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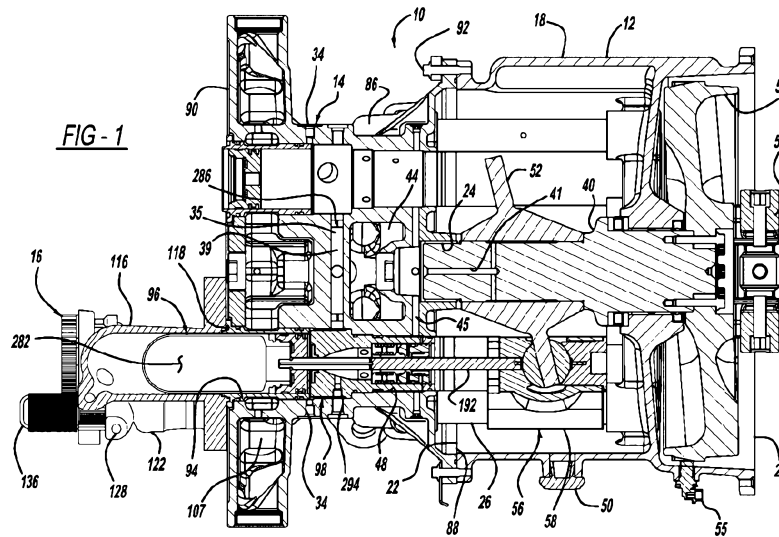


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(57) **Abstract:** An improved Stirling engine of the multiple cylinder double acting type. The engine in accordance with this invention includes numerous improved features, including but not limited to: piston design, piston rod seal design, components and methods for providing pressure balancing among the discrete cycle volumes of the engine, and a control valve configuration for reducing starting torque and unloading the engine if desired.

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## PISTON ASSEMBLY FOR A STIRLING ENGINE

### FIELD OF THE INVENTION

5 [0001] The present invention is related to a piston assembly for a Stirling engine. The present disclosure also relates to heat engine and particularly to an improved Stirling cycle engine incorporating numerous refinements and design features intended to enhance engine performance, manufacturability, and reliability.

### 10 BACKGROUND AND SUMMARY OF THE INVENTIONS

[0002] The basic concept of a Stirling engine dates back to a patent registered by Robert Stirling in 1817. Since that time, this engine has been the subject of intense scrutiny and evaluation. Various Stirling engine systems have been prototyped and put into limited operation throughout the world. One potential  
15 application area for Stirling engines is for automobiles as a prime mover or engine power unit for hybrid electric applications. Other fields of potential use of a Stirling engine such as stationary auxiliary power units, marine applications and solar energy conversion.

[0003] Stirling engines have a reversible thermodynamic cycle and therefore  
20 can be used as a means of delivering mechanical output energy from a source of heat, or acting as a heat pump through the application of mechanical input energy. Using various heat sources such as combusted fossil fuels or biogases, or concentrated solar energy, mechanical energy can be delivered by the engine. This energy can be used to generate electricity or can be directly mechanically  
25 coupled to a load.

[0004] The present Applicant and its predecessor company have made significant advances in the technology of Stirling machines through a number of years. Although the Applicant has achieved significant advances in Stirling machine design, there is a constant need to further refine the machine, particularly  
30 if the intended application is in large volume production.

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**[0005]** The present Stirling engine bears many similarities to those previously developed by Applicant and its predecessor company, including those described in U.S. Patent Nos. 4,439,169; 4,481,771; 4,532,855; 4,579,046; 4,615,261; 4,669,736; 4,836,094; 4,885,980; 4,707,990; 4,996,841; 4,977,742; 4,994,004; 5 and 5,074,114, which are hereby incorporated by reference. Basic features of many of the Stirling machines described in the above referenced patents are also implemented in connection with the present disclosure.

**[0006]** According to one aspect of the present invention there is provided a piston assembly for a Stirling cycle engine of the type having two or more of the piston assemblies reciprocating within cylinder bores, each of the piston assemblies separating isolated cycle volumes of a working gas contained within the engine, the piston assembly comprising:

- a piston dome forming a top end and a bottom end, the dome having a hollow interior,
- 15 a piston base affixed to the piston dome bottom end,
- a connecting rod affixed to the piston base,
- an upper and a lower ring set positioned within a ring groove for sealing with the cylinder bore,
- a land ring positioned within the ring groove between the upper and lower
- 20 ring sets, a first ring of the upper ring set positioned on a side of the land ring toward the dome top end and the second ring of the upper ring set positioned below the first ring and adjacent to the land ring, a first ring of the lower ring set positioned on a side of the land ring toward the piston base, and a second ring of the lower ring set positioned between the first ring of the lower ring set and the
- 25 land ring, and
- an upper and a lower expander ring respectively positioned radially inboard of the upper and lower ring sets and each expander ring formed of elastomeric material,
- wherein the first rings of the upper and lower ring sets have a radial split,
- 30 and

wherein each expander ring has a lip engaging respectively the first ring of the upper or lower ring set and in that the second rings of the upper and lower ring sets are solid rings.

**[0006A]** According to another aspect of the present invention there is provided a piston assembly for a Stirling cycle engine of the type having two or more of the piston assemblies reciprocating within cylinder bores, each of the piston assemblies separating isolated cycle volumes of a working gas contained within the engine, the piston assembly comprising:

a piston dome forming a top end and an open bottom end, the dome having a hollow interior,

a piston base affixed to the piston dome at the bottom end,

a connecting rod affixed to the piston base,

upper and lower ring sets positioned within a ring groove,

a land ring positioned within the ring groove between the upper and lower ring sets, the land ring having an outer diameter surface which has a radial clearance with the surface of the cylinder bore, a first ring of the upper ring set positioned on a side of the land ring toward the dome top end and a second ring of the upper ring set positioned between the first ring of the upper ring set and the land ring, a first ring of a lower ring set positioned on a side of the land ring toward the piston base, and a second ring of the lower ring set positioned between the first ring of the lower ring set and the land ring, and

an upper expander ring and a lower expander ring each respectively positioned radially inboard of the upper and lower ring sets and each formed of an elastomeric material and each having a lip engaging respectively the first ring of each of the upper and the lower ring sets,

wherein the first rings of the upper and lower ring sets have a radial split, and

wherein the second rings of the upper and lower ring sets are solid rings.

**[0006B]** The described Stirling engine has a so-called "modular" construction. The major components of the engine, comprising the drive case and cylinder block, are bolted together along mating surfaces. Piston rod seals for the pistons

traverse this mating plane. A sliding rod seal can be used which is mounted either to the drive case or cylinder block. The rod seal controls leakage of the high pressure engine working gas at one end of the piston connecting rod to atmosphere.

5 **[0007]** In many past designs of Stirling engines, a large volume of the engine housing is exposed to the high working pressures of the working gas. In accordance with the present engine, the high pressure working fluid is confined to the extent possible to the opposing ends of the cylinder bores and the associated heat transfer devices and passageways. Thus the high pressure gas areas of the  
10 described Stirling engine are analogous to that which is encountered in internal combustion engines, and therefore this Stirling engine can be thought of in a similar manner in terms of consideration for high pressure component failure. This benefit is achieved by maintaining the drive case at a relatively low pressure which may be close to ambient pressure, while confining the high pressure working fluid  
15 within the cylinder block and the connected components including the cylinder extension, regenerator housing, and heater head.

**[0008]** The pistons of the engine are connected to cross heads by piston rods. The cross heads of the engine embrace the swashplate and convert the reciprocating movement of the piston connecting rods and pistons to rotation of  
20 the swashplate. The described Stirling engine implements a pair of parallel guide rods mounted within the drive case for each cross head. The cross heads feature a pair of journals which receive the guide rods.

**[0009]** The combustion exhaust gases after passing through the heater head of the engine still contain useful heat. It is well known to use an air preheater to  
25 use this additional heat to heat incoming combustion air as a means of enhancing thermal efficiency. In accordance with the present disclosure, an air preheater is described which provides a compact configuration with high thermal efficiency.

**[0010]** In the Stirling engine of the type employing four double acting cylinders, there are four discrete volumes of working gas which are isolated from one  
30 another (except by leakage across the pistons). In order to enable the engine to operate smoothly and with minimal force imbalances, the mean pressure of each

of these four volumes need to be equalized. In accordance with this engine, this is achieved in part by connecting together the four volumes through small orifices. In addition, a system is provided for determining that the mean pressure in each cycle is within a predetermined range. Upon the occurrence of a component failure causing leakage, a significant imbalance could result which could have a destructive effect on the engine. The described Stirling engine can feature a pressure control system which unloads the engine upon the occurrence of such failure.

**[0011]** The Stirling engine can feature a control valve component which, in part, provides the unloading feature mentioned previously. The control valve also provides one of the intended working gas leakage paths which forms part of the pressure balancing system.

**[0012]** A critical component in the Stirling engine of the type described previously involves providing highly reliable seals between the high pressure displacer pistons and the low pressure drive case of the machine. Separating these two volumes is a piston rod seal assembly. Each piston connecting rod reciprocates through a piston rod seal which needs to reliably seal against the piston rod to maintain a low loss rate of working gas to the atmosphere. Absolute sealing of gas leakage through this area is likely not achievable. However, the piston rod seal assembly provides low levels of leakage and reduces contamination of the working gas through "pumping" of lubricating oil in the drive case region.

**[0013]** Another critical design feature for enhancing efficiency of the Stirling engine comes from the design of the piston assembly. The displacer piston separates the hot and cold fluid spaces of the engine and reacts against gas pressures in these areas to deliver mechanical power. Thermal conduction losses across the piston between the hot and cold spaces need to be minimized to enhance efficiency. Moreover, a highly reliable sliding gas seal is required between the piston rings and the cylinder bore. In addition to constituting a thermal

## 5A

loss, such leakage across the piston seals further results in a net mass exchange of working gases between the individual cycle volumes of the Stirling engine. Significant differences in leakage across the piston seals can result in rapidly changing gas volumes in the cycle volumes. Although means are provided for reducing such imbalances, it is desirable to reduce the rate at which these imbalances occur.

**[0014]** Additional benefits and advantages of the present invention will become apparent to those skilled in the art to which this invention relates from the subsequent description of the preferred embodiments and the appended claims, taken in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0015]** The drawings described herein are for illustration purposes only and are not intended to limit the scope of the present teachings.

**[0015A]** Figure 1 is a longitudinal cross-sectional view through a Stirling engine;

**[0016]** Figure 2 is an enlarged cross-sectional view of the drive case assembly shown in Figure 1;

**[0017]** Figure 3 is an enlarged cross-sectional view of the cylinder block section shown in Figure;

**[0018]** Figure 4 is an enlarged cross-sectional view taken from Figure 1 showing in greater detail the heater assembly of the engine;

**[0019]** Figure 5 is an end view of the cylinder block component taken from the heater assembly end of the engine with the heater assembly omitted;

**[0020]** Figure 6 is a cross-sectional view of the piston assembly;

**[0021]** Figure 7 is an enlarged view of the piston seal portion of Figure 6;

**[0022]** Figure 7 a is an elevational view of a seal shown in Figure 7;

**[0023]** Figure 8 is a cross-sectional view of the rod seal assembly;

**[0024]** Figure 9 is an enlarged cross-sectional view of the cap seal assembly also shown in Figure 8;

**[0025]** Figure 9a is an elevational view of a seal shown in Figure 9;



## 5B

**[0026]** Figure 10 is an enlarged cross-sectional view of the base seal assembly shown in Figure 8;

**[0027]** Figure 11 is a diagrammatic view showing the pressure balancing circuits of the Stirling engine; and

**[0028]** Figure 12 is a cross-sectional view of a solenoid operated control valve.

## DETAILED DESCRIPTION OF THE INVENTION

**[0029]** Stirling engine in accordance with a preferred embodiment of the invention is shown in an assembled condition in Figure 1 and is generally designated by reference number 10. Stirling engine 10 includes a number of primary components and assemblies including drive case assembly 12, cylinder block assembly 14, and heater assembly 16 (best shown in Figure 4).

## OVERALL CONSTRUCTION

**[0030]** Drive case assembly 12 includes a housing 18 having a pair of generally flat opposed mating surfaces 20 and 22 at opposite ends. Mating surface 22 is adapted to be mounted to cylinder block assembly 14. Drive case housing 18 has a hollow interior and includes a journal 24 for mounting a drive shaft bearing. Arranged around the interior perimeter of drive case housing 18 is a series of cross head guides 26. A pair of adjacent guides 26 is provided for each of the four cross head assemblies 56 of the engine (which are described below). As will be evident from a further description of Stirling engine 10, it is essential that adjacent guides 26 have running surfaces which are parallel within extremely close tolerances.

**[0031]** At one end of drive shaft 40 there is provided journal bearing 24. Drive case housing 18 also provides a central cavity within which oil pump 44 is located

Oil pump 44 could be of various types such as a gerotor type. Through drilled passageways 45, high pressure lubricating oil is forced into spray nozzles which spray a film of lubricant onto the piston rods (described below). In addition, lubricant is forced through internal passages 41 within drive shaft 40 to provide lubrication for swashplate 52.

**[0032]** At a lower portion of drive case 18, a sump port 50 is provided. The lubrication system of engine 10 can be characterized as a sump type with oil collecting in the interior cavity of drive case 12 being directed to oil pump 44 by suction, where it is then pumped to various locations and sprayed as mentioned previously.

**[0033]** Driveshaft 40 supports swashplate 52 which is generally circular and planar but is oriented at an angle inclined with respect to the axis of rotation of the driveshaft. Rotation of driveshaft 40 causes swashplate 52 to rotate about an inclined axis. This basic swashplate configuration is a well known design implemented by the Assignee and its predecessor company in prior Stirling engine configurations. Attached to an end of drive shaft 40 is an output coupler 54 enabling connection to a mechanical load, which as previously stated, may be of various types. Flywheel 53 rotates with drive shaft 40. Inductive pickup 55 is positioned near the outer diameter of flywheel 53 and responds to teeth or gaps in the outer diameter to provide electrical signals related to flywheel rotation.

**[0034]** Cylinder block assembly 14 defines a series of four counter bored rod seal bores 48 with passageways 37 and 35 connecting between them (shown in Figure 5). A number of components attached to mounting surface 49 including regenerator housings 122 and cylinder extensions 116 which are described in more detail in the following sections. Cylinder block assembly 14 further defines four cylinder bores 94 aligned with the rod seal bores 48. Additional components are attached to cylinder block surface 90. Cylinder extension 116 and regenerator housings 122 are connected with cylinder block surface 90 which are bolted to the cylinder block.

## CROSS HEAD ASSEMBLY

**[0035]** With continued reference to Figures 1 and 2, cross head body 58 forms a caliper with a pair of legs 60 and 62 connected by center bridge 64. Each of legs 60 and 62 define surfaces for running along guides 26. Cross head leg 62 also forms slider cup bore 72. Within bore 72 is positioned slider cup 74 which forms a semispherical surface 75. Crosshead leg 60 has a surface machined with a semispherical surface 76. Slider elements 78 and 80 also define spherical outside surfaces which are nested into the mating slider cup surfaces 75 and 76. Opposing flat surfaces 82 and 84 are formed by the slider elements and engaged swashplate 52. The swashplate surfaces may be made conical or crowned to generate line contact with the slider elements.

#### CYLINDER BLOCK

**[0036]** Cylinder block assembly 14, best shown in Figures 1 and 3, includes a cylinder block casting 86 having a pair of opposed parallel generally flat mating surfaces 88 and 90. Mating surface 88 enables cylinder block casting 86 to be mounted to drive case housing mating surface 22. Bolts 92 hold these two parts together. Stirling engine 10 according to the present invention is a four cylinder engine. Accordingly, cylinder block casting 86 defines four cylinder bores 94 which are mutually parallel. As shown in Figure 1, cylinder bores 94 define a larger diameter segment through which piston assembly 96 reciprocates, as well as a reduced diameter clearance bore section for rod seal assembly 98. Four cooler bores 102 are also formed in cylinder block casting 86 and are mutually parallel as well as parallel to cylinder bores 94. Cylinder bores 94 are arranged in a square cluster but lie on a circle outside that of cooler bores 102 as best shown in Figure 5. In that Stirling engine 10 is a double acting type, cylinder block casting 86 including working gas passageways (not shown) which connect the bottom end of regenerator bore 102 to the bottom end of an adjacent cylinder bore 94. Cylinder block casting 86 further forms coolant passageways which provide for a flow of liquid coolant through cylinder block 14. Pressure transducer ports 34 enable mounting of pressure transducers (not shown) for measuring cycle pressure at the bottom of each piston assembly 96.

#### COOLER ASSEMBLY

**[0037]** Cooler assemblies (not shown) are disposed within cylinder block cooler bores. Cooler assemblies may comprise a shell and tube type heat exchanger with a number of tubes arranged to extend between ends of the housing. The Stirling cycle working gas is shuttled back and forth between the ends of the cooler housing and passed to the inside of the tubes. A coolant, preferably a liquid, is pumped in a cross flow manner through block coolant passages 107 and through the cooler assemblies to remove heat from the working gas.

#### CYLINDER EXTENSIONS

**[0038]** Cylinder block assembly 14 further mounts tubular tops or extensions 116 which form a continuation of cylinder block bores 94. At their open ends, tubular cylinder extensions 116 form a skirt 117 which allows them to accurately align with cylinder bores 94 by piloting. Seals 118 provide a fluid seal between cylinder block bores 94 and tubular cylinder extensions 116. Cylinder extensions 116 at their opposite ends form a heater tube manifold 120.

#### REGENERATOR HOUSING

**[0039]** Cup shaped regenerator housings 122 are provided which are aligned coaxially with cooler bores 102. Regenerator housing 122 define an open end and a closed top 126 having manifold 128 for communication with the heater assembly 16. Within regenerator housing 122 is disposed a regenerator (not shown) which, in accordance with known regenerator technology for Stirling engines, is comprised of a material having high gas flow as well as high thermal conductivity and heat absorption characteristics.

#### HEATER ASSEMBLY

**[0040]** Heater assembly 16 provides a means for inputting thermal energy into the Stirling cycle working gas and is shown in Figure 4. A combustor (not shown) is used to burn a fossil fuel and other combustible material. Alternatively, heat can be inputted from another source such as concentrated solar energy, or other sources. In Stirling engine 10, combustion gases flow axially toward the center of the engine where it is deflected to outwardly flow in a radial direction. An array of heater tubes

136 is arranged to conduct heat from the high gases that flow radially out of the engine. Heater tubes 136 are arranged to form an inner band and outer band with heat absorbing fins 140 therebetween. Heater tube manifolds 120 and 128 have internal passageways which connect the inner and outer bands of heater tubes 136.

#### AIR PREHEATER

**[0041]** Combustion gases which pass through heater tubes 136 are still at an elevated temperature and have useful heat energy which can be recovered to enhance the thermal efficiency of engine 10. This is achieved through the use of an air preheater (not shown) which has an annular ring configuration and surrounds the outer bank of heater tubes 136. The air preheater transfers waste heat from the exhaust gases.

#### PISTON ASSEMBLY

**[0042]** Piston assembly 96 is shown in assembled condition in Figure 6. As illustrated, piston assembly 96 principally comprises piston dome 146, piston base 148, and ring assembly 150. Piston assembly 96 slides within cylinder liner 144 which is mounted within cylinder block bores 94.

**[0043]** Piston dome 146 forms a hollow dome top 152 and a machined base section 154. Dome top 152 has a hollow interior 156. Since piston assembly 96 separates hot and cool spaces formed by the working gas, it is desirable to minimize heat exchange between the top and bottom ends of piston assembly 96 (with the top end at the right hand side of Figure 6 and the bottom end at the left hand side). Heat transfer through piston assembly 96 between its ends represents a thermal efficiency loss for Stirling engine 10. Accordingly, dome top 152 has a thin wall construction to minimize conductive heat transfer and interior 156 is hollow to minimize conductive heat paths. Piston base section 154 has a machined outer stepped diameter. The end of base section 154 forms threaded section 158 for assembly with piston base 148.

**[0044]** Piston base 148 has a machined bore section forming internal threaded section 162 which meshes with external threaded section 158 to enable

piston dome 146 and base section 154 to be threaded together and assembled as shown in Figure 6. Seal 164, located in seal groove 160, provides sealing connection between these components.

**[0045]** Referring also to Figure 7, the outer surface of piston base 148 features bearing groove 166 which receives elastomeric piston bearing 168. Bearing 168 has a thickness sufficient to bear directly against the inside surface (or bore) 145 of cylinder liner, keeping the metal components of piston assembly 96 from directly contacting the inside bore surface of cylinder liner 144. Bearing 168 does not provide gas sealing with bore 145 (i.e., it acts as a bearing and not a seal). The lower end of piston base section 148 provides a region for installation of piston ring assembly 150 which is sandwiched in place by fastening piston base plate 170 using cap screws 172. Ring assembly 150 is shown in greater detail in Figure 7.

**[0046]** Ring assembly 150 is fit within annular groove 174. Ring assembly 150 forms a pair of ring sets including upper ring set 176 and lower ring set 178. Ring sets 176 and 178 are positioned symmetrically on opposite radial surfaces of piston base land 184 which is held into position through clamping engagement between piston base plate 170 and piston base 148. Piston base land 184 is preferably formed of steel material and features an annular outer groove 186. Upper ring set 176 includes rings 177 and 179. Lower ring set 178 includes rings 181 and 183. The rings of ring sets 176 and 178 are preferably formed of an elastomeric material. Expander rings 180, also formed of an elastomeric material, are placed radially inboard of the ring sets 176 and 178, and have a sealing lip 182 which bears against ring 177 of the upper set and 181 of the lower set. Rings sets 176 and 178, expander rings 180, and bearing 168 may all be formed from a PEEK (polyetheretherketone) material.

**[0047]** Ring 177 of upper ring set 176 and ring 181 of lower ring set 178, both illustrated in Figure 7a feature a radial split 185 which provides a small leakage path for working gas to pass across the rings in a controlled manner. Rings 179 and 183 however are solid and do not feature a radial split. The radial splits 185 of rings 177 and 181 prevent pressure imbalances from occurring which otherwise can lead to pumping conditions.

**[0048]** Piston base section 148 forms a central tapered bore 188. Piston rod 192 has a tapered upper end 187 which fits within tapered bore 188. Piston rod 192 may have a threaded end 190 which can be engaged by an assembly tool to press-fit the piston rod tapered end into piston base taper bore 188. Piston rod 192 can be press-fit into tapered bore 188 and, after that operation is completed, these parts are connected. Piston dome 146 may be threaded in an assembled condition with base 154.

#### ROD SEAL ASSEMBLY

**[0049]** Rod seal assembly 98 is best shown with reference to Figures 8, 9, and 10. As illustrated, piston rod 192 is shown passing through rod seal assembly 98. As illustrated, piston rod 192 includes a central drilled bore 196 extending from its threaded end 190 to a point within rod seal assembly 98 intersecting with radial passageway 194. Passageways 196 and 194 communicate with piston dome interior 156 and to a hollow interior cavity 210 of the rod seal assembly 98 with the cavities maintained at a cycle minimum pressure, as described previously. Rod seal assembly 98 includes additional principal components including housing 202, cap seal assembly 204, and base seal assembly 206.

**[0050]** Housing 202 is formed of a rigid material such as steel and forms a recessed stepped bore 208 at its end facing piston assembly 96. Interior bore 210 forms a hollow interior volume and a stepped bore for accommodating base seal assembly 206. Radial passageways 212 are provided to communicate the interior cavities 210 of each of four rod seal assemblies 98 through passageways 37 drilled into the block. Interior cavities 210 are connected together with piston cavities 156 and define a volume at near minimum cycle pressure, designated later in this description as volume 282 in Figure 12. Radial passageway 214 provides a flow passageway for lubricating oil to be sprayed against the outer surface of piston rod 192 for providing lubrication and cooling. The outer diameter of housing 202 features a number of grooves and locating features to enable it to be sealed and mounted in position within rod seal bores 48 of block 14.

**[0051]** Cap seal assembly 204 is shown in detail in Figure 9 and is maintained in position by fastening cap seal plate 216 using screws. Cap seal assembly 204 is

trapped within the hollow interior cavity provided when cap seal plate 216 is fastened and positioned. As shown, at its end closest to piston assembly 96, cap seal assembly includes cap seal spacer 220 having an L-shaped cross-sectional configuration. Wave springs 222 are loaded into the radial cavity formed by cap seal spacer 220 and are used to place an axial load against other components of cap seal assembly 204. Cap seal spacer 220 bears against cap seal 224 which has an inner diameter 226 which bears against the outer surface of piston rod 192. Cap seal 224 has a semi-circular outer groove 228 and coil spring 230 is positioned around cap seal 224 and places a radially inward compressive force on the cap seal for enhanced sealing against the piston rod. Cap seal 224 features a radial split 232 which provides an intended gas leakage path. Cap seal 224 bears against cap seal seat washer 234. Cap seal assembly 204 is used to provide a wiping function along the outer diameter of piston rod 192. This provides a reduction in the pressure variation across cap seal assembly 204 to provide more effective gas sealing for the remaining components of the seal assembly 98. Cap seal assembly 204 further provides an oil wiping function to remove lubricating oil from the outer surface of piston rod 192 to prevent contamination of the cycle gases.

**[0052]** Base seal assembly 206, best shown in Figure 10, is positioned within housing interior bore 210. A pair of annular spring seats 236 and 238 is provided which produce an axial loading force for base seal assembly 206. Spring seats 236 and 238 feature posts 240 and 241 which locate coil springs 242. As illustrated, spring seat 236 bears against a shoulder within interior bore 210 to provide the axial loading force. Seal plug 244 is located in position within the housing bore and is maintained there through a snap ring 246 installed within groove 248. Seal plug 244 further features passageway 214 for the transfer of lubricating oil to spray against piston rod 192. The radial end face surface 254 of plug 244 is polished. Bearing against it is washer 256 made from a polyimide material and inner O-ring 258. Washer 256 and O-ring 258 permit seat 260 to shift relative to plug 244 with low friction. This allows seal seat 260 to stay centered up with rod 192 during operation of the engine 10.

**[0053]** Seal seat 260 features a concave semi-spherical surface 262 and a projecting inner post 264 which traps O-ring 258 in this trapped position. Rod seal



266 forms a projecting tubular section 268 and head 270 forming a convex semi-spherical surface 272 which further forms seal groove 274 which retains seal 276. Ideally, seal groove 274 is formed such that its side surfaces are tangent to the semi-spherical surface 272 of seal 266. The semi-spherical surface 262 of the seal seat 260 and its mating surface 272 of seal 266 enable the seal to respond to bending of piston rod 192 during operation of engine 10, as well as adjust to any misalignments of the piston rods with respect to rod seal assembly 98. The elastomeric components of cap seal assembly 204, including cap seal 224 and rod seal 266 may be formed from a PTFE (polytetrafluoroethylene) material. Although surfaces 262 and 272 are described as "semi-spherical", other matching concave and convex shapes deviating from purely spherical may also be used.

#### PRESSURE EQUALIZATION SYSTEM AND CONTROL VALVE ASSEMBLY

**[0054]** In operation of Stirling engine 10, it is important that the total mass of working fluid contained in the four enclosed volumes of the engine are maintained to have closely equal masses of working fluid. This is necessary to prevent average pressure differences between the enclosed volumes and therefore force imbalances from occurring in the engine. There are unavoidable losses of working gas through heater head assembly 16 and other leakage paths, as well as minute leakage across piston assembly 96 and across rod seal 98. Consequently, the Stirling engine in accordance with this invention provides a mechanism for allowing equalization in the mass of working gas existing in the four separate cycle volumes (each bounded at the top of one piston assembly 96 and the bottom of an adjacent piston assembly). In addition, it is desirable to reduce the starting torque required acting on driveshaft 40. This enables smaller capacity starting motors having lower torque outputs to be used for starting the engine. These systems are best described with reference to Figures 11 and 12. Cycle volumes of working gas 278 (typically hydrogen and helium) are designated in the figures as cycle volumes #0, #1, #2, and #3.

**[0055]** Figure 11 shows diagrammatically a system providing pressure balance. As the diagram illustrates, the gas of each of the cycles are represented in the figure as cycle volumes 278 designated individually as "cycle # 0", etc. These cycle volumes are interconnected through a number of pathways. Two pressure

volumes are formed within engine 10 including passageways 37 drilled into cylinder block 14 in a square arrangement when viewing the engine as shown in Figure 5 which are connected with rod seal internal cavities 210 and piston interiors 156 to collectively form a minimum pressure volume 282. Passageways 35 having restrictors 286, which may be in the form of capillary tubes having a diameter for example of 0.4mm, communicate with the working fluid space formed at the bottom of piston assemblies 96 and are therefore exposed to cyclically varying cycle pressure. The internal volume of passageways 35 at their point of intersection past restrictors 286 in the center space 39 of the engine form a mean pressure volume 280.

**[0056]** As stated previously, a minute leakage occurs between cycle volumes #0, #1, #2, and #3 across the rings of piston assemblies 96. This leakage pathway is designated diagrammatically in Figure 11 as restrictor 284. Passageways 35 drilled within cylinder block 14 provide a common volume through which cycle leakage occurs through restrictors 286. This allows a small net flow of working gas to be maintained within the mean pressure volume 280. Since the pressure applied to restrictors 286 cycles between the cycle volumes 278 maximums and minimums, a small net flow periodically occurs in both directions through the restrictors and thus maintaining volume 280 at near mean cycle pressure (here "mean" refers not only to a pressure which is the average of the minimum and maximum pressures, but to any intermediate pressure between the cycle minimums and maximums). Restrictors 286 are represented diagrammatically in Figure 11. As stated previously, rod seal volumes 210 are held a minimum pressure volume 282. Valve port 294 is exposed to minimum cycle pressure volume 282 through rod seal passageway 215, and to cycle pressure 278 in a radial space 235 surrounding rod seal assembly 98 (connected together through passageways 35 and restrictors 286). Housing ports 294 are aligned with cap seal passageway 215 in cap seal housing 202. A radial space 235 between cap seal housing 202 and the cylinder block 86 communicates with the bottom of the pistons 96 and therefore undergoes the cyclically varying gas pressure of the working gas volumes.

**[0057]** Valve assemblies 288 are provided for each of the cycle volumes and are described in more detail as follows. Diagrammatically, valve assemblies 288 act

as a solenoid actuated check valve 290. Valve assembly 288 also produces a leakage path through valve orifice 292 acting as a restrictor. When valve 288 is electrically actuated, a free flow between the cycle volumes 278 into minimum pressure volume 282 occurs. This minimizes engine starting torque and allows piston assemblies 96 to be reciprocated with low starting torque.

**[0058]** Valve 288 is illustrated in detail in Figure 12. Valve assemblies 288 are each installed within ports 294 in cylinder block 86 with plug 293 extending into cap seal passageway 215. As illustrated in Figure 11, valve assemblies 288 control fluid movement between the minimum pressure volume 282 and the cycle volumes 278. These two pressure volumes are separated through sealing provided by O-ring 300 around the head end 295 of plug 293. Valve assembly 288 includes valve body 302 having a threaded end 304, allowing it to be fixed into position within the associated ports 294. Valve body 302 forms an internally stepped bore 306. Sleeve assembly 308 is fastened in position relative to valve body 302 by installing threading cap 310. Within sleeve assembly 308 is moveable plunger 312 which is held in a normal position against seat 314 by coil spring 316. Coil winding 320 surrounds sleeve assembly 308. When electric current is passed through winding 320, plunger 312 is caused to move away from seat 314, allowing free passage of fluid between the volumes 282 and 278, thus effectively connecting together the cycle volumes. This free passage of gas between cycles reduces starting torque and can rapidly reduce power output in a condition of a failure of an engine component or other need to quickly unload the engine. Since plunger 312 is spring loaded into engagement with seat 314, higher pressure in passageway 296 urges plunger 312 to move away from sealing engagement with seat 314 and thus the valve assembly 288 acts as a check valve 290 in conditions where current is not flowing into coil windings 320. In one embodiment, valve 288 has a plunger lift-off (or cracking) pressure of less than about 1.0 Mpa (i.e., plunger 312 unseats at that pressure difference). Unless plunger 312 is actuated, gas flow in a reverse direction (from cycle volumes 278 to minimum pressure valve 282) is inhibited (although a controlled "leak" occurs across restrictor 292).

**[0059]** Referring back to Figure 11, whenever the minimum pressure volume 282 is at a pressure less than the lowest pressure occurring in the cyclical pressure

variations of any of the cycle volumes 278 by more than the lift-off pressure of plunger 312, no fluid is transferred through valve assembly 288. If however, the minimum pressure experienced in any one of the cycle volumes 278 is less than the pressure of minimum pressure volume 282 by more than the lift-off pressure, a net force acts on valve assembly plunger 312 to urge it to open. A spring force applied to plunger by coil spring 316 is adjusted such that if this difference in pressure exceeds a predetermined amount (the lift-off pressure), plunger 312 unseats allowing fluid to be moved out of minimum pressure volume 282, thus maintaining at its desired low pressure value in that volume. Orifice 292, shown in Figure 12 and diagrammatically in Figure 11 provides a controlled leak between the cycle volumes 278 and minimum pressure volume 282. This mechanism is another way in which gas is exchanged between the cycle volumes 278 which maintains the mass of gas in each cycle #0, #1, #2, and #3 to be balanced as engine 10 is operating.

**[0060]** As mentioned previously, if valve assembly 288 is actuated, the "short circuit" or free flow of gas of cycle volumes 278 to one another interrupts the thermodynamic cycle of operation of Stirling engine 10 but permits low starting torque to put the mechanical components of the engine in motion, and also provides the unloading feature mentioned previously. During a prolonged period after stopping operation of engine 10, the various pressure volumes in the engine will tend to equalize in pressure. Once engine 10 is operated and valve assembly 288 is de-energized (allowing plunger 312 to seat) the cycle volumes 278 undergo their pressure variations from a minimum to a maximum level in a cyclical manner. As mentioned previously, whenever any one of cycle volumes 278 goes to a pressure level less than the existing pressure in minimum pressure volume 282 by an amount exceeding the check valve lift-off pressure, minimum pressure volume 282 is "pumped down" to a steady state pressure which is slightly greater than the minimum pressure experienced in the cycle volumes 278. Thus during operation, if any one of the cycles #0, #1, #2, or #3 exhibits a pressure imbalance with the other cycles in which its minimum pressure during cyclical variation is below that of the other cycles, a net flow of working gas into that cycle will occur as its respective check valve 290 operates. The continuous leakage paths provided by each of restrictors 292 causes a net periodic flow through each of the restrictors which is

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another means by which the volume or mass of working gas in each of the cycle volumes 278 are equalized during operation of the engine. Another mechanism for the exchange of gas between the cycle volumes 278 occurs by the leakage path to the center space 39 of the engine which is held at the mean pressure as mentioned previously. A constant shuttling of minute quantities of gas occurs through each of the restrictors 286 during operation of the engine. Since the mean pressure volume 280 communicates with each of the cycle volumes 278, this mechanism provides a means of exchanging gas between the cycle volumes. It is acknowledged that any leakage of working gas in cycles 278 has the effect of reducing the magnitude of maximum and minimum pressures which leads to an efficiency penalty for the engine. However, by maintaining the leakage gas through restrictors 288 and 286 to minute levels, any degradation in performance becomes negligible.

**[0061]** It is to be understood that the invention is not limited to the exact construction illustrated and described above, but that various changes and modifications may be made without departing from the spirit and scope of the invention as defined by the following claims.

**[0062]** Throughout this specification and the claims which follow, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

**[0063]** The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that that prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

## THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A piston assembly for a Stirling cycle engine of the type having two or more of the piston assemblies reciprocating within cylinder bores, each of the piston assemblies separating isolated cycle volumes of a working gas contained within the engine, the piston assembly comprising:

a piston dome forming a top end and a bottom end, the dome having a hollow interior,

a piston base affixed to the piston dome bottom end,

a connecting rod affixed to the piston base,

an upper and a lower ring set positioned within a ring groove for sealing with the cylinder bore,

a land ring positioned within the ring groove between the upper and lower ring sets, a first ring of the upper ring set positioned on a side of the land ring toward the dome top end and the second ring of the upper ring set positioned below the first ring and adjacent to the land ring, a first ring of the lower ring set positioned on a side of the land ring toward the piston base, and a second ring of the lower ring set positioned between the first ring of the lower ring set and the land ring, and

an upper and a lower expander ring respectively positioned radially inboard of the upper and lower ring sets and each expander ring formed of elastomeric material,

wherein the first rings of the upper and lower ring sets have a radial split, and

wherein each expander ring has a lip engaging respectively the first ring of the upper or lower ring set and in that the second rings of the upper and lower ring sets are solid rings.

2. A piston assembly for a Stirling cycle engine in accordance with claim 1, wherein the first or second rings of the upper or lower ring sets are formed of an elastomeric material.

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3. A piston assembly for a Stirling cycle engine in accordance with claim 2, wherein the elastomeric material comprises PEEK.
4. A piston assembly for a Stirling cycle engine in accordance with any one of claims 1-3, wherein the land ring forms an outer diameter surface which has a radial clearance with the surface of the cylinder bore.
5. A piston assembly for a Stirling cycle engine in accordance with any one of claims 1-4, wherein the piston base forms at least part of a first ring groove section of the ring groove for the upper ring set and a piston base plate forming at least part of a second ring groove section of the ring groove for the lower ring set, the land ring being clamped between the piston base and the piston base plate.
6. A piston assembly for a Stirling cycle engine in accordance with claim 5, further comprising threaded fasteners clamping the piston base plate to the land ring and the piston base.
7. A piston assembly for a Stirling cycle engine in accordance with any one of claims 1-6, wherein the piston base forms a bearing groove with a piston bearing positioned in the bearing groove and engaging the surface of the cylinder bore.
8. A piston assembly for a Stirling cycle engine in accordance with any one of claims 1-7, wherein the piston base forms a tapered bore for receiving the connecting rod.
9. A piston assembly for a Stirling cycle engine in accordance with any one of claims 1-7, wherein the piston dome and the piston base are affixed together by meshing threads.

10. A piston assembly in accordance with any one of claims 1-8, wherein the working gas is hydrogen or helium.

11. A piston assembly for a Stirling cycle engine of the type having two or more of the piston assemblies reciprocating within cylinder bores, each of the piston assemblies separating isolated cycle volumes of a working gas contained within the engine, the piston assembly comprising:

a piston dome forming a top end and an open bottom end, the dome having a hollow interior,

a piston base affixed to the piston dome at the bottom end,

a connecting rod affixed to the piston base,

upper and lower ring sets positioned within a ring groove,

a land ring positioned within the ring groove between the upper and lower ring sets, the land ring having an outer diameter surface which has a radial clearance with the surface of the cylinder bore, a first ring of the upper ring set positioned on a side of the land ring toward the dome top end and a second ring of the upper ring set positioned between the first ring of the upper ring set and the land ring, a first ring of a lower ring set positioned on a side of the land ring toward the piston base, and a second ring of the lower ring set positioned between the first ring of the lower ring set and the land ring, and

an upper expander ring and a lower expander ring each respectively positioned radially inboard of the upper and lower ring sets and each formed of an elastomeric material and each having a lip engaging respectively the first ring of each of the upper and the lower ring sets,

wherein the first rings of the upper and lower ring sets have a radial split, and

wherein the second rings of the upper and lower ring sets are solid rings.

12. A piston assembly for a Stirling cycle engine in accordance with claim 11, wherein the first or second rings of the upper or lower ring sets are formed of an elastomeric material.



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13. A piston assembly for a Stirling cycle engine in accordance with claim 12, wherein the elastomeric material comprises PEEK.

14. A piston assembly for a Stirling cycle engine in accordance with any one of claims 11-13, wherein the piston base forms at least part of a first ring groove section of the ring groove for the upper ring set and a piston base plate forming at least part of a second ring groove section of the ring groove for the lower ring set, the land ring being clamped between the piston base and a piston base plate.

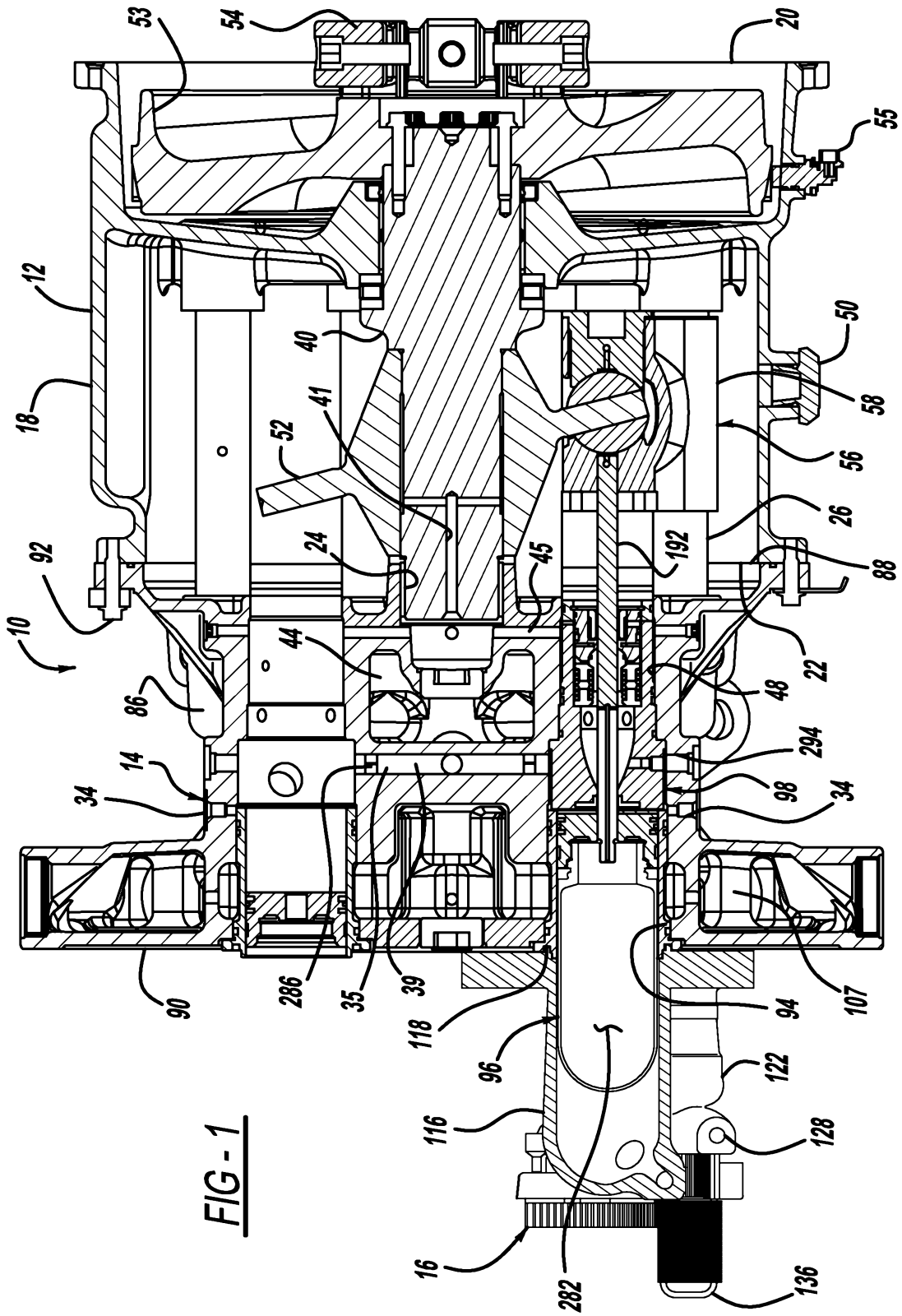
15. A piston assembly for a Stirling cycle engine in accordance with claim 14, further comprising threaded fasteners clamping the piston base plate to the land ring and the piston base.

16. A piston assembly for a Stirling cycle engine in accordance with any one of claims 11-15, wherein the piston base forms a bearing groove with a piston bearing positioned in the bearing groove and engaging the surface of the cylinder bore.

17. A piston assembly for a Stirling cycle engine in accordance with any one of claims 11-16, wherein the piston base forms a tapered bore for receiving the connecting rod.

18. A piston assembly for a Stirling cycle engine in accordance with any one of claims 11-17, wherein the piston dome and the piston base are affixed together at meshing threads.

19. A piston assembly in accordance with any one of claims 11-18, wherein the working gas is hydrogen or helium.



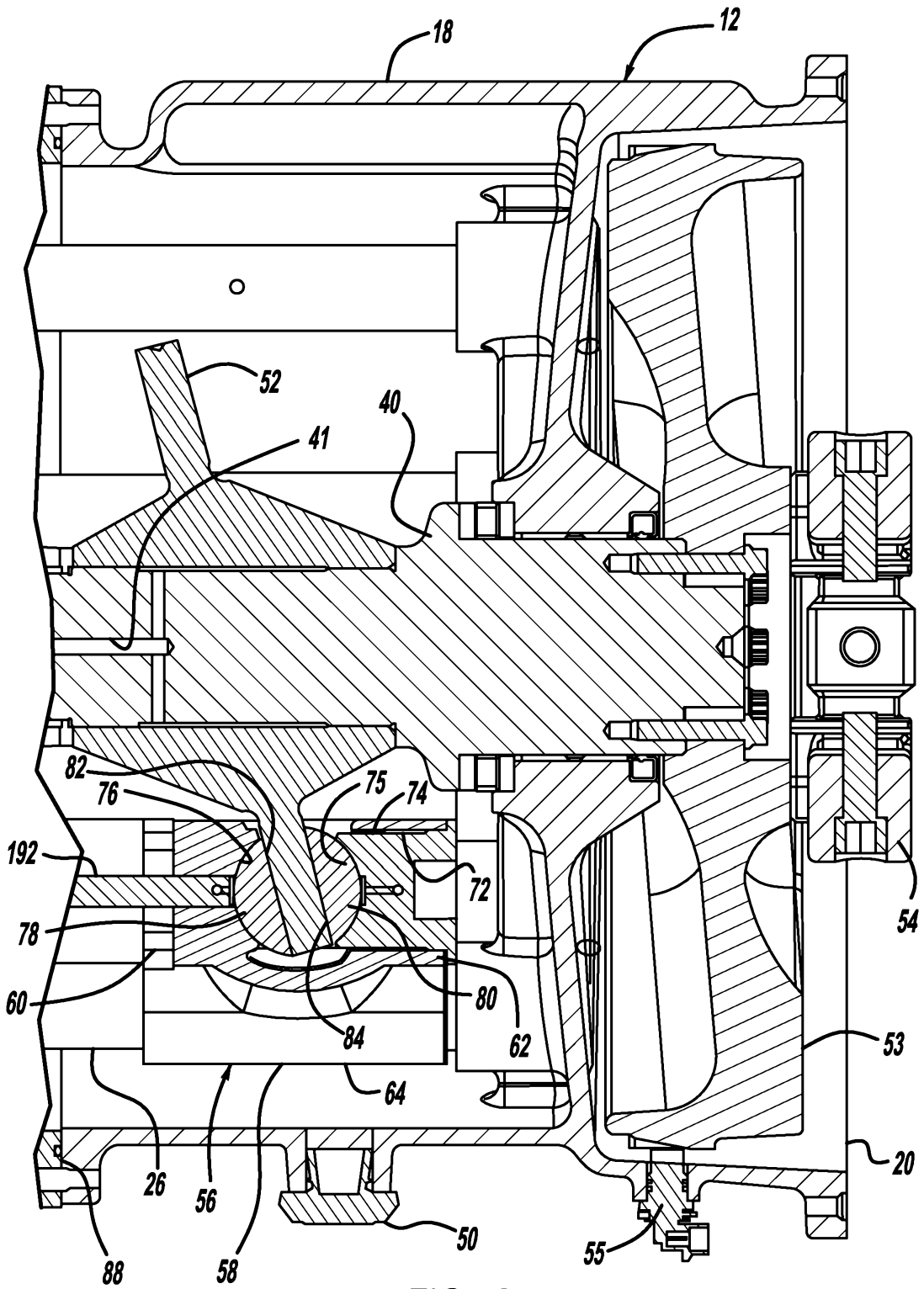
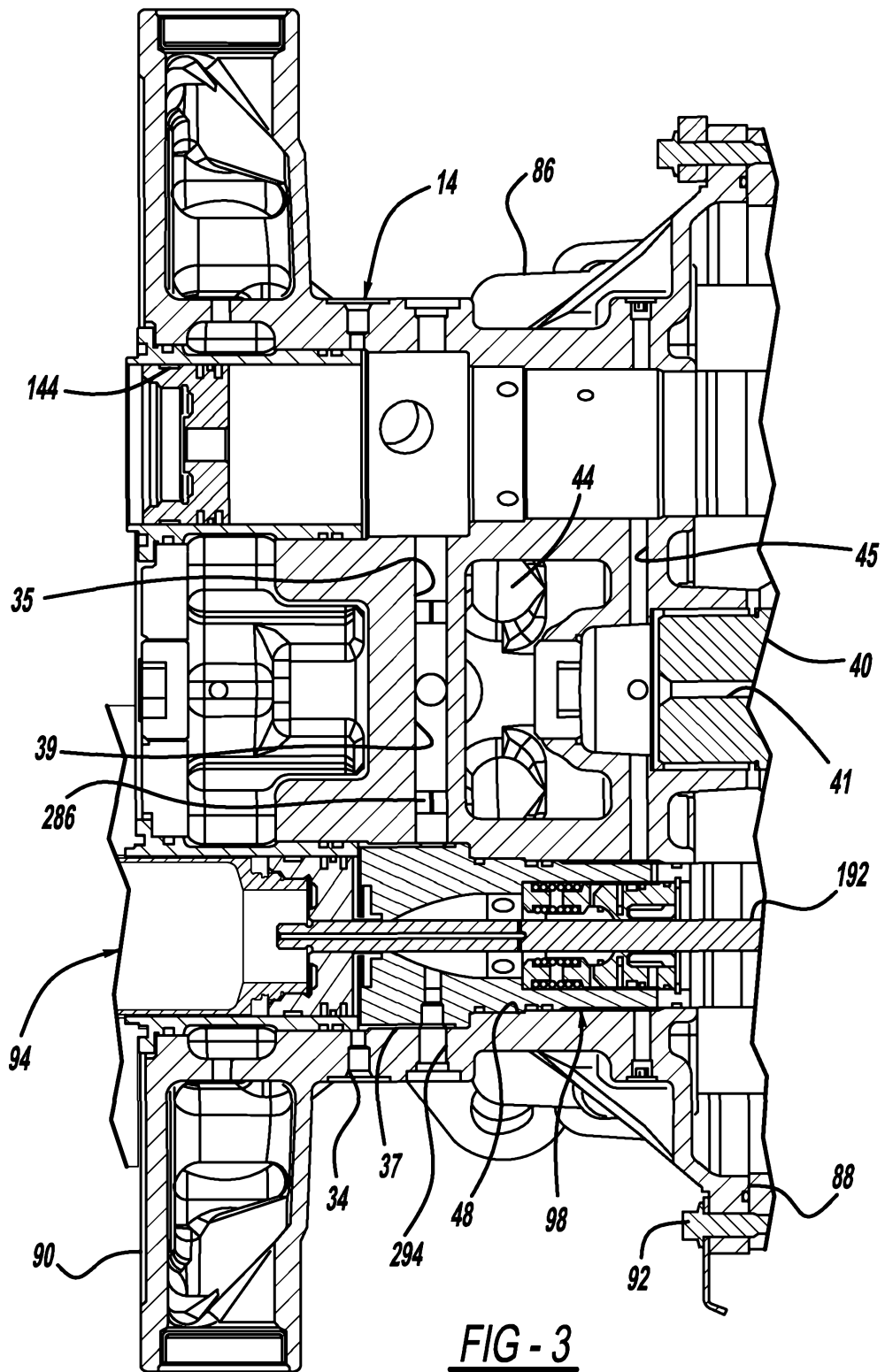
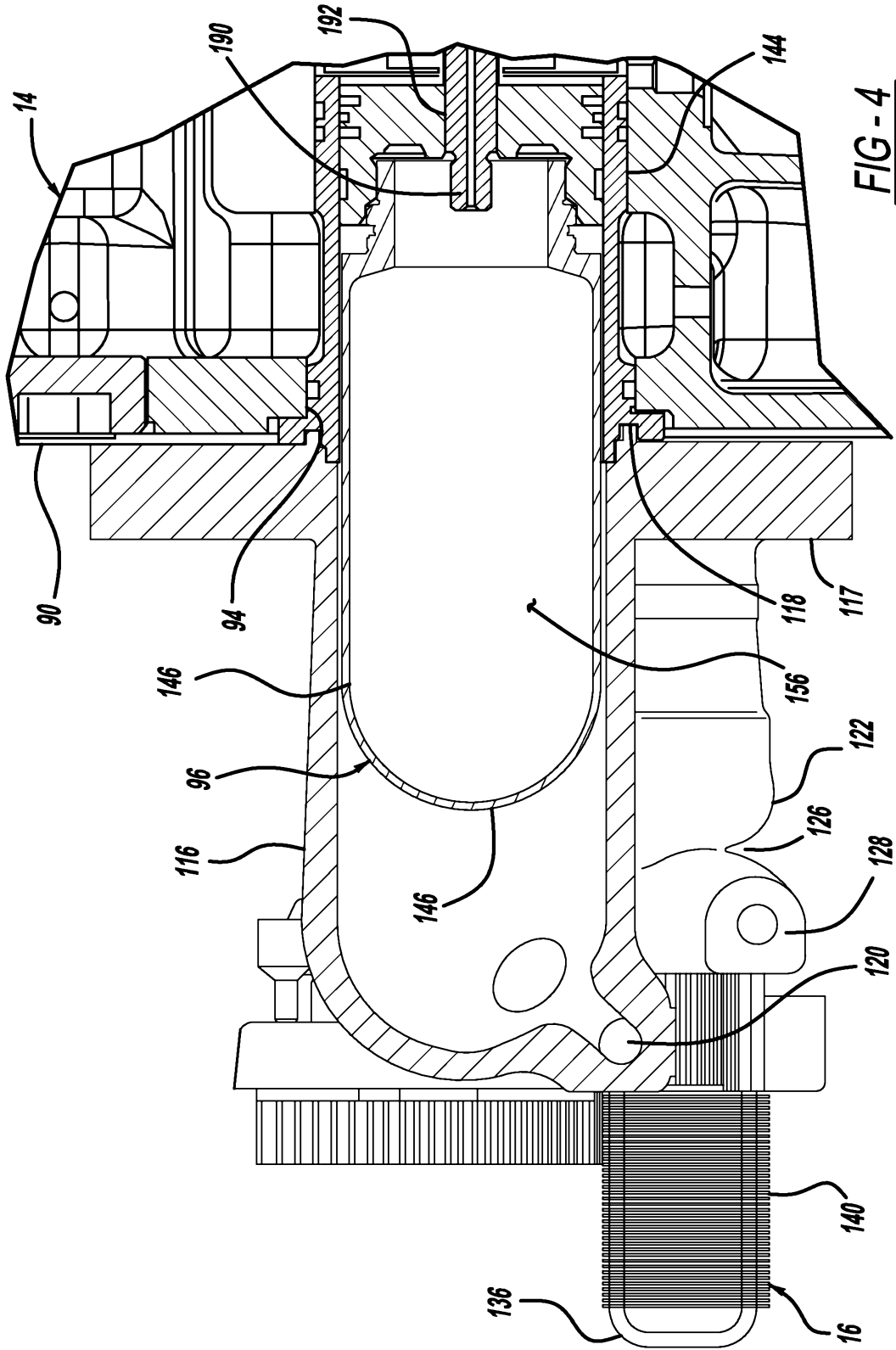


FIG - 2





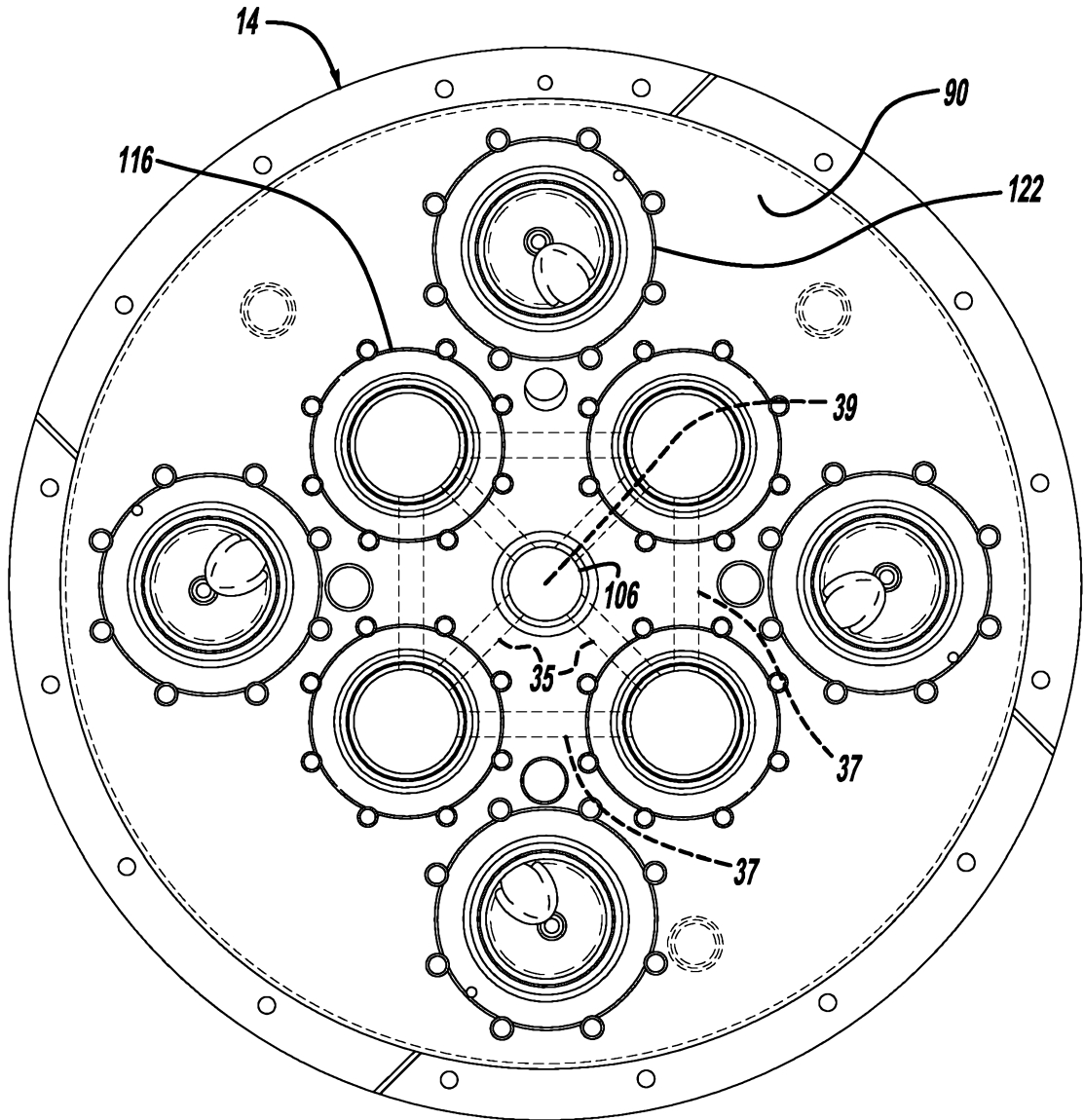


FIG - 5

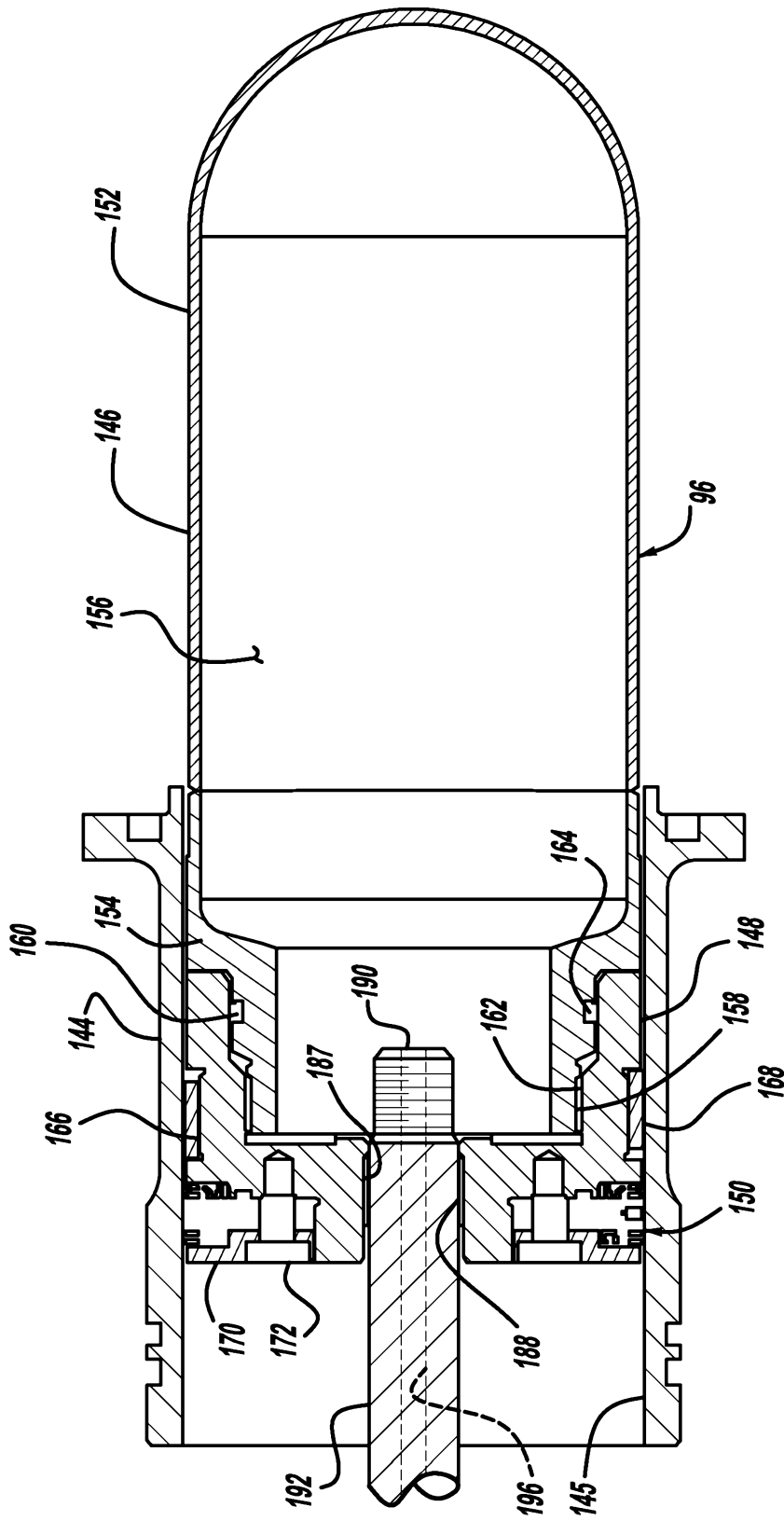
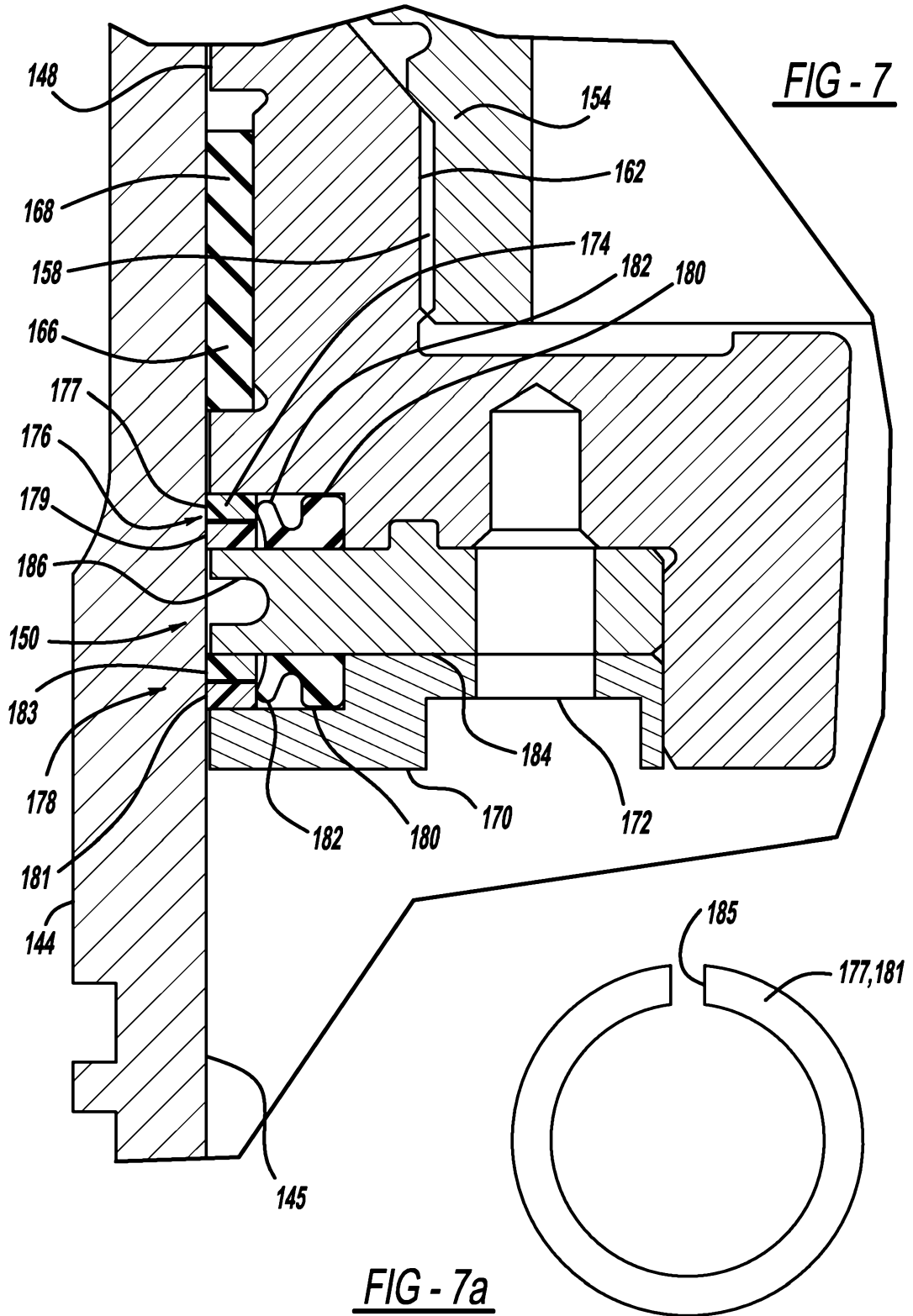
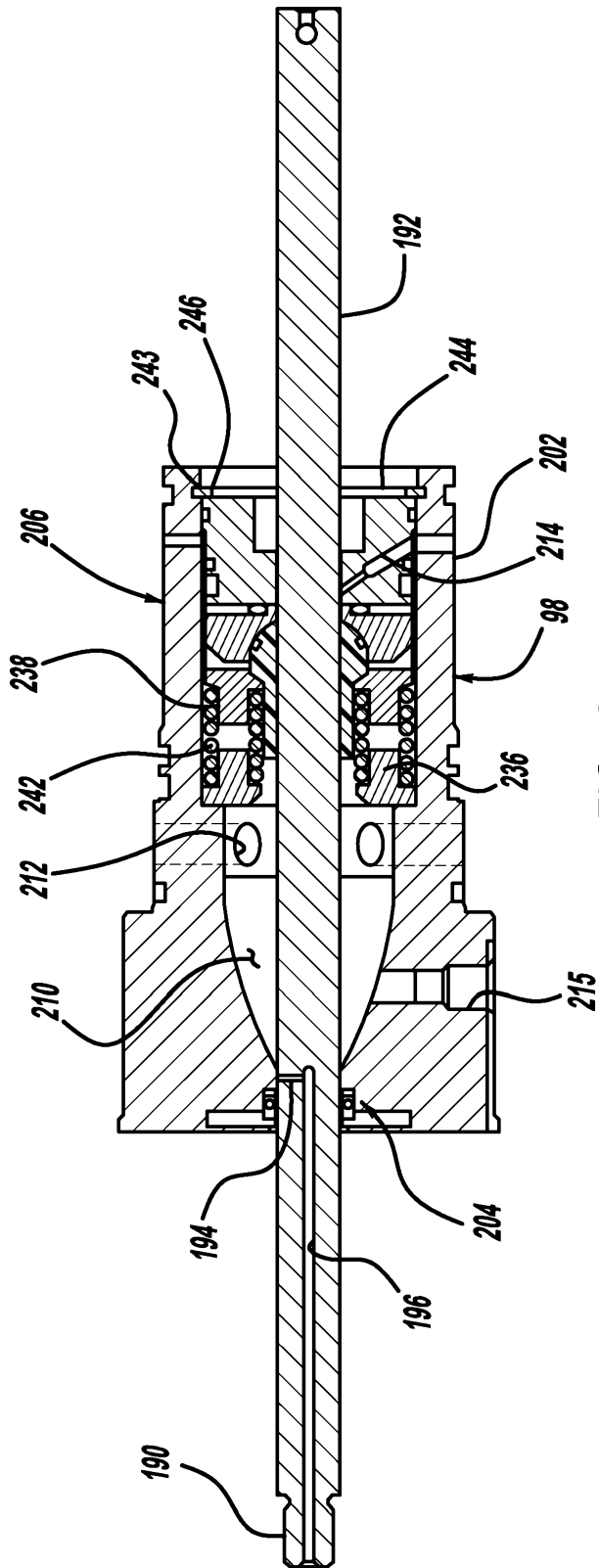


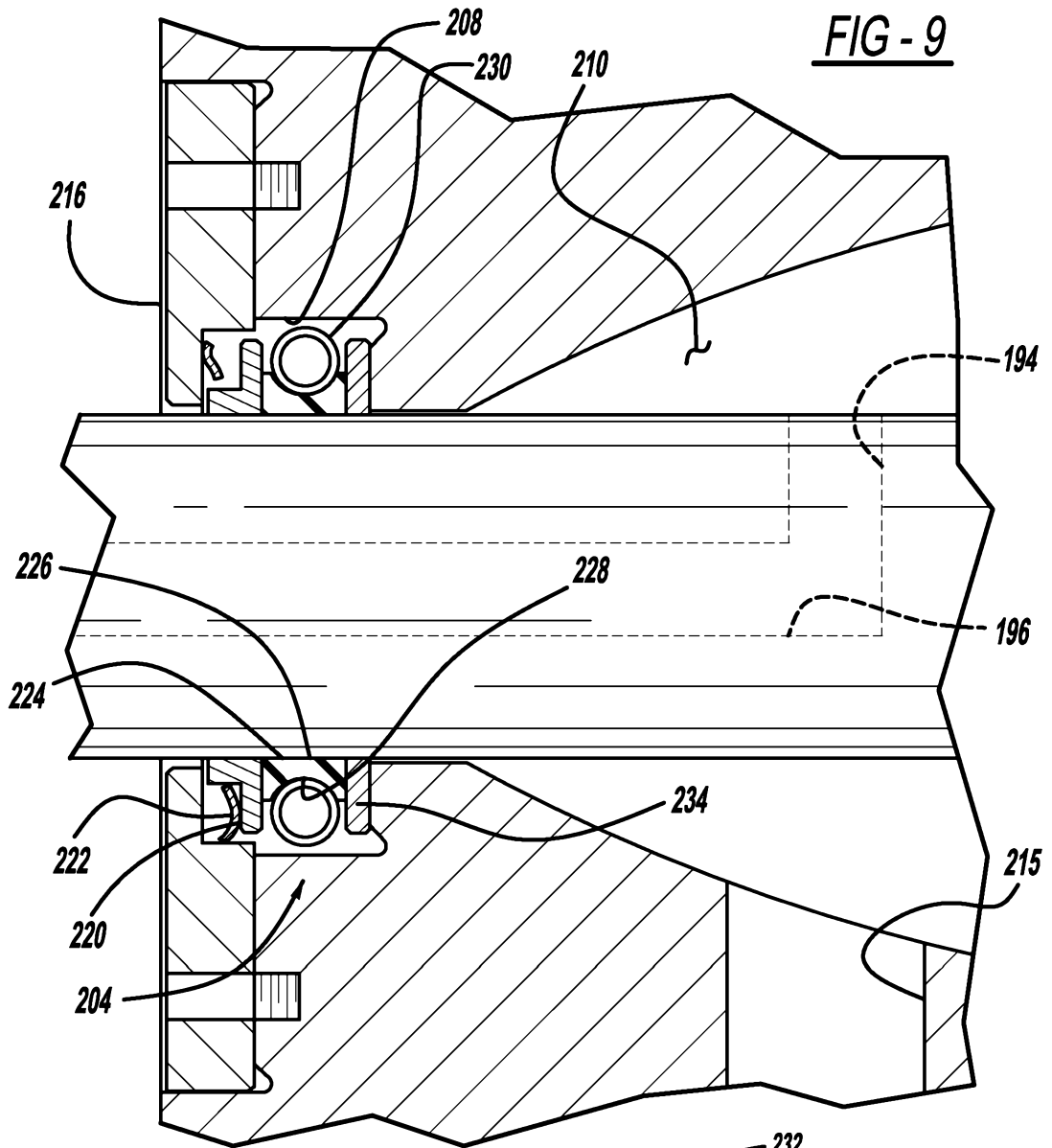
FIG - 6







**FIG - 8**



**FIG - 9**

**FIG - 9a**

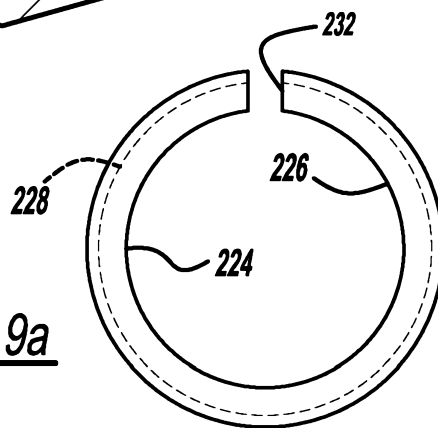
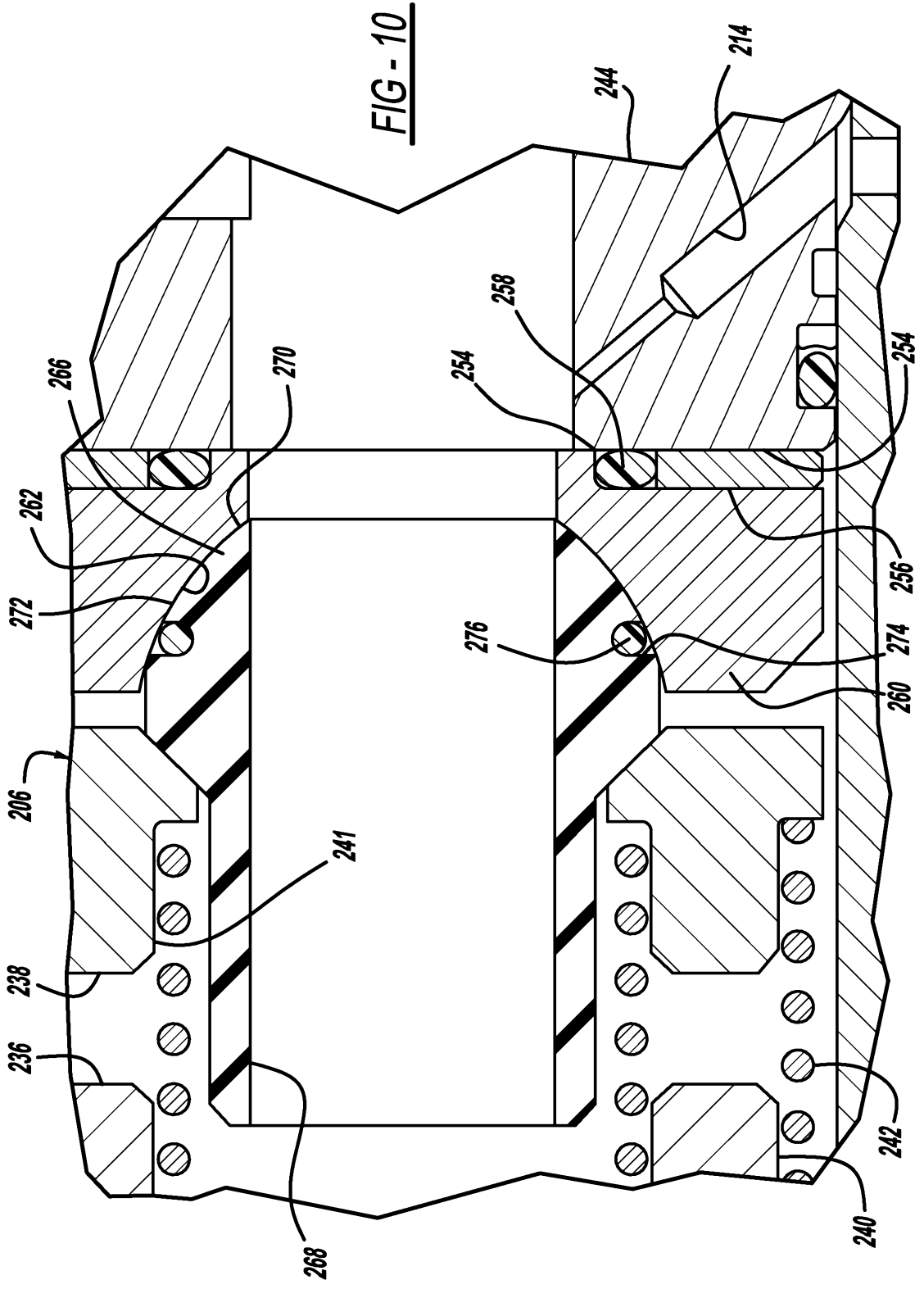
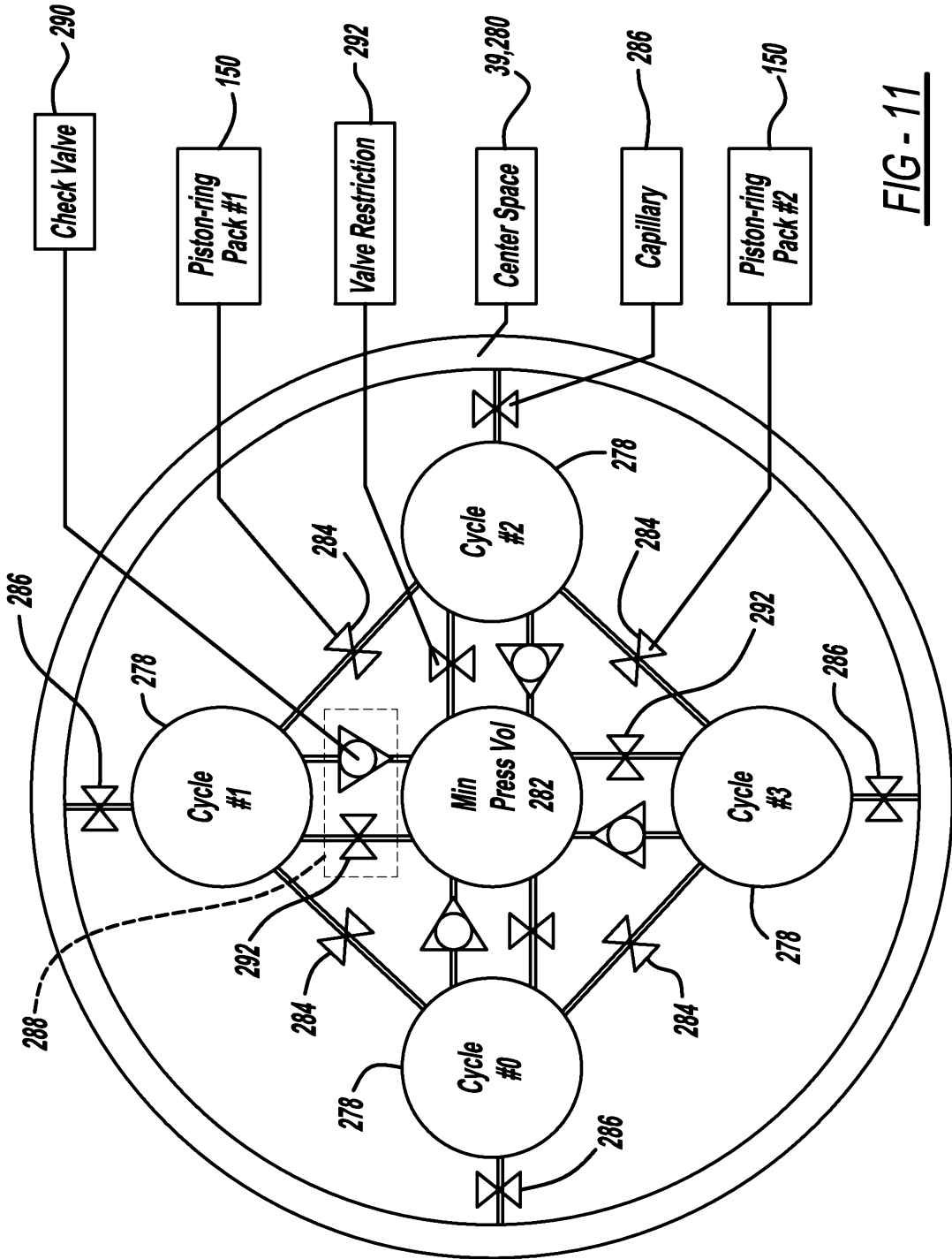


FIG - 10





**FIG - 11**

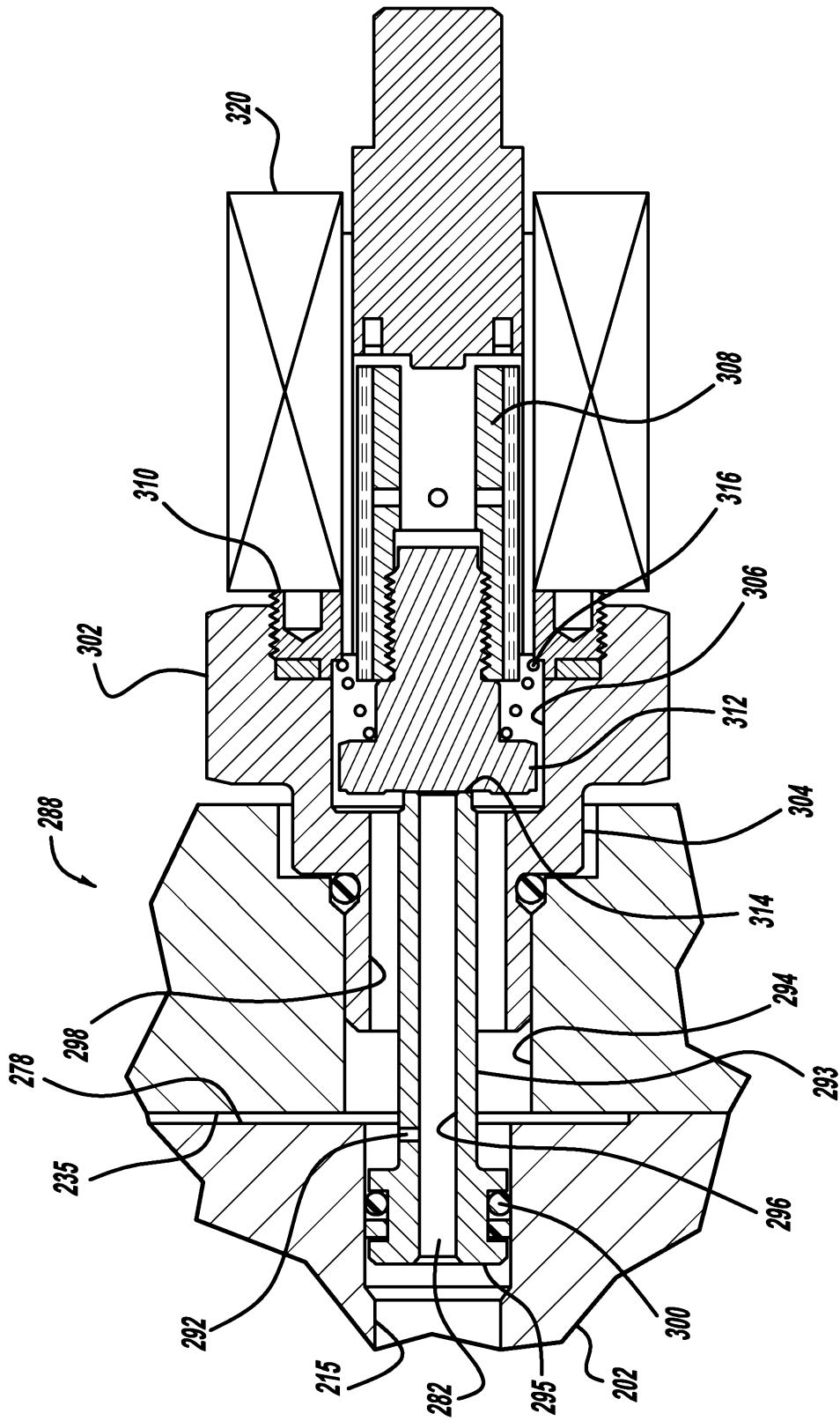


FIG - 12