water reactor (PWR) type is diagrammatically depicted. An illustrated primary vessel **10** contains a reactor core **12**, internal helical steam generators **14**, and internal control rods **20**. The illustrative reactor vessel includes four major components, namely: 1) a lower vessel **22**, 2) upper internals **24**, 3) an upper vessel **26** and 4) an upper vessel head **28**. A mid-flange **29** is disposed between the lower and upper vessel sections **22**, **26**. Other vessel configurations are also contemplated. Note that FIGURE 1 is diagrammatic and does not include details such as pressure vessel penetrations for flow of secondary coolant into and out of the steam generators, electrical penetrations for electrical components, and so forth.

[0024] The lower vessel **22** of the illustrative reactor vessel **10** of FIGURE 1 contains the reactor core **12**, which can have substantially any suitable configuration. One suitable configuration includes a stainless steel core former structure that contains the fuel assemblies and is replaceable in order to refuel the reactor, and which is supported by the lower vessel. The illustrative upper vessel **26** houses the steam generators **14** for this illustrative PWR which has an internal steam generator design (sometimes referred to as an integral PWR design). In FIGURE 1, the steam generator **14** is diagrammatically shown. A cylindrical inner shell or upper flow shroud **30** separates a central riser region **32** from an annular downcomer region **34** in which the helical steam generators **14** are located. The illustrative steam

generator **14** is a helical coil design, although other designs are contemplated. Primary reactor coolant flows across the outside of tubes of the steam generator **14** and secondary coolant flows inside the tubes of the steam generator **14**. In a typical circulation pattern the primary coolant is heated by the reactor core **12** and rises through the central riser region **32** to exit the top of the shroud **30** whereupon the primary coolant flows back down via the downcomer region **34** and across the steam generators **14**. Such primary coolant flow may be driven by natural convection, by internal or external primary coolant pumps (not illustrated), or by a combination of pump-assisted natural convection. Although an integral PWR design is illustrated, it is also contemplated for the reactor vessel to have an external steam generator (not illustrated), in which case pressure vessel penetrations allow for transfer of primary coolant to and from the external steam generator. The illustrative upper vessel head **28** is a separate component. It is also contemplated for the vessel head to be integral with the upper vessel **26**, in which case the steam generator **14** and upper shroud **30** are optionally supported by lugs on the inside of the vessel head.

[0025] The illustrative embodiment is an integral PWR in that it includes the internal steam generators **14**, which in general may have various geometric configurations such as helical, vertical, slanted, or so forth. For the purpose of redundancy, it is generally advantageous to have more than one steam generator, whose pipes or tubes are typically interleaved within the downcomer region **34** to facilitate thermal uniformity; however, it is contemplated to include only a single steam generator. Although the illustrative steam generators **14** are shown disposed or wrapped proximate to the shroud **30**, in general the steam generators may fill a substantial volume of the downcomer region **34**, and in some embodiments the steam generators may substantially fill the annular volume between the outer surface of the shroud **30** and the inside surface of the pressure vessel **10**. It is also contemplated for the internal steam generators or portions thereof to be disposed in whole or in part in the riser region **32**,above the shroud **30**, or

elsewhere within the pressure vessel **10**. On the other hand, in some embodiments the PWR may not be an integral PWR, that is, in some embodiments the illustrated internal steam generators may be omitted in favor of one or more external steam generators. Still further, the illustrative PWR is an example, and in other embodiments a boiling water reactor (BWR) or other reactor design may be employed, with either internal or external steam generators.

[0026] With reference to FIGURE 2, the upper internals section **24** in greater detail. In the illustrative design the upper internals section **24** provides support for control rod drives or drive mechanisms **40**, **42** and control rod guide frames **44** and is also the structure through which control rod drive power and control instrumentation signals pass. This allows the upper vessel **26** and integral steam generator **14** to be removed independently of the control rod drives and associated structure. However, a more integrated design is also contemplated, such as using a common section for both the CRDM support and the integral steam generator support.

[0027] With particular reference to the illustrative embodiment of FIGURE 2, the upper internals structure **24** includes an upper internals basket **46**, a CRDM support structure **48**, control rod guide frames **44**, and the control rod drive mechanisms **40**, **42** themselves. The upper internals basket **46** is suitably a welded structure that includes the mid-flange **29** and the support structure for the control rod guide frames **44**. In one suitable embodiment, the control rod guide frames **44** are separate 304L stainless steel welded structures that are bolted in place, the mid-flange **29** is a SA508 Gr 4N Cl 2 carbon steel forging, and the balance of the structure is 304L stainless steel. The CRDM support structure **48** includes support lattices for the control rod drives **40**, **42** and guide structure for the in-core instruments. All of these are suitably 304L stainless steel. The CRDM support structure **48** is bolted to the upper internals basket **46**. These are merely illustrative materials and construction, and other configurations and/or reactor-compatible materials are also contemplated.

[0028] The illustrative example of FIGURE 2 employs two types of control rod drives **40**, **42**: a hydraulic control rod drive type **42** that operates the shutdown rods which are either fully withdrawn or fully inserted into the core; and an electrical control rod drive type **40** that operates the gray rods which are inserted various amounts throughout the life of the core to control the nuclear reaction rate during normal reactor operation. The gray rods are also configured to scram, that is, to be rapidly inserted into the reactor core **12**, during certain emergency conditions. In other embodiments, it is contemplated to omit the shutdown rods entirely in which case the gray rods also provide shutdown operation.

[0029] With continuing reference to FIGURE 2 and with further reference to FIGURES 3-5, aspects of the shutdown rods are illustrated. The shutdown rods are suitably arranged in clusters mounted on spiders or the like that are all operated in single bank and are all moved by a single shutdown rod drive **42**. FIGURES 3-5 show only the single shutdown rod drive **42**, but not the spiders and individual shutdown rods. This configuration is cognizant of the fact that the shutdown rods are used in a binary "on/off" manner, and are either all wholly inserted into the reactor core **12** in order to shut down the reaction, or are all wholly withdrawn from the reactor core **12** in order to allow normal reactor operation.

[0030] With particular reference to FIGURE 3, the shutdown rod drive **42** includes a cylinder housing **50**, a cylinder cap **52**, a cylinder base plate **54**, and a connecting rod **56** providing connection to the shutdown rod lattice (not shown). The illustrative shutdown rod drive **42** of FIGURES 3-5 is a hydraulically actuated drive using reactor coolant inventory clean-up return fluid from high pressure injection pumps at approximately 500 °F (260 °C) and 1600 psi to hold the shutdown rod bank out of the reactor core **12**.

[0031] With particular reference to FIGURE 4, a sectional view of the piston region with the rod in the withdrawn position is shown. In an enlarged portion of FIGURE 4 a vent port **60** of the cylinder cap **52** is shown, together with a lift

piston **62**, piston rings **64** (which in some embodiments are metallic), a scram buffer **66**, and a buffer cocking spring **68**. The withdrawn position shown in FIGURE 4 corresponds to the shutdown control drive cylinder **42** being pressurized.

[0032] With particular reference to FIGURE 5, a sectional view of the piston region with the rod in the inserted position is shown. An enlarged portion of FIGURE 5 shows the lift piston **62**, the piston rings **64**, the scram buffer or scram buffer piston **66**, a rod guide bushing **70**, and rod sealing rings **72** (which in some embodiments are metallic). The cylinder base plate **54** is seen in the enlarged portion to include a pressure port or inlet port **74**. The inserted position shown in FIGURE 5 corresponds to the shutdown control drive cylinder **42** being unpressurized.

[0033] In some embodiments, the coolant is allowed to bleed past the piston and shaft seals **64**, **72** and becomes part of the inventory returned to the reactor vessel **10**. The shutdown rod drive cylinder **42** is mounted above the reactor core **12**. A hydraulic line (not shown) to actuate the cylinder **42** is routed through the flange **29** and instrument lines are routed through pressure tight conduit to common connectors that are also optionally used for the gray rod drives **40**. The extension rods that connect the control rod spiders to the shutdown rod lattice are optionally designed so that they will slide through the lattice so that a single stuck cluster will not prevent the other sets of control rods from dropping. Additionally, the extension rods are designed to be disengaged from the control rod spider so that the shutdown rods remain in the core when the upper internals **24** are removed. Disengagement and reengagement is done using remote tooling at during refueling operations.

[0034] During normal reactor operation, the shutdown rods are suspended completely out of the reactor core (that is, in the withdrawn position) by pressurization of the shutdown rod hydraulic cylinder **42**. For example, in one suitable embodiment coolant inventory clean-up return fluid from the high pressure injection pumps is supplied at 500°F (260 °C) and 1600 psi to the

underside of the lift cylinder piston **62**, via the inlet port **74** of the cylinder base **54**. In this example, the fluid present in the cylinder **50** above the piston **62** is supplied from the reactor vessel **10** through the cylinder cap vent port **60**, and is therefore at the reactor vessel conditions of 600 °F (315 °C) and 1500 psi, resulting in a net 100 psi pressure differential across the piston **62**. Piston sizing is selected such that the developed pressure differential is sufficient to support the specified load of the shutdown rods and supporting spiders and other associated components and lift the shutdown rod bank through the cylinder stroke to the top stop of the piston **62**.

[0035] In the event of a vessel-pressurized scram, the shutdown rod bank is abruptly released by ceasing the supply of pressurized coolant to the bottom side of the lift piston **62** and venting the supply line to atmospheric pressure. In the aforementioned example the vessel pressure at the top surface of the lift piston **62** is expected to create an initial 1500 psig pressure differential across the lift piston, which acts along with the influence of gravity to propel the translating assembly (including the lift piston **62**, scram buffer piston **66**, cocking spring **68**, connecting rod **56**, and shutdown rod lattice (not shown) downward toward the full insertion position illustrated in FIGURE 5. During the descent of the translating assembly, the force of the buffer cocking spring **68** holds the buffer piston **66** out of the bore of the lift piston **62**, preserving a fluid-filled buffer cavity between the two pistons **62**, **66**. When the bottom surface of the buffer piston **66** impacts the fixed base plate **54** of the cylinder assembly, the continued travel of the lift piston **62** expels the trapped fluid through controlled flow restrictions, thereby dissipating the kinetic energy of the translating assembly. Additionally, kinetic energy is dissipated through elastic deformation of the translating assembly components, especially the long, relatively slender, connecting rod **56**. Other kinetic energy dissipation mechanisms are also contemplated. When the fluid is expelled from the cavity, the lift piston **62** impacts the buffer piston **66**, bringing the translating assembly to rest.

[0036] With continuing reference to FIGURES 1 and 2 and with further reference to FIGURES 6-14, an illustrative embodiment of the gray rods and associated drive mechanisms **40** is described. As seen in FIGURE 6, in the illustrative embodiment there are two different gray rod configurations (Type 1 and Type 2). The gray rods **80** are arranged as gray rod clusters, which in turn are yoked together in groups of two or four and supported by connecting rods **82** as shown in FIGURE 6. The configuration Type 1 also includes a counterweight **84** in place of one connecting rod/cluster unit. More particularly, a yoke **86** connects two connecting rods **82** and the counterweight **84** to form a configuration of Type 1. A yoke **88** connects three connecting rods **84** to form a configuration of Type 2. The gray rod drives **40** are mounted above the reactor core **12**. FIGURE 7 shows a plan view of the locations of the gray rod drives **40** and of the shutdown rods lift cylinder **50**, respective to the CRDM support structure **48**. The shutdown rods lift cylinder **50** is centrally located. Four outboard gray rod drives **40**, each moving two rod configurations of Type 1 including yokes **86**, move simultaneously. Two inboard drives **40**, each moving four rod configurations of Type 2 including yokes **88**, move simultaneously. These different sets of drives **40** optionally move together or independently. Power and signal connections are suitably routed through a pressure tight conduit or in-core instrumentation guide **90** to connectors on the mid-flange **29** (not shown in FIGURE 7).

[0037] As with the shutdown rods, the extension rods that connect the control rod spiders to the rod lattice are optionally designed so that they will slide through the lattice so that a single stuck cluster will not prevent the other sets of control rods from dropping. Additionally, the extension rods are optionally designed to be disengaged from the control rod spider so that the gray rods can remain in the core when the upper internals are removed or be removed while the upper internals are on their support stand. Two suitable design styles for the gray rod control mechanism include the "magnetic jack" type and the "power screw" type. Of these, the power screw type is expected to provide more precise position control for the gray rod clusters, and

accordingly the illustrated embodiment employs the power screw type control mechanism.

[0038] With reference to FIGURE 8, in one illustrated embodiment the gray rod control mechanism **40** employs a ball nut lifting rod configuration. FIGURE 8 shows both the fully inserted state (left-side drawing) and fully withdrawn state (right-side drawing). The drawings of FIGURE 8 show the yoke **88** of the Type 2 configuration; for the Type 1 arrangement the yoke **88** is replaced by the yoke **86**. In the embodiment shown in FIGURE 8, a bottom stop/buffer assembly **100** is mounted on a reactor support **101**, optionally with additional lateral support provided for the electromagnet coil assembly. Lower and upper support tubes **102**, **104**, which mount to the top of the bottom stop **100**, provide the guidance for the lead screw/torque taker assembly. A ball nut/motor assembly **106** mounts on top of the upper support tube **104** and an electromagnet coil assembly **108** mounts to the top of the motor. Within the electromagnet coil assembly **108** resides a lifting rod-to-lead screw latching assembly **110** that (when latched) supports a lifting/connection rod assembly **112** (seen extended in the inserted state, i.e. left-side drawing).

[0039] A position indicator assembly is mounted to the support tubes **102**, **104** between the ball nut/motor assembly **106** and the bottom stop assembly **100**. In some embodiments, the position indicator is a string potentiometer suitably mounted below the latching assembly **110**, although other mounting locations are contemplated. The illustrated string potentiometer includes a tensioned spool **120** mounted on the support tube **102** and a "string" or cable or the like **122** having an end attached to the lifting/connection rod assembly **112** such that the string or cable **122** is drawn off the spool **120** against the tension as the lifting/connection rod assembly **112** (and, hence the attached gray rod clusters) move toward the reactor core **12** (not shown in FIGURE 8). When the motion is reversed, the tension in the tensioned spool **120** causes the string or cable **122** to roll back onto the spool **120**. A rotational sensor **124** measures the rotation of the tensioned spool **120** using an encoder that counts passage of fiducial markers or another rotational metric. The mounting

of the string potentiometer can be otherwise than that illustrated, so long as the tensioned spool **120** is mounted at a location that does not move with the gray rods and the string or cable **122** is secured to move with the gray rods. It is also contemplated to integrate the rotational sensor **124** with the tensioned spool **120**. The string potentiometer provides an electrical output signal consistent with the location of the connecting rod or other component **112** that moves with the gray control rod, thus providing positional information for the gray control rods within the reactor core **12**. The electrical position indication signal is conveyed out of the reactor vessel **10** through an electrical feedthrough (not shown), which can be made small and/or integrated with other electrical feedthroughs. The position indicator device is configured and calibrated for operation at reactor vessel temperature and radiation level.

[0040] With continuing reference to FIGURE 8 and with further reference to FIGURES 9-14, in the illustrated embodiment the translating assembly of the gray rod CRDM **40** includes three elements: a lead screw/torque taker assembly; a lifting rod/connecting rod assembly; and a latching system that operatively connects the lifting rod with the lead screw. FIGURE 9 shows the lead screw/torque taker assembly in perspective (left side) and sectional (right side) views. A motor assembly includes a stator housing **130** housing a stator **132** and a rotor **134**. An upper stator end plate **136** and a radial bearing **138** with adjustable spacer **140** complete an upper portion of the motor assembly, while a lower housing **142** and a thrust bearing **144** complete a lower portion of the motor assembly. A lower ball-nut assembly **150** disposed within the lower housing **142** is threaded to the rotor **134**, and an upper ball nut assembly **152** is also threaded to the rotor **134**. Both ball-nut assemblies **150**, **152** are coupled in threaded fashion with a lead screw **160** (shown in part in FIGURE 9). FIGURE 9 further shows portions of the lifting rod **112** and the upper support tube **104**.

[0041] With reference to FIGURE 10, the latching system is illustrated, including the lifting rod-to-lead screw latching assembly **110** and a portion of the electromagnet coil assembly **108**. Also shown in FIGURE 10 are an end

111 of the lifting rod 112 and a proximate end of the lead screw 160 terminating at or in the latching assembly 110. Latches 170 directly connect the top end 111 of the lifting rod 112 to the lead screw 160 for normal operation, and disconnect the lifting rod 112 during scram (see FIGURE 11). The bottom of the lifting rod 112 is threaded to the top of the connecting rod 82 (optionally by the intermediary yoke 86 or intermediary yoke 88) thereby creating a continuous lifting rod/connecting rod assembly. The bottom of the connecting rod 82 couples directly to the control rod spiders thereby attaching the control rods to the mechanism. Optionally, a magnet 113 is disposed proximate to the top 111 of the lifting rod 112 to provide a magnetic signal for a magnetically-based position indicator (see FIGURE 21). FIGURE 10 also shows a portion of the motor including portions of the motor housing 130, stator 132, and rotor 134, which is shown in full in FIGURE 9.

[0042] The latches 170 are housed in a latch housing 172 that includes a spring guide for a latch spring 174. Additional components of the illustrated latching system embodiment include an electromagnet housing 176 housing electromagnets 177 forming an electromagnet coil stack, and permanent magnets 178 on the latches 170. The lead screw 160 is threaded into a latching system base 179 of the latch housing 172. The latches 170 are arranged to pivot about pivot locations 180 to provide a failsafe scram due to downward rod load.

[0043] In this embodiment, the lead screw 160 is continuously supported by a ball nut motor assembly (best seen in FIGURE 9) which allows for very fine control of lead screw position and consequently very fine control of the position of the control rod assembly. In the illustrated embodiment, the motor (e.g., stator 132, rotor 134) is a synchronous motor in which the rotor 134 is a permanent magnet. This design has advantages such as compactness and simplicity; however, other motor configurations are also contemplated.

[0044] The lead screw 160 does not scram. Instead, during a scram the top end of the lifting rod 112 of the lifting rod/connection rod assembly is

disconnected from the lead screw **160** by the magnetically activated latching system (see FIGURE 11). When power is cut to the electromagnets **177** the failsafe latching system releases the lifting/connection rod assembly (and thus the control rod assembly) from the lead screw **160** thereby initiating a scram. A bottom stop and buffering system (not illustrated, but suitably similar to the bottom stop and buffering system of the illustrative shutdown rods described herein with reference to FIGURES 4 and 5) is incorporated into the base/buffer assembly to dissipate the kinetic energy at the end of the scram stroke and to set the rod bottom elevation. A torque taker (not shown) is attached to the lead screw **160** to react the motor torque thereby providing translation of the lead screw/control rod assembly.

[0045] The normal state, that is, the state prior to scram, is shown in FIGURES 9 and 10. FIGURE 9 illustrates the ball nut motor assembly and FIGURE 10 shows the latching system engaged for normal operation. As seen in FIGURE 10, the permanent magnets **178** on the latches **170** are magnetically attracted toward the powered electromagnets **177** thus pivoting the latches **170** about the pivot locations **180** and engaging the latches **170** with a mating region of the lifting rod **112**. Thus, the latches **170** are secured with the lifting rod **112** in the normal state shown in FIGURE 10. Further, the latching system base **179** is threaded to or otherwise secured with the lead screw **160**. Accordingly, in the normal state of FIGURE 10 the lifting rod **112** is secured with the lead screw **160** via the latching system, and so as the ball nut motor assembly shown in FIGURE 9 translates the lead screw **160** the lifting rod **112** is translated with the lead screw **160**.

[0046] Scram is described with reference to FIGURE 11, which shows the lifting rod **112**, and consequently the control rod assembly, during a scram. To initiate scram the power to the electromagnets **177** is cut, that is, turned off. This removes the attractive force on the permanent magnets **178** on the latches **170**, and the latch spring **174** extends to pivot the latches **170** about the pivot locations **180** and away from the mating region of the lifting rod **112**. This disengages the latches **170** from the lifting rod **112**, and the

lifting/connection rod assembly (and thus the control rod assembly) falls toward the reactor **12**. The lead screw **160** is seen in FIGURE 11 still at the previous withdrawal height (that is, the lead screw **160** is not scrammed), but power to the electromagnet coils **177** has been cut so that the magnetic field from the coils is removed.

[0047] As further shown in FIGURE 11, the pivoting of the latches **170** about the pivot locations **180** is stopped by impingement at a location **181** with the spring guide of the latch housing **172**.

[0048] With continuing reference to FIGURE 11 and further reference to FIGURES 12 and 13, to re-engage the mechanism after a scram, the lead screw **160** is driven to the fully inserted position via the ball nut motor (see again FIGURE 9). A lead screw on-bottom sensor is used to confirm lead screw full insertion. With particular reference to FIGURE 12, as the lead screw **160** nears the fully inserted position an angled camming surface **182** on the top **111** of the lifting rod **112**, which is scrammed to the bottom, will cam the latches **170** to their near full out position. With particular reference to FIGURE 13, when power is restored to the electromagnets **177**, the latches **170** will fully re-engage with the mating region of the lifting rod **112** so that the lifting/connection rod assembly is once again connected to the lead screw **160**. Normal operation can then resume as per FIGURE 10. To reiterate, FIGURE 12 shows the lead screw **160** being driven back down to the fully inserted position in preparation for re-engagement of the lifting rod **112**. Power to the electromagnet coils **177** is still cut and the latches **160** are still disengaged. The angled camming surfaces **182** on the top **111** of the lifting rod **112** are camming the latches **170** back into partial engagement with the top **111** of the lifting rod **112**. FIGURE 13 shows the lead screw **160** still on bottom but with the power restored to the electromagnet coils **177**. The restored magnet field has now re-engaged the latches **170** with the mating region of the lifting rod **112**.

[0049] FIGURE 9 diagrammatically shows a suitable embodiment of the ball nut/motor assembly **106**, including lower and upper ball nut assemblies **150**, **152**. In general, substantially any type of motor can be used, suitably configured for operation in the pressure vessel environment.

[0050] With reference to FIGURES 14 and 15, an illustrative embodiment is shown which employs a brushless DC electronically controlled (BLDC) motor **184** with lower ball nut assembly **185**. The assembly **184**, **185** is an illustrative embodiment of the ball nut/motor assembly **106**. With particular reference to FIGURE 14, the illustrative BLDC motor **184** includes a wound stator core assembly **186** disposed between a stator outer shell **187** and a stator inner shell **188** and secured by a stator upper housing **189** and stator lower housing **190**. A permanent magnet rotor **191** includes permanent magnets **192**. The BLDC motor **184** produces torque from interaction of magnetic flux of the rotor magnets **192** and the current carrying stator conductors of the stator core assembly **186**. The lower ball nut assembly **185** is analogous to the lower ball-nut assembly **150** of FIGURE 9; however, in the illustrative assembly of FIGURE 14 there is no upper ball-nut assembly corresponding to the upper ball nut assembly **152** of FIGURE 9. The assembly of FIGURE 14 also includes a radial bearing **193**, a thrust bearing **194** secured by a thrust bearing lock nut **195**, and a motor top cap **196**. An insulated and environmentally robust electrical connection to the motor is provided by a lead wire gland **197**. For example, some suitable insulated lead wire glands are available from Conax® Technologies (Buffalo, New York, USA). With particular reference to FIGURE 15, the BLDC motor **184** and lower ball-nut assembly **185** are illustrated in the context of the control rod drive mechanism (CRDM) of FIGURES 10-13. The illustrative CRDM of FIGURE 15 also includes the previously described electromagnet coil stack assembly **177**, lifting rod-to-lead screw latching assembly **110**, lead screw **160**, and lifting rod **112**. The ball-nut assembly **185** engages the lead screw **160** so that, as the motor **184** rotates the permanent magnet rotor **191** and the secured ball-nut assembly **185**, the lead screw **160** is driven linearly.

[0051] With returning reference to FIGURES 1 and 2, an advantage of the disclosed reactor design is that the middle section includes the internals support flange or "mid-flange" **29**. This section can be made relatively thin, and provides support for the control rod drive mechanism and guides for the in-core instrumentation. This section provides electrical and hydraulic inputs for the control rod drive mechanisms (CRDMs). A reactor coolant drain penetration (not illustrated) is optionally also incorporated in this section. This drain line, if incorporated, is optionally isolated by an internal valve whenever the reactor is pressurized to limit or eliminate its potential as a loss of coolant accident (LOCA) site.

[0052] The illustrated upper internals **24** including the CRDM do not include illustrated thermal insulation. However, it is contemplated to insulate these components using an insulation system capable of withstanding a design temperature of at least about 650 °F (343 °C). By using the insulation system, external cooling water will not be required although may optionally also be used. For example, cooling water can be supplied to the electrical devices to reduce the severity of the heat duty imposed by the operating environment. The insulation system facilitates locating the electrical CRDM within the pressure vessel, which reduces the overall height of the reactor vessel **10**, significantly reduces the number of penetrations into the reactor vessel **10**, and enables a complete reactor module to be shipped as a single unit. Another advantage is reduction of the overall height of the containment structure (not shown). Although the use of insulation is believed to be advantageous, other contemplated solutions include the use of water cooling and/or selecting materials capable of withstanding the high operating temperature without insulation.

[0053] The illustrative reactor embodiment is an integral pressurized water reactor (PWR) configuration. However, one or more of the disclosed techniques, apparatuses, or so forth are also expected to be suitably used in other types of nuclear reactor vessels, such as boiling water reactors (BWRs)

that can advantageously incorporate internal CRDM assemblies, efficient control rod position sensors, and so forth.

[0054] The CDRM configuration of FIGURES 2-15 provides two separate scram mechanisms: a hydraulic scram provided by the shutdown rods described with reference to FIGURES 3-5; and a magnetic latch scram mechanism described with reference to FIGURES 6-15 with the magnetic latch system described with particular reference to FIGURES 10-15. This advantageously provides redundant hydraulic and magnetic scram mechanisms thus reducing likelihood of a complete scram failure in the event of a loss of coolant accident (LOCA) or other safety-related event.

[0055] With reference to FIGURES 16-20, in another control rod system embodiment is described, which provides electromagnetic gray rod functionality and a hydraulic latch system providing scram functionality. Like the control rod system of FIGURES 6-15, the control rod system of FIGURES 16-20 allows for failsafe scram of the control rod cluster without scramming the lead screw.

[0056] With particular reference to FIGURE 16, the motor/ball nut assembly of FIGURE 15 is employed, such that a lead screw **200** is permanently engaged to the ball-nut assembly **185** which provides for axial translation of the lead screw **200** by driving the motor **184**. A control rod cluster (not shown in FIGURE 16) is connected to the lead screw **200** via a connecting rod or connecting rod assembly **204** and a latch assembly **206**. The lead screw **200** is substantially hollow, and the connecting rod assembly **204** fits coaxially inside the inner diameter of the lead screw **200** and is free to translate vertically within the lead screw **200**. The latch assembly **206**, with two spring loaded latches, is permanently attached to the top of the lead screw **200**. When the latches are engaged with the connecting rod **204** they couple the connecting rod **204** to the lead screw **200** and when the latches are disengaged they release the connecting rod **204** from the lead screw. In the illustrated embodiment, latch engagements and disengagements are

achieved by using a four-bar linkage cam system including two cam bars **208** and at least two (and, in the illustrated embodiment four) cam bar links **209** per cam bar **208**. The additional cam bar links add support for the cam bar. When the cam bars **208** move upward the cam bar links **209** of the four-bar linkage also cams the cam bars **208** inward so as to cause the latches to rotate into engagement with the connecting rod **204**. In the illustrated embodiment, a hydraulic lift assembly **210** is used to raise the cam bar assemblies **208**. In an alternative embodiment (not illustrated), an electric solenoid lift system is used to raise the cam bar assemblies. When a lift force is applied to the cam system, the upward and inwardly-cammed motion of the cam bars **208** rotates the latches into engagement thereby coupling the connecting rod **204** to the lead screw **200**. This causes the control rod cluster to follow lead screw motion. When the lift force is removed, the cam bars **208** swing down and are cammed outward by the cam bar links **209** of the four-bar linkage allowing the latches to rotate out of engagement with the connecting rod **204**. This de-couples the connecting rod **204** from the lead screw **200** which causes the control rod cluster to scram. During a scram, the lead screw **200** remains at its current hold position. After the scram event, the lead screw **200** is driven to the bottom of its stroke via the electric motor **202**. When the lift force is reapplied to the cam system via the hydraulic lift assembly **210**, the latches are re-engaged and the connecting rod is re-coupled to the lead screw **200**, and normal operation can resume. Still further, other latch drive modalities are contemplated, such as a pneumatic latch drive in which pneumatic pressure replaces hydraulic pressure in the illustrated lift assembly **210**.

[0057] With continuing reference to FIGURE 16, the lead screw **200** is arbitrarily depicted in a partially withdrawn position for illustration purposes. It can be seen in FIGURE 16 that the latching assembly **206** is attached to the top of the lead screw **200**. In FIGURE 16 the latches are engaged the connecting rod **204**, which is coupled to the lead screw, is also at the same partially withdrawn position as the lead screw **200**. The ball nut **185** and motor

184 are at the bottom of the control rod drive mechanism (CDRM), the latch cam bars 208 extend for the full length of mechanism stroke, and the hydraulic lift system 210 is located at the top of the mechanism. In some embodiments, the CRDM of FIGURES 16-20 is an integral CDRM in which the entire mechanism, including the electric motor 184 and ball nut 185, the latching system 206, and a position indicator (not shown in FIGURE 16), are located within the reactor pressure vessel 10 at full operating temperature and pressure conditions.

[0058] With reference to FIGURES 17 and 18, the lower end of the control rod drive mechanism (CRDM) including the latching assembly 206 is illustrated in additional detail. The latching assembly 206 includes a latch housing 212 and latches 214. The latch housing 212 provides a frame or support for pivot positions 216 (e.g., pivot pins or rods) about which the latches 214 can pivot. In FIGURE 16, the connecting rod 204 is withdrawn, that is, latches 214 of the latching assembly 206 are pivoted inwardly into engagement with mating region at an upper end215 of the connecting rod 204. In the illustrative embodiment, the top of the connecting rod 204 includes the optional magnet 113 to provide a magnetic signal for a magnetically-based position indicator (see FIGURE 21). FIGURE 17 shows the connecting rod 204 scrammed, that is, latches 214 are pivoted outwardly so as to be disengaged from the mating region at the upper end 215 of the connecting rod 204 so that the connecting rod 204 is mechanically decoupled from the lead screw 200 and is free to move within the inner diameter of the lead screw 200. Thus decoupled as shown in FIGURE 17, the connecting rod 204 (and hence the control rod bundle or bundles secured to the connecting rod 204) fall toward the reactor core 12 under the influence of gravity. In both FIGURES 16 and 17, the lead screw 200 is again shown slightly withdrawn to an arbitrarily position –as seen in FIGURE 17 the lead screw 200 does not scram.

[0059] Referring particularly to FIGURE 17, the two cam bars 208 are shown raised at their maximum inward (that is, engaged) position. The inward

movement of the cam bars **208** caused by the cam bar links **209** rotates or pivots the latches **214** inward into full engagement with the mating region at the upper end **215** of the connecting rod **204**. When moved inward to full engagement, the cam bars **208** are supported along their full length by a cam bar housing cover **222** which provides a positive stop for the inward movement of the cam bars **208**. The cam bar housing cover **222** is slotted down its center for the full mechanism stroke length to allow latch fingers **224** or other outward extensions of the latches **214** to pass through the cam bar housing cover **222** and contact the cam bars **208** at any withdrawal position of the lead screw **200**.

[0060] In the illustrative embodiment, there are two latches **214** and two cam bars **208**, one per latch. However, other numbers of latches and cam bars are contemplated – as another example, there can be four latches and four corresponding cam bars spaced at 90° intervals around the central axis of the lead screw **200**/connecting rod **204**. The illustrated two cam bars **208** drive a corresponding two latches **214** in a two-fold rotationally symmetric arrangement respective to the central axis of the lead screw **200**/connecting rod **204**. Again, more generally, it is contemplated for the number of cam bars/latches to be greater than two, with the number of cam bars/latches being selected and arranged to provide balanced latching support for the connecting rod **204**.

[0061] The lower portions of FIGURES 17 and 18 also show an upper portion of the motor **184**, whose details are described with reference to FIGURE 14 herein. Again, the illustrative motor **184** is merely an illustrative example, and various types of motors can be employed, such as the illustrative brushless DC electronically controlled (BLDC) motor **184** with a wound stator core and a permanent magnet rotor which produces torque from interaction of magnetic flux and the current carrying stator conductors, or a variable reluctance stepper motor (VRS) having a wound stator core and a laminated steel rotor which produces torque from the variation in reluctance as a function of rotor position, or a hybrid stepper motor (HBS) which is a

combination of the BLDC and VRS types and utilizes permanent magnets in the rotor and a reluctance component to produce torque, or so forth. In some embodiments it is contemplated to omit the separate the ball nut assemblies and instead or additionally provide engagement with the lead screw directly via the rotor by forming thread engagements on an inner diameter surface of the rotor. Additionally, a torque taker (not shown) is provided to prevent rotation of the lead screw **200** responsive to operation of the motor **184**. In some suitable embodiments, the cam bar housing cover **222** includes guide features (not shown) that engage the latch housing **212** to prevent the latch housing **212** from rotating and thus serve as a torque taker to prevent rotation of the lead screw **200** responsive to operation of the ball nut motor **202**. In this arrangement, the lead screw **200** is suitably secured together with a bottom portion **226** of the latch housing **212** so that preventing rotation of the latch housing **212** also prevents rotation of the lead screw **200**.

[0062] Again with particular reference to FIGURE 17, the cam bars **208**, when rotated inward, provide a positive full stroke track to guide the engaged latches **214** via camming of the latch fingers **224** against the cam bars **220** as the translating assembly (including the lead screw **200**, latch housing **212** and latches **214**, and latched connecting rod **204**) is withdrawn (i.e., moved upward) or inserted (i.e., moved downward). The hydraulic lifting of the cam bars **208** instigates a four-bar linkage action via cam bar links **209** that connect the cam bars **208** with a cam bar support housing **232**. Each cam bar link **209** is pivotally pinned to the cam bar support housing **232** via a pivot location **234** and to the cam bar **208** by a pivot location **235**. In this way, two cam bar links **209** together with the portion of the cam bar support housing **232** between the pivot locations **234** of the cam bar links and the portion of the cam bar **208** between the pivot locations **235** of the cam bar links together define a four-bar linkage. Optionally, more than two cam bar links **209** per cam bar **208** can be provided – in the illustrative example four cam bar links **209** per cam bar **208** are provided (see FIGURE 16). Hydraulic lifting of the cam bars **208** causes the cam bar links **209** to pivot upward about the pivot

locations **234** and thus force the lifting cam bars **208** inward via the pivot locations **235**. When the cam bars **208** are moved to their full inward position, the cam bar links **209** are closest to, but below, horizontal, e.g. at a minimum angle of 20° from the horizontal in some contemplated embodiments, which reduces the likelihood that the four-bar linkage may jam in a horizontal null position.

[0063] With particular reference now to FIGURE 18, the cam bars **208** are shown lowered at their maximum outward position. Again said briefly, hydraulic lowering of the cam bars **208** (or, gravitational, spring-biased, and/or other lowering of the cam bars **208** responsive to removal of the hydraulic lifting force) causes the cam bar links **209** to pivot downward about the pivot locations **234** and thus force the lifting cam bars **208** outward by a four-bar linkage action. The outward movement of the cam bars **208** allows the latches **214** to freely rotate or pivot outward about the pivot locations **216** and disengage from the connecting rod **204** to initiate scram of the connecting rod **204** and hence of the control rods connected with the connecting rod **204**. The scram action is failsafe in that the weight of the connecting rod **204**, with the assist of latch springs **240**, disengages the latches **214**. More particularly, the latch springs **240** are compressively held between the latch housing **212** and the upper portions of the latches **214** (above the pivot positions **216)** so that they bias the upper portions of the latches **214** inward and consequently bias outward the lower portions of the latches **214** (below the pivot positions **216**, i.e. including the latch fingers **224**).

[0064] When moved outward to full disengagement, the cam bars **208** are supported along their full length by the cam bar support housing **232** which provides a positive stop for their outward movement. When the cam bars **208** are moved to their full outward position, the cam bar links **209** are closest to, but not exactly, vertical, for example at a minimum angle of 20° from the vertical in some embodiments, which reduces the likelihood that the four-bar linkage may jam in a vertical null position.

[0065] With reference to FIGURES 19 and 20, the upper end of the control rod drive mechanism (CRDM) including the hydraulic lift system **210** is illustrated in additional detail. The hydraulic lift system **210** includes a hydraulic cylinder **250** and hydraulic piston **252**. Cam bar hangers **254** are coupled with the top of the piston **252**, and connection links **256** extend downward from the cam bar hangers **254** to the upper portions of the cam bars **208**. During normal operation (FIGURE 19) the hydraulic cylinder **250** is pressurized so as to raise the piston **252** and so raise the cam bars **208** via the linkages **254**, **256**. This causes the latches **214** to engage with the upper end **215** of the connecting rod **204**, as described herein with reference to FIGURE 17. During scram (FIGURE 20), the hydraulic cylinder **250** is depressurized so that the piston **252**, linkages, **254**, **256**, and cam bars **208** fall under the force of gravity. This causes the latches **214** to disengage from the connecting rod **204**, as described herein with reference to FIGURE 18. In the hydraulic lift system illustrated in FIGURES 19 and 20, the scram is made failsafe by inclusion of a scram assist spring **260** that spring-biases the piston **252** downward by compression of the scram assist spring **260** between the piston **252** and a hydraulic assembly cap **262**.

[0066] In FIGURES 19 and 20, the lead screw **200** is shown fully withdrawn for illustration purposes, so that the latch system is also visible in the view of FIGURES 19 and 20. However, the operation of the hydraulic lift system **210** as described with reference to FIGURES 19 and 20 is applicable for any position of the lead screw **200**.

[0067] With particular reference to FIGURE 19, as was described previously with reference to FIGURE 17, in the normal (latched) state the cam bars **208** are raised and, due to action of the cam bar links **209**, are at their maximum inward position. The inward movement of the cam bars **208** rotates or pivots the latches **214** into full engagement with the top end **215** of the connecting rod **204**. Also, when moved inward to full engagement the cam bars **208** are supported along their full length by the cam bar housing cover **222** which provides a positive stop for their inward movement.

[0068] With continuing reference to FIGURE 19, in the engaged condition the hydraulic piston **252** is in the fully raised position due to pressurization of the hydraulic cylinder **250**. As the piston is raised the cam bar hanger **254** is lifted by the piston **252** and pulls upward on the pair of connection links **256** which in turn lift the cam bars **208**. The piston **252** also lifts against the downward force produced by the scram assist spring **260**. In some contemplated embodiments, the hydraulic piston lift assembly operates at a differential pressure of only 5.5 psi, although design for higher differential pressure operation is also contemplated.

[0069] With particular reference to FIGURE 20, as was described previously with reference to FIGURE 18, in the scrammed (unlatched) state the cam bars **208** are lowered and, due to the four-bar linkage action of the cam bar links **209**, are at their maximum outward position. The outward movement of the cam bars **208** allows the latches **214** to freely pivot or rotate and disengage from the connecting rod **204**. In illustrative FIGURE 20, the connecting rod **204** has scrammed out of view to the fully inserted position, and hence the connecting rod **204** is not shown in FIGURE 20. When moved outward to full disengagement, the cam bars **208** are supported along their full length by the cam bar support housing **232** which provides a positive stop for their outward movement.

[0070] With continuing reference to FIGURE 20, in order to scram the pressure in the hydraulic cylinder **250** at the bottom side of the piston **252** is evacuated to allow the piston **252** to lower. In a suitable approach, the depressurization is accomplished by a double-acting valve (not shown) that simultaneously cuts the supply pressure to the piston **252** while evacuating the piston cavity to the reactor environment. If the valve fails, it fails in an open state to the dump side for scram reliability. A large flow area valve is optionally employed to provide fast evacuation of the (typically small-volume) piston cavity. Once the pressure is dumped, the combined weight of the cam bars **208**, the linkages **254**, **256**, and the piston **252** gravitationally drive lowering of the cam bars **208** and resultant disengagement of the latches **214**.

Optionally, as in the illustrated embodiment the scram assist spring **260** is provided in or with the hydraulic lift assembly to assist in lowering the pistion **252** and cam bars **208**. The scram action is preferably also failsafe in that the connecting rod weight, with the assist of the latch springs, disengages the latches. Camming action by the cam bar links **209** also pushes the cam bars **208** outward toward disengagement.

[0071] Reengagement of the latch assembly **206** with the connecting rod **204** after a scram can be performed similarly to the reengagement process described with particular reference to FIGURES 12 and 13 for the embodiment of FIGURES 6-15. The electric motor **184** is driven to move the latching assembly **206** and lead screw **200** (which, again, are secured together) downward toward the top **215** of the scrammed connecting rod **204**. The hydraulic cylinder **250** remains depressurized and the latches **214** remain in the disengaged position due to bias of the latch springs **240**, as shown in FIGURE 18. Thus, the latches **214** can be driven downward by the motor **184** to align with the mating region at the upper end **215** of the connecting rod **204**. In the illustrated embodiment, the magnet **113** disposed at or near the top **215** of the connecting rod **204** is magnetically sensed by a position indicator (not shown) in the latching assembly **206** in order to detect when the latches **214** are aligned with the mating region at the upper end **215** of the connecting rod **204**. Once the latches **214** are aligned with the mating region at the upper end **215** of the connecting rod **204**, the hydraulic cylinder **250** is re-pressurized to lift the hydraulic piston **252** and thus raise the cam bars **208** and reengage the latches **214**. Thereafter, the electric motor **184** can be operated to drive the lead screw **200** and re-latched connecting rod **204** upward to a desired operational position.

[0072] In an alternative embodiment, the hydraulic lift system **210** described with illustrative reference to FIGURES 19 and 20 can be replaced by an electric solenoid lift assembly, for example suitably located at the top of the control rod drive mechanism (CRDM) in place of the illustrative hydraulic lift assembly **210**. Such an electric solenoid lift assembly can be suitably

connected with the illustrative four-bar linkage latch cam system, and the latch assembly **206** functions as described herein. In this alternative embodiment, instead of applying pressure to the hydraulic piston **252** to provide the lifting force for engaging the cam bar assemblies, the lifting force is provided by applying electrical power to the solenoid. When electric power is cut the lifting force is immediately lost, the cam bars disengage the latches and the control rod cluster scrams as described herein.

[0073] With reference back to FIGURE 17 and with further reference to FIGURE 21, a section **S** indicated in FIGURE 17 is shown in FIGURE 21. The section **S** passes through a coupling between each cam bar **208** and one of its coupling cam bar links **209**, and through the finger **224** of each latch **214**, and through the position sensor magnet **113**. The sectional view **S** shown in FIGURE 21 includes the cam bar support housing **232** and an supporting cam housing assembly **232a**, and the latch housing **212**, and the top **215** of the connecting rod **204** with sectioning through the position sensor magnet **113**. The sectional view **S** further includes sectioning through the two cam bars **208** and their latch fingers **224**, and shows cam links **209** and their pivot locations **234** connecting with the cam bar support housing **232**, with sectioning through their pivot locations **235** connecting with the latch housing **212**. As seen in FIGURE 21, the pivot locations **234**, **235** are suitably embodied by pins. The sectional view **S** of FIGURE 21 also shows an illustrative magnetic position indicator assembly **270** that senses the magnet **113** in the top end **215** of the connecting rod **204** based on magnetic coupling between the indicator assembly **270** and the magnet **113**.

[0074] As already mentioned, the connecting rod **204** is connected at its lower end with a control rod bundle. Optionally, this connection is via one or more intermediate linkages, for example the illustrative yokes **86**, **88** shown in FIGURE 6.

[0075] With reference to FIGURES 22 and 23, the nuclear reactor typically includes an array or other plurality of control rod clusters operated by

corresponding control rod drive mechanisms supported by a suitable support frame **274** (for example, as shown in greater detail in FIGURE 2). In some embodiments, the electric motor **184** is the bulkiest component of the CDRM. In the illustrative array shown in FIGURES 22 and 23, the bulky motors **184** are accommodated in a compact array by vertically staggering the positions of the motors **184** so that the motors **184** of any two adjacent CRDM are not at the same vertical level or height. This enables a more compact array as compared with conventional arrangements in which all the motors are at the same vertical level or height.

[0076] The CRDM embodiments described with reference to FIGURES 6-21 advantageously provide both "grey rod" incremental control capability and also provide an efficient scram capability and hence can perform the task normally allocated to dedicated shutdown rods (e.g., as described herein with reference to FIGURES 3-5). Accordingly, it is contemplated to omit dedicated shutdown rods and instead rely wholly on control rods of embodiments such as those of FIGURES 6-21, for example arranged as shown in FIGURES 22 and 23. In a variant embodiment, to provide further redundancy in a LOCA or other emergency event, it is contemplated to employ a configuration including: (i) no dedicated shutdown rods; (ii) a first set of control rods with hydraulic lift as described herein with reference to FIGURES 16-21 so that in an emergency the rods perform the shutdown function via a hydraulic mechanism; and (iii) a second set of control rods with configured to perform the shutdown function via an electromagnetic mechanism. The latter set (iii) can be embodied, for example, by control rods conforming with the embodiment described herein with reference to FIGURES 6-15, or alternatively by control rods conforming with the embodiment described herein with reference to FIGURES 16-21 but with the hydraulic lift system **210** replaced by a solenoidal lift system. Such an arrangement advantageously uses (or can use) all available control rods for reactivity control while also providing a two-fold redundant (hydraulic and electromagnetic) safety system.

[0077] With reference back to the CRDM embodiments of FIGURES 6-20, an advantage of employing a latch to decouple the connecting rod **204** from the lead screw **200** (and, hence, to decouple the connecting rod **204** from the CRDM) is that the CRDM can be configured for removal of the connecting rod **204** through the CRDM without first removing the CRDM. To provide this capability, the CRDM is constructed with a hollow central region providing a pass-through by which the connecting rod **204**, once unlatched from the lead screw **200**, may pass. A cylindrical opening **280** (see FIGURES 18 and 20) through the latch assembly is made large enough for the connecting rod **204** to pass through when the latches **214** are open. In the embodiment of FIGURES 6-15, such an opening can be provided by replacing the centrally positioned latch spring **174** with a side-positioned biasing mechanism similar to the latch springs **240** of the embodiment of FIGURES 16-21. For the embodiment of FIGURES 16-21, a cylindrical opening **282** is also provided through the hydraulic lift system **210** (see FIGURES 19 and 20). Both openings **280**, **282** are made large enough for the connecting rod **204** to pass through when the latches **214** are open. Regarding the latter opening **282**, the scram assist spring **260** is suitably an annular spring providing for the opening **282**, and the piston **252** is also suitably made hollow with the requisite inner diameter. In the case of an alternative lifting mechanism, such as a solenoidal lift, the solenoid is suitably hollow.

[0078] With reference to FIGURES 24 and 25, for the connecting rod **204** to be removable through the CRDM it should be detachably connected with the spider or other mechanical control rod structure in such a way that (i) it can be detached from the spider from above the CRDM and (ii) so that the outer diameter of the connecting rod **204** at the detachable connection is not so large so as to prevent withdrawal of the lower end of the connecting rod **204** through the openings **280**, **282**. FIGURES 24 and 25 show one suitable detachable connection, in which a low-profile "J-groove" couples the connecting rod **204** with the control rod bundle. In this illustrative detachable connection, one or more inverted "J" shaped grooves **300** are formed in the

lower end of the connecting rod **204**. Since these grooves are recessed into the connecting rod **204**, the J-grooves **300** do not increase the outer diameter of the connecting rod **204** at the lower end. A biasing spring **302** is terminated at the end proximate to the connecting rod **204** by a spring guide/capture element **304**, and the elements **302**, **304** are disposed inside a generally cylindrical rod cluster threaded cap **306** that secures to the top of a rod cluster **310**. The cluster cap **306** includes mating tabs **312** that are sized and positioned to slide into the inverted J-shaped grooves **300** of the connecting rod **204**. To establish the coupling, the long vertical portions of the inverted J-shaped grooves **300** are aligned with the mating tabs **312** of the cluster cap **306**, and the connecting rod **204** is then pushed downward against the compressive force of the spring **302** such that the tabs **312** enter the long vertical portions of the grooves **300**. When the connecting rod **204** is pushed down far enough for the tabs **312** to reach the horizontal portions of the inverted J-shaped grooves **300**, the connecting rod is rotated by a rotation **314** (which is clockwise in FIGURES 24 and 25) until the tabs **312** align with the short vertical portions of the inverted J-shaped grooves **300**. At that point, removal of the downward force allows the upward spring force generated by the spring **302** to push the connecting rod **204** upward in order to lock the tabs **312** into the short vertical portions of the inverted J-shaped grooves **300**. The process is reversed to decouple the connecting rod **204** from the rod cluster **310**. After removal, the spring **302** and guide/capture element **304** are retained at the rod cluster **310** by the cluster cap **306**.

[0079] Thus, the coupling/decoupling of the connecting rod **204** with the rod cluster **310** advantageously can be performed with the latches **214** disengaged, so that the connecting rod **204** can be installed or removed with the CDRM in place. This is made possible because the lead screw **200** and the connecting rod **204** are not directly connected together, but rather are coupled by the latch assembly **206**. When the latches **214** are disengaged, the connecting rod **204** can move freely inside the substantially hollow lead screw **200**, and if the hydraulic piston **252** (or hollow solenoid, in the case of

an electromagnetic lifting mechanism) is also made substantially hollow and the hydraulic cylinder **250** is annular with a sufficiently large inner diameter, then the connecting rod **204** can also pass through the hydraulic lift assembly **210**. Thus, installation of the connecting rod **204** amounts to inserting the connecting rod **204** into the opening of the CDRM and pushing it down until it presses against the spring **302** (see FIGURES 24 and 25) and then rotating the connecting rod **204** as per the illustrated rotation **314** and releasing the connecting rod **204** so that the force of the spring **302** completes locking of the coupling. To remove the connecting rod **204**, the process is reversed.

[0080] The preferred embodiments have been illustrated and described. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS:

1. A control rod mechanism for use in a nuclear reactor, the control rod mechanism comprising:

at least one control rod configured for insertion in a reactor core to absorb neutrons;

a hollow lead screw;

a motor operatively coupled with the hollow lead screw to drive the hollow lead screw linearly toward or away from the reactor core;

a connecting rod connected with the at least one control rod and disposed partially inside the hollow lead screw;

a latch assembly having latches that when closed operatively connect the connecting rod and the lead screw so that when the latches are closed the connecting rod and the at least one control rod move together with the lead screw when the lead screw is driven by the motor; and

a release mechanism configured to cause the latches of the latch assembly to open responsive to a scram condition to detach the connecting rod from the lead screw such that the connecting rod and the at least one control rod scram but the lead screw remains operatively coupled with the motor and does not scram.

2. The control rod mechanism as set forth in claim **1**, wherein the at least one control rod comprises a plurality of control rods connected with the connecting rod via at least one of a spider and a yoke.

3. The control rod mechanism as set forth in claim **1**, wherein the release mechanism is hydraulically driven and opens responsive to removal of hydraulic pressure.

4. The control rod mechanism as set forth in claim **1**, wherein the latch assembly and the lead screw are secured together such that the latch

assembly including the latches moves together with the lead screw as the motor drives the lead screw linearly toward or away from the reactor core.

5. The control rod mechanism as set forth in claim **4**, wherein the release mechanism comprises:

a lifting assembly;

elongate members arranged parallel with the lead screw and configured to be lifted by the lifting assembly; and

a mechanical linkage configured to cause the elongate members to engage with and close the latches of the latching assembly when the cam bars are lifted by the lifting assembly.

6. The control rod mechanism as set forth in claim **5**, wherein the elongate members have elongation sufficient to engage with and close the latches of the latching assembly for any position of the lead screw obtainable using the motor.

7. The control rod mechanism as set forth in claim **5**, wherein the mechanical linkage comprises at least one four-bar linkage.

8. A control rod drive mechanism (CRDM) comprising:

a lead screw;

a motor threadedly coupled with the lead screw to linearly drive the lead screw in an insertion direction or an opposite withdrawal direction;

a latch assembly secured with the lead screw and configured to (i) latch to a connecting rod and to (ii) unlatch from the connecting rod, the connecting rod being free to move in the insertion direction when unlatched; and

a release mechanism configured to selectively unlatch the latch assembly from the connecting rod.

9. The CRDM as set forth in claim **8**, wherein the lead screw is hollow and a portion of the connecting rod is disposed inside the hollow lead screw.

10. The CRDM as set forth in claim **9**, wherein the CRDM is configured to allow the connecting rod to be removed from the CRDM by (i) operating the release mechanism to unlatch the latch assembly from the connecting rod and (ii) withdrawing the connecting rod in the withdrawal direction through the CRDM.

11. The CRDM as set forth in claim **10**, wherein the latch assembly is hollow to allow the connecting rod to be withdrawn in the withdrawal direction through the latch assembly.

12. The CRDM as set forth in claim **8**, wherein the release mechanism is a hydraulic mechanism that latches the latch assembly when pressurized and unlatches the latch assembly when depressurized.

13. The CRDM as set forth in claim **8**, wherein the release mechanism comprises:

elongate members arranged parallel with the lead screw; and

mechanical linkages arranged to cause the elongate members to engage with and latch the latch assembly responsive to an applied force.

14. The CRDM as set forth in claim **13**, wherein the release mechanism further comprises:

a lift mechanism selectively operable to provide the applied force.

15. The CRDM as set forth in claim **14**, wherein the lift mechanism is selected from a group consisting of (i) a hydraulic piston and (ii) an electric solenoid.

16. The CRDM as set forth in claim 13, wherein the mechanical linkages comprise at least one four-bar linkage.

17. The CRDM as set forth in claim 8, further comprising:

at least one ball nut assembly providing the threaded coupling between the motor and the lead screw.

18. A control rod drive mechanism (CRDM) comprising:

a plurality of CRDM units each comprising a lead screw and a motor configured to drive the lead screw; and

a support mounting the plurality of CRDM units in a nuclear reactor vessel with the motors of adjacent CRDM units arranged at different heights respective to a reactor core of the nuclear reactor vessel;

wherein each CRDM unit is connected with one or more control rods such that the motor driving the lead screw moves the connected one or more control rods toward, away from, or within the reactor core.

19. The CRDM as set forth in claim 18, wherein each CRDM unit further comprises:

a latch assembly secured with the lead screw and configured to latch to connect the connecting rod and the lead screw; and

a release mechanism configured to unlatch the latch assembly to disconnect the connecting rod and the lead screw responsive to a scram condition.

20. The CRDM as set forth in claim 18, wherein the lead screw and motor of each CRDM unit and the support are all disposed entirely within the nuclear reactor vessel.

21. A control rod drive mechanism (CRDM) comprising:

a lead screw;

a drive assembly configured to linearly drive the lead screw in an insertion or opposite withdrawal direction, the drive assembly including a motor and at least one non-separable ball nut coupling with the lead screw; and

a latch assembly connected with the lead screw and having (i) a latched state in which the latch assembly is latched to a connecting rod and (ii) an unlatched state in which the latch assembly is not latched to the connecting rod.

22. The CRDM as set forth in claim 21, further comprising:

a latch closing mechanism selectively operable to latch the latch assembly to the connecting rod.

23. The CRDM as set forth in claim 22, wherein the latch closing mechanism includes one of (i) a hydraulic piston and (ii) an electric solenoid.

24. The CRDM as set forth in claim 22, wherein the latch closing mechanism includes a mechanical linkage having a length parallel with the lead screw that is at least as long as a stroke of the drive assembly.

25. The CRDM as set forth in claim 24, wherein the mechanical linkage comprises a four-bar mechanical linkage.

26. A control rod mechanism for use in a nuclear reactor, the control rod mechanism comprising:

at least one control rod;

a connecting rod connected with the at least one control rod at a lower end of the connecting rod; and

a control rod drive mechanism (CRDM) including:

a latch assembly having (i) a latched state in which the latch assembly is latched to an upper end of the connecting rod

and (ii) an unlatched state in which the latch assembly is not latched to the upper end of the connecting rod, and

a linear drive mechanism configured to drive the latch assembly linearly toward or away from a nuclear reactor core.

27. The control rod mechanism as set forth in claim **26**, wherein the CRDM is configured to allow the connecting rod to be removed by placing the latch assembly in the unlatched state and drawing the connecting rod away from the nuclear reactor core through the CRDM.

28. The control rod mechanism as set forth in claim **27**, wherein the CRDM is hollow to allow drawing the connecting rod away from the nuclear reactor core through the CRDM.

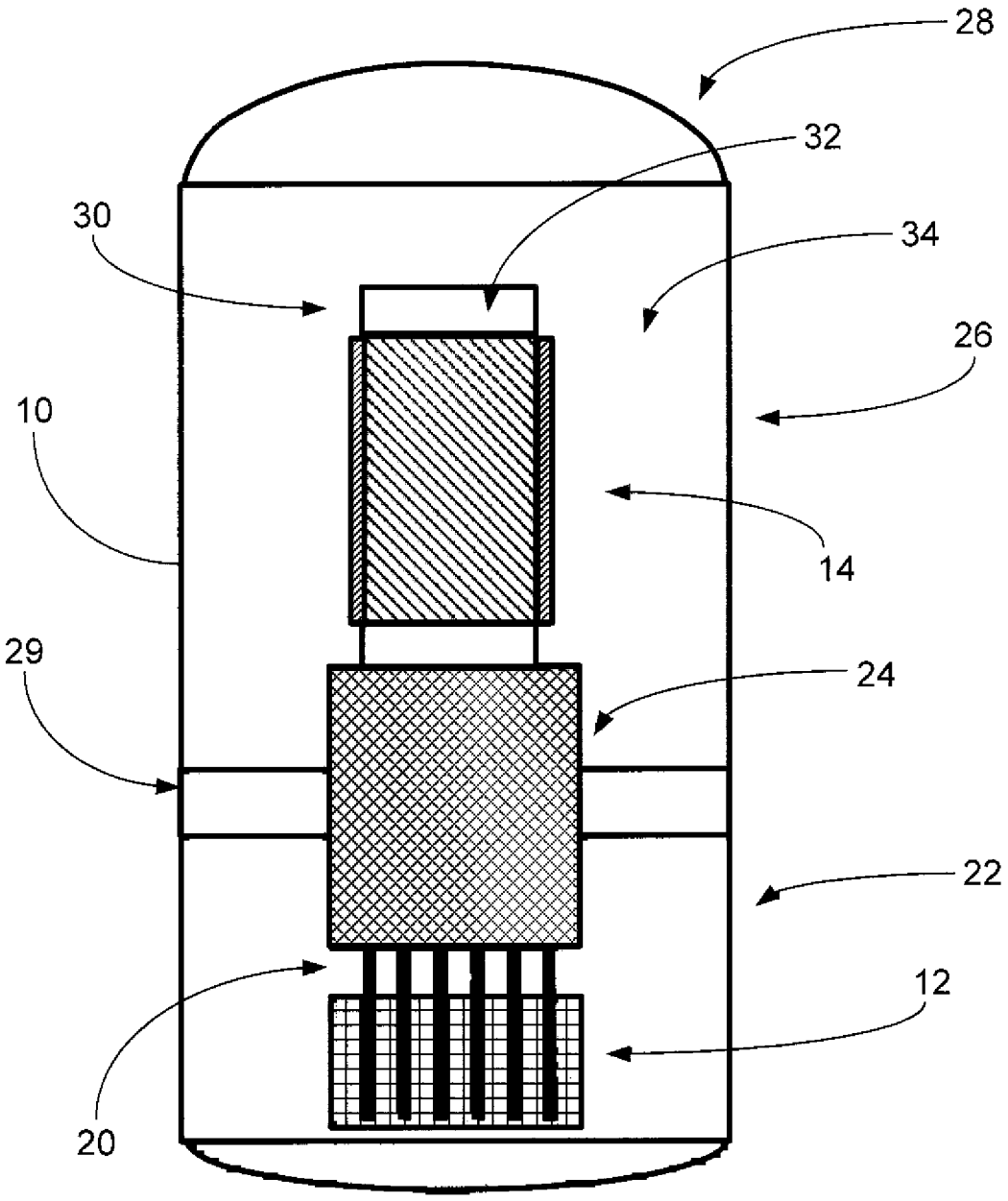


FIG. 1

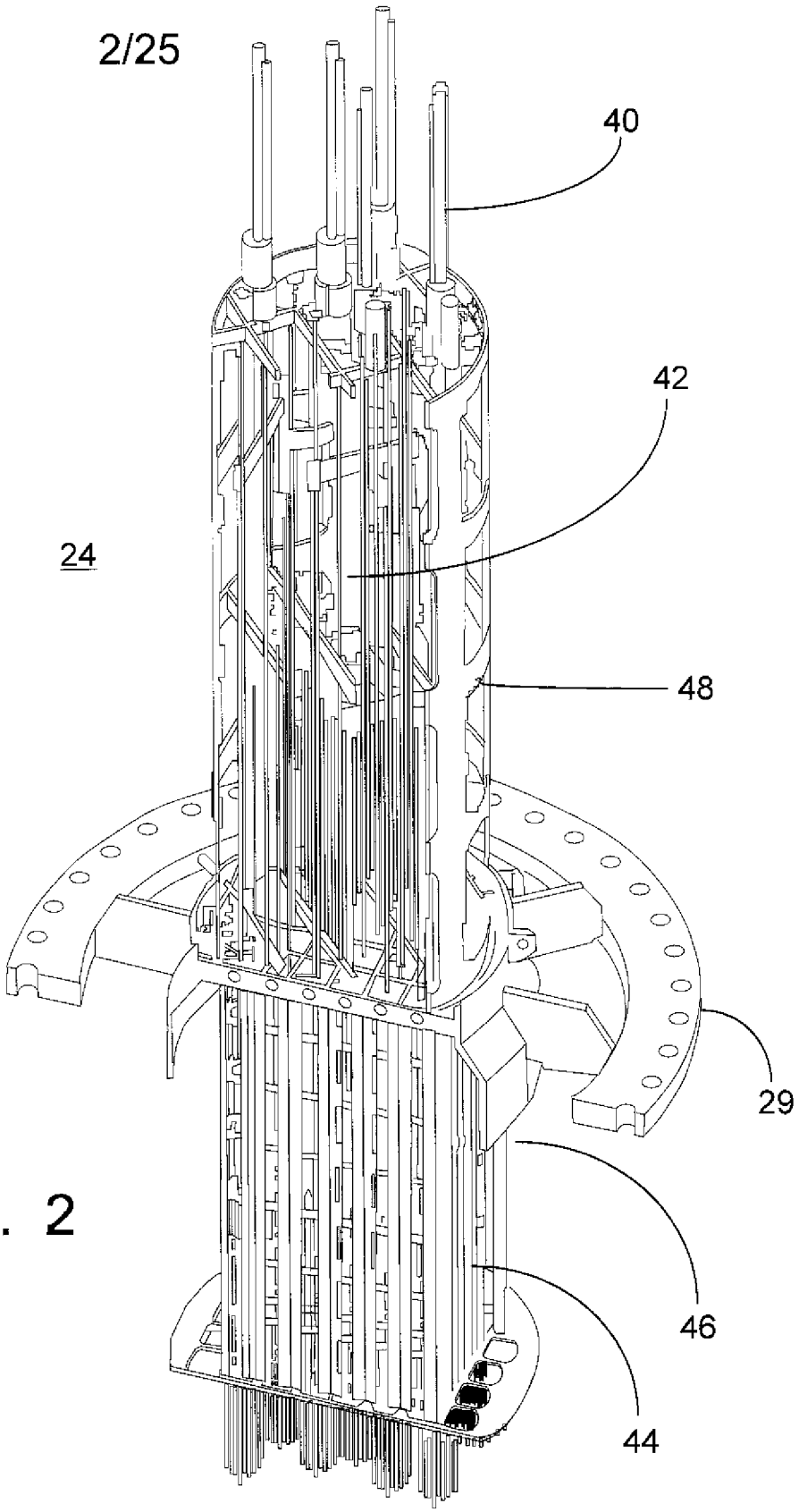


FIG. 2

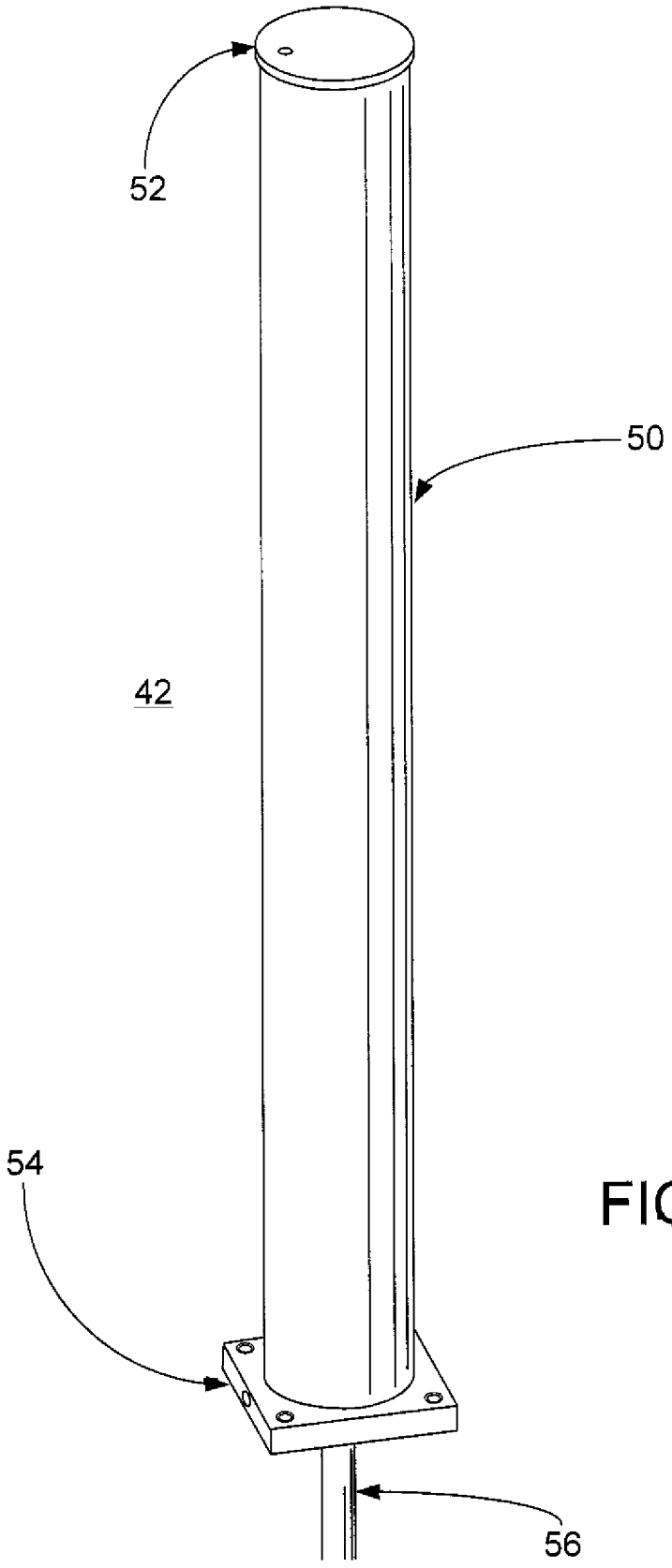


FIG. 3

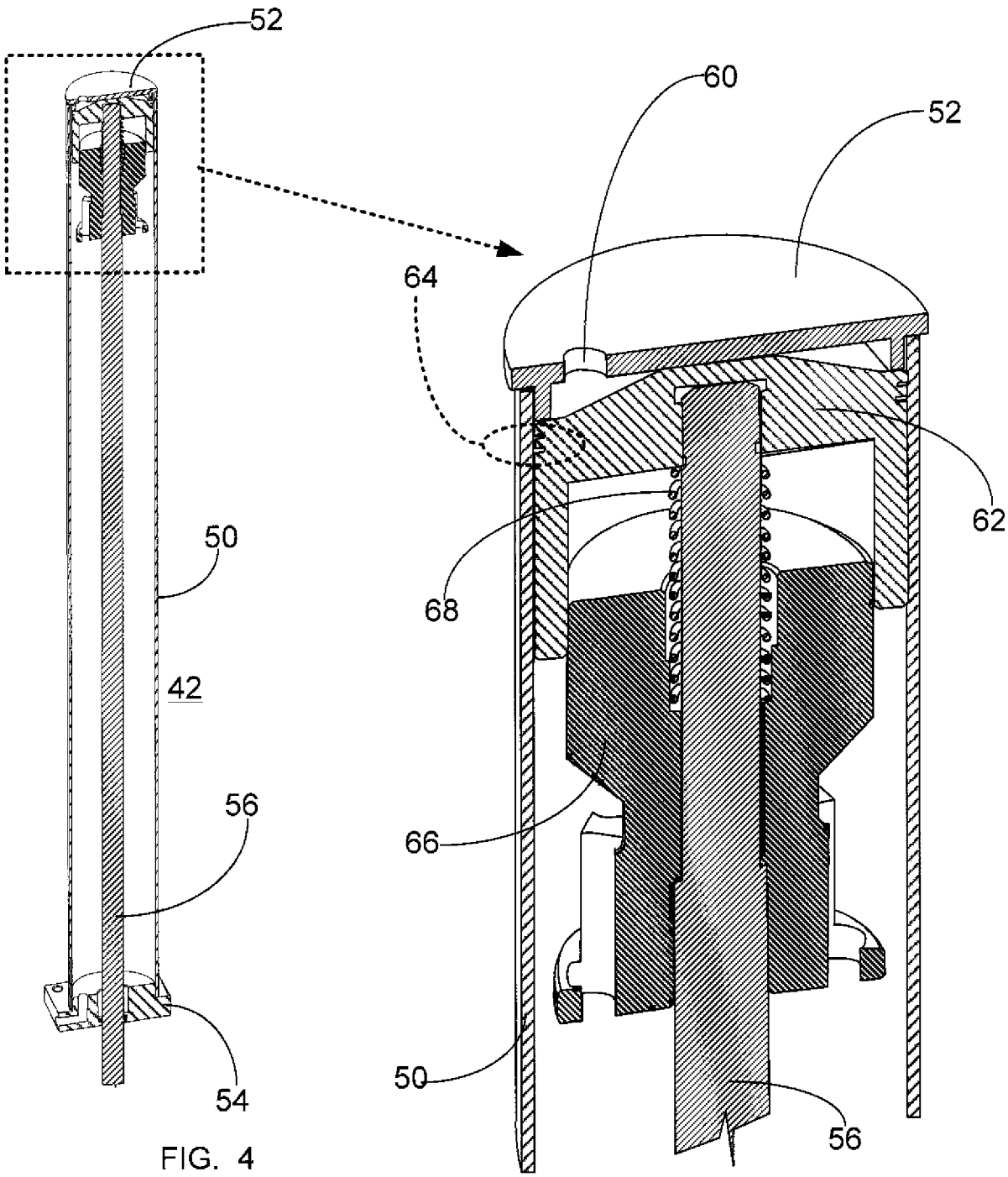


FIG. 4

FIG. 4

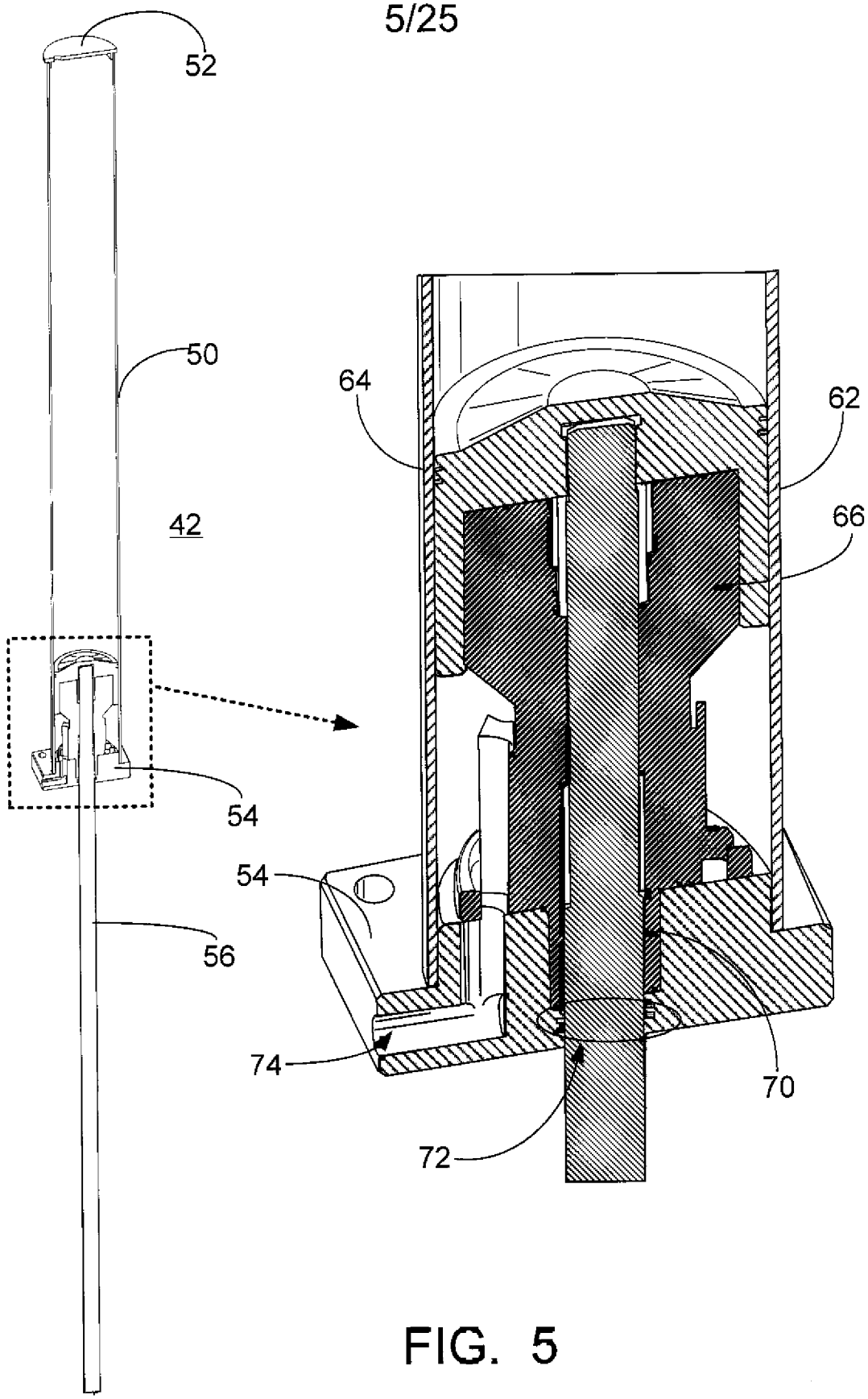
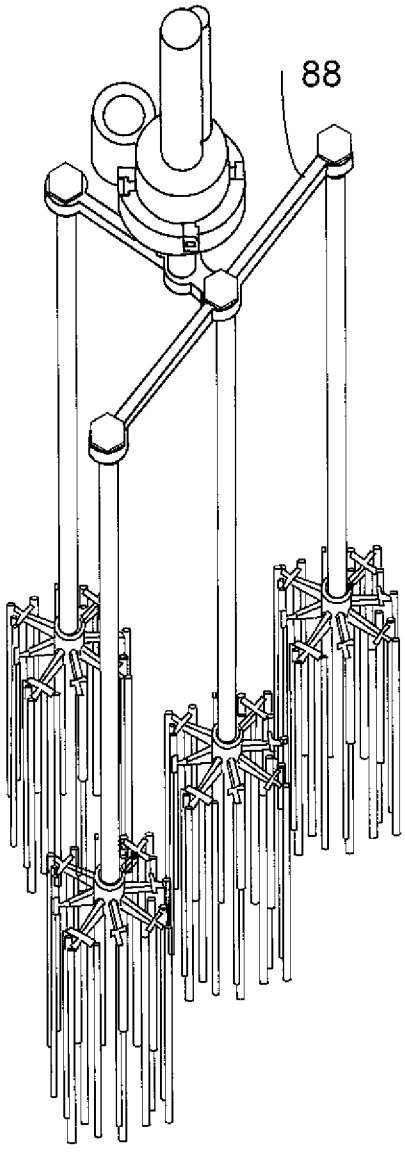


FIG. 5

Rod Cluster of Type 2



Rod Cluster of Type 1

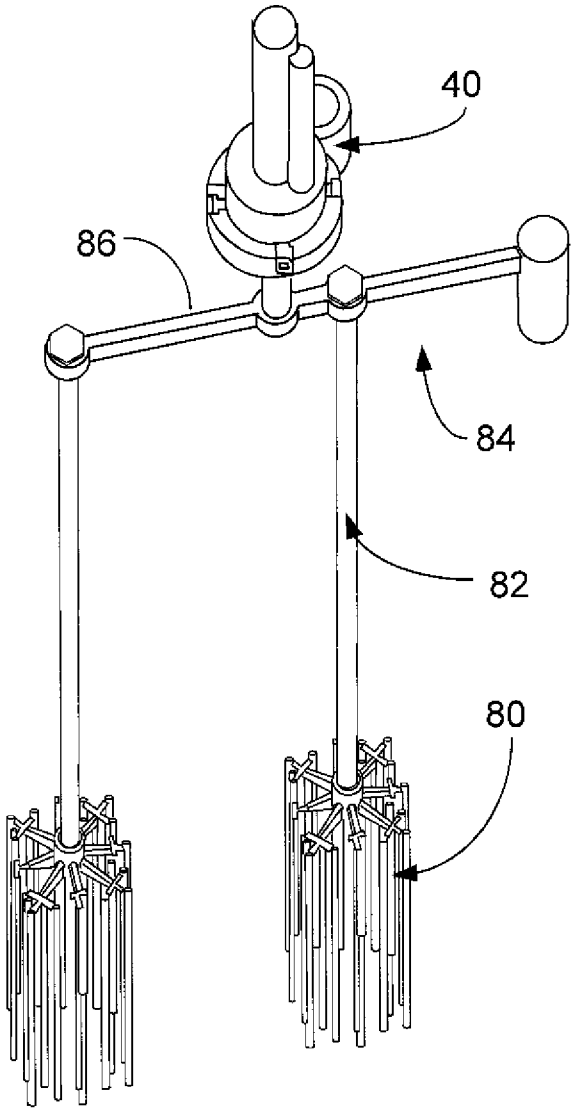


FIG. 6

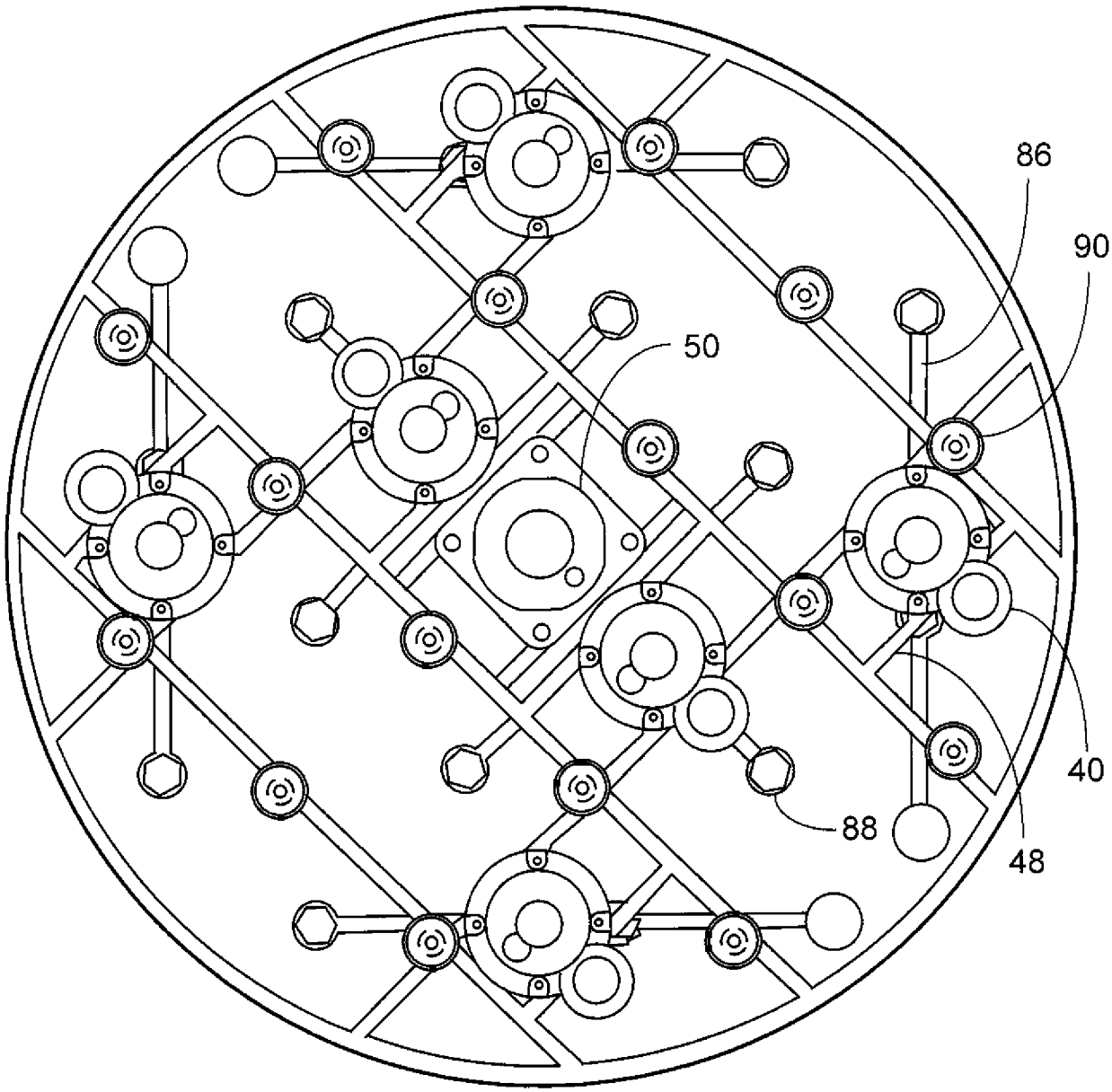


FIG. 7

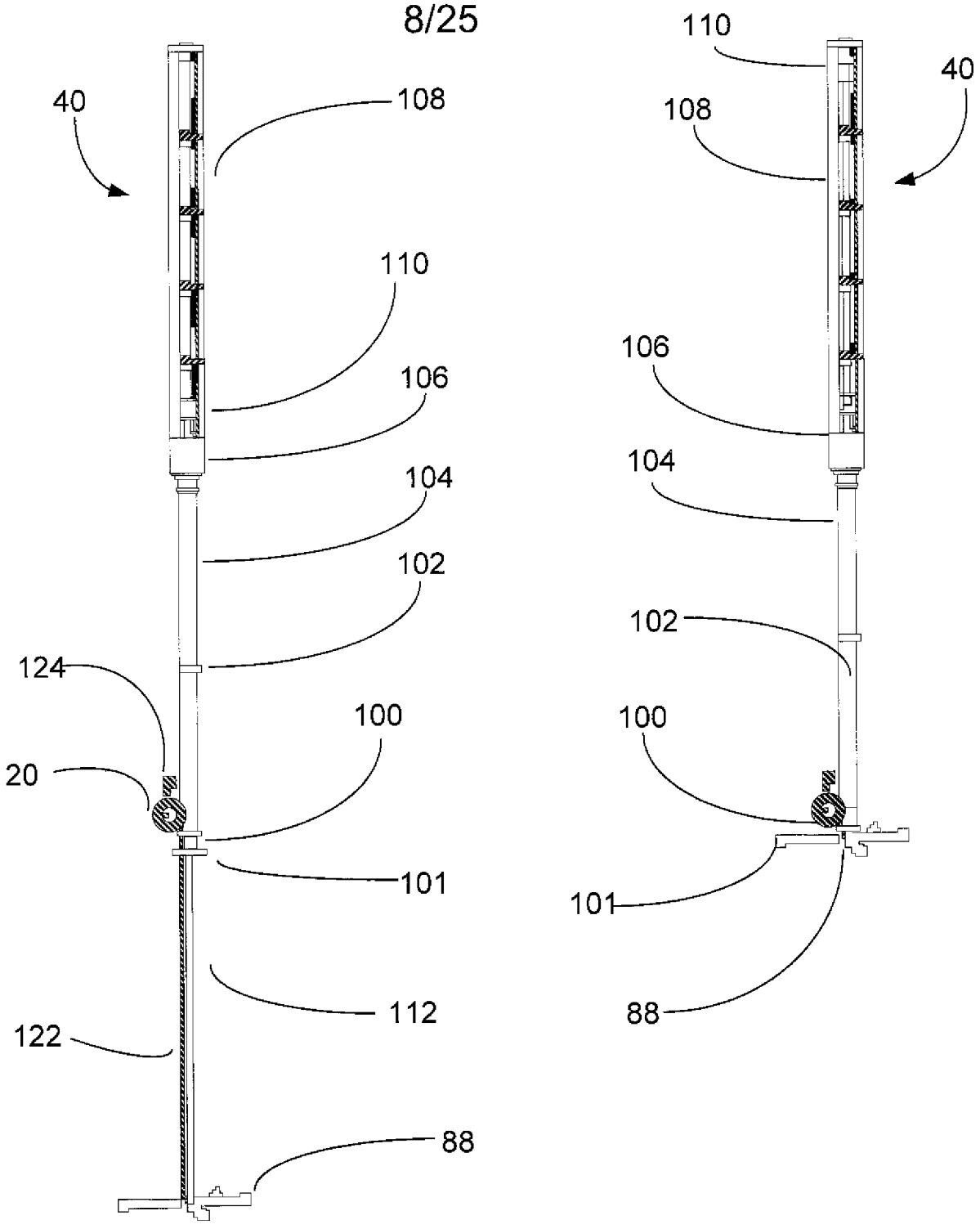

40
108
110
106
104
102
124
20
100
101
112
122
88
110
40
108
106
104
102
100
101
88

FIG. 8

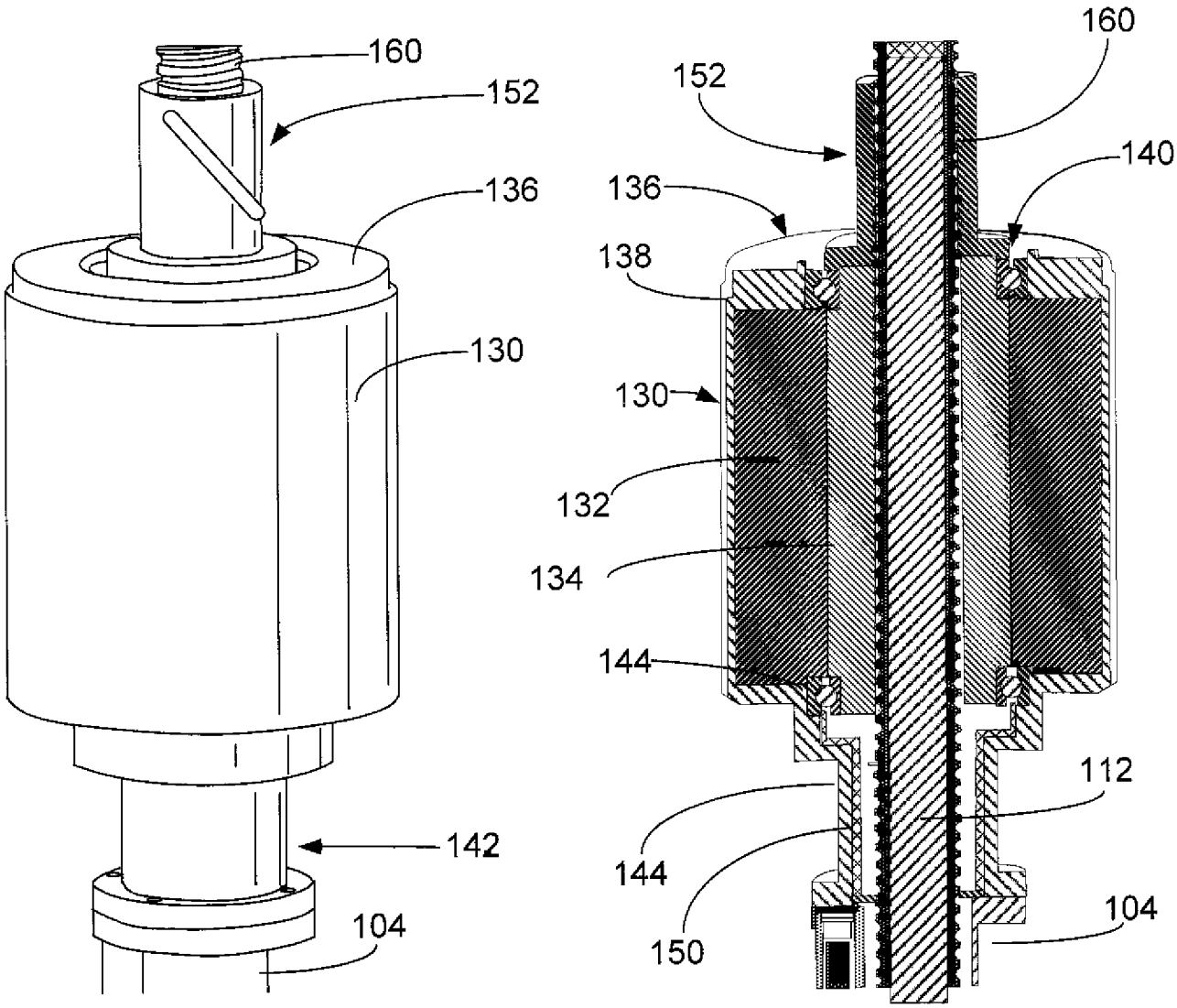

160
152
136
130
142
104
160
152
140
136
138
130
132
134
144
112
144
150
104

FIG. 9

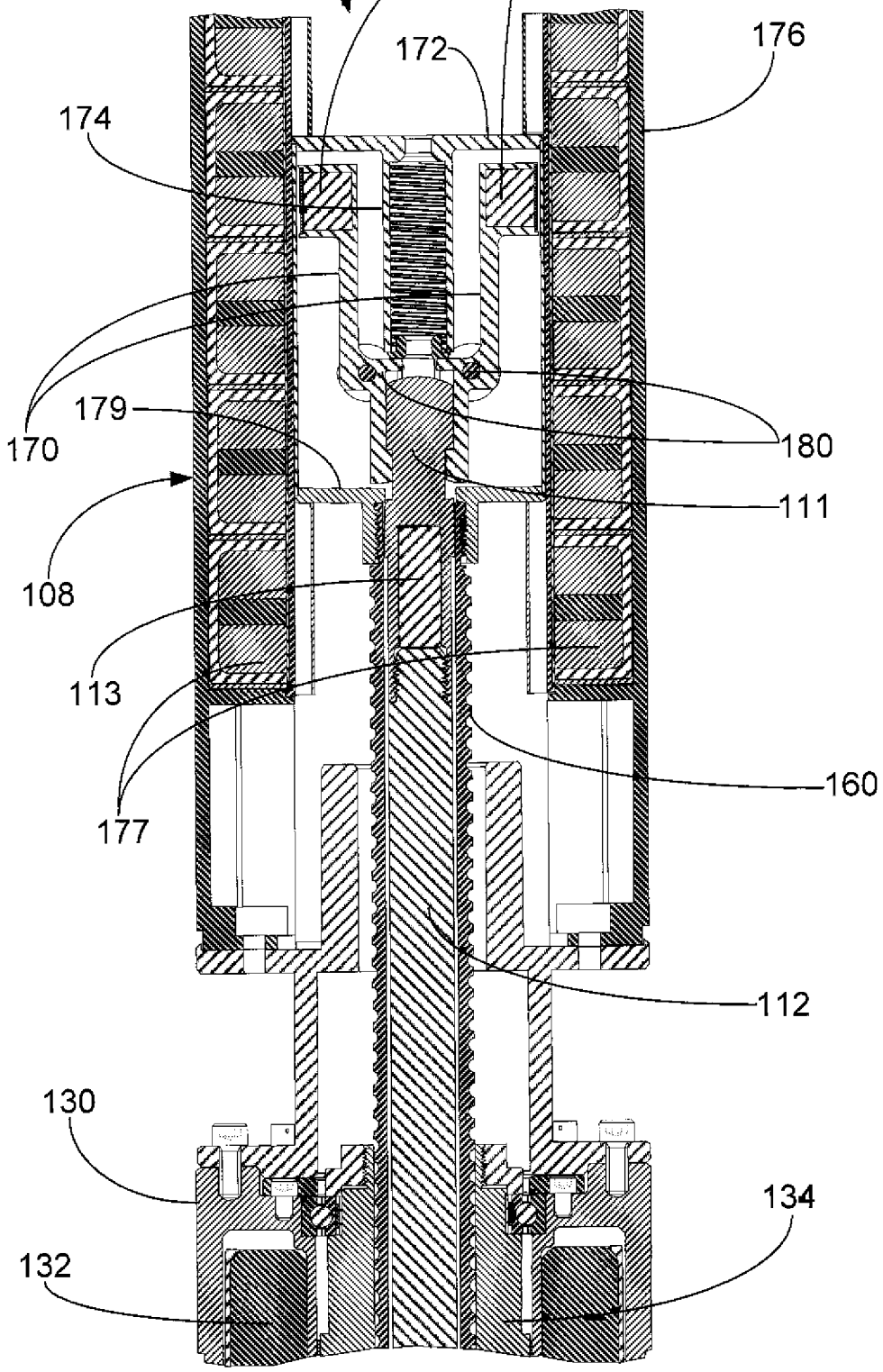

178
110
172
176
174
179
170
180
111
108
113
160
177
112
130
134
132

FIG. 10

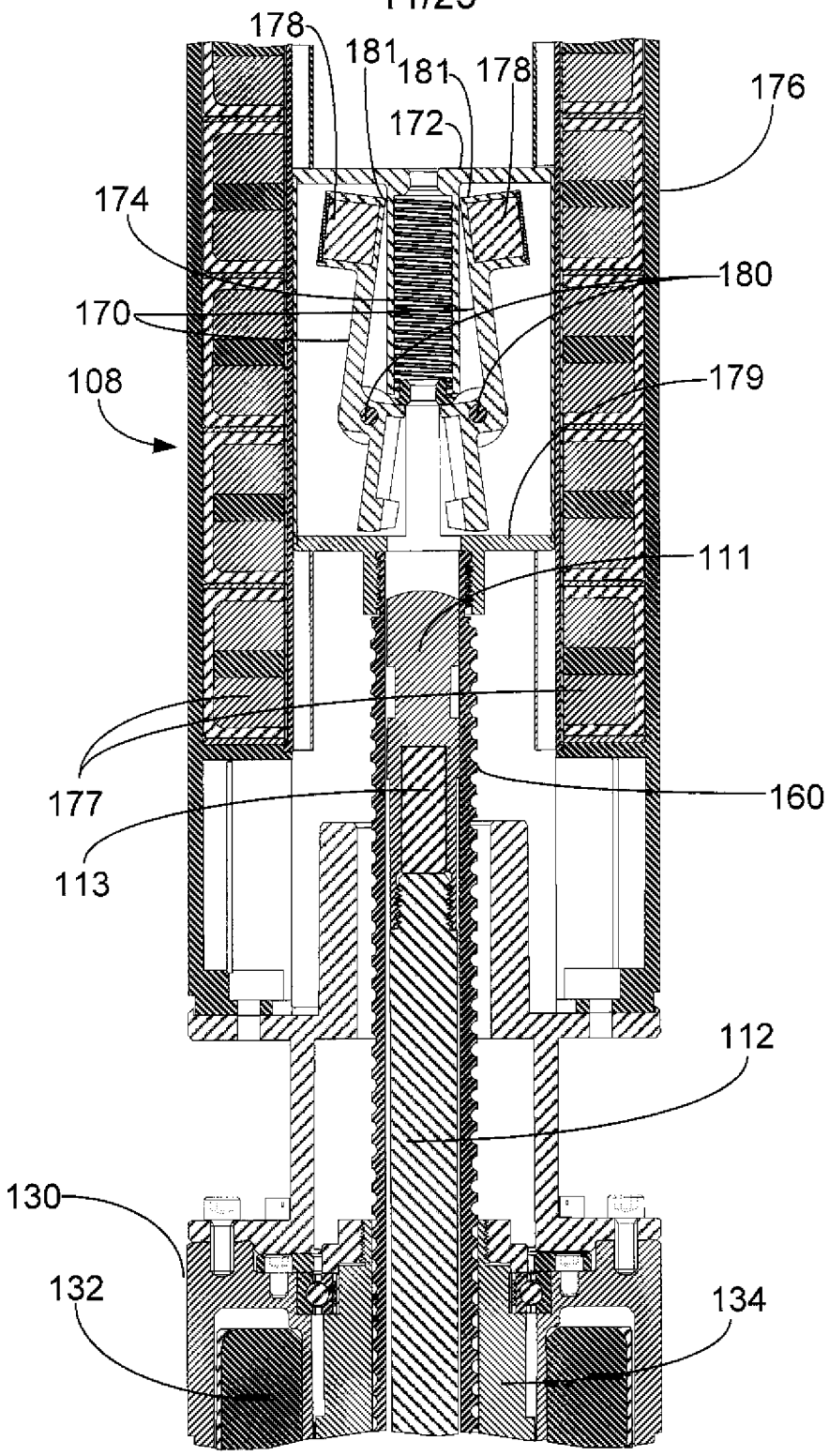

178
181
181
178
176
172
174
180
170
108
179
111
177
160
113
112
130
132
134

FIG. 11

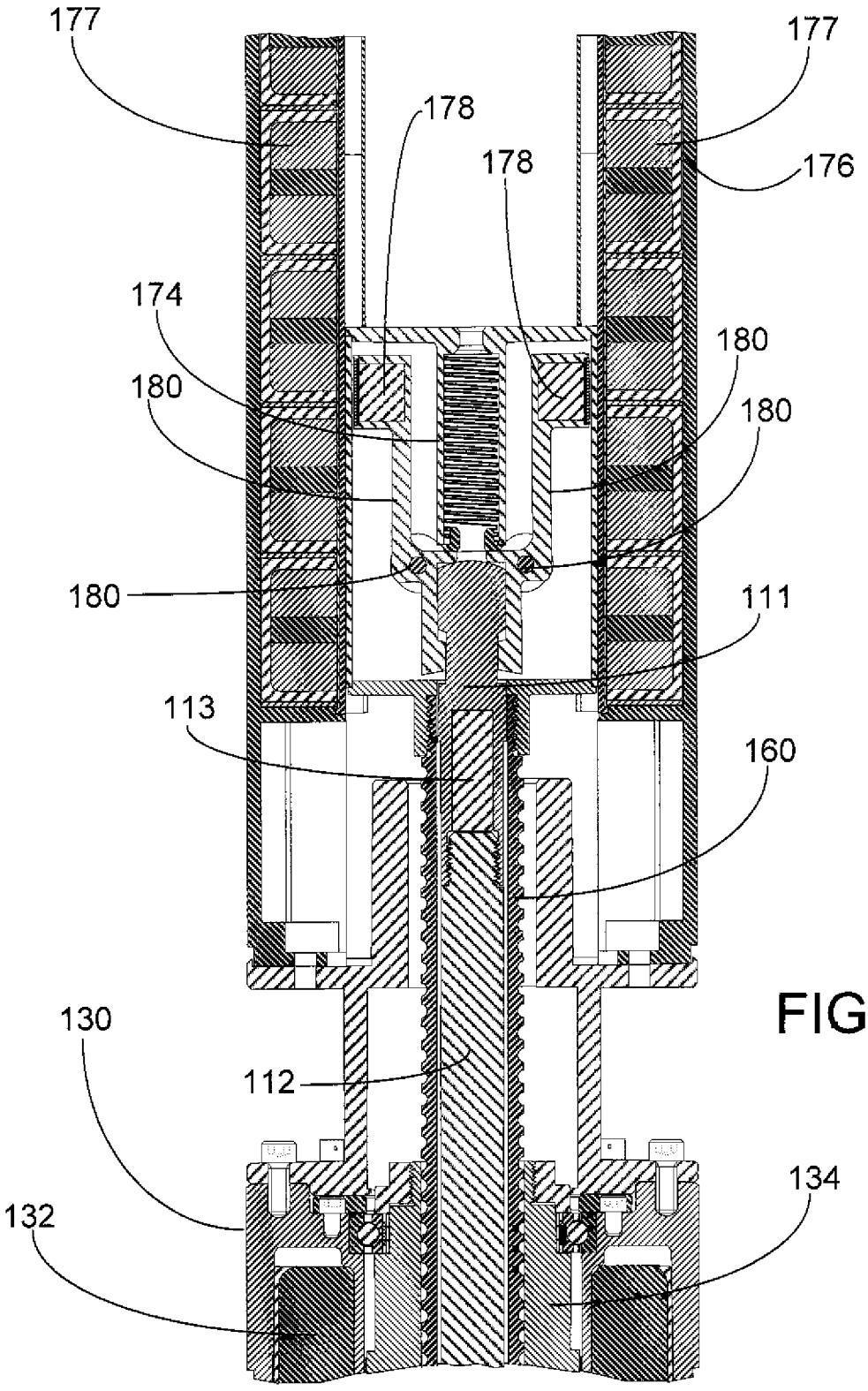

177
177
178
178
176
174
180
180
180
180
111
113
160
130
112
134
132

FIG. 12

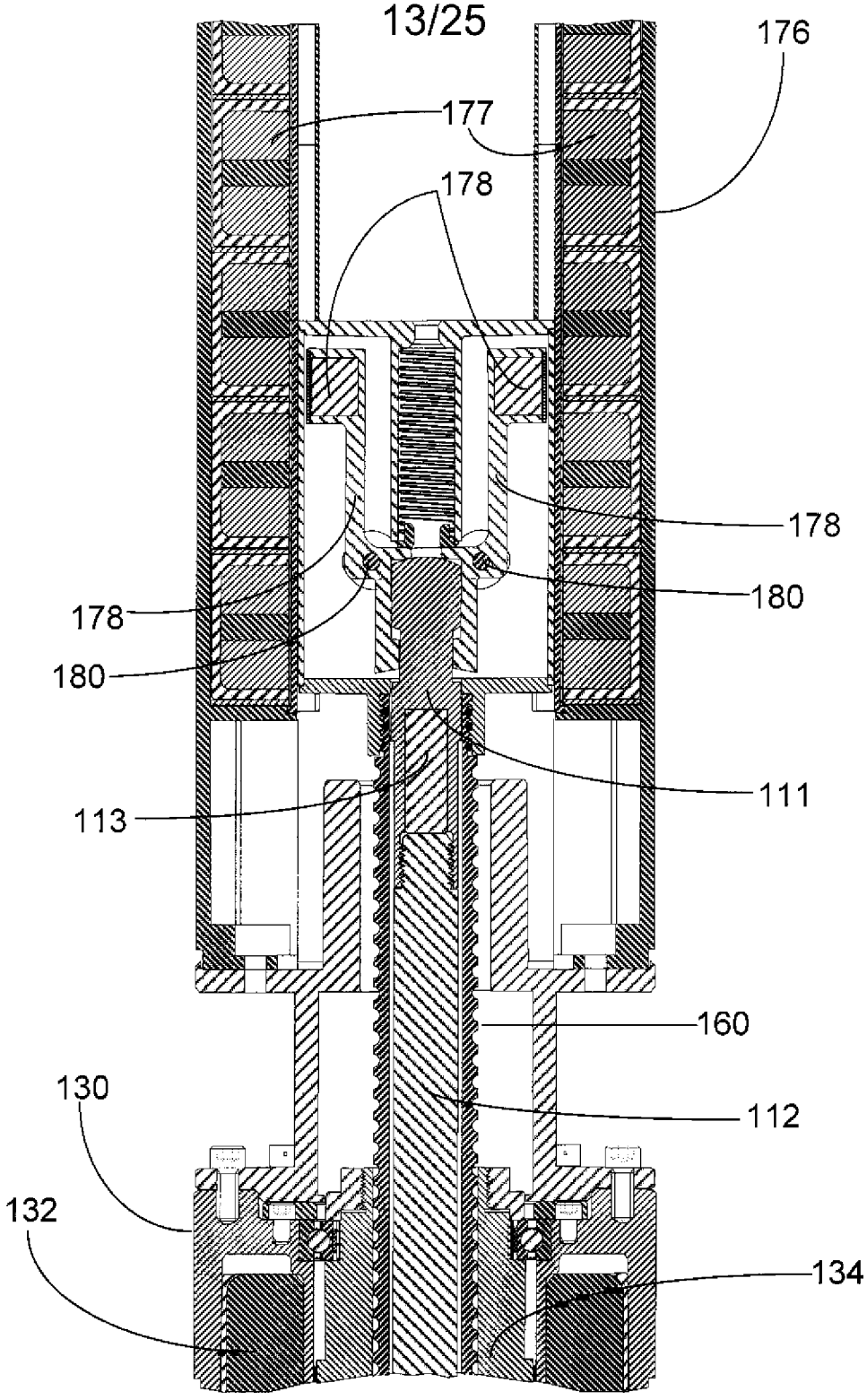


FIG. 13

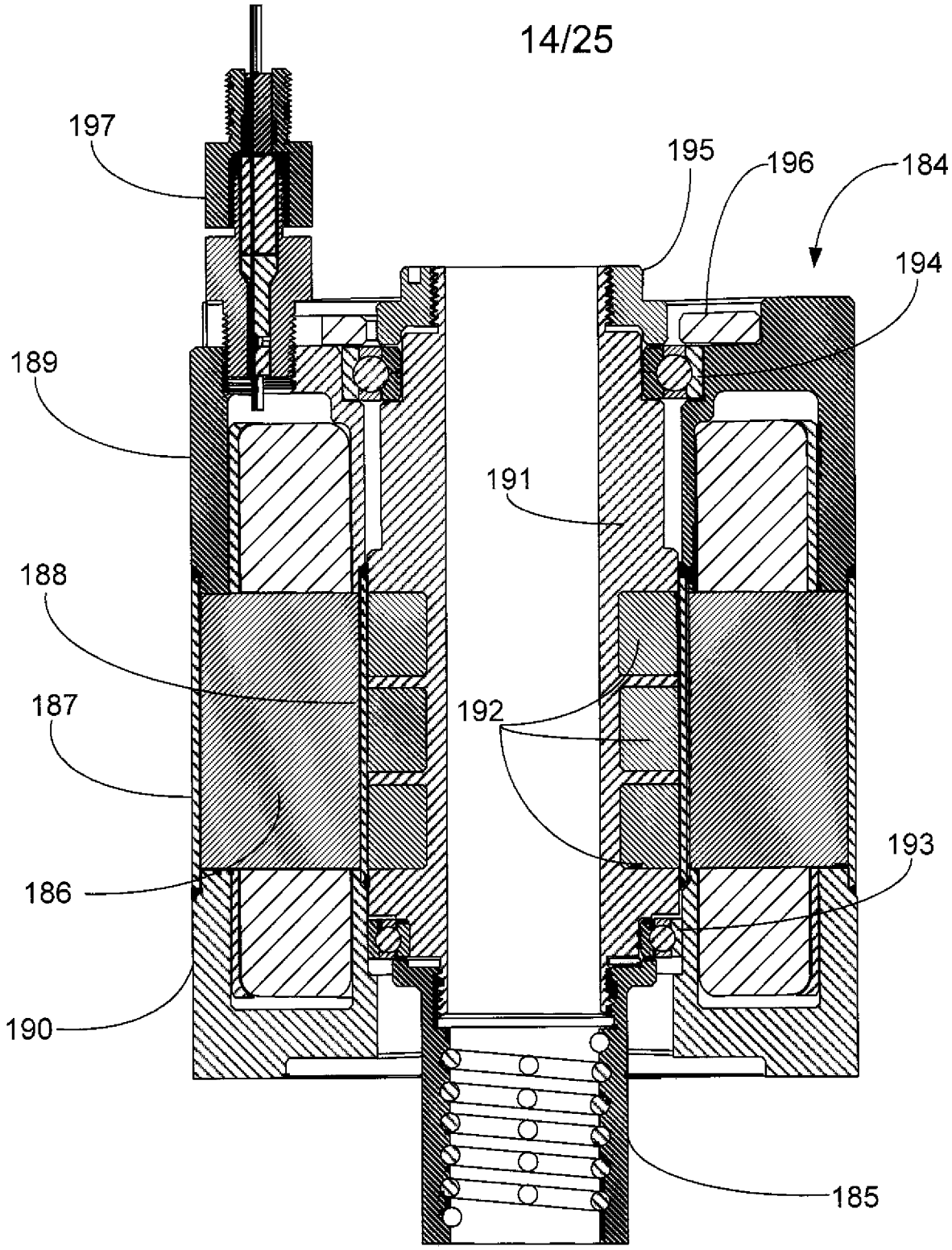


FIG. 14

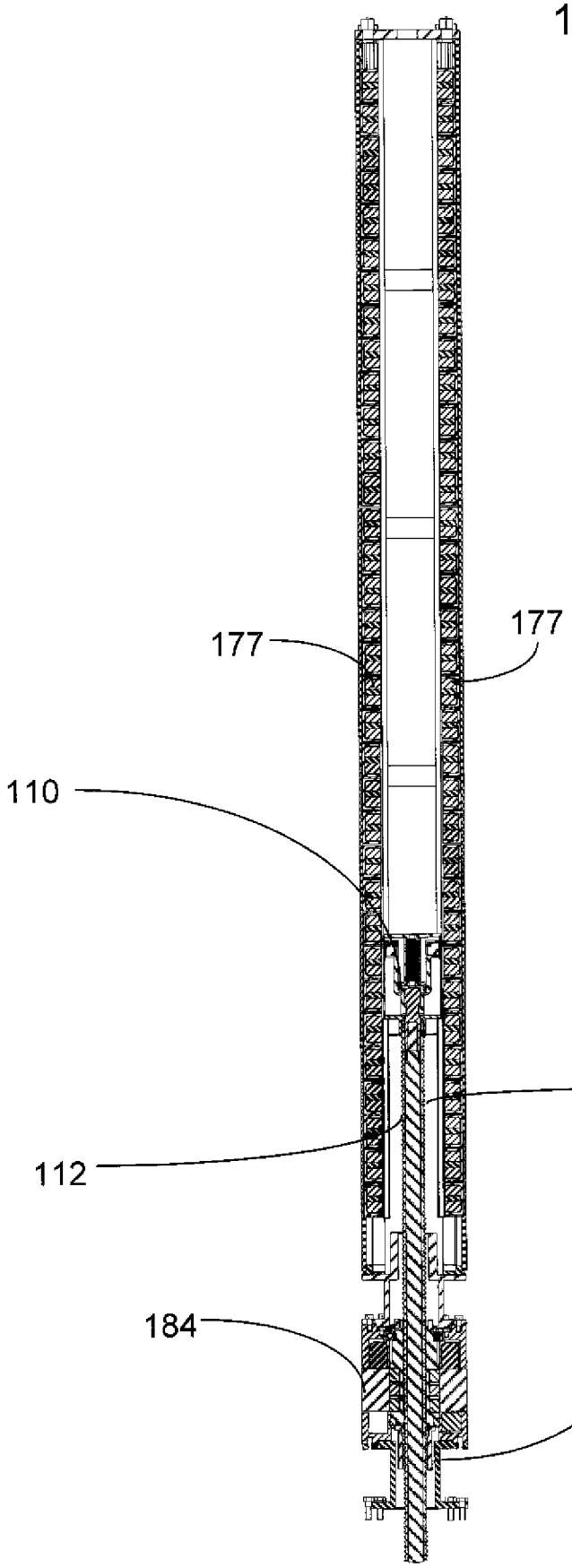


FIG. 15

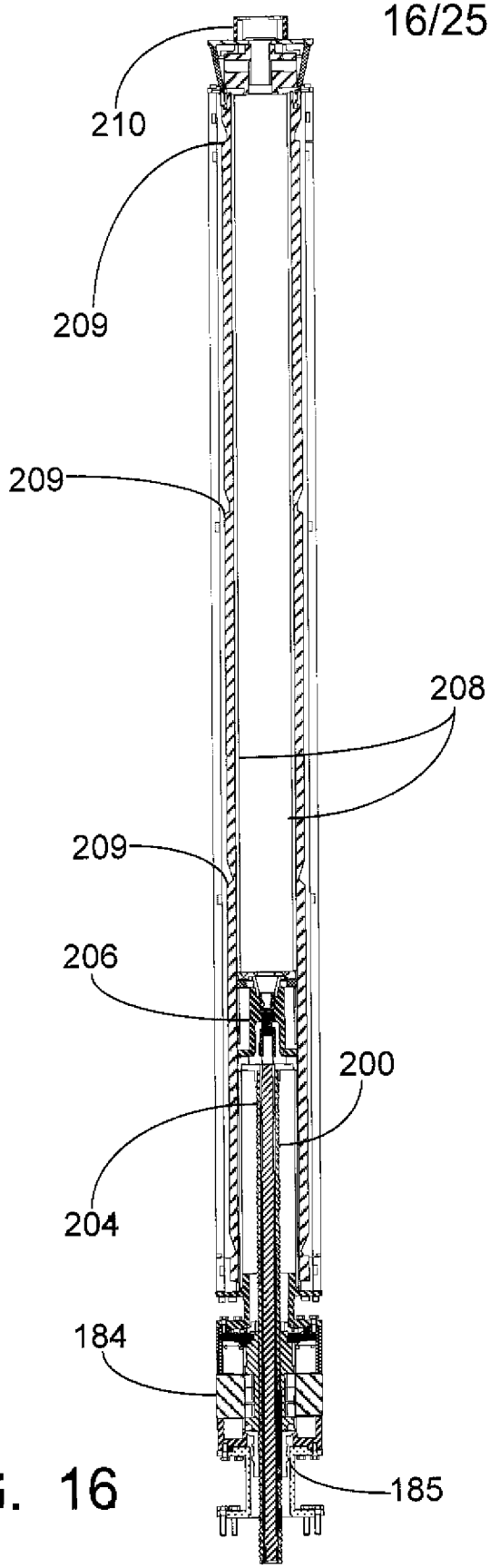


FIG. 16

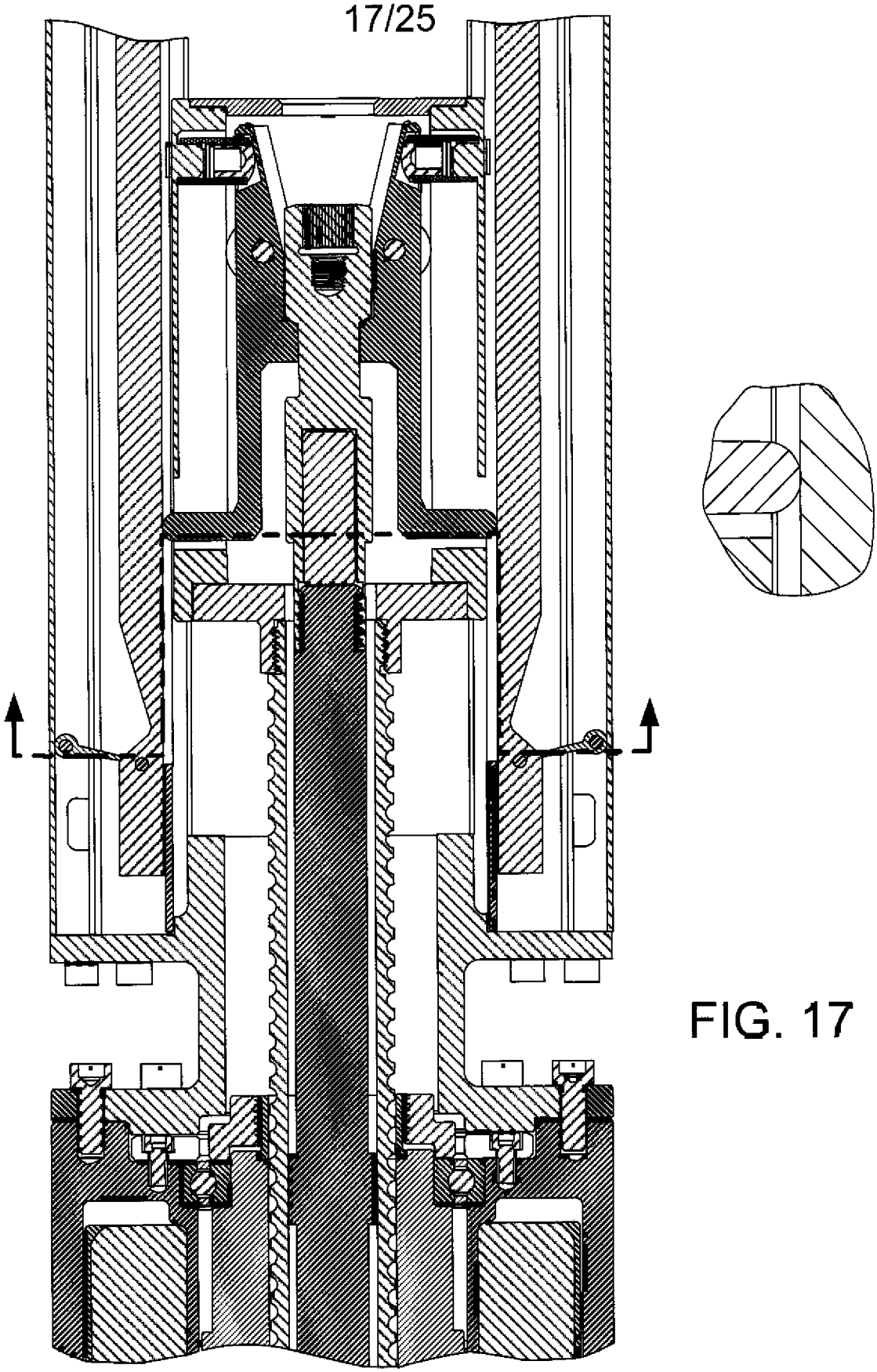


FIG. 17

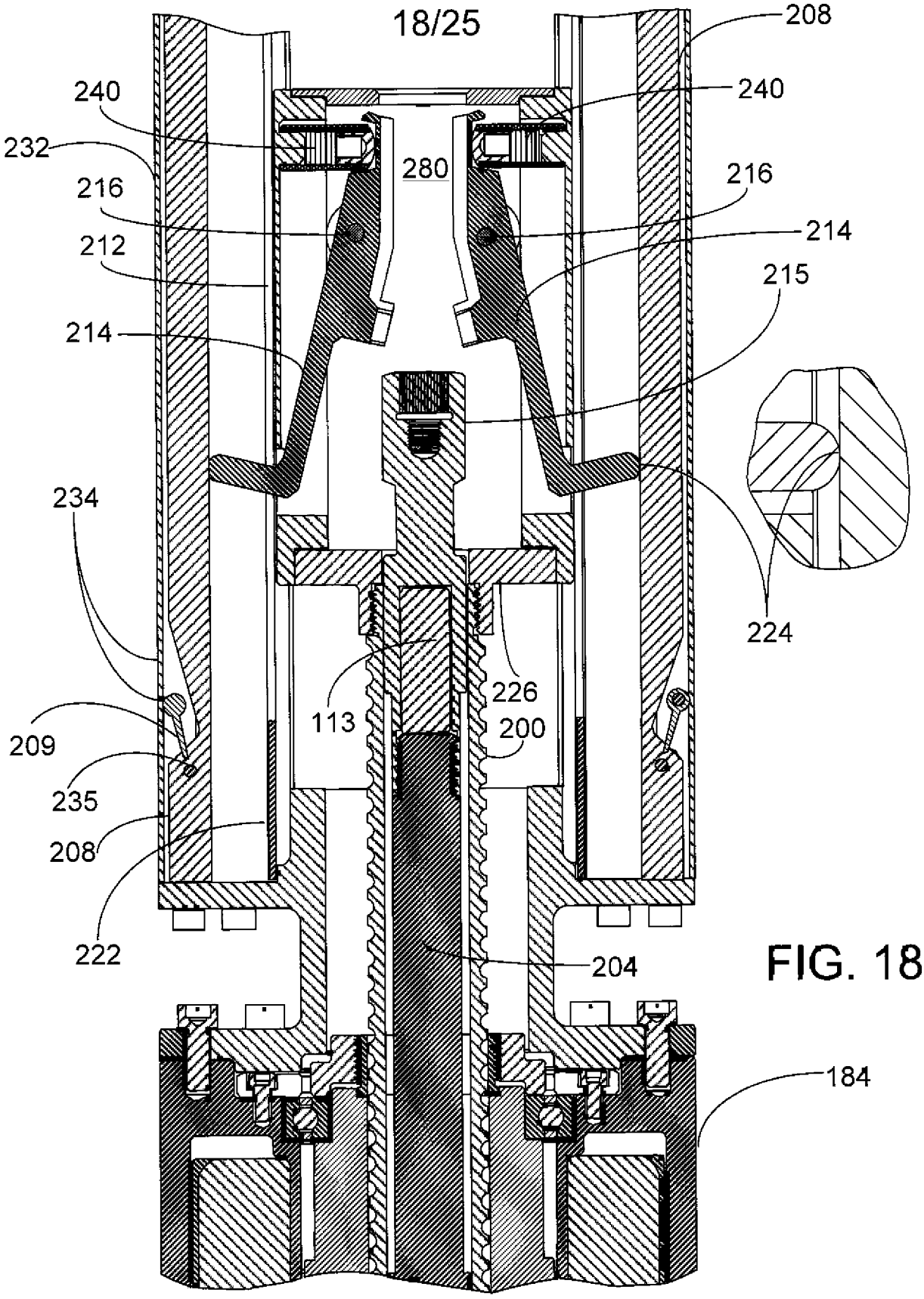

208
240
240
232
280
216
216
214
212
215
214
234
224
226
113
200
209
235
208
222
204
184

FIG. 18

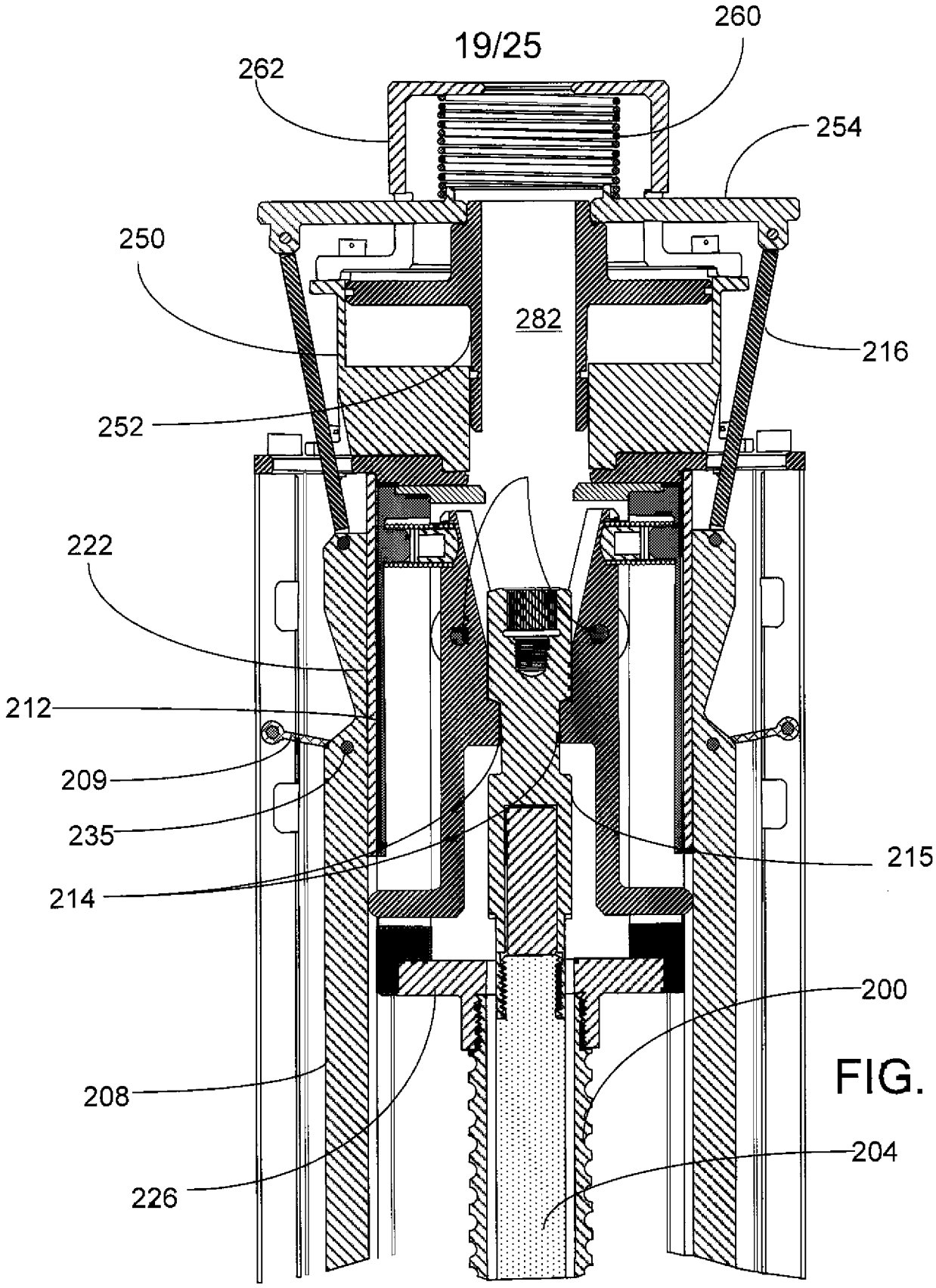

260
262
254
250
282
216
252
222
212
209
235
214
215
200
208
226
204

FIG. 19

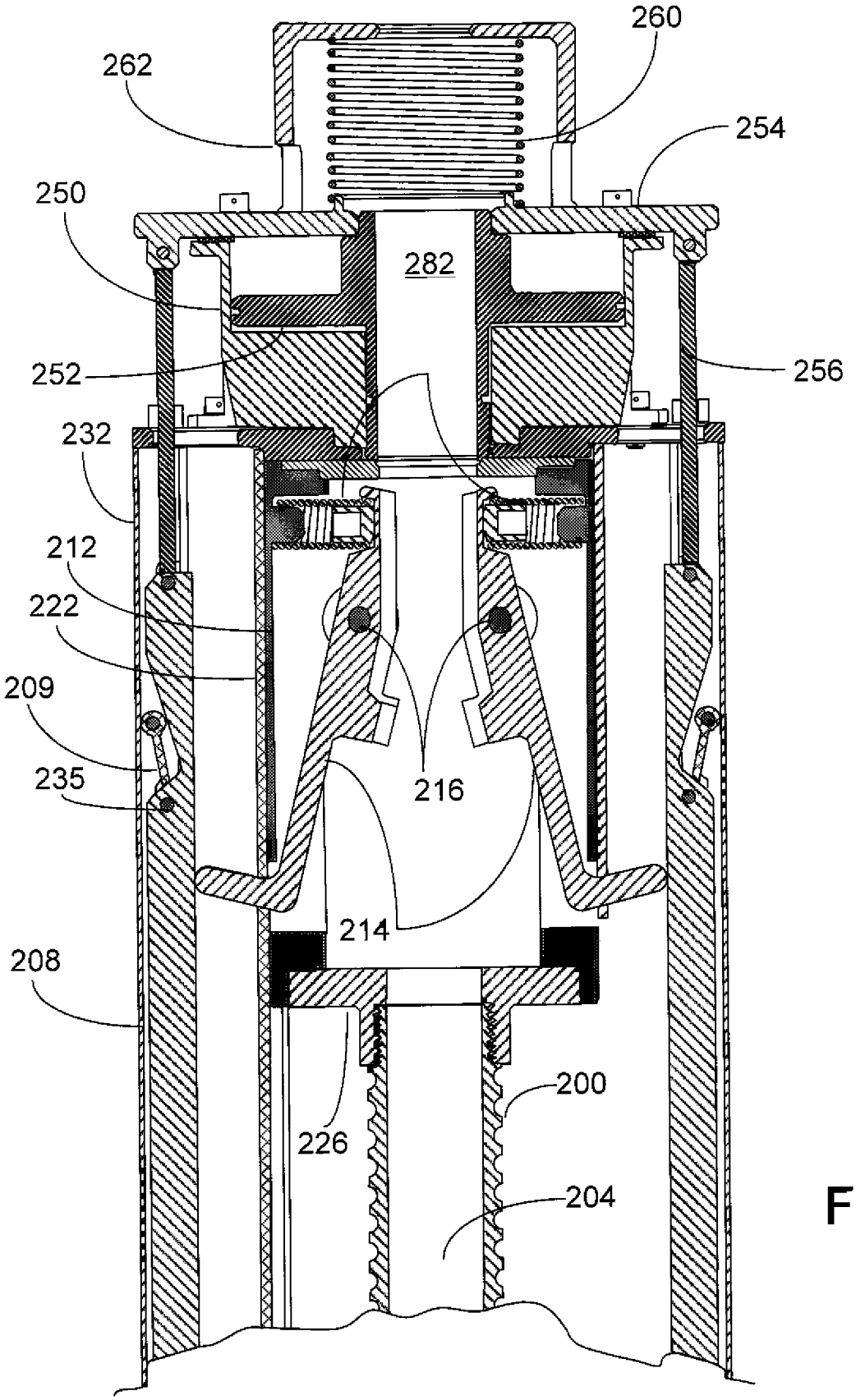

260
262
254
250
282
252
256
232
212
222
209
235
216
214
208
200
226
204

FIG. 20

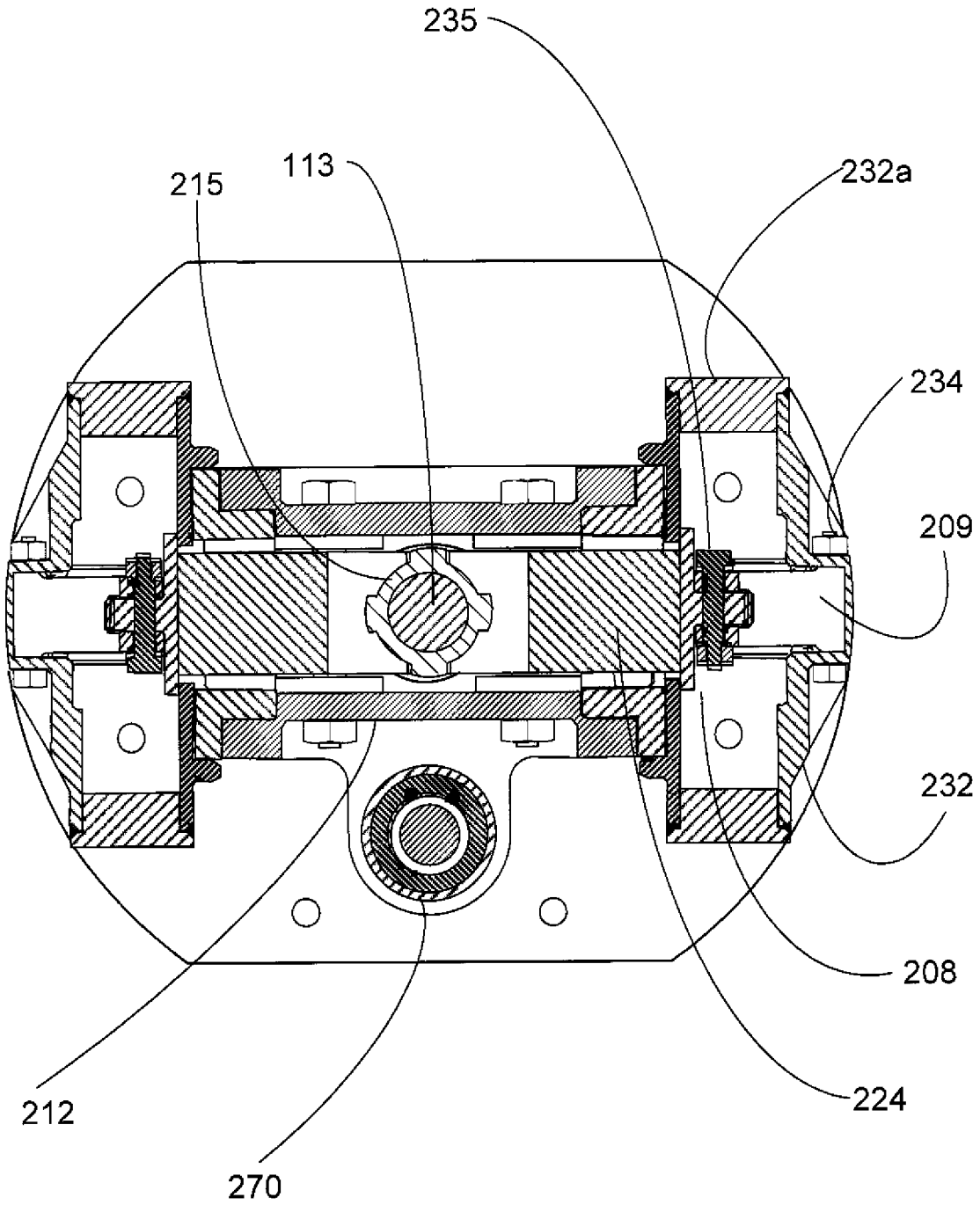


FIG. 21

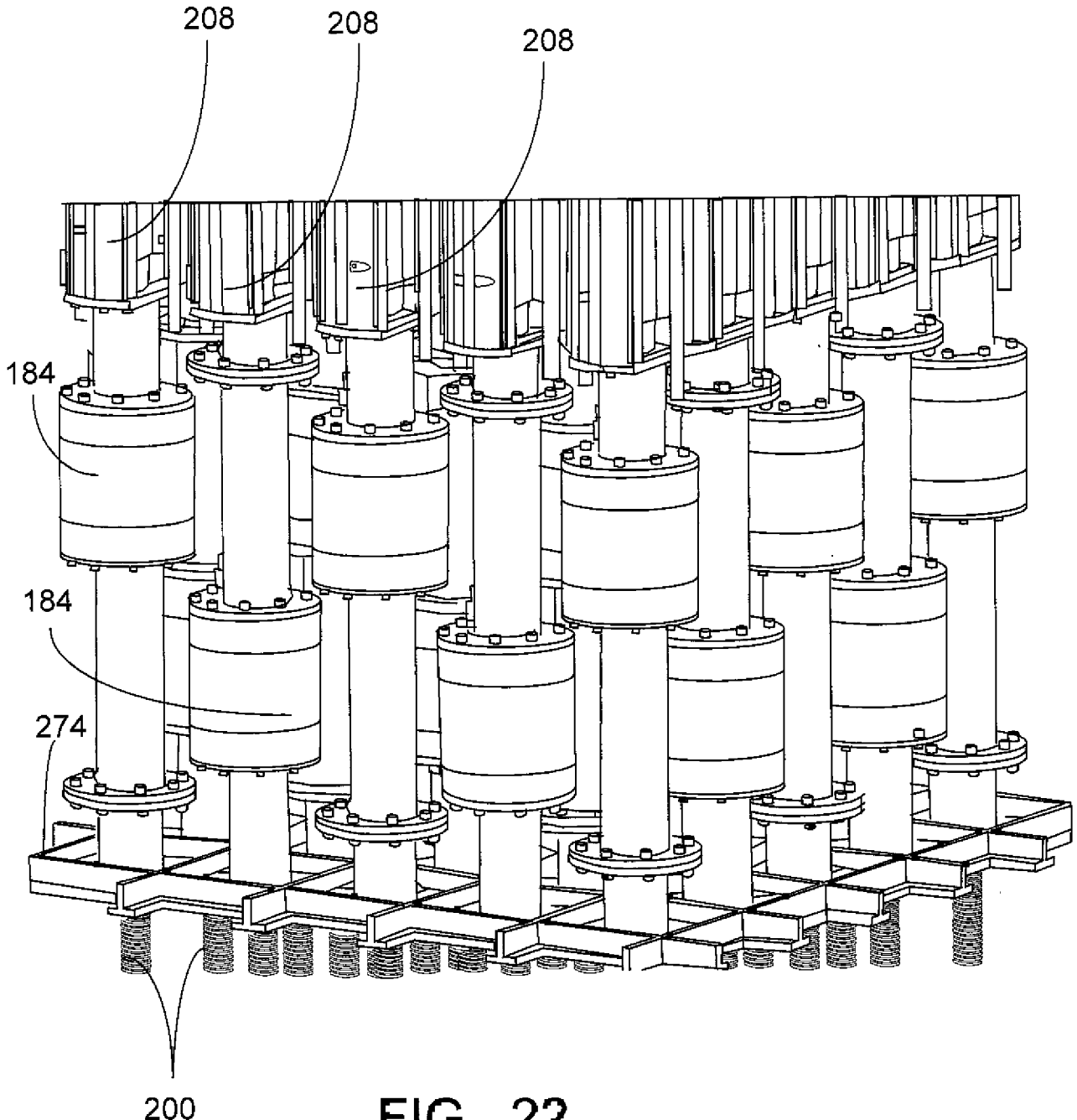


FIG. 22

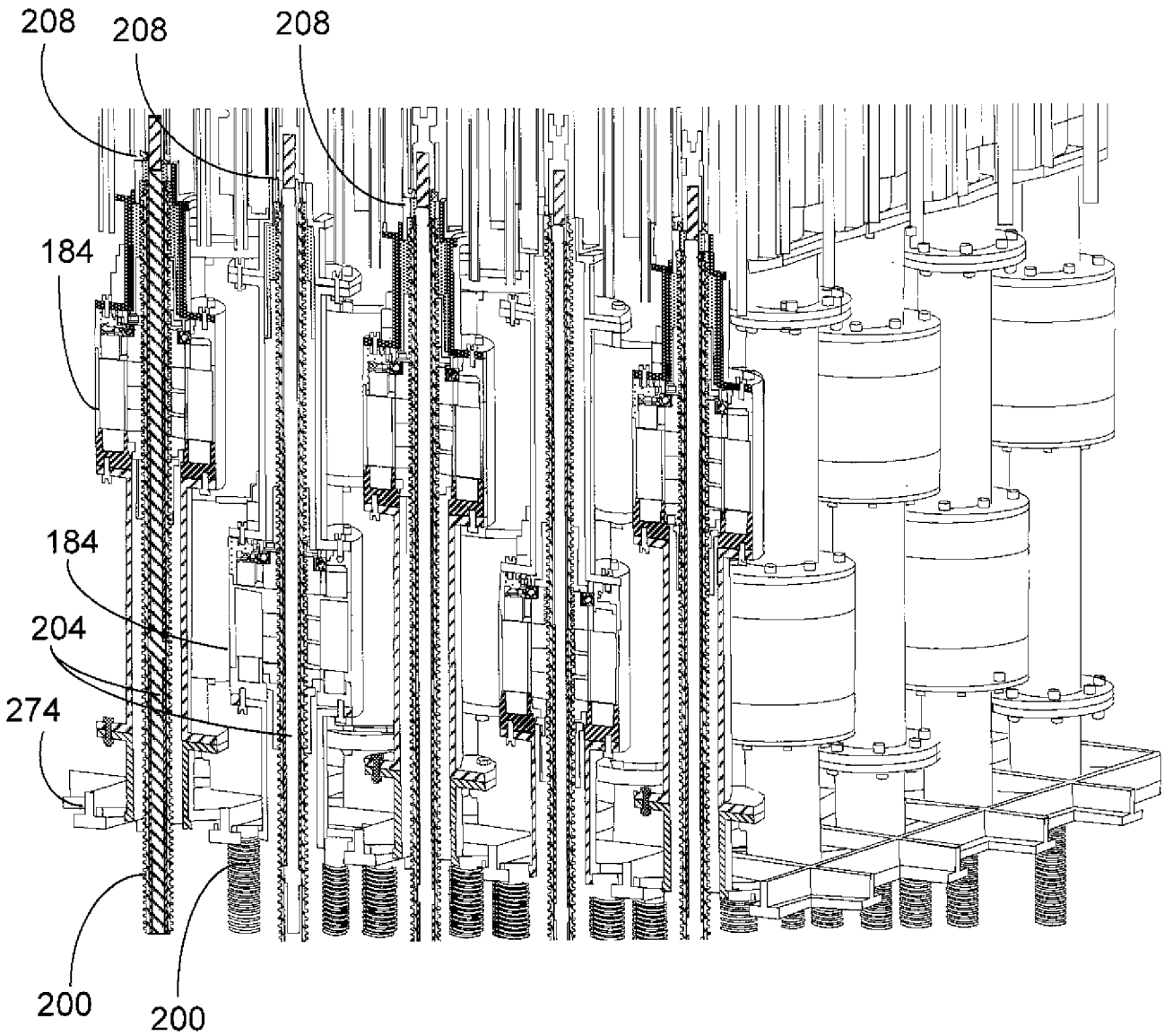


FIG. 23

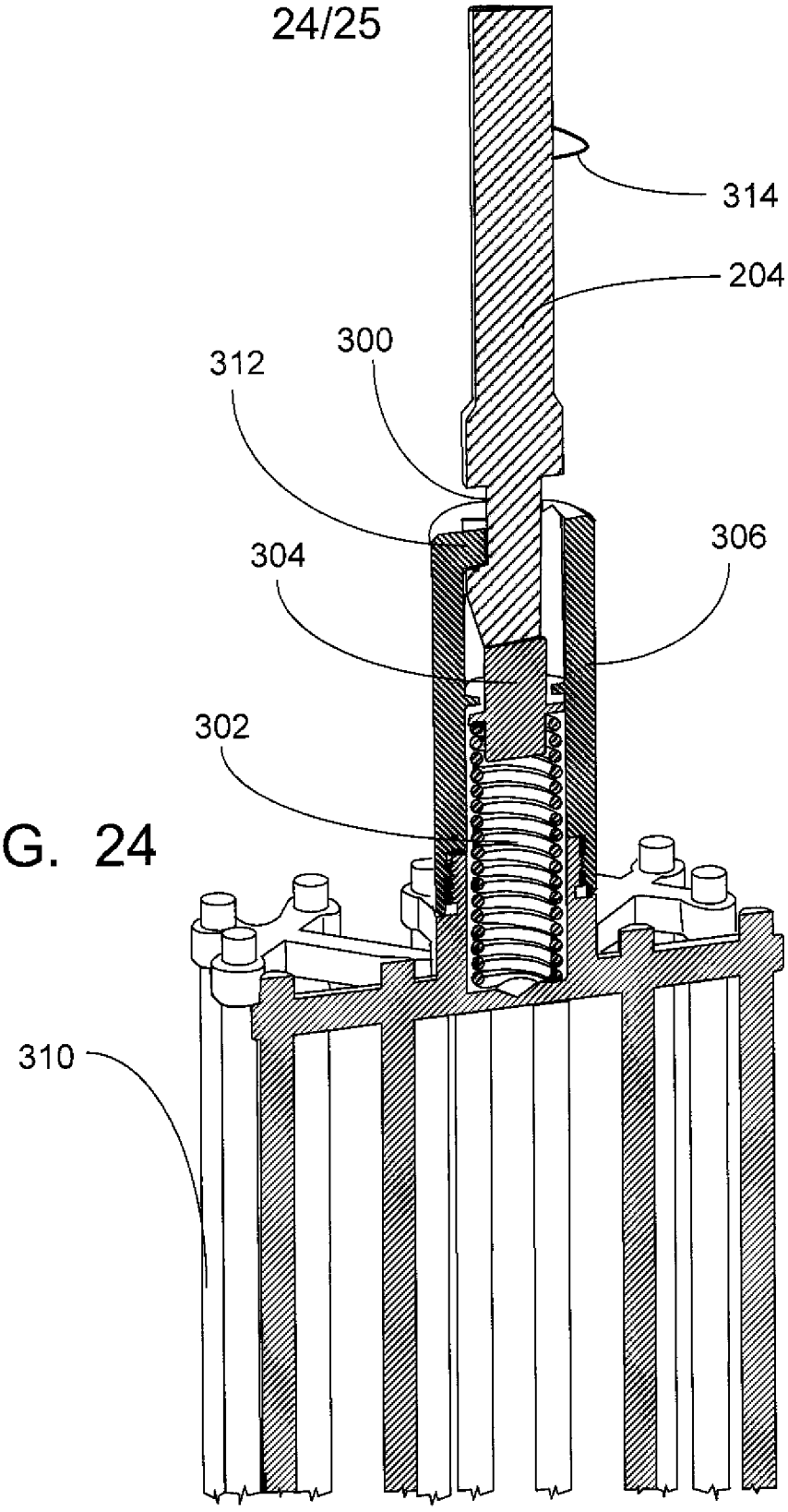


FIG. 24

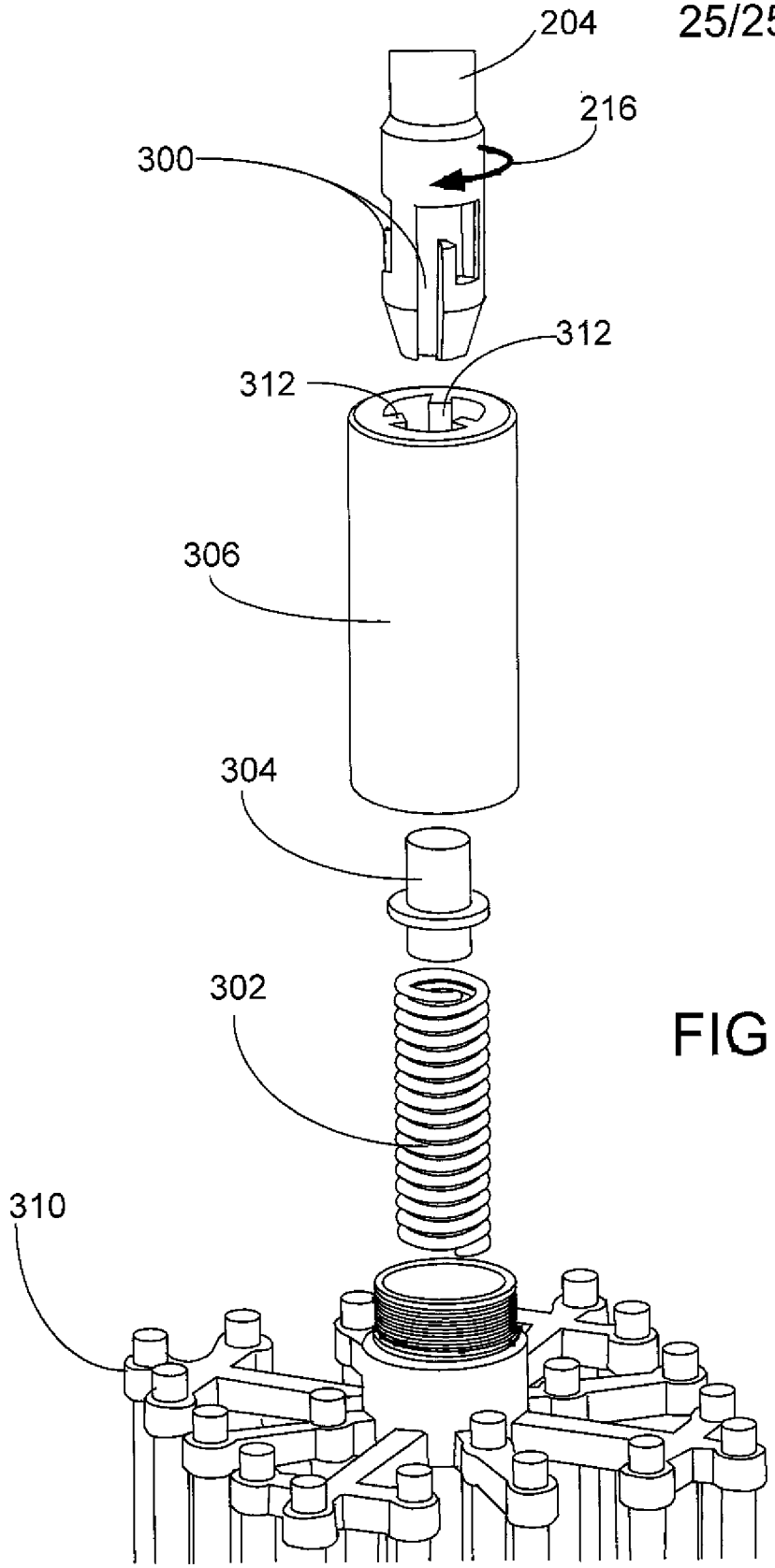


FIG. 25

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/027570

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G21C 7/10 (2011.01)
USPC - 376/233
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - G21C 7/10, 7/12 (2011.01)
USPC - 376/219, 233, 237, 239

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X – Y	US 3,079,323 A (HAWKE) 26 February 1963 (26.02.1963) entire document	1, 3, 4, 8-19, 21-28 --- 2, 20
Y	US 2009/0046824 A1 (POMIRLEANU et al) 19 February 2009 (19.02.2009) entire document	2
Y	US 5,089,211 A (DILLMANN) 18 February 1992 (18.02.1992) entire document	20
A	GB 948,890 A (GENERAL DYNAMICS) 05 February 1964 (05.02.1964) entire document	1-28
A	US 4,713,210 A (GERMER) 15 December 1987 (15.12.1987) entire document	1-28
A	US 3,613,512 A (TAFT) 19 October 1971 (19.10.1971) entire document	1-28

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 April 2011	12 MAY 2011
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)