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(54) Hydraulically-actuated fuel injector with direct control needle valve

Elektro-hydraulisch betätigtes Kraftstoffeinspritzventil mit einer Düsennadel, die direkt angesteuert wird

Injecteur de carburant à actionnement hydraulique avec une soupape à pointeau à commande directe

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Description

[0001] The present invention relates generally to fuel injection, and more particularly to hydraulically-actuated fuel injectors with direct control needle valve members, and fuel injection systems.

[0002] Known hydraulically-actuated fuel injection systems and/or components are shown, for example, in US-A-5,121,730, US-A-5,271,371, US-A-5,297,523 and US-A-5 522 545. In these hydraulically actuated fuel injectors, a spring biassed needle check opens to commence fuel injection when pressure is raised by an intensifier piston/plunger assembly to a valve opening pressure. The intensifier piston is acted upon by a relatively high pressure actuation fluid, such as engine lubricating oil, when a solenoid driven actuation fluid control valve opens the injector's high pressure inlet. Injection is ended by deactivating the solenoid to release pressure above the intensifier piston. This in turn causes a drop in fuel pressure causing the needle check to close under the action of its return spring to end injection. While these hydraulically actuated fuel injectors have performed magnificently over many years, there remains room for improvement, especially in the area of shaping an injection rate trace from beginning to end to precisely suit a set of engine operating conditions.

[0003] Over the years, engineers have discovered that engine emissions can be significantly reduced at certain operating conditions by providing a particular injection rate trace. In many cases emissions are improved when the initial injection rate is controllable, and when there is a nearly vertical abrupt end to injection. While these prior hydraulically actuated fuel injection systems have some ability to control the injection rate shape, there remains room to improve the ability to control injection rate shape with hydraulically actuated fuel injection systems.

[0004] The present invention is directed to improving the ability of hydraulically actuated fuel injectors to reliably produce better injection rate shapes during each injection event.

[0005] According to the present invention there is provided a hydraulically actuated fuel injector comprising:

an injector body that defines an actuation fluid cavity, a piston bore, and a nozzle outlet;
said piston bore includes a first bore, and a second bore;
a piston with a top being slidably received in said piston bore and movable between a retracted position and an advanced position;
said top of said piston including a first area that is separate from a second area;
said first area and said first bore defining a first cavity connected to said actuation fluid cavity through a relatively unrestricted flow area when said piston is in said retracted position;
said second area and said second bore defining a second cavity connected to said actuation fluid cavity through a relatively restricted flow area when said piston is in said retracted position; and
said first area being exposed to fluid pressure in said first cavity and said second area being exposed to fluid pressure in said second cavity over a portion of said piston's movement from said retracted position toward said advanced position;
at least one of said piston said injector body further defining a restricted passage connecting said actuation fluid cavity to said second cavity, and said restricted passage includes said restricted flow area; and
a needle valve member positioned in said injector body and movable between an open position in which said nozzle outlet is open and a closed position in which said nozzle outlet is blocked.

[0006] In the accompanying drawings:

Fig. 1 is a schematic view of a fuel injection system according to the present invention.
Fig. 2 is a sectioned side elevational view of a fuel injector.
Fig. 3 is a partial sectioned side elevational view of an upper portion of the fuel injector shown in Fig. 2.
Fig. 4 is a partial sectioned side elevational view of the lower portion of the injector shown in Fig. 2.
Fig. 5 is a sectioned side elevational view of a fuel injector according to the present invention.
Fig. 6 is a partial sectioned side elevational view of an upper portion of the fuel injector shown in Fig. 5.
Fig. 7 is a partial sectioned side elevational view of the lower portion of the injector shown in Fig. 5.
Figs. 8a-f are a group of curves showing component positions and injection parameters versus time over a single "ramp-square" injection event.
Figs. 9a-e are a group of curves showing component positions and injection parameters versus time over a "pilot plus square" injection event.
Fig. 10 is a partial sectioned side view of a stepped piston/barrel assembly according to another embodiment of the present invention.
Fig. 11 is a partial sectioned side view of a stepped piston/barrel assembly according to still another embodiment of the present invention.
Fig. 12a is the partial sectioned side view of a stepped piston/barrel assembly according to another embodiment of the present invention.
Fig. 12b is a top view of the central portion of the stepped piston shown in Fig. 12a.
Fig. 13 is a partial sectioned side view of the stepped piston/barrel assembly according to still another embodiment of the present invention.
Fig. 14 is a partial sectioned side view of a stepped piston/barrel assembly according to still another embodiment of the present invention.

[0007] Referring now to Fig. 1, there is shown an embodiment of a hydraulically-actuated electronically-controlled fuel injection system 10 in an example configuration as adapted for a direct-injection diesel-cycle internal combustion engine 12. Fuel system 10 includes one or more hydraulically-actuated electronically-controlled fuel injectors 14, which are adapted to be positioned in a respective cylinder head bore of engine 12. Fuel system 10 includes an apparatus or means 16 for supply actuating fluid to each injector 14, an apparatus or means 18 for supplying fuel to each injector, a computer 20 for electronically controlling the fuel injection system and an apparatus or means 22 for re-circulating actuation fluid and for recovering hydraulic energy from the actuation fluid leaving each of the injectors.

[0008] The actuating fluid supply means 16 preferably includes an actuating fluid sump 24, a relatively low pressure actuating fluid transfer pump 26, an actuating fluid cooler 28, one or more actuation fluid filters 30, a high pressure pump 32 for generating relatively high pressure in the actuation fluid and at least one relatively high pressure actuation fluid manifold 36. A common rail passage 38 is arranged in fluid communication with the outlet from the relatively high pressure actuation fluid pump 32. A rail branch passage 40 connects the actuation fluid inlet of each injector 14 to the high pressure common rail passage 38.

[0009] Actuation fluid leaving the actuation fluid drain 52, 54 (see Fig. 2) of each injector 14 enters a re-circulation line 27 that carries the same to the hydraulic energy re-circulating or recovering means 22. A portion of the re-circulated actuation fluid is channeled to high pressure actuation fluid pump 32 and another portion is returned to actuation fluid sump 24 via re-circulation line 33.

[0010] Any available engine fluid is preferably used as the actuation fluid in the present invention. However, in the preferred embodiments, the actuation fluid is engine lubricating oil and the actuation fluid sump 24 is an engine lubrication oil sump. This allows the fuel injection system to be connected as an additional subsystem to the engine's lubricating oil circulation system. Alternatively, the actuation fluid could be fuel provided by a fuel tank 42 or another source, such as coolant fluid, etc.

[0011] The fuel supply means 18 preferably includes a fuel tank 42, a fuel supply passage 44 arranged in fluid communication between fuel tank 42 and the fuel inlet 60 (Fig. 2) of each injector 14, a relatively low pressure fuel transfer pump 46, one or more fuel filters 48, a fuel supply regulating valve 49, and a fuel circulation and return passage 47 arranged in fluid communication between injectors 14 and fuel tank 42.

[0012] The computer 20 preferably includes an electronic control module 11 which controls 1) the fuel injection timing; 2) the total fuel injection quantity during an injection cycle; 3) the fuel injection pressure; 4) the number of separate injections or injection segments during each injection cycle; 5) the time intervals between the injection segments; 6) the fuel quantity of each injection segment during an injection cycle; 7) the actuation fluid pressure; and 8) any combination of the above parameters. Computer 20 receives a plurality of sensor input signals S_1 - S_8, which correspond to known sensor inputs, such as engine operating condition, load, etc., that are used to determine the precise combination of injection parameters for a subsequent injection cycle. In this example, computer 20 issues control signal S_9 to control the actuation fluid pressure and a control signal S_{10} to control the fluid control valve(s) within each injector 14. Each of the injection parameters are variably controllable independent of engine speed and load. In the case of injector 14, control signal S_{10} is current to the solenoid commanded by the computer.

[0013] Referring now to Figs. 2-4, a fuel injector 14 with a single three-way solenoid 75 is shown. Injector 14 includes an injector body 15 having an actuation fluid inlet 50 that is connected to a branch rail passage 40, actuation fluid drains 52 and 54 that are connected to actuation fluid recirculation line 27 and a fuel inlet 60 connected to a fuel supply passage 44. (See Fig. 1). Injector 14 includes a hydraulic means for pressurizing fuel within the injector during each injection event and a needle control valve that controls the opening and closing of nozzle outlet 63.

[0014] The hydraulic means for pressurizing fuel includes an actuation fluid control valve that alternately opens actuation fluid cavity 51 to the high pressure of actuation fluid inlet 50 or the low pressure of actuation fluid drain 52. The actuation fluid control valve includes a three-way solenoid 75 attached to a pin spool valve member 76. An intensifier spool valve member 78 responds to movement of pin spool valve member 76 to alternately open actuation fluid cavity 51 to actuation fluid inlet 50 or low pressure drain 52. The hydraulic pressurizing means also includes actuation fluid cavity 51 that opens to a piston bore 56, within which an intensifier piston 83 reciprocates between a return position (as shown) and a forward position. Injector body 15 also includes a plunger bore 58, within which a plunger 85 reciprocates between a retracted position (as shown) and an advanced position. A portion of plunger bore 58 and plunger 85 define a fuel pressurization chamber 64, within which fuel is pressurized during each injection event. Plunger 85 and intensifier piston 83 are returned to their retracted positions between injection events under the action of compression spring 84. Thus, the hydraulic means for pressurizing fuel includes the fuel pressurization chamber 64, plunger 85, intensifier piston 83, actuation fluid inlet 50, actuation fluid cavity 51 and the various components of the actuation fluid control valve, which includes solenoid 75, pin spool valve member 76, ball 53 and intensifier spool valve member 78, etc.

[0015] Fuel enters injector 14 at fuel inlet 60 and travels along fuel supply passage 66, past ball check valve 68 and into fuel pressurization chamber 64, when plunger 85 is retracting. Ball check 68 prevents the reverse flow of fuel from fuel pressurization chamber 64 into fuel supply passage 66 during the plunger's downward stroke. Unused fuel is re-circulated from each injector via a return opening 74. Pressurized fuel travels from fuel pressurization chamber 64 via a connection passage 69 to nozzle chamber 62. A needle valve member 86 moves within nozzle chamber 62 between an open position in which nozzle outlet 63 is opened and a closed position in which nozzle outlet 63 is closed. Needle valve member 86 is mechanically biassed to its closed position by a compression spring 89.

[0016] Needle valve member 86 includes opening hydraulic surfaces 87 exposed to fluid pressure within nozzle chamber 62 and a closing hydraulic surface 88 exposed to fluid pressure within a needle control chamber 72. Needle valve member 86 includes a needle portion 91 and intensifier portion 92 that are shown as separate pieces for ease of manufacturing, but both portions could be machined as a single integral component.

[0017] It should be appreciated that pressurized fuel acts upon the opening hydraulic surfaces 87 whereas actuation fluid acts upon the closing hydraulic surface 88. Preferably, the closing hydraulic surface and the opening hydraulic surface are sized and arranged such that the needle valve member 86 is hydraulically biassed toward its closed position when the needle control chamber is open to a source of high pressure fluid. Thus, in order to maintain direct control of needle valve member 86 despite high fuel pressure within nozzle chamber 62, there should be adequate pressure on the closing hydraulic surface 88 to maintain nozzle outlet 63 closed. When needle control chamber 72 is opened to a low pressure passage, needle valve member 86 performs as a simple check valve of a type known in the art, in that it opens when fuel pressure acting upon opening hydraulic surfaces 87 is greater than a valve opening pressure sufficient to overcome return spring 89. Thus, opening hydraulic surfaces 87 and closing hydraulic surface 88 are preferably sized and arranged such that the needle valve member is hydraulically biassed toward its open position when the needle control chamber is connected to a low pressure passage and the fuel pressure within the nozzle chamber is greater than the valve opening pressure.

[0018] In this injector, pin spool valve member 76 is not only considered part of the actuation fluid control valve, but also acts as the needle control valve to alternately open actuation fluid control passage 71 to the high pressure of actuation fluid inlet 50 or the low pressure in actuation fluid drain 54. One can control the opening and closing of nozzle outlet 63 when fuel is above a valve opening pressure by controlling the exposure of closing hydraulic surface 88 to either a source of high pressure fluid or a low pressure passage. Thus, in this injector, actuation fluid drain 54 constitutes a low pressure passage and actuation fluid inlet 50 constitutes a source of high pressure fluid.

[0019] Intensifier spool valve member 78 is biassed by a compression spring 82 from a closed position, as shown, toward an open position. When intensifier spool valve member 78 is in its closed position as shown, actuation fluid cavity 51 is closed to actuation fluid inlet 50, but open to low pressure actuation fluid drain 52. When intensifier spool valve member 78 moves under the action of compression spring 82 to its open position, actuation fluid cavity 51 is opened to actuation fluid inlet 50 and closed to drain 52. The position of intensifier spool valve member 78 is controlled by three position solenoid 75, which is capable of moving actuation pin spool valve member 76 between a first position, a second position, and a third position against the action of compression spring 77.

[0020] When solenoid 75 is de-energized, as shown, compression spring 77 pushes pin spool valve member 76 to the right to its first position in which actuation fluid control passage 71 is opened to second low pressure actuation fluid drain 54 past seat 65. At the same time, pin spool valve member 76 pushes ball 53 to close seat 59 and open seat 61 so that the end hydraulic surface 79 of intensifier spool valve member 78 is exposed to the low pressure of second drain 54. This causes the high pressure actuation fluid acting on the other end of intensifier spool valve member 78 to hold it in its closed position as shown against the action of compression spring 82. Thus, when solenoid 75 is de-energized, actuation fluid cavity is open to actuation fluid drain 52 and closed to actuation fluid inlet 50.

[0021] When solenoid 75 is energized with a full or pull-in current, pin spool valve member 76 is pulled to the left against its stop to a second position. When this occurs, the high pressure actuation fluid pushes ball 53 off of seat 59 to close seat 61. This causes intensifier spool valve member 78 to become hydraulically balanced and it moves toward the right to its open position under the action of compression spring 82. At the same time, pin spool valve member 76 closes control passage 71 to second drain 54 and opens actuation fluid control passage 71 to a transfer passage 70, which is open to the high pressure in actuation fluid cavity 51.

[0022] When solenoid 75 is energized with a medium or hold-in current, pin spool valve member 76 moves slightly to the right to a third position that is a sufficient distance to close actuation fluid control passage 71 to the high pressure in transfer passage 70 and re-open the same to low pressure drain 54. However, the hold-in current is not sufficient to cause any change in the position of intensifier spool valve member 78, which remains in its open position with actuation fluid cavity 51 open to high pressure actuation fluid inlet 50. When intensifier spool valve member 78 is in its open position, actuation fluid flows through inlet 50 into the hollow interior 80 of intensifier spool valve member 78, through radial openings 81, and then simultaneously into connection passage 70 and actuation fluid cavity 51.

[0023] Referring now to Figs. 5-7, a two-way solenoid fuel injector 14' is presented as an alternative to the three-way solenoid fuel injector 14 just described. Fuel injector 14' utilizes a single two-way solenoid 130 to alternately open actuation fluid cavity 109 to actuation fluid inlet 106 or low pressure actuation fluid drain 104, and uses the same solenoid 130 to control the exposure of a needle control chamber 118 to a low pressure passage or a source of high pressure fluid. Fuel injector 14' could be substituted in for the injectors 14 shown in Fig. 1 since both injectors perform substantially similar while one uses a single three-way solenoid and the other uses a single two-way solenoid to accomplish the same tasks. The single two-way solenoid of injector 14' accomplishes what the three-way solenoid of injector 14 does by exploiting a hysteresis effect in the actuation fluid control valve versus the quick response of the needle valve member to the needle control valve.

[0024] Injector 14' includes an injector body 105 having an actuation fluid inlet 106 that is connected to a branch rail passage 40, an actuation fluid drain 104 that is connected to actuation fluid re-circulation line 27 and a fuel inlet 120 connected to a fuel supply passage 44. (See Fig. 1). Injector 14' includes a hydraulic means for pressurizing fuel within the injector during each injection event and a needle control valve that controls the opening and closing of nozzle outlet 117.

[0025] The hydraulic means for pressurizing fuel includes an actuation fluid control valve that includes two-way solenoid 130 which is attached to a pin 135. An intensifier spool valve member 140 responds to movement of pin 135 and ball valve member 136 to alternately open actuation fluid cavity 109 to actuation fluid inlet 106 or low pressure drain 104. Actuation fluid cavity 109 opens to a stepped piston bore 110 within which a stepped intensifier piston 150 reciprocates between a return position (as shown) and a forward position. Injector body 105 also includes a plunger bore 111, within which a plunger 153 reciprocates between a retracted position (as shown) and an advanced position. A portion of plunger bore 111 and plunger 153 define a fuel pressurization chamber 112, within which fuel is pressurized during each injection event. Plunger 153 and intensifier piston 150 are returned to their retracted positions between injection events under the action of compression spring 154. Thus, the hydraulic means for pressurizing fuel includes the fuel pressurization chamber 112, plunger 153, intensifier piston 150, actuation fluid inlet 106, actuation fluid cavity 109 and the various components of the actuation fluid control valve, which includes solenoid 130, ball 136, pin 135 and intensifier spool valve member 140, etc.

[0026] Fuel enters injector 14' at fuel inlet 120 and travels past ball check 121, along a hidden fuel supply passage 124, and into fuel pressurization chamber 112, when plunger 153 is retracting. Ball check 121 prevents the reverse flow of fuel from fuel pressurization chamber 112 into the fuel supply passage during the plunger's downward stroke. Pressurized fuel travels from fuel pressurization chamber 112 via a connection passage 113 to nozzle chamber 114. A needle valve member 160 moves within nozzle chamber 114 between an open position in which nozzle outlet 117 is open and a closed position in which nozzle outlet 117 is closed. In this embodiment, needle valve member 160 includes a lower needle portion 161 and an upper intensifier portion 162 separated by spacers 164 and 166, which are all machined as separate components but could be machined as a single integral piece if spring 165 were relocated. Needle valve member 160 is mechanically biassed to its closed position by a compression spring 165. Unlike the previous embodiment, compression spring 165 is compressed between spacer 164 and intensifier portion 162. Thus, in this embodiment, when needle valve member 160 is closed and needle control chamber 118 is open to low pressure, intensifier portion 162 is pushed to its upper stop.

[0027] Needle valve member 160 includes opening hydraulic surfaces 163 exposed to fluid pressure within nozzle chamber 114 and a closing hydraulic surface 167 exposed to fluid pressure within needle control chamber 118. As in the previous embodiment the closing hydraulic surface and the opening hydraulic surfaces are sized and arranged such that the needle valve member 160 is hydraulically biassed toward its closed position when the needle control chamber 118 is open to a source of high pressure fluid. Thus, there should be adequate pressure on the closing hydraulic surface 167 to maintain nozzle outlet 117 closed despite the presence of high pressure fuel in nozzle chamber 114 that is otherwise above a valve opening pressure. The opening hydraulic surfaces 163 and closing hydraulic surface 167 are also preferably sized and arranged such that needle valve member 160 is hydraulically biassed toward its open position when the needle control chamber 118 is connected to a low pressure passage and the fuel pressure within nozzle chamber 114 is greater than the valve opening pressure.

[0028] The actuation fluid control valve of injector 14' can be thought of as including two-way solenoid 130 that is attached to a pin 135 which is normally in contact with ball 136 except when pin 135 is fully retracted. Pin 135 is biassed by a compression spring 138 and the hydraulic force on ball 136 toward a retracted position. In this position, ball 136 closes seat 172 and opens seat 173 so that high pressure actuation fluid flows into contact with the end hydraulic surface 141 of intensifier spool valve member 140. When solenoid 130 is de-energized, actuation fluid cavity 109 is opened to actuation fluid drain 104 past seat 170, and intensifier spool valve member 140 is hydraulically balanced and forced down, as shown, to close seat 171 and open seat 170. When solenoid 130 is energized, pin 135 moves downward causing ball 136 to open seat 172 and close seat 173. This causes end hydraulic surface 141 to be exposed to the low pressure in drain passage 129, which is connected to a second drain 108. This creates a hydraulic imbalance in intensifier spool valve member 140 causing it to move upward against the action of compression spring 145 to close seat 170 and open seat 171. This allows actuation fluid to flow from inlet 106, into the hollow interior 147 of intensifier spool valve member 140, through radial openings 146, past seat 171 and into actuation fluid cavity 109 to act upon the stepped top of the intensifier piston 150.

[0029] The opening and closing of the nozzle outlet 117 via needle valve member 160 is controlled by the needle control valve which includes solenoid 130. As stated earlier, when de-energized, pin 135 retracts under the action of compression spring 138 so that high pressure actuation fluid flowing through hollow interior 147 pushes ball 136 to open seat 173 and close seat 172. When in this configuration, the high pressure actuation fluid inlet 106 flows past seat 173 along a hidden passage into actuation fluid control passage 119. Actuation fluid control passage 119 opens to needle control chamber 118 and acts upon the closing hydraulic surface 167 of needle valve member 160, pushing the same downward to close nozzle outlet 117. When solenoid 130 is energized, pin 135 is moved downward pushing ball 136 to close seat 173 and open seat 172. This opens actuation fluid control passage 119 to the low pressure within drain passage 129, which is connected to second low pressure fluid drain 108. Drains 104 and 108 merge together outside of injector body 105. Thus, with the solenoid 130 energized, the closing hydraulic surface 167 of needle valve member 160 is now exposed to a low pressure passage and the needle valve member begins to behave like a simple check valve in that it will now open if fuel pressure within the nozzle chamber 114 is greater than a valve opening pressure sufficient to overcome return spring 165. In this embodiment, the needle control valve includes solenoid 130, pin 135, ball 136, seat 172 and seat 173. The actuation fluid control valve includes all the components of the needle control valve plus intensifier spool valve member 140, compression spring 145, seat 170 and seat 171.

[0030] Referring again to Fig. 6, stepped piston bore 110 includes an upper bore 115 and a larger diameter lower bore 116. The stepped top of piston 150 includes a first area 122 that is separated from a second area 132 by a regular cylindrical portion 133. First area 122 and upper bore 115 define an upper cavity 123 that is connected to actuation fluid cavity 109 through a relatively unrestricted flow area 127 when piston 150 is in its retracted position, as shown.

[0031] Second area 132 and lower bore 116 define a lower cavity 126 that is connected to the actuation fluid cavity 109 via a restricted passage 128 that includes a restricted flow area 131, when the piston is in its retracted position. When the piston begins its movement from its retracted position toward its advanced position, the first area 122 is exposed to the full fluid pressure in upper cavity 123, whereas second area 132 is exposed to the fluid pressure in lower cavity 126. Because of the rate at which the volume of lower cavity 126 grows as the piston 150 moves in its downward stroke, the restricted flow area 131 prevents second area 132 from experiencing the full fluid pressure in actuation fluid cavity 109 until the piston moves a sufficient distance downward that fluid can also flow around annular taper 134 onto second area 132. In this embodiment, restricted passage 128 is defined by injector body 105.

[0032] Also shown in Fig. 6 are the design parameters "A", "B", "C", and "D". The height of annular taper 134 is preferably chosen to be sufficiently long that the movement rate of the piston is not influenced by the height of the annular taper. This eliminates one possible area of variability when injectors of this type are mass produced. Control over the design parameters A, B, C and D gives one substantial control over the initial movement rate of piston 150, and hence the initial injection rate profile from the injector. The hole diameter "A" that defines restricted flow area 131, the diameter "B" of upper bore 115 and the height "C" of the regular cylindrical portion 133 can be sized such that when the regular cylindrical portion 133 is still in upper bore 115, the fluid pressure in lower cavity 126 can be made to be essentially a low constant pressure. Thus, the height of regular cylindrical portion 133 controls the duration of the slowed piston movement in order to produce a boot injection profile. As the piston 150 continues its downward movement, the regular cylindrical portion 133 moves out of upper bore 115 to open an annular gap between annular taper 134 and upper bore 115. Fig. 8e shows that the pressure on second area 132 remains low until cylindrical portion 133 clears upper bore 115. This reduced pressure slows the initial movement rate of piston 150 and reduces the initial injection rate. After sufficient movement of piston 150, actuation fluid flows freer into lower cavity 126 both through restricted passage 128 and past annular taper 134 so that pressure in lower cavity 126 begins to rise. As a result, fuel pressure increases, producing the ramp up portion of an injection profile. The slope "D" of annular taper 134 controls the slope of the ramp up portion.

[0033] The height "C" of regular cylindrical portion 133 controls the duration of a flat portion of a boot shaped injection profile. If dimension "C" is short enough, the initial flat portion would disappear, resulting in a ramp up only portion as illustrated in Fig. 8f. Still, dimension "C" preferably has some minimal lead distance length because some movement of the piston is typically necessary to compress the fuel below plunger 153 to a satisfactory injection pressure. Thus, by varying dimensions "A", "B", "C", and "D", the present invention provides near total flexibility in controlling the front portion of the injection rate trace, which is very important in controlling engine emissions.

[0034] Referring now to Fig. 10, an alternative embodiment of the present invention is shown which includes a piston 180 with a stepped top slidably received in a piston bore 176, which includes a lower bore 177 and an upper bore 178. Like the earlier embodiment, stepped piston 180 includes a first area 181 that is separated from a second area 182 by a regular cylindrical portion 184. Stepped piston 180 sits atop a plunger 153 and a return spring 154, which are identical to the embodiment previously described.

[0035] Like the previous embodiment, the first area 181 and upper bore 178 define an upper cavity 190 that is connected to an actuation fluid cavity 175 through a relatively unrestricted flow area. The second area 182 and the lower bore 177 define a lower cavity 191 connected to actuation fluid cavity 175 through a relatively restricted flow passage 174 defined by the area between regular cylindrical portion 184 and upper bore 178. This version performs substantially similar to the earlier version but instead of the injector body defining a separate restricted passageway, the piston and barrel define restricted passage 174. Also, this embodiment is different in that instead of an annular taper on the upper stepped portion of the piston, a slot 187 is machined therein. In this case, the width of slot 187 is the counterpart to the slope "D" shown in Fig. 2. In other words, the wider the slot, the steeper the ramp up portion of the injection profile. In this embodiment, the difference in the height of the upper step portion from the depth of the slot corresponds to the dimension "C" shown in Fig. 6. In other words, the deeper the slot the less a flat portion (boot) will appear in the injection rate profile.

[0036] Referring now to Fig. 11, still another embodiment of the present invention is shown in which the piston itself defines the restricted passage to 224. Like the previous embodiments a stepped piston 280 is slidably received in a piston bore 270, which includes a lower bore 271 and an upper bore 272. A first area 281 is separated from a second area 282 by a regular cylindrical portion 284. The first area 281 and upper bore 272 define an upper cavity 290 that is open to the actuation fluid cavity 222 via a relatively unrestricted flow area. Like the previous embodiments, the second area 282 and the lower bore 271 define a lower cavity 291 that is connected to actuation fluid cavity 222 via a restricted passage 224. Like the embodiment shown in Fig. 2, regular cylindrical portion 284 substantially isolates the lower cavity from the upper cavity. This embodiment of the invention operates substantially identical to the earlier embodiments described, but just contains different geometry to accomplish the same purposes.

[0037] Referring now to Figs. 12a, and 12b, still another embodiment is shown in which a stepped plunger 380 is slidably received and a piston bore 370 that includes a lower bore 371 and an upper bore 372. A first area 381 and the upper bore 372 define an upper cavity, as in the previous embodiments. Likewise, a second area 382 and lower bore 371 define a lower cavity that is connected to actuation fluid cavity 322 via a restricted passage 324, which in this embodiment is created by slots cut into annular taper 385. Thus, in this embodiment like the embodiment shown in Fig. 10, the piston and barrel define the restricted passage 324. However, this embodiment is like the embodiment shown in Fig. 6 in that it includes a regular cylindrical portion 384 and an annular taper portion 385.

[0038] Referring now to Fig. 13, another embodiment of the present invention is shown that behaves identical to the previous embodiments but includes different geometry. In this case, the second area 482 is located inside of the first area 481. Like the previous embodiments, a restricted passage 424 opens into a first cavity 491. A relatively unrestricted flow area 423 opens to a second cavity 490. Like the previous embodiments, a stepped piston 480 is slidably received in a piston bore 470 that includes an upper bore 471 and a lower bore 472. Also like the embodiment shown in Fig. 6, the stepped piston includes a regular cylindrical portion 484 and an annular taper 485.

[0039] Fig. 14 shows another embodiment of the present invention in which still another geometrical variation of the present invention is shown. In particular, a stepped piston 580 is slidably received in a piston bore 570. The first area 581 is separated from a second area 582 by a regular cylindrical portion 584. Like the previous embodiments, a first cavity 591 is connected to an actuation fluid cavity (not shown) through a restricted passage 524 that includes a restricted flow area 525. Also like the previous embodiment, a second cavity 590, which acts upon first area 581, is connected to an actuation fluid cavity via an unrestricted flow area 523.

[0040] Referring now to the fuel injector 14 illustrated in Figs. 2-4, each injection sequence is started by applying pull-in current to solenoid 75 in order to move pin spool valve member 76 to the left. Oil pressure that entered the injector and was trapped at seat 59 is now able to push ball valve 53 to close seat 61. High pressure oil can flow past seat 59 through cross grooves in the back side of intensifier spool valve member 78 to act on end hydraulic surface 79. The intensifier spool valve member 78 is now pressure balanced and spring 82 moves it to the right. This opens seat 55 and closes seat 57. The main oil supply can flow through radial openings 81, past seat 55, into actuation fluid cavity 51 to the top of intensifier piston 83, starting it moving downward. Oil is also flowing through a connection passage 70 to the pin spool valve member 76. With the movement of pin spool valve member 76, seat 67 opens and seat 65 closes causing the high pressure in transfer passage 70 to be connected to actuation fluid control passage 71. The high pressure acting on closing hydraulic surface 88 holds needle valve member 86 in its closed position. With intensifier piston 83 and plunger 85 moving downward, fuel pressure starts to build within fuel pressurization chamber 64, closing ball check 65.

[0041] In order to provide direct control of needle valve member 86, the solenoid pull-in current is reduced to its hold-in current after fuel pressure reaches valve opening pressure. By providing two force levels from the solenoid (pull-in and hold-in) a different injection characteristic takes place. Dropping back to a hold-in current from the initial pull-in current causes the pin spool valve member 76 to close seat 67 and open seat 65. Hold-in current will provide enough force to prevent the solenoid spring 77 from pushing ball valve 53 off of seat 61. The high pressure oil can no longer flow past seat 67 into actuation fluid control passage 71 to pressurize needle control chamber 72. If the solenoid hold-in current is maintained, fuel pressure within nozzle chamber 62 will build via its connection passage 69 to fuel pressurization chamber 64 until a valve opening pressure (VOP) is reached and the needle valve member opens against the action of needle return spring 89.

[0042] With the full pull-in current being applied, fuel pressure continues to build from the intensifier piston 83 and plunger 85 moving downward (or stopped at a point where the fuel is fully compressed rendering the plunger hydraulically locked), but the needle valve member 86 will not open because high pressure oil is allowed to flow into needle control chamber 72 to act on closing hydraulic surface 88 of needle valve member 86. This pressure on needle valve member 86 provides a force required to keep it closed. To open needle valve member 86, solenoid 75 changes from pull-in current to its lower hold-in current. The needle control chamber is opened to the low pressure of drain 54 past seat 65. This removes the force keeping the needle valve member closed, and now it opens allowing fuel to exit nozzle chamber 62 through nozzle outlet 63. Fuel injection can be paused or temporarily halted by returning the solenoid current to its pull-in level. This re-pressurizes the closing hydraulic surface 88 of needle valve member 86 causing it to close. This direct control of needle valve member 86 allows the nozzle outlet to be opened and closed any number of times during each injection cycle without affecting the hydraulic pressurizing means.

[0043] To end injection and allow the injector to refuel itself for the next cycle, solenoid 75 is de-energized. This causes actuation pin spool valve member 76 to close seat 67 and open seat 65. This releases the pressurized oil acting on closing hydraulic surface 88. The solenoid spring 77 causes the actuation valve member 76 to push ball valve 53 from seat 61 back to close seat 59. The high pressure oil supply is closed off at seat 59 and oil pressure on the hydraulic end surface 79 of intensifier spool valve member 78 is released past seat 61 to low pressure drain 54. Intensifier spool valve member 78 is again hydraulically unbalanced causing it to move left against the action of spring 82 to close seat 55 and open seat 57. This releases pressurized oil acting on top of intensifier piston 83 by opening actuation fluid cavity 51 to low pressure drain 52 past seat 57. The intensifier piston 83 and plunger 84 are then returned upward by return spring 84. The lowering fuel pressure causes ball check 68 to open and allow replenishing fuel to flow into fuel pressurization chamber 64.

[0044] Changing the current levels from pull-in to hold-in creates true freedom for delivering fuel during the injection cycle. An injection characteristic tailored to specific engine operating conditions can be obtained. This injection system provides the ability to vary injection pressures by controlling the pressure of the actuation fluid and provides the ability to control injection characteristics through the direct control of the needle valve member. The direct control of the needle valve member allows the computer to control when the needle valve member is opened at any pressure between valve opening pressure and a maximum injection pressure. This provides a significant amount of control over initial injection mass flow rate in order to produce some rate shaping, if desired. At the same time, the direct control aspects of the present invention allow for a desirable abrupt end to injection by providing the means by which the needle valve member can be quickly closed at any desired time.

[0045] Referring now to the injector 14' illustrated in Figs. 5-7 and the graphs of Figs. 8 and 9, each injection sequence is started by energizing the solenoid 130 in order to move ball 136 to open seat 172 and close seat 173. The pressurized fluid previously acting on the end hydraulic surface 141 of spool valve member 140 can drain past seat 172. Intensifier spool valve member 140 is now hydraulically imbalanced and begins to move upward against the action of compression spring 145. This opens seat 171 and closes seat 170. The main oil supply can now flow through radial openings 146, past seat 171, into actuation fluid cavity 109 to the top of intensifier piston 150, starting it moving downward. With intensifier piston 150 and plunger 153 moving downward, fuel pressure starts to build within fuel pressurization chamber 112, closing ball check 121. With the solenoid energized, needle control passage 119 is open to low pressure drain 129 such that needle valve member 160 will open when fuel pressure exceeds a valve opening pressure sufficient to compress return spring 165.

[0046] Since only the inner stepped top portion 155 of intensifier piston 150 is exposed to the high pressure oil in actuation fluid cavity 109, the intensifier piston accelerates downward at a rate lower than it otherwise would if the full fluid pressure were acting over the complete top surface of the intensifier piston. The volume above annular top surface 156 of intensifier piston 150 is filled by fluid flowing through restricted passage 128. As the intensifier piston continues to move downward, it eventually reaches a point where the volume above space 156 is growing faster than fluid can be supplied via passage 128. This causes a momentary hesitation in the piston's downward movement resulting in a slower build-up of fuel pressure underneath plunger 153 in fuel pressurization chamber 112.

[0047] If a "ramp-square" injection profile of the type shown in Fig. 8f is desired, current to solenoid 130 is continued as shown in Fig. 8a throughout the duration of the injection event. After the ball and spool have moved as shown in Figs. 8b and 8c due to the initial energization of solenoid 130, the solenoid current is dropped to a hold-in current which keeps the solenoid pin in its same position yet saves energy since less energy is required to hold pin 135 in this position. Because of the slower acceleration and hesitation produced in the movement of intensifier piston 150 by the use of a stepped top in a stepped bore, the initial mass injection rate desirably ramps upward in a way that improves exhaust emissions over certain engine operating conditions.

[0048] To end injection and allow the injector to re-fuel itself for the next cycle, solenoid 130 is de-energized. This causes ball 136 to open seat 173 and closes seat 172. This resumes the pressurized oil acting on closing hydraulic surface 167 and, with the help of return spring 165, causes needle valve member 160 to close and provide an abrupt end to the injection. The opening of seat 173 causes intensifier spool valve member 140 to again become hydraulically balanced so that compression spring 145 moves the same downward to close seat 171 and open seat 170. This allows actuation fluid in actuation fluid cavity 109 to drain into actuation fluid drain 104 so that intensifier piston 150 and plunger 153 can retract under the action of return spring 154. The lowering of fuel pressure within fuel pressurization chamber 112 causes ball check 121 to open. Replenishing fuel begins to flow into the injector for the next injection event. Thus, in this injector, simple energizing and de-energizing of the solenoid will result in a ramped initial injection rate due to the intensifier piston stepped top and an abrupt end to injection due to the direct needle valve member control features of the present invention.

[0049] The present invention is capable of far more complex injection rate profiles than that illustrated in Fig. 8f. For instance, the graphs in Figs. 9a - 9e show that, as an example, the injector 14' can be made to produce a pilot injection segment C followed by a "square" main injection segment E. In order to produce such an injection rate profile, solenoid 130 is initially energized with a maximum current so that ball 136 moves to open seat 172 and close seat 173. Shortly after the ball moves, the intensifier spool valve member begins to move from its closed position to its open position so that high pressure actuation fluid begins to flow into actuation fluid cavity 109 beginning the piston and plunger moving in their downward stroke. When fuel pressure within nozzle chamber exceeds the valve opening pressure sufficient to compress return spring 165, the needle valve member briefly opens to allow pilot injection segment C to occur.

[0050] In order to produce a split injection, the solenoid is briefly de-energized a sufficient amount of time that the ball 136 moves back to its original position to open seat 173 and close seat 172. This again pressurizes the closing hydraulic surface of needle valve member 160 causing it to close. At the same time, intensifier spool valve member becomes hydraulically balanced and begins to move to close seat 171. However, because spring 145 is relatively weak, the intensifier spool valve member moves rather slowly. Before intensifier spool valve member moves sufficiently far to close seat 171, the solenoid is again energized causing ball 136 to again close seat 173 and re-open seat 172. This allows needle valve member to re-open with fuel pressure substantially higher than the valve opening pressure in order to provide an abrupt beginning, or "square" to the injection. At the same time, intensifier spool valve member reverses direction as in segment D (Fig. 9c) and returns to its fully open position. Thus, since ball 136 and needle valve member 160 can react far quicker to the movement of solenoid 130, the needle control valve can be opened and closed faster than the intensifier spool valve member can react to close seat 171.

[0051] Those skilled in the art will appreciate that a wide variety of mass injection rate profiles can be created with the present invention. For example, a simple "square" injection rate profile can be created by de-energizing the solenoid before fuel pressure in the nozzle chamber reaches the valve opening pressure, and then re-energizing the solenoid before intensifier spool valve member 140 is moved to close seat 170, but after fuel pressure has reached a desired injection pressure above the valve opening pressure. Those skilled in the art will also appreciate that by choosing specific mass properties for ball 136 and intensifier spool valve member 140, as well as the strength of spring 145, along with the performance characteristics of solenoid 130, a sufficient time lag can be created in the reaction of the spool valve member in order to allow direct control of the needle valve member in an injector having only a single two-way solenoid while maintaining adequate control of the hydraulic pressurizing means.

[0052] The stepped piston aspect of the present invention finds potential application to any piston and barrel assembly that is hydraulically driven and in which it is desirable to slow the initial movement rate of the piston. This slowing of the initial movement rate of the piston is accomplished by machining various geometrical relationships between the piston and the piston bore rather than through control of the pressure of the fluid acting on the piston as a whole. The present invention finds special application in the case of hydraulically-actuated fuel injectors in which it is desirable to slow the initial movement rate of the piston in order to provide a more desirable front end injection rate trace to reduce undesirable engine emissions.

[0053] While any of the embodiments illustrated could be utilized in a fuel injector, the embodiment shown in Fig. 6 is most desired because of the ease with which circular features can be machined in a bore or on a cylindrical piston to relatively tight tolerances. In other words, the slots illustrated in some of the embodiments could prove more difficult to reliably manufacture is mass quantities while maintaining the tight dimension tolerances necessary to produce consistent results.

[0054] In any event, the above description is intended for illustrative purposes only and is not intended to limit the scope of the present invention in any way. In other words, the various geometrically shaped piston and barrel assemblies illustrated above are not intended as an exhaustive presentation of examples which would fall within the scope of the present invention. Those skilled in the art will appreciate that other piston and barrel assembly geometries, which are not shown, will fall within the scope of the present invention. Other aspects, objects, and advantages of this invention can be obtained from a study of the drawings, the disclosure, and the appended claims. The subject invention is capable of varying peak fuel injection pressure independent of engine speed and load. The subject invention is capable of variably controlling the fuel quantity of each separate fuel injection segment during an injection cycle. The invention is also capable of variably controlling each time interval between each separate fuel injection segment during an injection cycle. Moreover, the injector solenoid can be energized and de-energized once or a selected plurality of times during an injection cycle to produce one or a variably-selected plurality of injection segments.

Claims

1. A hydraulically actuated fuel injector (14') comprising:

an injector body (105) that defines an actuation fluid cavity (109,175,222,322), a piston bore (110,176,270,370,470,570), and a nozzle outlet (117);
said piston bore (110,176,270,370,470,570) includes a first bore (115,178,272,372,471), and a second bore (116,177,271,371,472);
a piston (150,180,280,380,480,580) with a top being slidably received in said piston bore (110,176,270,370,470,570) and movable between a retracted position and an advanced position;
said top of said piston (150,180,280,380,480,580) including a first area (122,181,281,381,481,581) that is separate from a second area (132,182,282,382,482,582);
said first area (122,181,281,381,481,581) and said first bore (115,178,272,372,471) defining a first cavity (123,190,290,390,490,590) connected to said actuation fluid cavity (109,175,222,322)through a relatively unrestricted flow area (127,423,523) when said piston (150,180,280,380,480,580) is in said retracted position;
said second area (132,182,282,382,482,582) and said second bore (116,177,271,371,472) defining a second cavity (126,192,291,391,491,591) connected to said actuation fluid cavity (109,175,222,232) through a relatively restricted flow area (131,174,224,324,424,524) when said piston (150,180,280,380,480,580) is in said retracted position; and
said first area (122) being exposed to fluid pressure in said first cavity (123,190,290,390,490,590) and said second area (132,182,282,382,482,582) being exposed to fluid pressure in said second cavity (126,192,291,391,491,591) over a portion of said piston's (150,180,280,380,480,580) movement from said retracted position toward said advanced position;
at least one of said piston (150,180,280,380,480,580) or said injector body (105) further defining a restricted passage (128,174,224,324,424,524) connecting said actuation fluid cavity (109,175,222,322) to said second cavity (126,192,291,391,491,591), and said restricted passage (128,174,224,324,424,524) includes said restricted flow area (131,174,224,324,424,524); and
a needle valve member (160) positioned in said injector body (105) and movable between an open position in which said nozzle outlet (117) is open and a closed position in which said nozzle outlet (117) is blocked.

Patentansprüche

1. Hydraulisch betätigte Brennstoffeinspritzvorrichtung (14'). die Folgendes aufweist:

einen Einspritzvorrichtungskörper (105), der einen Betätigungsströmungsmittelhohlraum (109, 175, 222, 322), eine Kolbenbohrung (110, 176, 270, 370, 470, 570) sowie einen Düsenauslass (117) definiert;
wobei die Kolbenbohrung (110, 176, 270, 370, 470, 570) eine erste Bohrung (115, 178, 272, 372, 471) und eine zweite Bohrung (116, 177, 271, 371, 472) umfasst;
einen Kolben (150, 180, 280, 380, 480, 580) mit einem oberen Ende, welches gteitbar in der Kolbenbohrung (110, 176, 270, 370, 470, 570) aufgenommen ist und beweglich ist zwischen einer zurückgezogenen Position und einer vorgeschobenen Position;
wobei das obere Ende des Kolbens (150, 180, 280, 380, 480, 580) eine erste Fläche (122, 181, 281, 381, 481, 581) umfasst, die getrennt bzw. separat von einer zweiten Fläche (132, 182, 282, 382, 482, 582) ist;
wobei die erste Fläche (122, 181, 281, 381, 481, 581) und die erste Bohrung (115, 178, 272, 372, 471) einen ersten Hohlraum (123, 190, 290, 390, 490, 590) definieren, die mit dem Betätigungsströmungsmittelhohlraum (109,

175, 222, 322) durch eine relativ uneingeschränkte Strömungsfläche (127, 423, 523) verbunden ist, wenn der Kolben (150, 180, 280, 380, 480, 580) in der Zurückgezogenen Position ist;
wobei die zweite Fläche (132, 182, 282, 382, 482, 582) und die zweite Bohrung (116, 177, 271, 371, 472) einen zweiten Hohlraum (126, 192, 291, 391, 491, 591) definieren, die mit dem Betätigungsströmungsmittelhohlraum (109, 175, 222, 322) durch eine relativ eingeschränkte Strömungsfläche (131, 174, 224, 324, 424, 524) verbunden ist, wenn der Kolben (150, 180, 280, 380, 480, 580) in der zurückgezogenen Position ist; und
wobei die erste Fläche (122) Strömungsmitteldruck in dem ersten Hohlraum (123, 190, 290, 390, 490, 590) ausgesetzt ist und wobei die zweite Fläche (132, 182, 282, 382, 482, 582) Strömungsmitteldruck in dem zweiten Hohlraum (126, 192, 291, 391, 491, 591) ausgesetzt ist, und zwar während eines Teils der Bewegung des Kolbens (150, 180, 280, 380,480, 580) von der zurückgezogenen Position zu der vorgeschobenen Position hin;
wobei der Kolben (150, 180, 280, 380, 480, 580) und/oder der Einspritzvorrichtungskörper (105) ferner einen eingeschränkten Durchlass (128, 174, 224, 324, 424, 524) definiert bzw. definieren, welcher den Betätigungsströmungsmittelhohlraum (109, 175, 222, 322) mit dem zweiten Hohlraum (126, 192, 291, 391, 491, 591) verbindet, und wobei der eingeschränkte Durchlass (128, 174, 224, 324, 424, 524) die erwähnte eingeschränkte Strömungsfläche (131, 174, 224, 324, 424, 524) umfasst; und
ein Nadelventilglied (160), das in dem Einspritzvorrichtungskörper (105) angeordnet ist und beweglich ist zwischen einer offenen Position, in der der Düsenausfass (117) offen ist, und einer geschlossenen Position, in der der Düsenauslass (117) blokkiert ist.

Revendications

1. Injecteur de carburant à actionnement hydraulique (14') comprenant :

un corps d'injecteur (105) qui définit une cavité pour fluide d'actionnement (109, 175, 222, 322), un alésage pour piston (110, 176, 270, 370, 470, 570), et une sortie de buse (117) ;
l'alésage pour piston (110, 176, 270, 370, 470, 570) comportant un premier alésage (115, 178, 272, 372, 471), et un second alésage (116, 177, 271, 371, 472) ;
un piston (150, 180, 280, 380, 480, 580) dont un sommet est disposé à coulissement dans l'alésage pour piston (110, 176, 270, 370, 470, 570) et est mobile entre une position rétractée et une position avancée ;
ledit sommet du piston (150, 180, 280, 380, 480, 580) comprenant une première zone (122, 181, 281, 381, 481, 581) qui est distincte d'une seconde zone (132, 182, 282, 382, 482, 582) ;
ladite première zone (122, 181, 281, 381, 481, 581) et le premier alésage (115, 178, 272, 372, 471) définissant une première cavité (123, 190, 290, 390, 490, 590) reliée à la cavité pour fluide d'actionnement (109, 175, 222, 322) par une zone d'écoulement relativement non restreinte (127, 423, 523) lorsque le piston (150, 180, 280, 380, 480, 580) est en position rétractée ;
ladite seconde zone (132, 182, 282, 382, 482, 582) et le second alésage (116, 177, 271, 371, 472) définissant une seconde cavité (126, 192, 291, 391, 491, 591) reliée à la cavité pour fluide d'actionnement (109, 175, 222, 232) par une zone d'écoulement relativement restreinte (131, 174, 224, 324, 424, 524) lorsque le piston (150, 180, 280, 380, 480, 580) est en position rétractée ; et
la première zone (122) étant soumise à la pression de fluide dans la première cavité (123, 190, 290, 390, 490, 590) et la seconde zone (132, 182, 282, 382, 482, 582) étant soumise à la pression de fluide dans la seconde cavité (126, 192, 291, 391, 491, 591) pendant une partie du mouvement du piston (150, 180, 280, 380, 480, 580) de la position rétractée vers la position avancée ;
au moins un dit piston (150, 180, 280, 380, 480, 580) ou dit corps d'injecteur (105) définissant en outre un passage restreint (128,.174, 224, 324, 424, 524) reliant la cavité pour fluide d'actionnement (109, 175, 222, 322) à la seconde cavité (126, 192, 291, 391, 491, 591), et ledit passage restreint (128, 174, 224, 324, 424, 524) comprenant ladite zone d'écoulement restreinte (131, 174, 224, 324, 424, 524) ; et
un élément de soupape à pointeau (160) disposé dans le corps d'injecteur (105) et mobile entre une position ouverte dans laquelle la sortie de buse (117) est ouverte et une position fermée dans laquelle ladite sortie de buse (117) est bloquée.

Fig 1

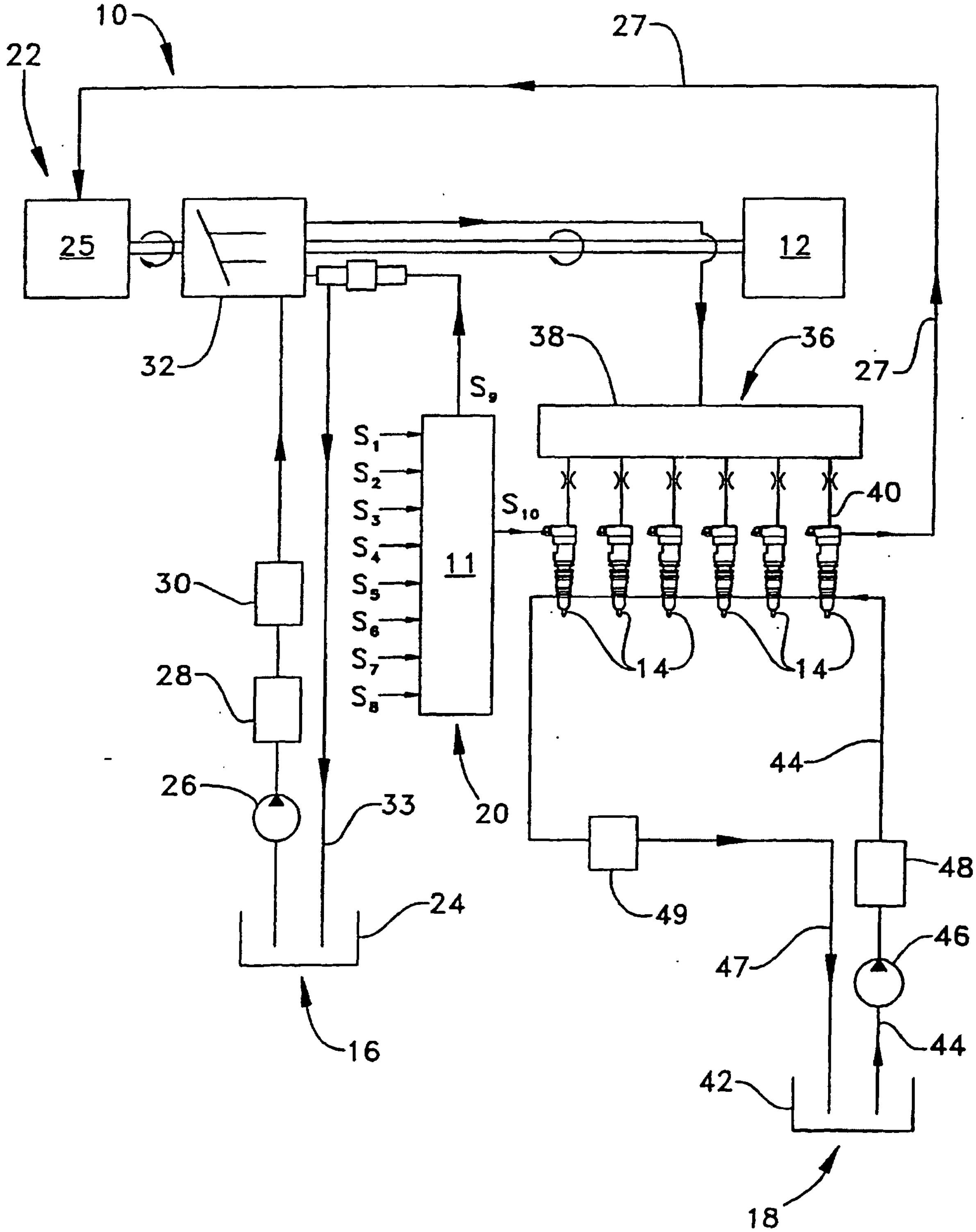
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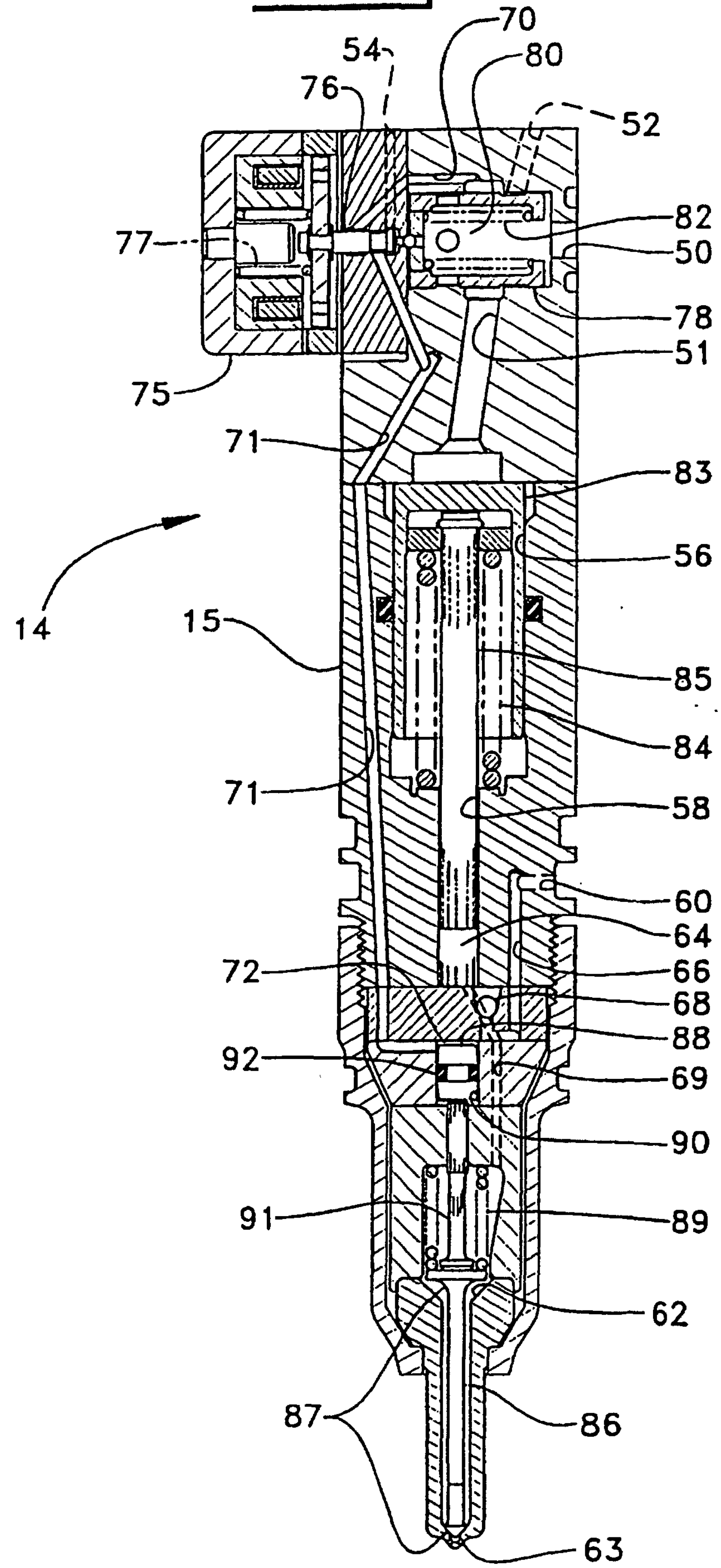
Fig_2_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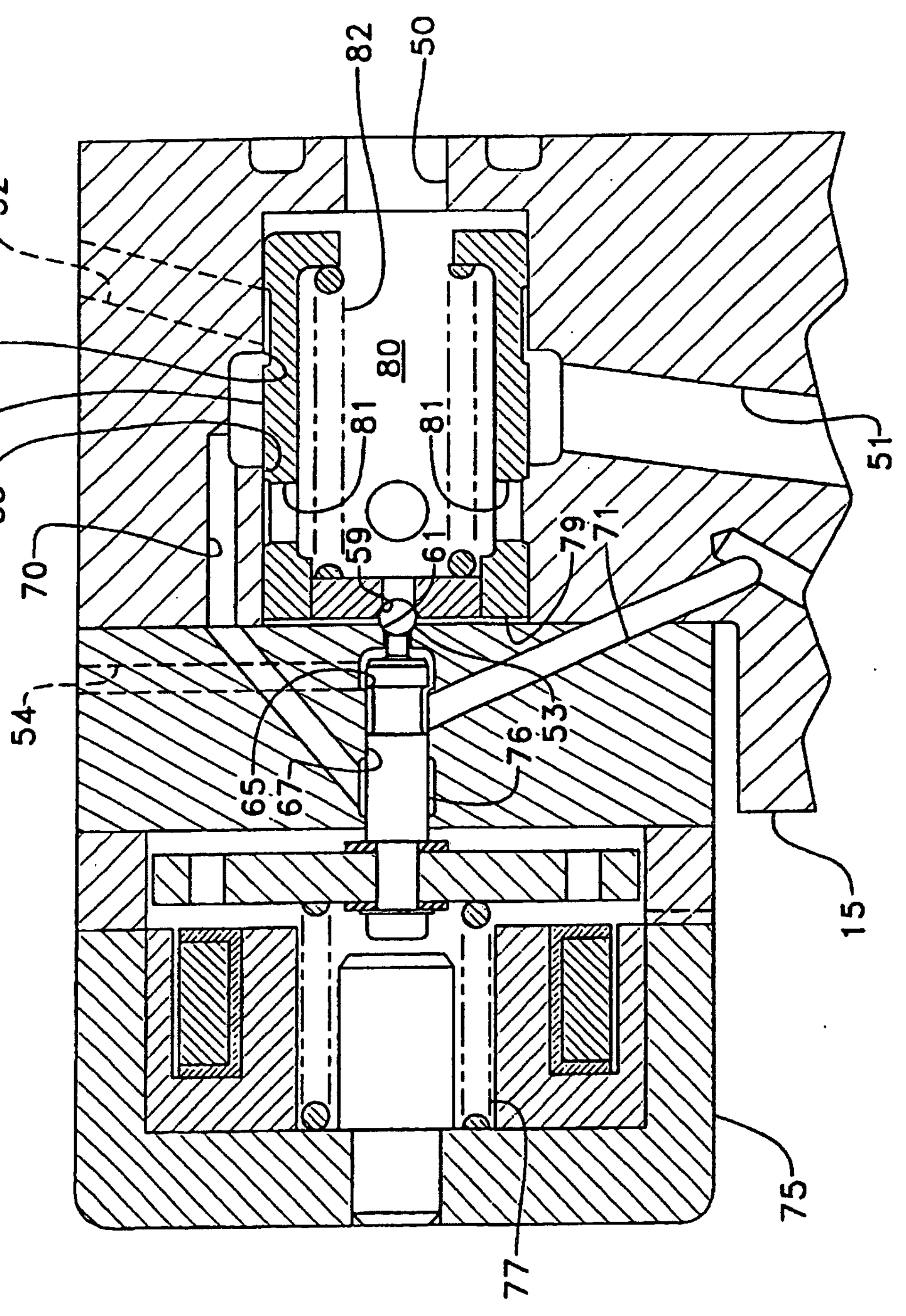

Fig-3

Fig. 4

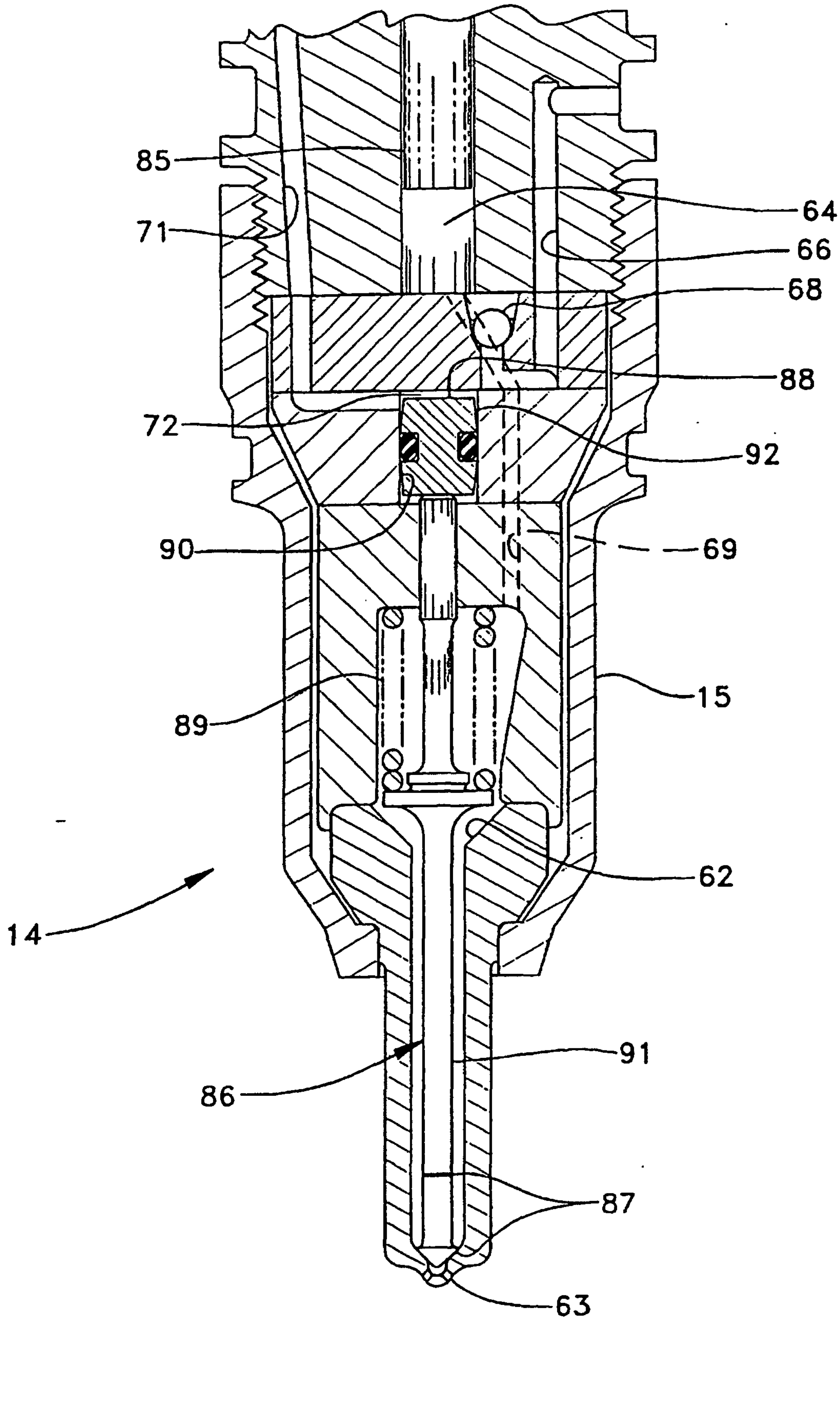

Fig. 5

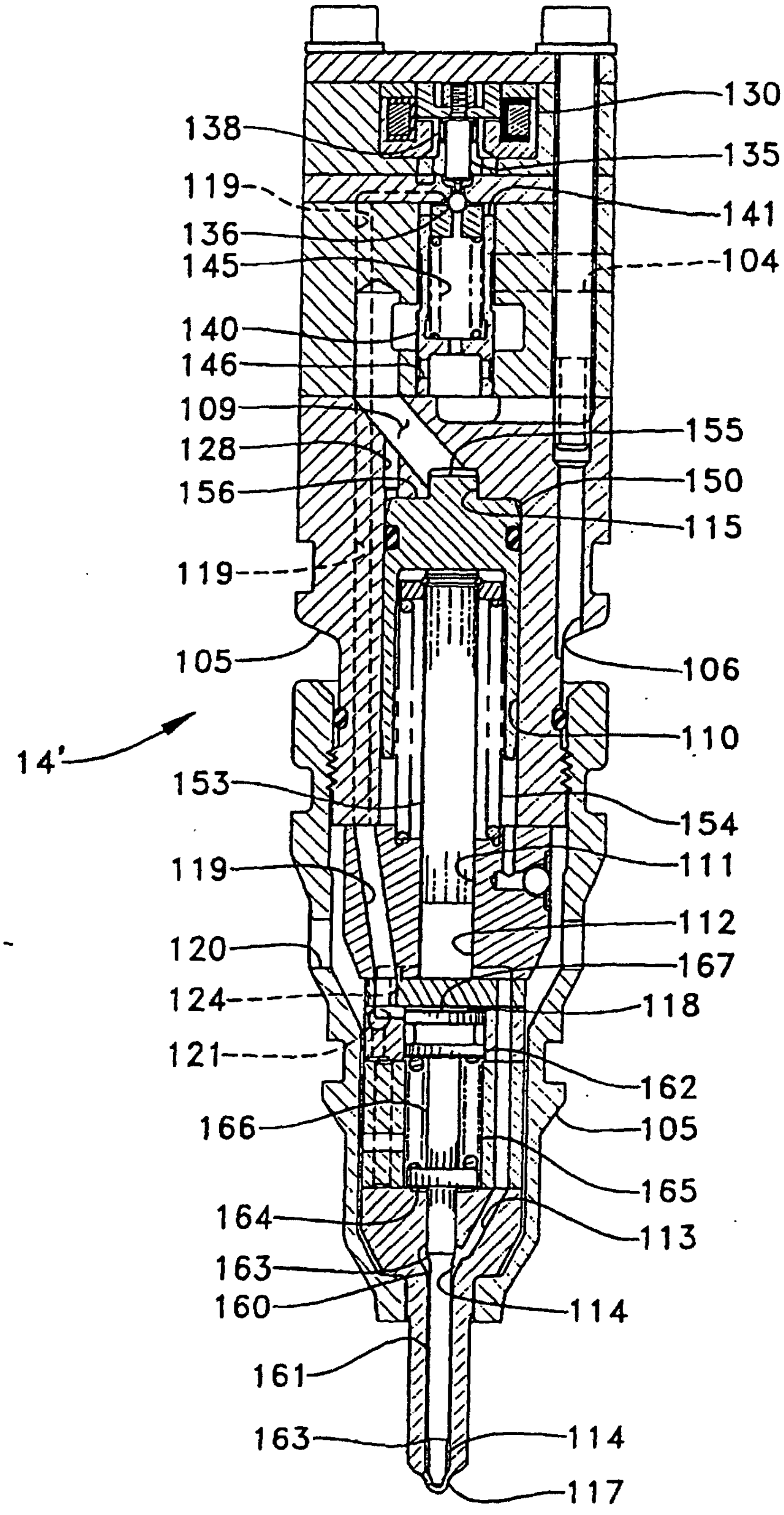
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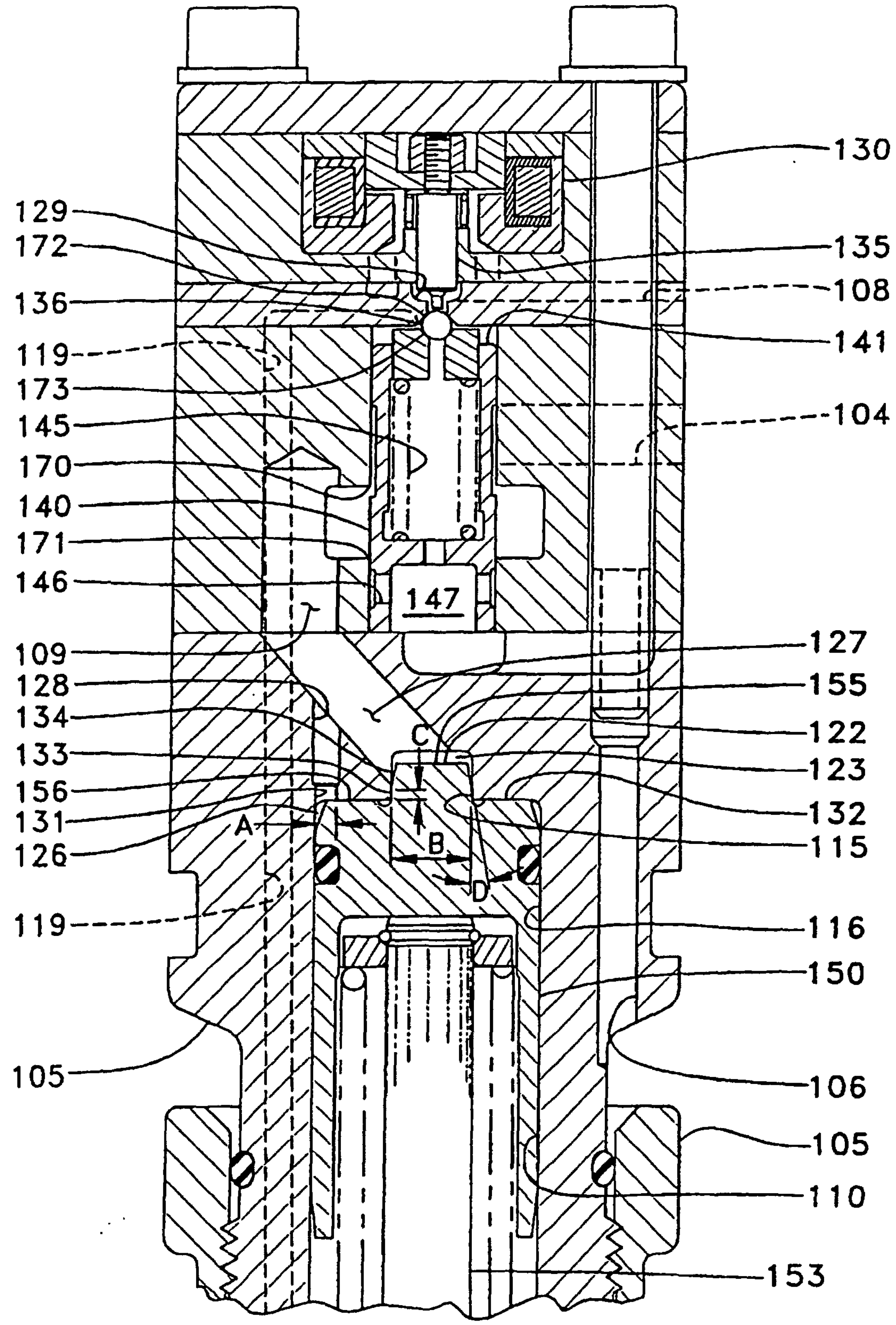
Fig. 6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122
C
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B
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106
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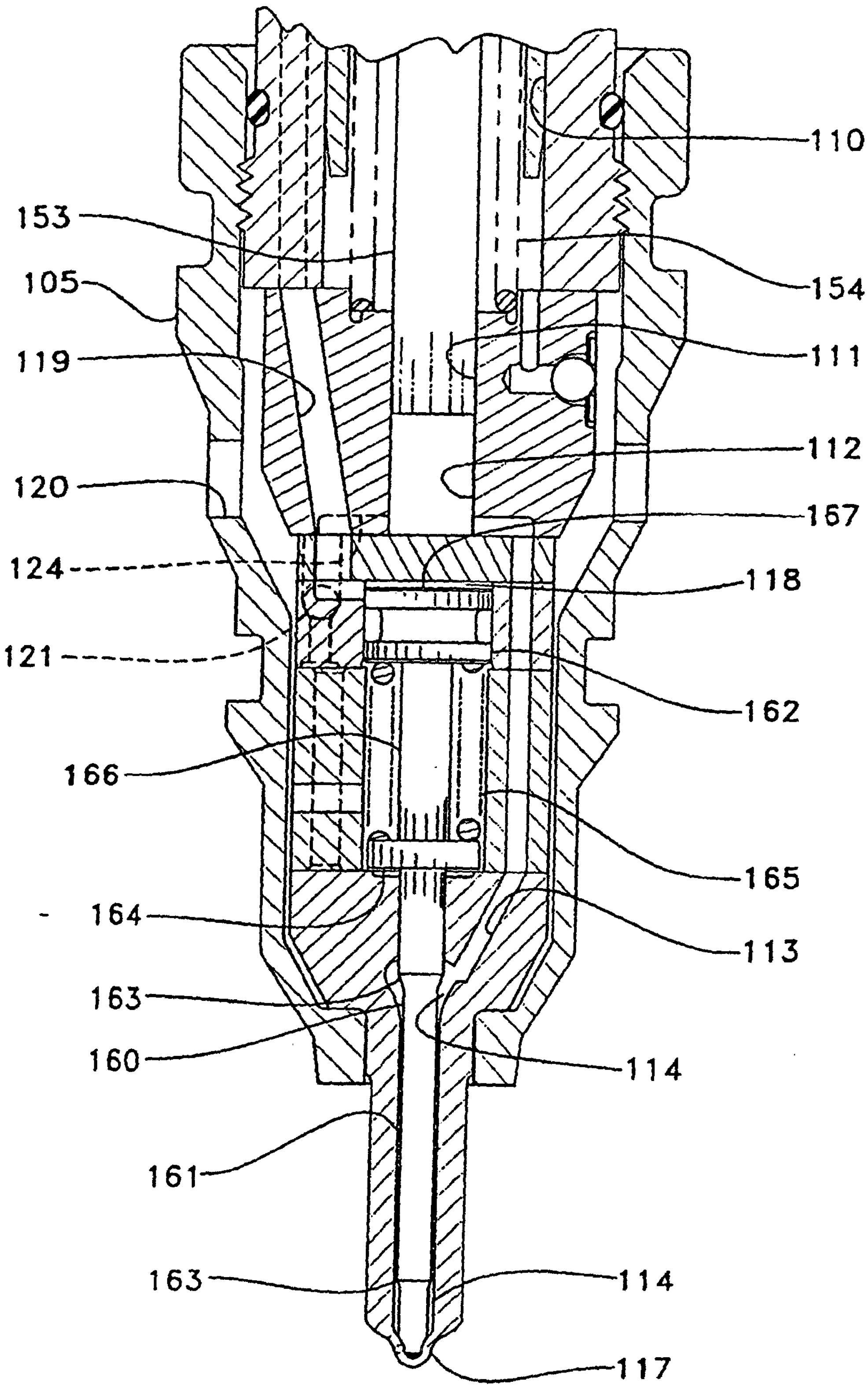
110
153

Fig_7_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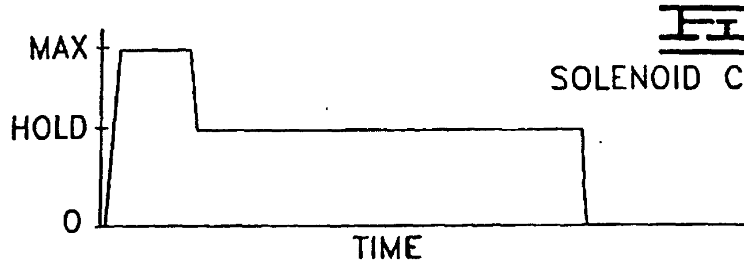

Fig_8a_
SOLENOID CURRENT (AMPS)

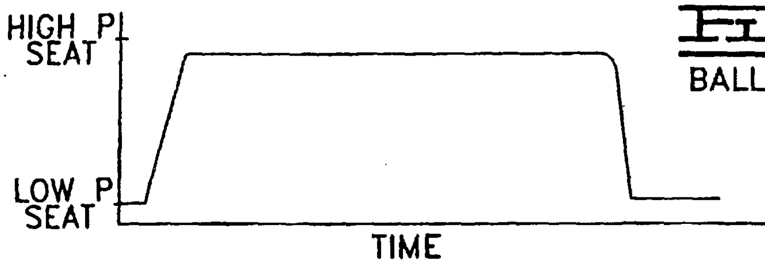

Fig_8b_
BALL POSITION

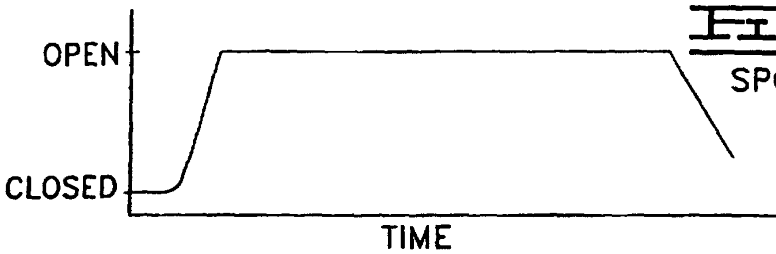

Fig_8c_
SPOOL POSITION

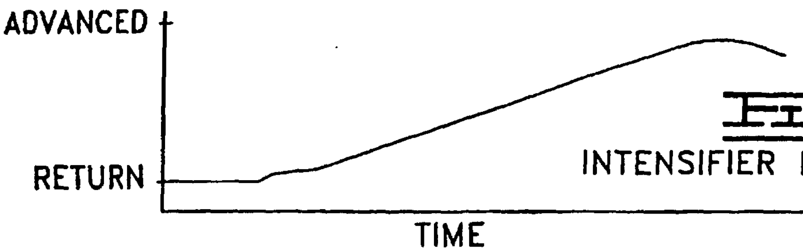

Fig_8d_
INTENSIFIER PISTON POSITION

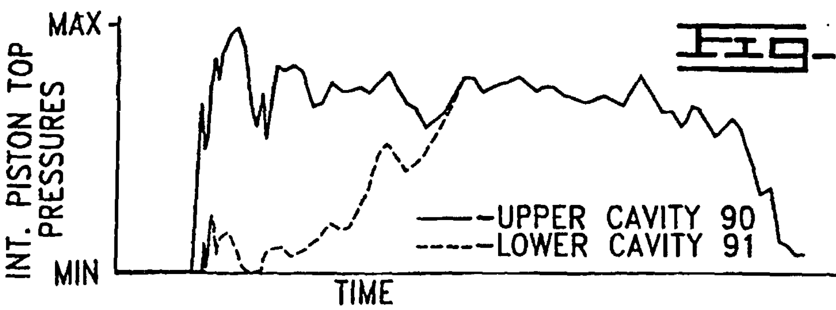

Fig_8e_

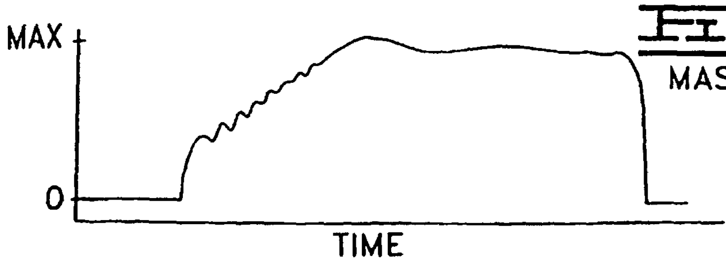

Fig_8f_
MASS INJECTION RATE

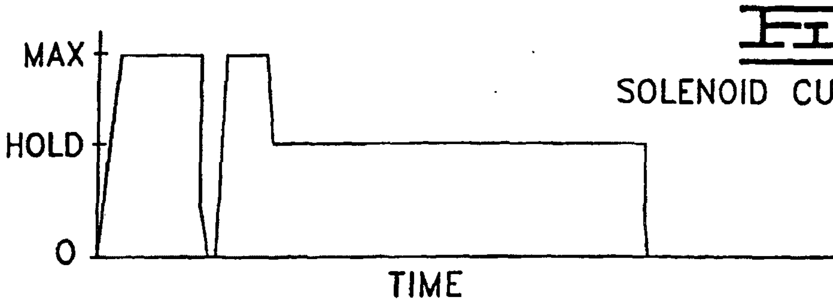

Fig_9a_
SOLENOID CURRENT (AMPS)

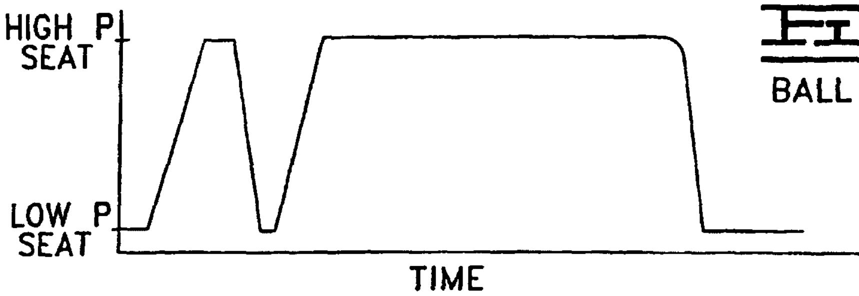

Fig_9b_
BALL POSITION

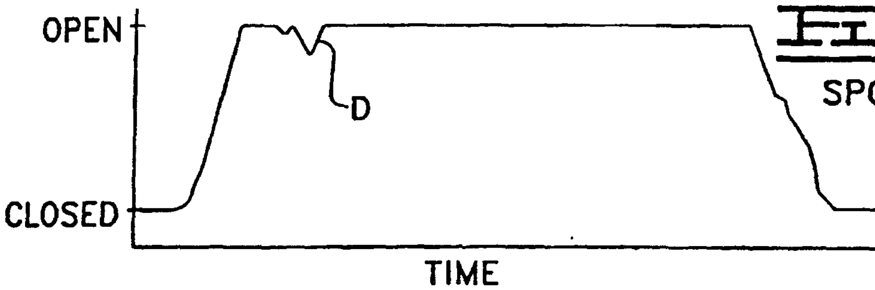

Fig_9c_
SPOOL POSITION

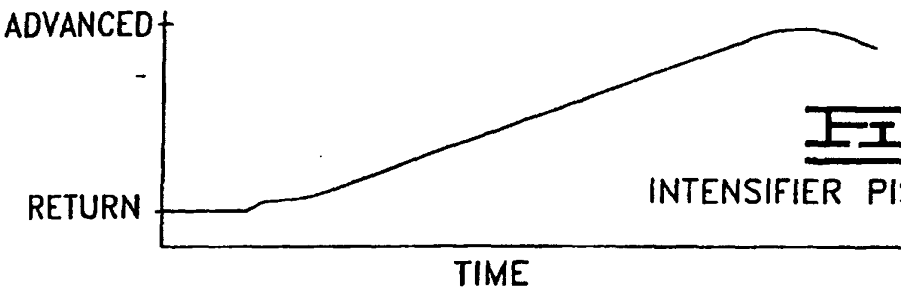

Fig_9d_
INTENSIFIER PISTON POSITION

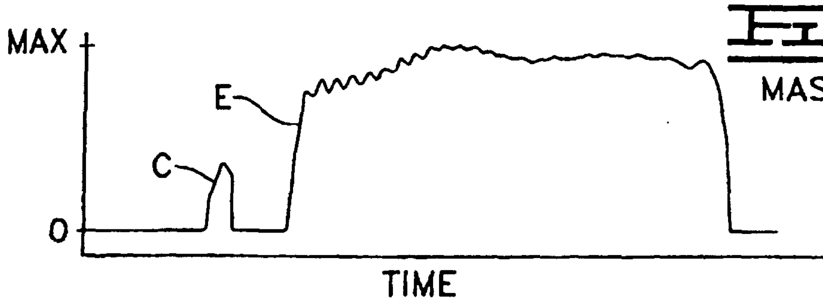

Fig_9e_
MASS INJECTION
RATE

Fig. 10

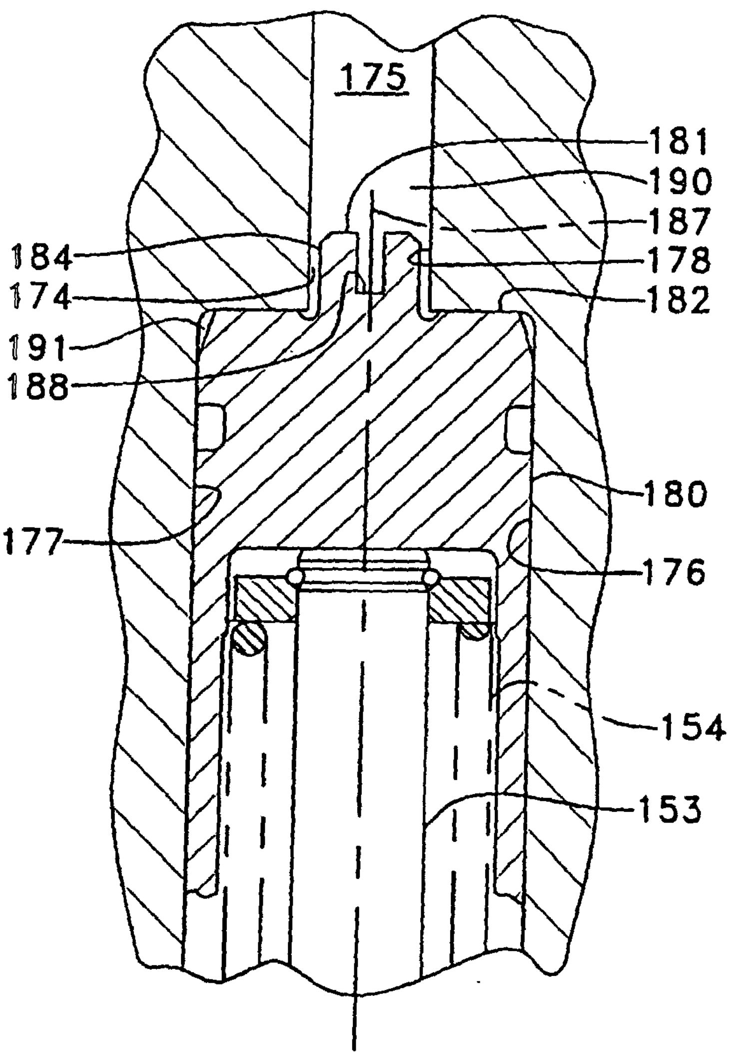

Fig. 11

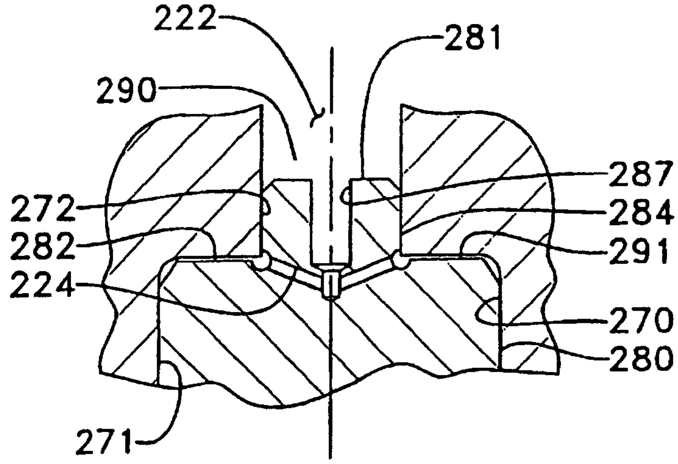

Fig. 12a

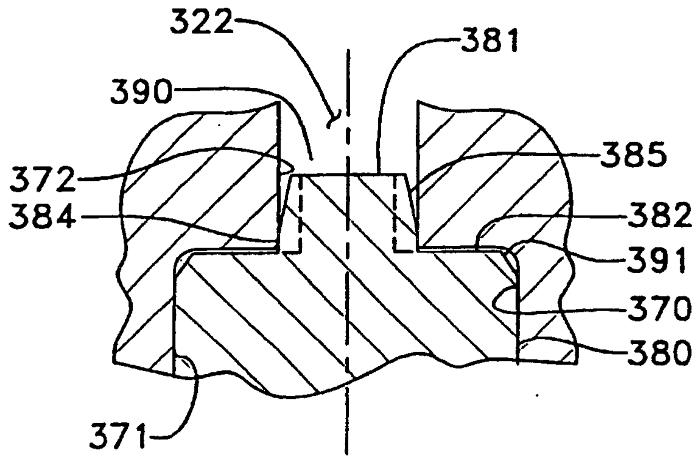

Fig. 12b

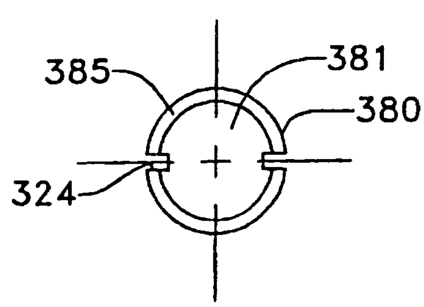

Fig 13

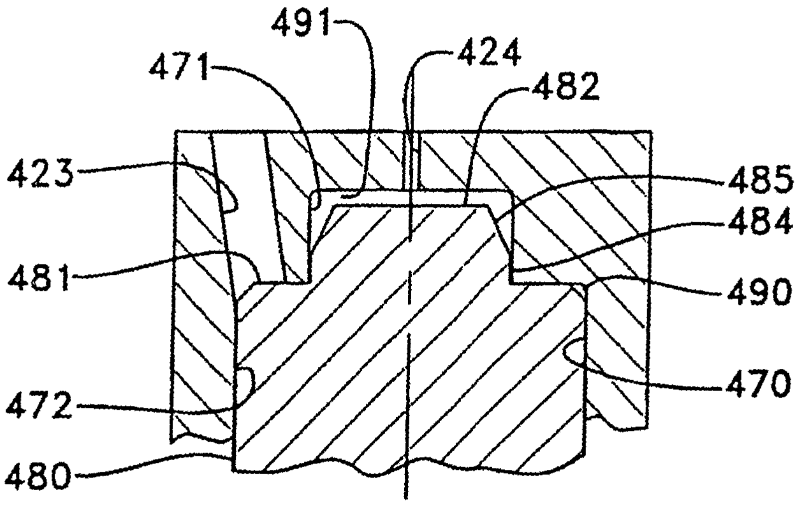
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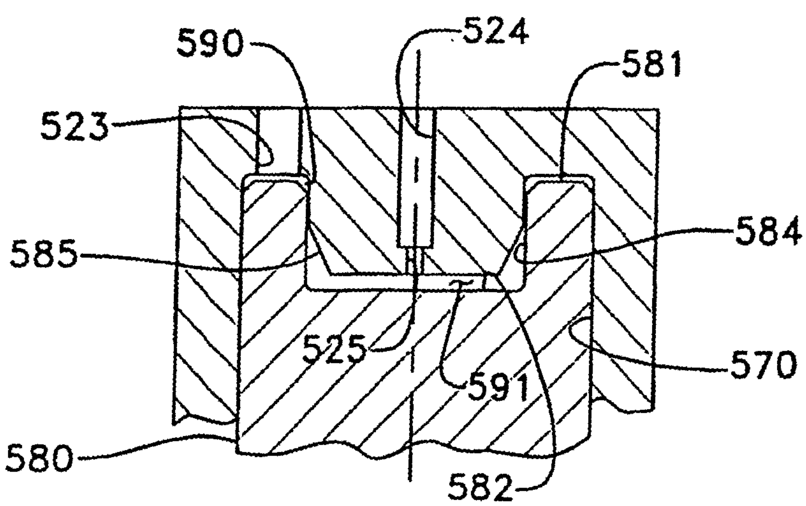
Fig 14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