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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
27 July 2017 (27.07.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/127678 A1

(51) International Patent Classification:
F16B 15/00 (2006.01) *F15B 1/26* (2006.01)
F15B 1/02 (2006.01) *F15B 11/024* (2006.01)
F15B 1/04 (2006.01) *F15B 11/042* (2006.01)

(21) International Application Number:
PCT/US2017/014337

(22) International Filing Date:
20 January 2017 (20.01.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/281,115 20 January 2016 (20.01.2016) US
62/345,495 3 June 2016 (03.06.2016) US

(71) Applicant: **NEXMATIX LLC** [US/US]; 8255 Brentwood Industrial Drive, St. Louis, MO 63144 (US).

(72) Inventors; and
(71) Applicants : **MELL, Ellen**; 4984 Hillsboro Road, Farmington, MO 63640 (US). **MELL, Dennis**; 4984 Hillsboro Road, Farmington, MO 63640 (US). **GOLDFARB, Michael**; 3030 Old Hillsboro Road, Franklin, TN 37064 (US).

(74) Agents: **KELLY, Don, V.** et al.; Evans & Dixon, L.L.C., 211 N. Broadway, Suite 2500, Metropolitan Square, St. Louis, MO 63102 (US).

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,

[Continued on next page]

(54) Title: FOUR-WAY CONTROL VALVE FOR PNEUMATIC CHARGING AND DISCHARGING OF WORKING VESSEL

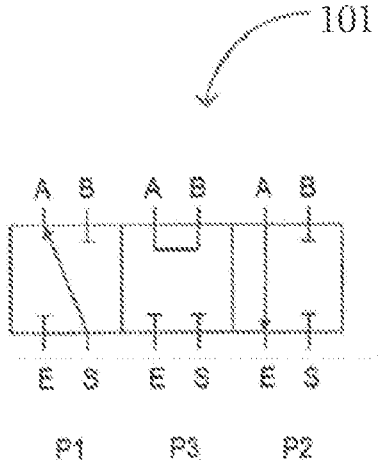


FIG. 4

(57) Abstract: A control valve comprises a body. A diverter is disposed within the body. The diverter is movably positionable within the body such that the diverter can assume a first position, second position and third position. The body includes one or more exhaust ports, a supply port, a first outlet port and a second outlet port. The body and diverter are configured such that: when the diverter is in the first position, the supply port and first outlet port fluidly communicate and the one or more exhaust ports and second outlet port are fluidly isolated; when the diverter is in the second position, the first outlet port and one of the one or more exhaust ports fluidly communicate and the supply port and second outlet port are fluidly isolated; and when the diverter is in the third position, the first outlet port and second outlet port fluidly communicate and the supply port and the one or more exhaust ports are fluidly isolated.

WO 2017/127678 A1

SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

Published:

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

FOUR-WAY CONTROL VALVE FOR PNEUMATIC CHARGING AND DISCHARGING OF WORKING VESSEL

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and incorporates by reference the entirety of US Provisional Patent Application No. 62281115 filed on January 20, 2016.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

SEQUENCE LISTING, TABLE OR COMPUTER PROGRAM ON COMPACT DISC

[0003] Not applicable.

FIELD OF INVENTION

[0004] This invention relates generally to control valves and particularly to pneumatic control valves, systems and methods.

BACKGROUND OF THE INVENTION

[0005] Certain industrial applications require the charging and subsequent discharging of a working vessel with compressed gas, in a repeated cycle. For example, in blow molding applications, a part mold is filled with compressed gas during the molding process. After the

part is formed, the compressed gas used to pressurize the mold is subsequently discharged from the mold. The process of charging (i.e., pressurizing) and subsequent discharging (i.e., depressurizing) of the mold with compressed gas is repeated for the next molded part. Another example of a process involving repeated charging and discharging of a working vessel is the actuation of the fluid chamber of a single-acting pneumatic cylinder. Single-acting pneumatic cylinders use the force of fluid (typically air) to move in one direction (either an extension or retraction stroke) and use a return force of another means (typically a spring) to move in the alternative direction. Alternately, a double-acting pneumatic cylinder uses the force of fluid (typically air) to move in both the extension and retraction strokes. The typical double-acting cylinder includes a piston housing (the cylinder) that encapsulates a piston that can slidably move within the housing along its length. The piston divides the piston housing into two chambers (a first and second chamber), the size of each chamber is variable and depends upon the location of the piston within the housing. Another example of a process involving repeated charging and discharging of a working vessel is the process of leak-checking a chamber. This chamber could, for example, be the internal volume of an engine, an automobile tire, a gasoline tank, or any other product that requires minimal leakage for proper function. To perform the leak-check, the chamber is filled with compressed gas and then, using industry standard procedures, a determination can be made as to the leak rate of compressed gas leaving said chamber. After determination of the leak rate, the compressed gas is subsequently discharged from the chamber. The process of charging (i.e., pressurizing) and subsequent discharging (i.e., depressurizing) of the chamber with compressed gas is then repeated for the next part being tested.

[0006] The process of pressurizing and depressurizing (or charging and discharging) a working vessel in applications such as are described above is typically controlled by a 2-position, 3-way, 3-port valve (hereafter called a 3-way valve). A typical 3-way valve is one that selectively connects three fluid ports in one of two respective port connectivity positions. A schematic diagram of the port connectivity provided by a standard 3-way valve **1** is shown in Figure 1, where the labels **P1** and **P2** correspond to first and second valve positions, respectively. Although various arrangements of the three ports are possible, in keeping with a conventional usage, the three ports will be respectively referred to here as the supply (conventionally labeled in technical drawings with the letter "**S**"), exhaust (conventionally labeled in technical drawings with the letter "**E**"), and the outlet port (conventionally labeled in technical drawings with the letter "**A**"). Given this nomenclature, a standard 3-way valve can either be configured into a first position **P1**, which provides a port connectivity configuration in which outlet port **A** is connected to supply port **S**, and exhaust port **E** is isolated; or into a second position **P2**, which provides a port connectivity configuration in which outlet port **A** is connected to (in fluid communication with) exhaust port **E**, and supply port **S** is isolated (fluid flow between the supply port and all of the other ports of the valve is prevented). As shown in Figure 2 supply port **S** is in fluid communication with pressure supply **5**, which supplies a compressed fluid for the relevant industrial application. Exhaust port **E** is in fluid communication with (discharges to) an exhaust **6**, which is typically atmosphere or exhaust piping or receptacle. In some cases, a valve may include a third position **P3**, which corresponds to a third port connectivity configuration, such as one in which all ports are isolated. In typical operation, however, only the first and second valve positions (i.e., port connectivity configurations) **P1**, **P2** are used.

[0007] Figures 2 and 3 show a typical configuration in which a 3-way valve **1** is used to control the charging and discharging of a pressure vessel **3** via gas line **30**. As shown in Figure 2, when valve **1** is in a first position **P1**, outlet port **A** is connected to supply port **S**, and pressure vessel **3** is charged (i.e., pressurized). As shown in Figure 3, when valve **1** is in a second position **P2**, outlet port **A** is connected to exhaust port **E**, and the compressed gas in pressure vessel **3** is discharged through exhaust port **E**. Although valve **1** might be moved between positions **P1** and **P2** manually, in most automated applications, valve **1** is moved between the first and second positions **P1**, **P2** via electrical actuation, such as via direct or pilot-actuated solenoid operation.

[0008] The control valve of the prior art suffers from the fact that it is not energy efficient and is not deployed in an energy efficient manner. In particular, during the course of a typical repeated charge and discharge cycle as illustrated in Figures 2 and 3, the entire mass of compressed gas contained within pressure vessel **3** is vented to atmosphere after each cycle. This discharge is inefficient and requires the provision of a new volume of compressed gas for each application. Rather than discard the entire mass of compressed gas during each discharge phase of the cycle, it would be desirable to reduce the consumption of compressed air by temporarily storing a portion of the compressed gas during the discharge process, and subsequently reusing a portion of the stored compressed gas during the following charging portion of the cycle.

SUMMARY OF THE INVENTION

[0009] The present invention is directed to an improved control valve and systems and methods that reserve compressed gas for use in an application cycle. More specifically, this

application describes embodiments of an energy-saving charge/discharge control valve, along with systems and methods, that control the repeated charging and discharging of a pressure vessel in a manner that enables the storage and subsequent reuse of compressed gas during the repeated charge and discharge cycle. In contrast to the control valve, systems and methods of the prior art, the present invention control valve and systems and methods do not discard the entire mass of compressed gas during each discharge phase of the cycle. An energy savings results from the recycling of compressed gas, which reduces the net consumption of compressed gas for a given charge/discharge cycle of a given pressure vessel.

[0010] In one aspect, the present invention is directed to a valve for controlling the flow of a fluid that re-uses compressed gas during the charging and discharging of pressure vessels. The valve comprises a valve body and a flow diverter disposed within the valve body. The flow diverter is movably positionable within the valve body such that the flow diverter can assume a first position, a second position and a third position. The valve body further comprises a plurality of external ports, the plurality of external ports comprising a supply port, a first outlet port, a second outlet port and one or more exhaust ports. The flow diverter is actuated to assume one of the three noted positions to create or block fluid communication pathways among the external ports of the valve. Specifically, the valve body and flow diverter are configured such that: a) when the flow diverter is in the first position, the supply port and the first outlet port are in fluid communication with each other and the one or more exhaust ports and second outlet port are each in fluid isolation; b) when the flow diverter is in the second position, the first outlet port and one of the one or more exhaust ports are in fluid communication with each other and the supply port and the second outlet port are each in fluid isolation; and c) when the flow diverter is in the third position, the first outlet port and the second outlet port are in fluid communication

with each other and the supply port and the one or more exhaust ports are each in fluid isolation. The invention is also directed to a system and method that employs the present invention valve in various configurations.

[0011] The inventive valve may be embodied in various types of valve structures, but is preferably embodied in a cylindrical spool valve as is described more fully herein. In this respect, the present invention valve comprises a body having a first end and a second end. The preferred embodiment valve further comprises a spool (the flow diverter) within the body. The spool is slidably movable within the body and capable of being moved to a first spool position, a second spool position and a third spool position. As is discussed below, an important feature of the embodiment inventive valve is that the third spool (diverter) position is physically located between the first spool position and the second spool position. As with conventional valves, the body of the valve comprises one or more external ports. In the case of one embodiment of the inventive valve, the plurality of ports includes a first exhaust port, a supply port, a first outlet port, and a second outlet port. Hence, the inventive valve includes at least four external ports. In the preferred embodiment, the inventive valve comprises a second exhaust port

[0012] The spool and body of the embodiment valves described herein are configured such that the various external ports are in fluid communication with one or more other ports or in fluid isolation depending upon the positioning of the spool in the body. As used in this application, the terms "in fluid communication," "fluidly connects" or "fluidly communicates" is used in reference to two or more ports or structures to describe the physical situation in which the valve permits fluid flow between those ports or structures. The terms "in fluid isolation" or "fluidly isolated" are used in reference to a port to describe the situation wherein the valve does not permit fluid flow between that port and any other port. However, and as explained below, in

the case where the valve has more than one exhaust port, when the exhaust ports are collectively referred to as being fluidly isolated, that means the exhaust ports are isolated from the valve's other ports, but may be fluidly connected to each other.

[0013] In the case of the four-port embodiment of the present invention valve, the valve regulates fluid communication and isolation among the ports as follows. When the spool is in the first position, the supply port and the first outlet port are in fluid communication with each other and the exhaust port and second outlet port are each in fluid isolation. When the spool is in the second position, the first outlet port and the exhaust port are in fluid communication with each other and the supply port and the second outlet port are each in fluid isolation. When the spool is in the third position, the first outlet port and the second outlet port are in fluid communication with each other and the supply port and the exhaust port are each in fluid isolation. Additional embodiments of the inventive valve and systems incorporating those embodiments are described herein and are not intended to be limiting.

[0014] The present invention control valve allows for the storage and reuse of compressed gas with a minimal amount of additional apparatus, and with minimal requirement for system reconfiguration, relative to a conventional implementation. As is discussed below, the recycling of compressed gas is enabled by a unique combination of 4-way port connectivity configurations provided by the present invention valve. Implementation of the valve in an energy-saving system requires only 1) replacement of a standard 3-way control valve with a present invention energy-saving control valve and 2) addition of a pressure reservoir to temporarily store the compressed gas between the charge and discharge cycles. As such, a minimum amount of apparatus is required to implement the recycling of compressed gas - the only additional component needed being a pressure

reservoir. The present invention control valve thus reduces the consumption of compressed air by permitting the temporary storing of a portion of the compressed gas during the discharge process. The valve can then be actuated to reuse a portion of the stored compressed gas during the following charging portion of the cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Figure 1 is a schematic diagram of port connectivity for a standard 2-position, 3-way, 3-port valve.

[0016] Figure 2 is a schematic diagram of a standard configuration for a working vessel charging via a standard 3-way control valve, the diagram showing the control valve in the first position.

[0017] Figure 3 is a schematic diagram showing a standard configuration for a working vessel discharging via a standard 3-way control valve, the diagram, showing the control valve in the second position.

[0018] Figure 4 is a schematic diagram depicting port connectivity for a 4-port embodiment of a present invention valve.

[0019] Figure 5 is a schematic diagram depicting port connectivity for a 5-port embodiment of a present invention valve.

[0020] Figure 6 illustrates an embodiment application of a 5-port embodiment of the present invention valve and is a schematic diagram showing a circuit of a pneumatic system that employs an embodiment 5-port directional control valve according to the present invention. The embodiment valve is shown in the first position, which results in charging of the pressure vessel.

[0021] Figure 7 is a schematic diagram depicting the embodiment application circuit of Figure 6. The embodiment valve is shown in the third position for transitioning from the first (charge) to the second (discharge) positions. The third position enables the first step in the discharging process by equilibrating pressure between the pressure vessel and reservoir (i.e., temporarily storing compressed gas from the pressure vessel in the reservoir). This state is the high-pressure equilibrium state, also called the first equilibrium state.

[0022] Figure 8 is a schematic diagram depicting the embodiment application circuit of Figure 6. The embodiment valve is shown in the second position, which discharges the remaining compressed gas from the pressure vessel.

[0023] Figure 9 is a schematic diagram depicting the embodiment application circuit of Figure 6. The embodiment valve is shown in the third position for transitioning from the second (discharge) to the first (charge) positions, which serves as the first step in the charging process by equilibrating pressure between the pressure vessel and reservoir (i.e., recycling compressed gas from the reservoir to the pressure vessel). This state is the low-pressure equilibrium state, also called the second equilibrium state.

[0024] Figure 10 is a schematic diagram showing a standard configuration for pressurization of a spring-return, single-acting cylinder with a standard 3-way control valve, the control valve being in the first position. The spring-return, single-acting cylinder returns to the extended position when depressurized and the retracted position when pressurized.

[0025] Figure 11 is a schematic diagram showing a standard configuration for exhaust (i.e., depressurization) of a single-acting cylinder with a standard 3-way control valve, the control valve being in the second position.

[0026] Figure 12 illustrates an alternate embodiment application of a 5-port embodiment of the present invention valve and is a schematic diagram showing a pneumatic circuit system that employs an embodiment directional control valve according to the present invention in connection with a single-acting cylinder. The embodiment valve is shown in the first position. Setting of the valve in the first position results in pressurization of the cylinder. This pressurization, in turn, results in retraction of the piston rod.

[0027] Figure 13 is a schematic diagram depicting the embodiment application circuit of Figure 12. The embodiment valve is shown in the third position when transitioning between piston rod retraction and extension. This position corresponds to the high-pressure equilibrium state, also called the first equilibrium state.

[0028] Figure 14 is a schematic diagram depicting the embodiment application circuit of Figure 12. The embodiment valve is shown in the second position. Setting of the valve in the second position results in the discharge of the remaining compressed gas from the cylinder and completes extension of the piston rod.

[0029] Figure 15 is a schematic diagram depicting the embodiment application circuit of Figure 12. The embodiment valve is shown in the third position when transitioning between piston rod extension and retraction. This position corresponds to the low-pressure equilibrium state, also called the second equilibrium state. Assuming load conditions such that P(LPE) is high enough to overcome the force of the spring in the cylinder, the actuator will be configured into the first actuator position (retracted) in this state. Pressurization of the cylinder is completed by subsequently switching back to the first position of the valve, as shown in Figure 12.

[0030] Figure 16 is a diagrammatic view of the flow-determining cross section of the body and spool configuration for a 3-position, 5-port spool valve constructed in accordance with

the present invention.

[0031] Figure 17 is a diagrammatic view of the flow-determining cross section of the spool and body configuration for a 3-position, 5-port spool valve constructed in accordance the present invention, the valve having body-mounted sealing elements.

[0032] Figures 18 is a diagrammatic view of the flow-determining cross section of the spool and body configuration for a 3-position, 5-port spool valve constructed in accordance with the present invention, the valve having spool-mounted sealing elements.

[0033] Figure 19 is a schematic diagram of an embodiment application circuit that includes a two-solenoid, 5-port embodiment of a present invention valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the first position, which position results when the first solenoid is energized and the second solenoid is de-energized.

[0034] Figure 20 is a schematic diagram depicting the embodiment application circuit of Figure 19 along with the two-solenoid, 5-port embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the second position, which position results when the first solenoid is de-energized and the second solenoid is energized.

[0035] Figure 21 is a schematic diagram depicting the embodiment application circuit of Figure 19 along with the two-solenoid, 5-port embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the third position, which position results when the first and second solenoids are de-energized.

[0036] Figure 22 is a schematic diagram of an embodiment application circuit that includes a three-solenoid embodiment of a present invention valve depicted in a diagrammatic,

flow-determining cross section view. The embodiment valve is shown in the first position, which position results when the first and third solenoids are energized and the second solenoid is de-energized.

[0037] Figure 23 is a schematic diagram depicting the embodiment application circuit of Figure 22 along with the embodiment three-solenoid embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the second position, which position results when the second and third solenoids are energized and the first solenoid is de-energized.

[0038] Figure 24 is a schematic diagram depicting the embodiment application circuit of Figure 22 along with the embodiment three-solenoid embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the third position, which position results when the third solenoid is energized and the first and second solenoids are de-energized.

[0039] Figure 25 is a schematic diagram depicting the embodiment application circuit of Figure 22 along with the embodiment three-solenoid embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the de-energized configuration (all solenoids de-energized), which results in fluid communication among the first outlet port, the second outlet port and exhaust.

[0040] Figure 26 is a schematic diagram depicting the embodiment application circuit of Figure 22 along with the embodiment three-solenoid embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the first manual override configuration, which moves the spool into the first position, and provides fluid communication exclusively between the supply port **S** and first outlet port **A**.

[0041] Figure 27 is a schematic diagram depicting the embodiment application circuit of Figure 22 along with the embodiment three-solenoid embodiment valve depicted in a diagrammatic, flow-determining cross section view. The embodiment valve is shown in the second manual override configuration, which moves the spool into the second position, and provides fluid communication exclusively between the exhaust port E_1 and first outlet port **A**.

[0042] Figures 28-35 illustrate an alternate embodiment application of the present invention valve and are schematic diagrams showing a pneumatic circuit system that employs two embodiment 5-port directional control valves according to the present invention in connection with a double-acting cylinder. The figures show the configuration of the valves as the system goes through the method states in which the chambers of the double-acting cylinder are charged and discharged.

[0043] Figure 36 depicts a section view of an embodiment 5-port valve according to the present invention with the spool shown in the first spool position.

[0044] Figure 37 depicts a section view of an embodiment 5-port valve according to the present invention with the spool shown in the second spool position.

[0045] Figure 38 depicts a section view of a three solenoid embodiment 5-port valve according to the present invention with the spool shown in the third spool position.

DETAILED DESCRIPTION

[0046] The inventive valve will now be described in the context of its preferred embodiment spool valve configuration. In a first preferred embodiment, the present invention valve includes a supply port **S**, first outlet port **A** and second outlet port **B** and one or more

exhaust ports **E**. A schematic diagram of the port connectivity provided by a 4-port embodiment of the present invention valve **101** is shown in Figure 4.

[0047] Although the valve **101** need only have four distinct fluid ports, in certain embodiments the function of the exhaust port **E** may be achieved by two physical ports, a first exhaust port $\mathbf{E_1}$ and a second exhaust port $\mathbf{E_2}$, both of which are characterized by the same (typically atmospheric) fluid potential. A schematic of the port connectivity provided by a 5-port embodiment valve **201** is shown in Figure 5.

[0048] Note that in Figure 5 one of the exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$ in the preferred 5-port embodiment valve **201** is not used. Despite this, the 5-port embodiment valve **201** is a preferred embodiment because a 5-port configuration is a standard, preferred configuration in the pneumatic industry, and as such, a 5-port embodiment of the valve maintains a standard connectivity with existing pneumatic apparatus (e.g., valve manifolds). As such, illustrations of the valve embodiment and functionality herein are provided in the context of the 5-port embodiment valve **201**. It should be clear to one having ordinary skill in the art that a 4-port embodiment, such as valve **101**, is merely a simplification of the 5-port version, because elimination of the fifth port (which is the second exhaust port) yields a 4-port embodiment of the inventive valve. For conciseness the inventions are explained herein in terms of a 5-port embodiment valve.

[0049] As shown in Figure 5, the inventive energy-saving control valve selectively connects the four distinct fluid potentials in one of three respective connectivity configurations. In the first valve position, the first outlet port **A** is in fluid communication with the supply port **S**, while the second outlet port **B** and the one or more exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$ maintained in fluid isolation. In the second valve position, the first outlet port **A** is in fluid communication with the

first exhaust port E_1, while the second outlet port **B**, the supply port **S** and second exhaust port E_2 are each separately maintained in fluid isolation. The third valve position, which is positioned between the first and second valve positions, is characterized by the first outlet port **A** and the second outlet port **B** being in fluid communication, and the supply port **S** and the one or more exhaust ports E_1, E_2 being fluidly isolated. Note that unless otherwise stated, in the case where the valve is equipped with more than one exhaust port, the exhaust ports need not be isolated from each other - only from the supply port **S** and the outlet ports **A** and **B**. This is what is meant by the phrases "isolation of the one or more exhaust ports" or "the one or more exhaust ports are in fluid isolation."

[0050] Figures 6 through 9 illustrate an exemplary circuit **2** configuration system employing a valve **201** according to the present invention for the repeated charge and discharge of a working vessel (pressure vessel) **3** (effectively a fluid chamber). As is the case with the typical charge/discharge control system, the process of charging and discharging working vessel **3** is singularly controlled by control valve **201**, although the system **2** is additionally supplemented with a reservoir **4**. Gas line **30** provides a fluid pathway in and out of vessel **3** to valve **201**. Gas line **31** provides a fluid pathway in and out of reservoir **4** to valve **201**. Further, the features discussed herein apply equally to any type of working vessels. Thus, the embodiment inventive system of Figures 6-9 includes valve **201** fluidly connected to fluid supply **5**, reservoir **4** and working vessel **3**.

[0051] Consider first the case in which working vessel **3** is in a charged state, which results from configuring valve **201** into the first valve position **P1**. In the first position **P1**, valve **201** provides the same connectivity between the first outlet port **A** and the supply port **S** as does a conventional 3-way control valve in the first position. Hence, first outlet port **A** is connected to

supply port **S**, resulting in charging (i.e., pressurization) of pressure vessel **3**, as illustrated in Figure 6. In addition to the connectivity between first outlet port **A** and supply port **S**, the valve also isolates all other ports (i.e., the one or more exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$ and second outlet port **B**).

[0052] The third position **P3** of valve **201** introduces two additional states to the charge/discharge cycle, relative to a standard 3-way control valve. Specifically, rather than immediately connect first outlet port **A** to one of the one or more exhaust ports (exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$), the discharge process in valve **201** is initiated by temporarily switching control valve **201** into the third position, **P3**, which, as shown in Figure 7, connects first outlet port **A** and second outlet port **B**, while isolating supply port **S** and the one or more exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$. The port connectivity created by third position **P3** provides a configuration in which the pressures in the chambers of vessel **3** and reservoir **4** will arrive at a common equilibrium pressure (given sufficient time). Vessel **3** is initially at the supply pressure, while the pressure in reservoir **4** is initially at an intermediate value, referred to here as the low-pressure equilibrium pressure. Because the low-pressure equilibrium pressure will be lower than the supply pressure, and given the constitutive behavior of compressed gas, equilibration of the chamber pressures of vessel **3** and reservoir **4** will require a portion of the compressed gas in chamber **3** to flow into reservoir **4**.

[0053] In the case where the volumes of vessel **3** and reservoir **4** are equal, for example, the two chambers of vessel **3** and reservoir **4** will reach an equilibrium in which the mass of compressed gas in both will be equal. This (first) equilibrium state is referred to as the high-pressure equilibrium state, and the equilibrium pressure in both vessel **3** and reservoir **4** referred to as the high-pressure equilibrium pressure. Following a sufficient period of time, referred to here as the first dwell time, in which system **2** is in the first equilibrium state, the discharge

process is completed by moving valve **201** into the second position **P2**. This is shown in Figure 8.

[0054] In the second position **P2**, valve **201** provides the same connectivity between first outlet port **A** and an exhaust port (either $\mathbf{E_1}$ or $\mathbf{E_2}$) as does a conventional 3-way valve in the second position. In the second position **P2**, first outlet port **A** is connected to exhaust port $\mathbf{E_1}$, and the remaining mass of compressed gas in the pressure vessel **3** is discharged to atmosphere (i.e., the vessel is depressurized). In addition to the connectivity between first outlet port **A** and exhaust port $\mathbf{E_1}$, valve **201** in this position also isolates all other ports (i.e., second outlet port **B**, supply port **S**, and remaining exhaust port $\mathbf{E_2}$). Note that, because second outlet port **B** is isolated while valve **201** is in second position **P2**, the pressure in reservoir **4** will remain at the high-pressure equilibrium pressure until the following equilibrium state.

[0055] In order to initiate the charge portion of the charge/discharge cycle, rather than immediately connect first outlet port **A** to the supply port **S**, the charge process is initiated by temporarily switching control valve **201** back to third position **P3**. This is shown in Figure 9. Temporarily switching valve **201** back to third position **P3** connects first outlet port **A** with second outlet port **B**, while isolating supply port **S** and the one or more exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$. This port connectivity enables an equilibration of the pressures in vessels **3** and reservoir **4**. Because the pressure in reservoir **4** is initially at the high-pressure equilibrium pressure, and the pressure in vessel **3** is initially at atmosphere, a portion of the compressed gas in reservoir **4** will flow to vessel **3**. In the case where the volume of both chambers of vessel **3** and reservoir **4** are equal, for example, the two chambers will reach an equilibrium in which the mass of compressed gas in both will be equal. This (second) equilibrium state is referred to as the low-pressure equilibrium state, and the equilibrium pressure in both chambers of vessel **3** and reservoir **4**

referred to as the low-pressure equilibrium pressure. Following a sufficient period of time (referred to here as the second dwell time) in which system **2** is in the second equilibrium state, the charging process is completed by moving valve **201** back to first position **P1**. This is shown in Figure 6. Moving valve **201** to first position **P1** results in vessel **3** being fully charged. The charge/discharge cycle can then be repeated. Note that, because second outlet port **B** is isolated while valve **201** is in first position **P1**, the pressure in reservoir **4** will remain at the low-pressure equilibrium pressure until the following equilibrium state.

[0056] The process of compressed gas saving can be modelled as follows. Assuming ideal gas constitutive behavior, isothermal processes, and constant-volume chambers, one can show that the high-pressure equilibrium pressure is given by:

$$P_{HPE}(k) = \left(\frac{1}{1+V_R}\right)\left(P_S + V_R P_{LPE}(k-1)\right) \tag{1}$$

where V_R is the volume ratio between the reservoir **4** and pressure vessel **3**, given by:

$$V_R = \frac{V_B}{V_A} \tag{2}$$

where V_A and V_B are the volumes of pressure vessel **3** and reservoir **4**, respectively, k denotes the charge/discharge cycle (where k=1 is the first cycle), $P_{HPE}(k)$ is the high-pressure equilibrium pressure at the current charge/discharge cycle, $P_{LPE}(k\text{-}1)$ is the low-pressure equilibrium pressure during the previous change/discharge cycle, and P_S is the supply pressure. Given similar assumptions, the low-pressure equilibrium pressure at the current cycle is given by:

$$P_{LPE}(k) = \left(\frac{1}{1+V_R}\right)\left(P_{ATM} + V_R P_{HPE}(k)\right) \tag{3}$$

where $P_{LPE}(k)$ is the low-pressure equilibrium pressure at the current charge/discharge cycle k, $P_{HPE}(k)$ is the high-pressure equilibrium pressure at the current cycle given by (1), and P_{ATM} is

atmospheric pressure. Equations (1) and (3) can be combined to yield a single recursive equation for the low-pressure equilibrium pressure:

$$P_{LPE}(k)=\left(\frac{1}{1+V_R}\right)\left(P_{ATM}+V_R\left(\frac{1}{1+V_R}\right)\left(P_S+V_R P_{LPE}(k-1)\right)\right) \tag{4}$$

This equation is a first-order difference equation of the form:

$$P_{LPE}(k)=aP_{LPE}(k-1)+b \tag{5}$$

where

$$a=\left(\frac{V_R}{1+V_R}\right)^2 \tag{6}$$

and

$$b=\left(\frac{1}{1+V_R}\right)\tilde{P} \tag{7}$$

where

$$\tilde{P}=\left(P_{ATM}+\left(\frac{V_R}{1+V_R}\right)P_S\right) \tag{8}$$

The solution for the first-order difference equation (5) is given by:

$$P_{LPE}(k)=a^k P_{LPE}(0)+\frac{b(a^k-1)}{a-1} \tag{9}$$

[0057] Assuming reservoir 4 is fully depressurized at the start of the charge/discharge process, the initial pressure, $P_{LPE}(0)$ in (9) is P_{ATM}. Equation (9) is stable if and only if $a<1$, which based on equation (6), will always be true. As such, the difference equation (9) will converge at a sufficient number of cycles to a steady-state equilibrium pressure given by:

$$\overline{P}_{LPE} = \frac{b}{1-a} \tag{10}$$

Substituting equations (6-8) into equation (11) yields a low-pressure equilibrium pressure in the steady state of:

$$\overline{P}_{LPE} = \left(\frac{1+V_R}{1+2V_R}\right)\overline{P} \tag{11}$$

Combining equations (9) and (10), one can show that the number of cycles required to obtain a fraction γ of the steady state pressure, assuming the initial pressure in the reservoir is P_{ATM}, is given by:

$$k = \left(\frac{\ln((1-\gamma)b) - \ln((a-1)P_{ATM} + b)}{\ln a}\right) \tag{12}$$

[0058] Assuming, for example, a reservoir **4** of equal volume to the pressure vessel **3** (i.e., V_R=1), one can show from equation (12) that the low-pressure equilibrium pressure will reach 95% of its steady-state value (i.e., $\gamma = 0.95$) after three cycles. Assuming the system reaches the steady-state low-pressure equilibrium pressure given by equation (12), and continuing the assumptions of ideal gas behavior and an isothermal process, the ratio of mass recycled during each cycle to total charge mass can be written as:

$$\frac{m_r}{m_A} = \frac{\overline{P}_{LPE}}{P_S} \tag{13}$$

where m_r is the mass of compressed gas recycled from the previous cycle and m_A is the total mass of compressed gas required to charge pressure vessel **3**. The amount of mass required to charge pressure vessel **3** without recycling is given by:

$$m_A = \frac{(P_S - P_{ATM})V_A}{RT} \tag{14}$$

where RT is the product of the ideal gas constant and the nominal gas temperature (i.e., a constant under the assumed isothermal conditions). The amount of mass required to charge vessel **3** with recycling is given by:

$$m_{AR} = \frac{(P_S - \overline{P}_{LPE})V_A}{RT} \tag{15}$$

As such, the amount of compressed gas required for each charge cycle relative to the amount without recycling is given by:

$$p = \frac{m_{AR}}{m_A} = \frac{P_S - \overline{P}_{LPE}}{P_S - P_{ATM}} \tag{16}$$

and therefore the compressed gas savings relative to a standard system is given by:

$$\eta = 1 - p \tag{17}$$

[0059] Assuming, for example, reservoir **4** is of equal volume to pressure vessel **3** (i.e., V_R=1), atmospheric pressure of 0.1 MPa (1 bar), and a supply pressure of 0.6 MPa (6 bars), the steady-state low-pressure equilibrium pressure would be:

$$\overline{P}_{LPE} = \left(\frac{2}{3}\right)\left(P_{ATM} + \left(\frac{1}{2}\right)P_S\right) = \left(\frac{2}{3}\right)\left(\frac{1}{6} + \frac{1}{2}\right)P_S = \left(\frac{2}{3}\right)^2 P_S \tag{18}$$

such that the compressed gas savings would be $p = \frac{2}{3}$ and the savings relative to a standard process given by $\eta = \frac{1}{3}$ (33% savings). In the limit that reservoir **4** becomes much larger than pressure vessel **3**, assuming the same ratio of atmospheric to supply pressure (1:6), the steady-state low-pressure equilibrium pressure will approach:

$$\overline{P}_{LPE} \approx \left(\frac{1}{2}\right)\left(P_{ATM} + P_S\right) = \left(\frac{1}{2}\right)\left(\frac{1}{6} + 1\right)P_S = \left(\frac{7}{12}\right)P_S \tag{19}$$

such that the compressed gas savings will approach $p \approx \frac{1}{2}$, and the savings relative to a standard process will similarly approach $\eta = \frac{1}{2}$ (50% savings). In the case that no pressure reservoir **4** is

used (i.e., V_R=0), the steady-state equilibrium pressure will be $\overline{\overline{P}}_{LPE} = P_{ATM}$, the relative mass requirement $p = 1$, and the relative savings $\eta = 0$ (i.e., no savings possible without a pressure reservoir).

[0060] As previously mentioned, a 5-port embodiment valve provides compatibility with a 5-port valve manifold interface (i.e., the porting footprint on which the valve is mounted), and therefore is a preferred embodiment of the present invention valve. The port connectivity required for a 5-port valve according to the present invention can be realized in a 3-position spool-type valve **301** as shown in the flow-determining schematic diagram in Figure 16. In embodiment valve **301** schematically shown, valve **301** includes valve spool **50** that slides linearly within valve body **60**. Valve body **60** interfaces with a given apparatus (i.e., manifold) via five external ports, which are typically associated with four distinct fluid potentials, referred to here as the supply port **S**, exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$, first outlet port **A** and second outlet port **B**. As shown in the figure, valve exhaust is provided via two physically distinct ports $\mathbf{E_1}$, $\mathbf{E_2}$. In addition to external ports, the valve body **60** contains a series of internal ports **41-45** located within valve body **60**, which correspond to each of the five external ports, in addition to four additional internal ports **46-49** associated with opposite ends of two respective internal flow paths (channels) **AB1** and **AB2**.

[0061] In one preferred embodiment, valve spool **50** employs four spool lobes **51-54**, which are the first, second, third, and fourth spool lobes, respectively. As valve spool **50** slides to each respective position within body **60**, internal ports **41-45** and **46-49** within body **60** are selectively isolated or exposed via lobes **51-54** on valve spool **50**, which results in a prescribed port (i.e., fluidic) connectivity between the external ports. In a preferred embodiment, spool **50** is axisymmetric and has a circular cross-section, which facilitates positive fluidic sealing

between body **60** and spool lobes **51-54**. Three-position valve **301** is described by three distinct port connectivity configurations, which are referred to as the first, second, and third valve positions (**P1**, **P2**, **P3**), respectively (see schematic in Figure 5), which corresponds to the three positions of spool **50** within valve body **60**. Although not shown in Figure 16, valve spool **50** is typically moved between these positions via electrical actuation, such as via direct or pilot-actuated solenoid actuation. As shown in Figure 16, when valve spool **50** is in first position **P1**, in which spool **50** is positioned furthest to the right in the figure, first outlet port **A** and supply port **S** are maintained in a state of fluid communication between the first lobe **51** and second lobe **52** of spool **50**, while first lobe **51** isolates first exhaust port $\mathbf{E_1}$, second lobe **52** isolates second outlet port **B**, and third spool lobe **53** isolates the internal flow channel **AB2** from the second exhaust port $\mathbf{E_2}$ and internal flow channel **AB1**. The resulting external port connectivity provides fluid communication between first outlet port **A** and supply port **S**, and fluid isolation of both exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$ and second outlet port **B**.

[0062] When valve spool **50** slides to the second position **P2**, in which the spool position is furthest to the left in Figure 16, first outlet port **A** and first exhaust port $\mathbf{E_1}$ are maintained in a state of fluid communication between the first lobe **51** and second lobe **52**, while second lobe **52** isolates supply port **S**; second outlet port **B** is isolated between second lobe **52** and third lobe **53**; second exhaust port $\mathbf{E_2}$ is isolated by third lobe **53**; and the **AB1** port **49** is isolated by fourth spool lobe **54**. The resulting external port connectivity provides fluid communication between first outlet port **A** and first exhaust port $\mathbf{E_1}$, and fluid isolation of the supply port **S** and second outlet port **B**. In other words, the second exhaust port $\mathbf{E_2}$ is fluidly isolated from all other ports and the second outlet port **B** is similarly fluidly isolated from all other external ports.

[0063] As seen in Figure 16, when valve spool **50** is in third position **P3**, which is the center position of the spool, first outlet port **A** is maintained in a state of fluid communication with the first internal flow channel **AB1** between first lobe **51** and second lobe **52**; second outlet port **B** is maintained in a state of fluid communication with second internal flow channel **AB2** between second lobe **52** and third lobe **53**; and first internal flow channel **AB1** is maintained in a state of fluid communication with second internal flow channel **AB2** between third lobe **53** and fourth lobe **54**. As such, first outlet port **A** is maintained in a state of fluid communication with the second outlet port **B**. Further, first exhaust port $\mathbf{E_1}$ is maintained in fluid isolation by first spool lobe **51**; supply port **S** is isolated by the second spool lobe **52**; and second exhaust port $\mathbf{E_2}$ by third lobe **53**. The resulting external port connectivity provides exclusive fluid communication between the first outlet port **A** and second outlet port **B**, and fluid isolation of supply port **S** and exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$.

[0064] Note that configuring the third spool position physically between the first and second spool positions, as enabled by the embodiment described here, enables effective ordering of port connectivity as per the previously described two-stage charge and discharge functionality. If either the first or second position were located in the center position of the valve, valve **301** would be required to move through the supply or exhaust condition, respectively, prior to the equilibration position, which in either case would decrease the efficacy of the compressed gas recycling, because the spool cannot move infinitely quickly through a given port connectivity configuration. As such, an important aspect of the preferred embodiment is one in which the third spool position is located physically between the first and second.

[0065] Note that the second exhaust port $\mathbf{E_2}$ (furthest to the right) in the preferred embodiment of the valve **301** shown in Figure 16 is not used in any of the valve positions. As

such, second exhaust port E_2 could be eliminated completely without otherwise affecting valve functionality. Thus, another preferred embodiment of the valve is one that is configured as shown in Figure 16, but without second exhaust port E_2, such that the valve is in effect a 4-port rather than a 5-port valve. As previously mentioned, however, valve **301** is depicted in Figure 16 in the context of 5 external ports, because the typical manifold (not shown) upon which the valve is mounted will commonly have a footprint consistent with the 5 external ports shown, and because conversion from a 5-port to 4-port embodiment is straightforward.

[0066] Figure 17 is an enhanced flow-determining schematic diagram that shows a preferred embodiment of the 5-port valve **401** in which sealing elements **70** are affixed to valve body **60** in order to seal the spaces between radially-projecting perimeter surfaces **58** of spool lobes **51-54** and valve body **60** and thus facilitate fluid isolation. Specifically, each sealing element **70** precludes fluid flow across the boundary established by a perimeter surface **58** of a spool lobe **51-54** and the respective sealing element **70**. The configuration of spool geometry and body sealing elements shown in Figure 17 for valve **401** provides the same 3-position port connectivity that characterizes the embodiment valves **201**, **301** and its connectivity is described above and shown in Figures 5 and 16.

[0067] Figure 18 is an enhanced flow-determining schematic diagram that shows another preferred embodiment of the 5-port valve **501**. Note that in embodiment valve **501** shown in Figure 18, valve spool **50** comprises five spool lobes **51-55**. Valve **501** includes sealing elements **70** affixed to the radially-projecting perimeter surfaces **58** of lobes **51-55** of spool **50** in order to preclude fluid flow across the boundary established by the inner surface **61** of the spool chamber **62** of valve body **60** and a respective sealing element on the perimeter surface **58** of any of spool lobes **51-55**. The configuration of spool geometry and spool sealing elements shown in

Figure 18 provides the same 3-position port connectivity of the present invention valve **201** described above and shown in Figure 5.

[0068] In any of the embodiment valves described herein the spool can be moved between the first, second, and third positions manually or by other actuation, such as by electrically-actuated solenoids. In a preferred embodiment, spool **50** is moved between positions within valve body **60** via a pilot-actuated solenoid configuration, in which electrically-actuated solenoids control a pilot flow of compressed gas, such that each respective pilot solenoid controls the pressurization or depressurization of a corresponding pilot cylinder. Such a preferred embodiment system is shown in Figures 19 through 21. In this preferred embodiment, the valve **601** employs first and second pilot solenoids, **81** and **82**, which pressurize or depressurize a respective first and second pilot cylinder, **91** and **92**, and where pressurization of each respective pilot cylinder **91**, **92** pushes the spool away from that pilot cylinder. As such, energizing the first pilot solenoid **81** will result in pressurization of the first pilot cylinder **91**, and simultaneous de-energizing of the second pilot solenoid **82** will result in depressurization of the second pilot cylinder **92**, which will configure spool **50** in the first spool position. Pressurization of second pilot cylinder **92** and simultaneous depressurization of first pilot cylinder **91** will configure spool **50** in the second position. Spool **50** is disposed between centering spring elements **24**, which return spool **50** to the center position in the absence of pilot cylinder pressurization. As such, depressurization of both pilot cylinders **91**, **92** will configure valve **601** into the third position. This pilot-operated embodiment **601** of the valve is shown in schematic in the three valve positions (**P1**, **P2**, **P3**) in Figures 19 through 21, respectively, where the pilot solenoids **81**, **82** are depicted in the schematic as single-pole switches that either pressurize (on logical 1) or depressurize (on logical 0) the respective pilot cylinders **91**, **92**.

[0069] Figure 36-38 show the three spool positions of a design embodiment **801** of the valve corresponding to the enhanced flow-determining schematic diagram shown in Figure 18, and corresponding to the pilot-actuation circuitry shown in Figs. 19-21. Embodiment **801** shows the invention realized in a 5-lobe spool design. Specifically, Figure 36 shows the valve **801** with spool **840** in the first spool position **P1** (positioned to the right in the drawing as shown), corresponding to the configuration shown in Figure 19. The five spool lobes **851-855** are shown along the length of spool **840**. In a preferred embodiment, spool **840** is axisymmetric and has a circular cross-section, which facilitates positive fluid sealing between valve body **860** and spool lobes **851-855**. In the preferred embodiment shown, the valve **801** includes a plurality of sealing elements **861** affixed to the radially-projecting perimeter surfaces **862** of lobes **851-855** of spool **840**. This first spool position as shown in Figure 36 provides fluid connectivity between supply port **S** and first outlet port **A**, and fluid isolation of the second outlet port **B** and exhaust ports $\mathbf{E_1}$ and $\mathbf{E_2}$. Figure 37 shows valve **801** with spool **840** in the second spool position **P2**, corresponding to the configuration shown in Figure 20, which provides fluid connectivity between exhaust port $\mathbf{E_1}$ and first outlet port **A**, and fluid isolation of the second outlet port **B**, supply port **S**, and exhaust port $\mathbf{E_2}$. Finally, Figure 38 shows valve **801** in the third spool position **P3**, corresponding to the configuration shown in Figure 21, which provides exclusive fluid connectivity between the first outlet port **A** and the second outlet port **B**, and fluid isolation of the supply port **S** and exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$. As shown in this preferred embodiment, the exclusive fluid connectivity between first outlet port **A** and second outlet port **B** is enabled by way of the fluid connectivity between internal flow channels **AB1** and **AB2**.

[0070] In one exemplary embodiment, a valve according to the present invention contains a pressure sensor **99** that measures fluid pressure in an internal flow channel **AB1** or

AB2. In this embodiment, measurement of the pressure during the first and second equilibrium states can be used to determine the first and second dwell times, respectively. Specifically, pressure measurement can be used to determine the period of time the valve should be held in the equilibration configuration when switching between the first and second valve positions. While in the equilibration configuration, the compressed air will flow between pressure vessel **3** and pressure reservoir **4** during the high-pressure equilibrium state and the low-pressure equilibrium state, until the pressure has equilibrated. The period during which this occurs is referred to as the first and second dwell times, respectively. Ideally these dwell times should be only long enough to allow equilibrium to occur. As such, in a preferred embodiment, the rate of change of pressure in an internal flow channel **AB1**, **AB2** can be used to determine the respective durations of the first and second dwell times, respectively. For example, in one embodiment, the valve can be maintained in the third valve position (i.e., equilibrium configuration) until the rate of change of pressure in the internal flow path falls below a predetermined threshold, indicating the system has essentially established equilibrium.

[0071] In another preferred embodiment, pressure sensors **99** are used to measure the pressure at each of first and second outlet ports **A**, **B**. In another preferred embodiment, pressure sensors **99** are mounted in the pressure vessel **3** and reservoir **4**. In both embodiments, the valve can be maintained in the third valve position until the pressure differential between first and second outlet ports **A**, **B**, or pressure vessel **3** and reservoir **4**, falls below a predetermined threshold. In another preferred embodiment, a pressure sensor **99** is mounted in the reservoir, and the pressure equilibration process is terminated when the rate of change of pressure falls below a predetermined threshold.

[0072] For purposes of satisfying the required dwell times, an embodiment system may include a controller **98** programmed to cause the valve to stop and remain in the third position for a specified period of time when the valve is being moved from the first position to the second position and from the second position to the first position. Embodiment inventions with a controller **98** and sensors **99** are shown in Figures 28 and 38. The specified period of time when moving from the first position to the second position may be different from the specified period of time when moving from the second position to the first position. In one embodiment, the controller **98** determines the specified period of time for which the valve remains in the third position based upon an input of the amount of time necessary for pressure in the pressure vessel 3 and reservoir 4 to equilibrate. In another embodiment system, the controller **98** will determine the specified period of time for which the valve remains in the third position using as an input the length of time required for the pressure difference between the pressure vessel **3** and the second reservoir **4** to fall below a predetermined threshold. In an embodiment system in which the valve includes a pressure sensor **99** at each of the first outlet port **A** and second outlet port **B**, the controller **98** will determine the specified period of time for which the valve remains in the third position using as an input the length of time required for the pressure difference between the first outlet port **A** and the second outlet port **B** to fall below a predetermined threshold.

[0073] In some applications it is desirable for the valve to connect the first and second valve outlet ports **A**, **B** to an exhaust port when the valve is de-energized, such that both the pressure vessel **3** and reservoir **4** will be depressurized when the valve is de-energized. Figures 22 through 27 illustrate a preferred embodiment of the valve **701** that employs three electrically-actuated solenoids, **81**, **82**, and **83**, to provide this feature. As in the previously described embodiment, first and second pilot solenoids **81**, **82** respectively pressurize or depressurize a first

and second pilot cylinders **91**, **92**. Pressurization of first pilot cylinder **91** and simultaneous depressurization of second pilot cylinder **92** will configure spool **50** in the first position, while pressurization of second pilot cylinder **92** and simultaneous depressurization of first pilot cylinder **91** will configure spool **50** in the second position. In valve **701** spool **50** is disposed between centering spring elements **24**, which return spool **50** to the center position in the absence of pilot cylinder pressurization. As such, depressurization of first and second pilot cylinders **91**, **92** will configure valve **701** into the third position.

[0074] Unlike the previously described embodiment, the preferred embodiment valve **701** shown in Figures 22 through 27 additionally employs a pilot-operated, 2-position, spring-return, 2-way valve **33**. Two-way valve **33** is moved to a first position when pilot **93** is depressurized and in a second position when the pilot **93** is pressurized. In the first position, 2-way valve **33** provides a fluid communication path between one of flow channels **AB1**, **AB2** and an exhaust port, while in the second position valve **33** isolates the flow channels **AB1**, **AB2** from the exhaust. Rather than be supplied directly via a pilot solenoid, 2-way valve pilot **33** is supplied by the outlet port **36** of shuttle valve **35**. Shuttle valve **35** contains first and second inlet ports **37**, **38**. First inlet port **37** is connected to the outlet of the first pilot solenoid **81**, and second inlet port **38** is connected to the outlet of the third pilot solenoid **83**. During typical operation of embodiment valve **701**, third solenoid **83** is constantly energized, which in turn pressurizes 2-way valve pilot **33**, configures the 2-way valve in the second position, and isolates the internal flow channels **AB1**, **AB2** from exhaust. As such, when third solenoid **83** is energized, embodiment valve **701** shown in Figures 22 through 27 operates in a similar manner to the embodiment valve **601** of Figures 19 through 21. Specifically, energizing solenoid **81** and de-energizing solenoid **82** will move spool **50** to the first position (as shown in Figure 22); de-

energizing solenoid **81** and energizing solenoid **82** will move spool **50** to the second position (Figure 23); and de-energizing both solenoids **81**, **82** will move spool **50** to the third position (Figure 24).

[0075] In the case where valve **701** is de-energized, all three solenoids **81**, **82** and **83** will become de-energized, such that the pilot cylinders **91**, **92**, and 2-way pilot **33**, will all become depressurized. In this case, spool **50** will be configured in the third spool position, while 2-way valve **33** will be configured in the first position, the combination of which will provide fluid communication between both the first and second outlet ports **A**, **B** and an exhaust port, as illustrated in Figure 25. As such, both pressure vessels **3** and reservoir **4** will be exhausted when the valve is de-energized.

[0076] It is also desirable in the embodiment valve **701** to indirectly manually move spool **50** into the first or second position via manual overrides employed in solenoids **81**, **82**. When using manual overrides, valve **701** should be movable into the first or second spool positions while third solenoid **83** is de-energized. As shown in Figure 26, manually energizing solenoid **81** with a manual override command enables solenoid **81** to pressurize first pilot cylinder **91** and moves spool **50** into the first position, and also results in pressurization of shuttle valve **35**, which moves 2-way valve **33** into the second position and prevents fluid communication between supply port **S** and exhaust ports E_1, E_2, and thus provides full compatibility with first position port connectivity. Finally, as shown in Figure 27, manually energizing solenoid **82** with a manual override command enables solenoid **82** to pressurize second pilot cylinder **92** and move spool **50** into the second position, thus providing full compatibility with second position port connectivity.

[0077] Another exemplary application of the present invention valve is in the actuation of a single-acting pneumatic actuator. Such an actuator **20** is shown in Figures 10-15. A single-acting pneumatic actuator is one that is configured into one of two piston positions, which in general are a first actuator position and second actuator position, respectively. In the case of a linear actuator (often referred to as a "pneumatic cylinder") **20**, these two positions can be regarded as retraction and extension, respectively, of the piston and rod assembly **21** (the assembly **21** comprising piston **22** and rod **23**). A single-acting pneumatic actuator **20** is actuated by a single compressed gas line **30**, wherein compressed gas (typically air) is used to effect either the retraction or extension stroke of a piston and rod assembly **21** within cylinder **26** of actuator **20**. A spring element **24** is used to provide a return force for the return stroke (i.e., extension or retraction, respectively). The repeated extension and retraction of the piston and rod assembly **21** requires repeated charging and discharging of the compressed gas side chamber **25** of the cylinder **26**.

[0078] The repeated charging and discharging of actuator **20** is typically implemented with a standard 3-way control valve **1**, configured as shown in Figures 10 and 11. For purposes of illustration, the configuration shown depicts actuator **20** for which pressurization of chamber **25** of cylinder **26** causes retraction of the piston and rod assembly **21** while depressurization of chamber **25** of cylinder **26** allows spring element **24** to return piston and rod assembly **21** to the extension configuration. It is understood, however, that the method applies equally to other configurations, such as those for which pressurization results in extension of the rod **23**. As shown in Figure 10, in order to configure the actuator **20** into a first position, chamber **25** of cylinder **26** is charged by configuring the 3-way valve **1** into the first valve position, such that chamber **25** of cylinder **26** is pressurized, rod **23** retracted, and return spring **24** compressed. As

shown in Figure 11, in order to configure actuator **20** into a second position, charged chamber **25** of cylinder **26** is discharged by configuring valve **1** into the second position, such that the gas in chamber **25** of cylinder **26** is exhausted, allowing spring **24** to return the piston and rod assembly **21** to the extended (i.e., depressurized) configuration. During the course of the repeated extension and retraction cycle illustrated in Figures 10 and 11, the entire mass of compressed gas contained within chamber **25** of cylinder **26** is vented to atmosphere after each cycle. Rather than discard the entire mass of compressed gas during each discharge phase of the cycle, it is desirable to reduce the consumption of compressed air by temporarily storing a portion of the compressed gas during the discharge process, and subsequently reusing a portion of the stored compressed gas during the following charging portion of the cycle. It is further desirable to perform the storage and reuse of compressed gas with a minimal amount of additional apparatus, and with minimal requirement for system reconfiguration, relative to a conventional implementation. The present invention valve provides for an apparatus, system and method that enables such storage and reuse of compressed gas in applications involving the repeated charge and discharge of single-acting cylinders.

[0079] Figures 12 through 15 illustrate an exemplary circuit configuration **2a** in which a valve **201** according to the invention controls the repeated charge and discharge of a single-acting pneumatic actuator **20** (i.e., the repeated configuring of the actuator between a first and second actuator position). Thus, the embodiment inventive system of Figures 12-15 includes valve **201** fluidly connected to fluid supply **5**, reservoir **4** and actuator **20**. Similar to the fixed-volume pressure-vessel case, relative to the standard configuration, the energy-saving configuration requires that the standard 3-way control valve be replaced with an control valve according to the present invention, and requires the addition of a supplemental pressure

reservoir. As with a standard 3-way control valve, actuator **20** is configured into a first actuator position (i.e., a charged or pressurized state) by configuring the valve into the first valve position **P1**. In the first position, the valve provides the same connectivity between the first outlet port (**A**) and the supply port (**S**) as does a conventional 3-way control valve in the first position, in which the first outlet port is connected to the supply port, resulting in charging (i.e., pressurization) of chamber **25** of cylinder **26**, and in this case, retraction of rod **23**, as illustrated in Figure 12. In addition to the connectivity between the first outlet port and supply port, the embodiment valve also isolates all other ports (i.e., both exhaust ports and the second outlet port).

[0080] Actuator **20** is configured from the first actuator position (i.e., charged cylinder) into the second actuator position (i.e., discharged cylinder) via a two-step process, in which the embodiment valve **201** is initially configured from the first valve position **P1** into the third valve position **P3**. As shown in Figure 13, placing the valve **201** into the third position **P3** connects the first and second outlet ports **A**, **B**, while isolating each of the supply port **S** and exhaust port E_1, E_2. This port connectivity enables an equilibration of the pressures in chamber **25** of cylinder **26** and reservoir **4**, and because the pressure in chamber **25** of cylinder **26** is initially at the supply pressure, the port connectivity configuration will result in compressed gas flow from chamber **25** of cylinder **26** to reservoir **4**. The equilibrium pressure is referred to in this state as the high-pressure equilibrium pressure. Note that, as discussed subsequently, the return spring force as typically configured is small. As such, in cases where the external load on actuator **20** is insufficient to overcome the force resulting from the high-pressure pressure, piston and rod assembly **21** will not move while in this state (i.e., the volume of chamber **25** of cylinder **26** will remain as in the fully pressurized state).

[0081] Following a sufficient period of time in the third position **P3** (referred to here as the first dwell time), which allows for compressed gas flow into reservoir **4**), the discharge process is completed by moving valve **201** into the second position **P2**, as shown in Figure 14. In the second position, valve **201** provides the same connectivity between first outlet port **A** and first exhaust port $\mathbf{E_1}$ as does a conventional 3-way valve in the second position. As such in that position, first outlet port **A** is connected to exhaust port $\mathbf{E_1}$, and the remaining mass of compressed gas in actuator **20** is discharged to atmosphere (i.e., depressurized), allowing return spring **24** to configure the piston and rod assembly **21** into the second actuator position. Note that, in addition to the connectivity between first outlet port **A** and first exhaust port $\mathbf{E_1}$, valve **201** also isolates all other ports (i.e., the second outlet port **B**, supply port **S**, and second exhaust port $\mathbf{E_2}$).

[0082] The process of configuring the cylinder from the second actuator position (i.e., cylinder depressurization) back to the first actuator position is initiated by temporarily switching control valve **201** from the second valve position **P2** to the third position **P3**, which as shown in Figure 15, connects the first and second outlet ports **A**, **B**, while isolating the supply port **S** and exhaust ports $\mathbf{E_1}$, $\mathbf{E_2}$. This port connectivity enables an equilibration of the pressures between reservoir **4** and cylinder **26**. Because cylinder **26** is currently at atmospheric pressure while reservoir **4** is currently at the high-pressure equilibrium pressure, compressed gas will flow from reservoir **4** to cylinder **26**. Note also that, at the onset of this state, actuator **20** is in the second actuator position (i.e., the spring is extended), and the volume of chamber **25** is small. As noted, return spring **24** force as typically configured is small. Accordingly, in cases for which the low-pressure equilibrium pressure is sufficient to overcome return spring **24** and actuator **20** load, actuator **20** will be moved by the low-pressure equilibrium pressure into the first actuator

position (i.e., the same as in the fully charged and first equilibrium states). The process of moving actuator **20** fully into the first actuator position (i.e., with full actuation force) is completed by moving valve **201** back to first position **P1**, as shown in Figure 12, such that the charge/discharge cycle can be repeated.

[0083] Note that the model of compressed gas saving when using the present invention valve to control the movement of a single-acting cylinder is somewhat different from the model of compressed gas savings in fixed-volume chambers described by equations (1) through (19). In particular, the volume of the cylinder (i.e., gas side chamber **25** in the previously described model) may vary during the charge/discharge cycle as a function of the force/displacement characteristics of return spring **24** and external actuator load. Specifically, relative to the fully pressurized volume of cylinder **26** (i.e., Figure 12), the volume of chamber **25** during the first (i.e., high-pressure) equilibrium could be less than the fully pressurized volume, which would result in an increased mass of compressed gas stored in reservoir **4** (relative to the fixed-volume model). This would result in an increased amount of compressed gas mass stored in the reservoir **4**, relative to the fixed-volume model. However, during the second (i.e., low-pressure) equilibrium state, the volume of chamber **25** could be further reduced, which would reduce the amount of compressed gas recycled from the reservoir **4** to the chamber **25** of cylinder **26**, relative to the fixed-volume model.

[0084] In general, the counteracting contributions to compressed gas savings will result in a decrease in expected saving relative to the fixed-volume model. Despite this, the return force provided by the spring element in a typical single-acting cylinder is much smaller than the actuation force resulting from pressurization of the cylinder. Although the ratio is dependent on the design of the cylinder and the supply pressure, a typical ratio of maximum spring force to

actuation force is less than 10%. Under such conditions, as long as the ratio of reservoir to cylinder volume results in a low-pressure equilibrium pressure greater than 10% of the supply pressure (which would be expected for any realistic implementation), the volume will not vary appreciably between the charged and equilibrium states as a result of the return spring influence, and therefore the expected compressed gas saving would be essentially the same as the savings predicted by the fixed-volume model. Thus, the expected compressed gas savings will depend upon the nature of the external loads on the actuator.

[0085] Maximum savings will be obtained in cases where the low-pressure equilibrium is sufficient to configure the actuator into the first actuator position (i.e., into the fully pressurized configuration). In the case of equal reservoir and cylinder volumes (i.e., V_R=1), the low-pressure equilibrium pressure will converge to approximately one half of the supply pressure, as given by equation (18). As such, applications that will optimally benefit from a valve according to the present invention will require that the actuator be configured into the first actuator position at approximately one half the supply pressure. Although such an application may be served by lowering the supply pressure corresponding to a given actuator, doing so requires additional cost (i.e., a localized pressure regulator) and complexity. Further, supply pressure is often restricted to be uniform across multiple valves, particularly when mounted to a common manifold. As such, a valve according to the present invention can provide compressed gas saving without requiring the supply pressure to be independently modulated for a particular actuator.

[0086] In order to minimize the requirement of connecting additional apparatus when implementing a valve according to the present invention for the control of a single-acting cylinder, a preferred embodiment valve incorporates a pressure reservoir **4** affixed to the valve, or to a manifold to which the valve is mounted. Such a configuring eliminates the requirement

of additional lines and fittings between the valve manifold and the reservoir. In this preferred embodiment, the pressure reservoir is affixed (i.e., fastened) directly onto the manifold, such that a single compressed gas line connects the valve manifold and reservoir assembly with the single-acting cylinder, which is fully consistent with the connectivity between a standard 3-way valve manifold and single-acting cylinder.

[0087] The inventive system and method of temporarily storing a portion of the compressed gas during the discharge process, and subsequently reusing a portion of the stored compressed gas during the following charging portion of the cycle to reduce the consumption of compressed air can be applied in systems employing a double-acting pneumatic actuator. Embodiment systems and methods employing pneumatic circuits including such actuators **220** are shown in Figures 28-35.

[0088] A double-acting pneumatic actuator is one that is configured into one of two piston positions (a first actuator position and second actuator position) via pneumatic forces. In the case of linear actuator **220**, these two positions can be regarded as retraction and extension of the piston and rod assembly **221** (the assembly **221** comprising rod **222** and piston **223**). A double-acting pneumatic actuator **220** is actuated by compressed gas entering in from two compressed gas lines **230a, 230b**, wherein compressed gas (typically air) is used to effect both the retraction and extension stroke of piston and rod assembly **221** within housing (shown as a cylinder in the drawings) **226** of actuator **220**. The repeated extension and retraction of the piston and rod assembly **221** requires repeated charging and discharging of the compressed gas chambers **224**, **225** of the housing **226**.

[0089] Figures 28 through 35 depict an exemplary energy-saving circuit configuration **202** in which present invention valves **201a**, **201b** control the repeated charge and discharge of a

double-acting pneumatic actuator **220**. As seen in Figures 28-35, valves **201a** and **201b** respectively include supply ports **Sa**, **Sb**, first outlet ports **Aa**, **Ab**, second outlet ports **Ba**, **Bb**, first exhaust ports $\mathbf{Ea_1}$, $\mathbf{Eb_1}$ and second exhaust ports $\mathbf{Ea_2}$, $\mathbf{Eb_2}$. Actuator **220** of system **202** is configured into a first actuator position (chamber **225** is in a charged or pressurized state) by configuring valve **201a** into first valve position **P1** and valve **201b** into the second valve position **P2**. This system configuration represents system state 1 and is illustrated in Figure 28. In this respect, first outlet port **Aa** is connected to supply port **Sa** resulting in charging of chamber **225** of cylinder housing **226** of actuator **220** while first outlet port **Ab** of valve **201b** is connected to second exhaust port $\mathbf{Eb_2}$ allowing chamber **224** of cylinder to discharge to exhaust. In addition, the valves are configured such that they isolate all other ports. Valve **201a** is connected to reservoir **204** via line **231a** and valve **201b** is connected to reservoir **204** via line **231b**.

[0090] Actuator **220** is configured from the first actuator position (i.e., charged chamber **225**/discharged chamber **224**) into the second actuator position (i.e., discharged chamber **225**/charged chamber **224**) via a multi-step process, in which valve **201a** is initially configured from the first valve position into the third valve position. This system configuration represents system state 2 and is illustrated in Figure 29. As shown in Figure 29, placing valve **201a** temporarily into the third position **P3** connects the first and second outlet ports, **Aa**, **Ba** while isolating each of the supply port **Sa** and exhaust ports $\mathbf{Ea_1}$, $\mathbf{Ea_2}$. This port connectivity enables an equilibration of the pressures in chamber **225** and reservoir **204** (i.e., in chamber **225** of actuator **220** and in reservoir **204**). Because the pressure in chamber **225** is initially at the supply pressure, the port connectivity configuration will result in compressed gas flow from chamber **225** to reservoir **204**. The equilibrium pressure is referred to in this state as the high-pressure equilibrium pressure. Note that, during the foregoing process valve **201b** remains in the second

position **P2**. Hence, chamber **224** is connected to exhaust so there is no return force acting on piston and rod assembly **221**. As such, in cases where the load in chamber **224** on the actuator is insufficient to overcome the force resulting from pressure in chamber **225**, piston and rod assembly **221** will not move while in this state (i.e., the chamber **225** volume of actuator **220** will remain as in the fully pressurized state).

[0091] Following a sufficient period of time in the third position **P3** (referred to here as the first dwell time), which allows for compressed gas flow into reservoir **204**), the discharge process is completed by moving valve **201a** into the second position **P2** while valve **201b** remains in the second position **P2**. This system configuration represents system state 3 and is illustrated in Figure 30. Note that, in addition to the connectivity between first outlet port **Aa** and first exhaust port $\mathbf{Ea_1}$, valve **201a** also isolates all other ports (i.e., the second outlet port **Ba**, supply port **Sa**, and second exhaust port $\mathbf{Ea_2}$). As such in that position, first outlet port **Aa** is connected to exhaust port $\mathbf{Ea_1}$, and the remaining mass of compressed gas in chamber **225** of actuator **220** is discharged to atmosphere (i.e., depressurized). Both chambers **224** and **225** of actuator **220** are now at atmospheric pressure.

[0092] As shown in Figure 31, after chamber **225** discharges, valve **201b** is moved to its third position **P3** resulting in outlet ports **Ab** and **Bb** being in fluid communication with each other. Valve **201a** remains in position **P2** venting chamber **225** via outlet port **Aa** and subsequently through exhaust port $\mathbf{Ea_1}$. This configuration of valves allows reservoir **204** to fluidly communicate with and charge chamber **224**, moving piston and rod assembly **221** into the second (extended) actuator position by means of a low pressure equilibrium state (state 4).

[0093] Following a sufficient period of time in which valve **201b** is in the third position **P3** (referred to here as the second dwell time), which allows for compressed gas to flow into

chamber **224** from reservoir **204**, the charging of chamber **224** is completed by moving valve **201b** into the first position **P1**, as shown in Figure 32. This system configuration represents system state 5. In the first position, valve **201b** provides the connectivity between first outlet port **Ab** and supply port **Sb**. As such in that position, first outlet port **Ab** is connected to supply port **Sb**, and a supply of compressed gas is delivered to chamber **224** to complete movement of piston and rod assembly **221** into the second actuator position. Note that, in addition to the connectivity between first outlet port **Ab** and supply **Sb**, valve **201b** isolates all other ports (i.e., the second outlet port **Bb**, first exhaust port $\mathbf{Eb_1}$, and second exhaust port $\mathbf{Eb_2}$). During this part of the process valve **201a** continues to remain in the second position **P2** in which first outlet port **Aa** and first exhaust port $\mathbf{Ea_1}$ are fluidly connected.

[0094] The process of configuring cylinder **226** from the second actuator position back to the first actuator position involves depressurizing chamber **224** and pressurizing chamber **225** and is initiated by temporarily switching control valve **201b** from the first valve position **P1** to the third position **P3**. This system configuration represents system state 6 and is illustrated in Figure 33. During this part of the process, valve **201a** continues to remain in the second position **P2** in which first outlet port **Aa** and first exhaust port $\mathbf{Ea_1}$ are fluidly connected. The configuration of valve **201b** connects first and second outlet ports **Ab**, **Bb**, while isolating the supply port **Sb** and exhaust ports $\mathbf{Eb_1}$, $\mathbf{Eb_2}$. This port connectivity enables an equilibration of the pressures between reservoir **204** and chamber **224** of cylinder **226**. Because chamber **224** is currently at high pressure while reservoir **204** is at low pressure equilibrium, compressed gas will flow from chamber **224** to reservoir **204**. Also, because chamber **225** is at atmospheric pressure, rod and piston assembly **221** will remain extended while chamber **224** and reservoir **204** are in high pressure equilibrium.

[0095] Following a sufficient period of time in which valve **201b** is in the third position **P3** (referred to here as the third dwell time), which allows for compressed gas to flow from chamber **224** into reservoir **204**, the discharging of chamber **224** is completed by moving valve **201b** into the second position **P2**, as shown in Figure 34. This figure depicts system state 7. In this position first outlet port **Ab** of valve **201b** is in fluid communication with second exhaust port $\mathbf{Eb_2}$, allowing chamber **224** to discharge to atmosphere. Valve **201a** continues to remain in the second position **P2** in which first outlet port **Aa** and first exhaust port $\mathbf{Ea_1}$ are fluidly connected. Thus, at this state, chambers **224** and **225** of actuator **220** are each at atmospheric pressure.

[0096] The final step of configuring actuator **220** from the second actuator position back to the first actuator position involves temporarily switching control valve **201a** from the second valve position **P2** to the third position **P3** for a short period of time (referred to here as the fourth dwell time), which allows compressed air in reservoir **204** to flow into chamber **225**. This state (state 8) is shown in Figure 35. During this part of the process valve **201b** remains in the first position **P2** in which first outlet port **Ab** and second exhaust port $\mathbf{Eb_2}$ are fluidly connected, while isolating supply port **Sb**, outlet port **Bb** and exhaust port $\mathbf{Eb_1}$. This port connectivity of valves **201a** and **201b** enables an equilibration of the pressures between reservoir **204** and chamber **225** of actuator **220**. The charge/discharge cycle can then be repeated.

[0097] In the system shown in Figures 28-35, the reservoir can include a pressure sensor **99** to control timing of the dwell periods. The reservoirs may also include additively or separately, a ball valve to empty the reservoirs if needed. While exemplary embodiments are described herein, it will be understood that various modifications to the systems and methods described can be made without departing from the scope of the invention. The foregoing

detailed description has been given for clearness of understanding only, and no unnecessary limitations should be understood therefrom, as modifications will be obvious to those skilled in the art.

CLAIMS

What is claimed is:

1. A valve for controlling the flow of a fluid, the valve comprising:

a valve body and a flow diverter disposed within the valve body and movably positionable within the valve body such that the flow diverter can assume a first position, a second position and a third position;

the valve body comprising a plurality of external ports, the plurality of external ports comprising a supply port, a first outlet port, and a second outlet port and one or more exhaust ports;

the flow diverter being disposed within the valve body such that:

a) when the flow diverter is in the first position, the supply port and the first outlet port are in fluid communication with each other and the one or more exhaust ports and second outlet port are in fluid isolation;

b) when the flow diverter is in the second position, the first outlet port and one of the one or more exhaust ports are in fluid communication with each other and the supply port and the second outlet port are in fluid isolation; and

c) when the flow diverter is in the third position, the first outlet port and the second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in fluid isolation.

2. A valve for controlling the flow of a fluid, the valve comprising:

a body having a first end and an second end;

a spool within the body, the spool being movable within the body and capable of being moved to a first spool position, a second spool position and a third spool position;

the third spool position being physically located between the first spool position and the second spool position;

the body comprising a plurality of external ports, the plurality of external ports comprising a supply port, a first outlet port, and a second outlet port and one or more exhaust ports;

the spool being disposed within the body such that:

a) when the spool is in the first position, the supply port and the first outlet port are in fluid communication with each other and the one or more exhaust ports and second outlet port are in respective fluid isolation;

b) when the spool is in the second position, the first outlet port and one of the one or more exhaust ports are in fluid communication with each other and the supply port and the second outlet port are in respective fluid isolation; and

c) when the spool is in the third position, the first outlet port and the second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in respective fluid isolation.

3. The valve of claim 2, wherein:

the one or more exhaust ports number two exhaust ports, the two exhaust ports comprising a first exhaust port and a second exhaust port;

the first exhaust port, the supply port, the first outlet port, the second outlet port and the second exhaust port are arranged sequentially between the first end of the body and the second end of the body; and

when the spool is in the first position, the first outlet port and the supply port are in fluid communication with each other and the one or more exhaust ports and the second outlet port are in respective fluid isolation;

when the spool is in the second position, the first outlet port and the first exhaust port are in fluid communication with each other and the supply port, the second exhaust port, and second outlet port are in respective fluid isolation; and

when the spool is in the third position, the first outlet port and second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in respective fluid isolation.

4. The valve of claim 3 further comprising seven internal ports arranged sequentially between the first end of the body and the second end of the body; and

wherein the first, second, third, fourth, fifth, sixth, and seventh internal ports are in fluid communication respectively with the first exhaust port, the first outlet port, the supply port, the second outlet port, the second exhaust port, the second outlet port and the first outlet port.

5. The valve of claim 4 wherein the spool includes a first, second, third, and fourth lobe arranged sequentially along the length of the spool.

6. The valve of claim 5 wherein the spool has a length along which lies a long axis and the spool is axisymmetric along the long axis of the spool.

7. The valve of claim 5 wherein in the first spool position:

the first internal port is isolated by the first spool lobe;

the second and third internal ports are in fluid communication between the first and second spool lobes;

the fourth internal port is isolated by the second spool lobe;

the fifth internal port is isolated between the second and third spool lobes;

the sixth internal port is isolated by the third spool lobe; and

the seventh internal port is isolated between the third and fourth spool lobes.

8. The valve of claim 5 wherein in the second spool position:

the first and second internal ports are in fluid communication between the first and second spool lobes;

the third internal port is isolated by the second spool lobe;

the fourth internal port is isolated between the second and third spool lobes;

the fifth internal port is isolated by the third spool lobe;

the sixth internal port is isolated between the third and fourth spool lobes; and

the seventh internal port is isolated by the fourth spool lobe.

9. The valve of claim 5 wherein in the third spool position:

the first internal port is isolated by the first spool lobe;

the second internal port is isolated between the first and second spool lobes;

the third internal port is isolated by the second spool lobe;

the fourth internal port is isolated between the second and third spool lobes;

the fifth internal port is isolated by the third spool lobe; and

the sixth and seventh internal ports are in fluid communication between the third and fourth spool lobes.

10. The valve of claim 5 further comprising:

one or more spool biasing elements;

a first pilot cylinder and second pilot cylinder;

a first pilot solenoid valve and a second pilot solenoid valve, the first and second pilot solenoid valves respectively pressurizing and depressurizing the first and second pilot cylinders; and

wherein:

the spool is moved to the first position when the first pilot cylinder is pressurized and the second pilot cylinder is de-pressurized;

the spool is moved to the second position when the second pilot cylinder is pressurized and the first pilot cylinder is de-pressurized; and

the spool is moved to the third position by the one or more spool biasing elements when the first and second pilot cylinders are both depressurized.

11. The valve of claim 10 wherein:

the valve further comprises within the body:

a third pilot solenoid valve;

a shuttle valve comprising a first inlet port, a second inlet port and an outlet port; and

a spring-return pilot-operated 2-way valve controlled by a third pilot cylinder;

the third pilot cylinder is in fluid communication with the outlet port of the shuttle valve;

the first inlet port of the shuttle valve is in fluid communication with the first pilot cylinder; and

the second inlet port of the shuttle valve is pressurized or depressurized by the third pilot solenoid valve; and

wherein:

when the first pilot cylinder is pressurized and the second pilot cylinder is depressurized the spool moves to the first position;

when the second pilot cylinder is pressurized and the first pilot cylinder is depressurized the spool moves to the second position;

when the first and second pilot cylinders are depressurized the spool is moved to the third position by the one or more spool biasing elements; and

the spring-return pilot-operated 2-way valve controls fluid communication between the first outlet port and the exhaust port, such that:

a) the first outlet port and the exhaust port are not in fluid communication when the third pilot cylinder is pressurized; and

b) the first outlet port and the exhaust port are in fluid communication when the third pilot cylinder is depressurized.

12. The valve of claim 4 wherein the spool includes a first, second, third, fourth and fifth lobe arranged sequentially along the length of the spool.

13. The valve of claim 12 wherein the spool has a length along which lies a long axis and the spool is axisymmetric along the long axis of the spool.

14. The valve of claim 12 wherein in the first spool position:

the first internal port is isolated by the first spool lobe;

the second and third internal ports are maintained in fluid communication between the first and second spool lobes;

the fourth internal port is isolated between the second and third spool lobes;

the fifth internal port is isolated between the third and fourth spool lobes;

the sixth internal port is isolated by the fourth spool lobe; and

the seventh internal port is isolated between the fourth and fifth spool lobes.

15. The valve of claim 12 wherein in the second spool position:

the first and second internal ports are in fluid communication between the first and second spool lobes;

the third internal port is isolated between the second and third spool lobes;

the fourth internal port is isolated between the third and fourth spool lobes;

the fifth internal port is isolated by the fourth spool lobe;

the sixth internal port is isolated between the fourth and fifth spool lobes; and

the seventh internal port is isolated by the fifth spool lobe.

16. The valve of claim 12 wherein in the third spool position:

the first internal port is isolated by the first spool lobe;

the second internal port is isolated between the first and second spool lobes;

the third internal port is isolated by the second spool lobe;

the fourth internal port is isolated between the second and fourth spool lobes;

the fifth internal port is isolated by the fourth spool lobe; and

the sixth and seventh internal ports are in fluid communication between the fourth and fifth spool lobes.

17. The valve of claim 12 further comprising:

one or more spool biasing elements;

a first pilot cylinder and second pilot cylinder;

a first pilot solenoid valve and a second pilot solenoid valve, the first and second pilot solenoid valves respectively pressurizing and depressurizing the first and second pilot cylinders; and

wherein:

the spool is moved to the first position when the first pilot cylinder is pressurized and the second pilot cylinder is de-pressurized;

the spool is moved to the second position when the second pilot cylinder is pressurized and the first pilot cylinder is de-pressurized; and

the spool is moved to the third position by the one or more spool biasing elements when the first and second pilot cylinders are both depressurized.

18. The valve of claim 17 wherein:

the valve further comprises within the body:

a third pilot solenoid valve;

a shuttle valve comprising a first inlet port, a second inlet port and an outlet port; and

a spring-return pilot-operated 2-way valve controlled by a third pilot cylinder;

the third pilot cylinder is in fluid communication with the outlet port of the shuttle valve;

the first inlet port of the shuttle valve is in fluid communication with the first pilot cylinder; and

the second inlet port of the shuttle valve pressurizing or depressurizing by the third pilot solenoid valve; and

wherein:

when the first pilot cylinder is pressurized and the second pilot cylinder is depressurized the spool moves to the first position;

when the second pilot cylinder is pressurized and the first pilot cylinder is depressurized the spool moves to the second position;

when the first and second pilot cylinders are depressurized the spool is moved to the third position by the one or more spool biasing elements; and

the spring-return pilot-operated 2-way valve controls fluid communication between the first outlet port and the exhaust port, such that:

a) the first outlet port and the exhaust port are not in fluid communication when the third pilot cylinder is pressurized; and

b) the first outlet port and the exhaust port are in fluid communication when the third pilot cylinder is depressurized.

19. A system for controlling fluid pressure during an industrial application, the system comprising:

a control valve,

the control valve comprising a spool within a body;

the spool being movable within the body and capable of being moved to a first spool position, a second spool position and a third spool position, the third position being physically located between the first position and the second position;

the valve body comprising an exhaust port, a supply port, a first outlet port, a second outlet port and two internal flow channels;

the valve being configured such that:

when the valve spool is in the first position, the first outlet port and the supply port are in fluid communication with each other, and the exhaust port and second outlet port are in respective fluid isolation;

when the valve spool is in the second position, the first outlet port and the exhaust port are in fluid communication with each other, and the supply port and second outlet port are in respective fluid isolation; and

when the valve spool is in the third position, the first outlet port and second outlet port are in fluid communication with each other, and the supply port and exhaust port are in respective fluid isolation; and

a first pressure vessel connected to the first outlet port and a second pressure vessel connected to the second outlet port.

20. The system of claim 19 further including a controller programmed to cause the valve to stop and remain in the third position for a specified period of time when the valve is being moved from the first position to the second position and from the second position to the first position.

21. The system of claim 20 wherein the specified period of time when moving from the first position to the second position is different from the specified period of time when moving from the second position to the first position.

22. The system of claim 20 wherein the specified period of time for which the valve remains in the third position includes an amount of time necessary for pressure in the first pressure vessel and second pressure vessel to equilibrate.

23. The system of claim 21 wherein the specified period of time for which the valve remains in the third position includes an amount of time necessary for pressure in the first pressure vessel and second pressure vessel to equilibrate.

24. The system of claim 20 wherein the first pressure vessel and the second pressure vessel each include a pressure sensor, and the specified period of time for which the valve remains in the third position is the length of time required for the pressure difference between the

first pressure vessel and the second pressure vessel to fall below a predetermined threshold while the valve is in the third position.

25. The system of claim 21 wherein the first pressure vessel and the second pressure vessel each include a pressure sensor, and the specified period of time for which the valve remains in the third position is the length of time required for the pressure difference between the first pressure vessel and the second pressure vessel to fall below a predetermined threshold while the valve is in the third position.

26. The system of claim 20 wherein the valve further includes a pressure sensor at each of the first outlet port and second outlet port, and the specified period of time for which the valve remains in the third position is the length of time required for the pressure difference between the first outlet port and the second outlet port to fall below a predetermined threshold while in the third position.

27. The system of claim 21 wherein the valve further includes a pressure sensor at each of the first outlet port and second outlet port, and the specified period of time for which the valve remains in the third position is the length of time required for the pressure difference between the first outlet port and the second outlet port to fall below a predetermined threshold while in the third position.

28. The system of claim 20 wherein the valve further includes a pressure sensor in one of the internal flow channels between the first and second outlet ports, and where the

specified period of time for which the valve remains in the third position is the length of time required for the rate of pressure decay to fall below a predetermined threshold while in the third position.

29. The system of claim 21 wherein the valve further includes a pressure sensor in one of the internal flow channels between the first and second outlet ports, and where the specified period of time for which the valve remains in the third position is the length of time required for the rate of pressure decay to fall below a predetermined threshold while in the third position.

30. The system of claim 19 wherein the first pressure vessel is a single-acting type actuator and the second pressure vessel is a pressure reservoir.

31. The system of claim 30 further including a valve manifold and the pressure reservoir is mounted to the valve manifold.

32. The system of claim 31, where the pressure reservoir is mounted to the valve body.

33. A system comprising:

a fluid supply, a double-acting actuator, a first control valve, a second control valve and a fluid reservoir;

the actuator comprising a piston housing and a piston slidably moveable within the piston housing, the piston dividing the piston housing into a first chamber capable of holding a volume of fluid on a first side of the piston and a second chamber capable of holding a volume of fluid on a second side of the piston;

the first control valve being pneumatically coupled to the fluid supply, the fluid reservoir and the first chamber of the actuator;

the second control valve being pneumatically coupled to the fluid supply, the fluid reservoir and the second chamber of the actuator;

each of the first and second control valves comprising a valve body and a spool disposed within the valve body and slidably positionable within the valve body such that the spool can assume a first position, a second position and a third position;

the valve body comprising a plurality of external ports, the plurality of external ports comprising a supply port, a first outlet port, a second outlet port and one or more exhaust ports; and

the spool being disposed within the valve body such that:

a) when the spool is in the first position, the supply port and the first outlet port are in fluid communication with each other and the one or more exhaust ports and the second outlet port are in fluid isolation;

b) when the spool is in the second position, the first outlet port and one of the one or more exhaust ports are in fluid communication with each other and the supply port and the second outlet port are in fluid isolation; and

c) when the spool is in the third position, the first outlet port and the second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in fluid isolation.

34. The system of claim 33, wherein:

the one or more exhaust ports numbers two exhaust ports, the two exhaust ports comprising a first exhaust port and a second exhaust port;

the first exhaust port, the supply port, the first outlet port, the second outlet port and the second exhaust port are arranged sequentially between the first end of the body and the second end of the body; and

when the spool is in the first position, the first outlet port and the supply port are in fluid communication with each other and the second outlet port and the one or more exhaust ports are in respective fluid isolation;

when the spool is in the second position, the first outlet port and the first exhaust port are in fluid communication with each other and the supply port, the second exhaust port, and second outlet port are in respective fluid isolation; and

when the spool is in the third position, the first outlet port and second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in respective fluid isolation.

35. The system of claim 33 wherein:

when the first control valve is in the first position and the second control valve is in the second position, the first chamber is coupled to the fluid supply and the second chamber is coupled to atmosphere;

when the first control valve is in the third position and the second control valve is in the second position, the first chamber is coupled to the fluid reservoir and the second chamber is coupled to atmosphere;

when the first control valve is in the second position and the second control valve is in the second position, the first chamber is coupled to atmosphere and the second chamber is coupled to atmosphere; and

when the first control valve is in the second position and the second control valve is in the third position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid reservoir.

36. The system of claim 33 wherein:

when the first control valve is in the second position and the second control valve is in the first position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid supply;

when the first control valve is in the second position and the second control valve is in the third position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid reservoir;

when the first control valve is in the second position and the second control valve is in the second position, the first chamber is coupled to atmosphere and the second chamber is coupled to atmosphere; and

when the first control valve is in the third position and the second control valve is in the second position, the first chamber is coupled to the fluid reservoir and the second chamber is coupled to atmosphere.

37. The system of claim 35 wherein:

when the first control valve is in the second position and the second control valve is in the first position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid supply;

when the first control valve is in the second position and the second valve is in the third position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid reservoir;

when the first control valve is in the second position and the second valve is in the second position, the first chamber is coupled to atmosphere and the second chamber is coupled to atmosphere; and

when the first control valve is in the third position and the second valve is in the second position, the first chamber is coupled to the fluid reservoir and the second chamber is coupled to atmosphere.

38. A system comprising:

a first valve and a second valve, the first and second valve each including a spool within a valve body and movable within the valve body from a first position, a second position, and a third position, the third position being physically located between the first position and the second position;

a double-acting pneumatic actuator pneumatically coupled to the first valve and the second valve;

a fluid supply pneumatically coupled to the first valve and the second valve;

a fluid reservoir pneumatically coupled to the first valve and second valve;

the double-acting pneumatic actuator comprising a first chamber and a second chamber; and

when the spool of the first valve is in the first position and the spool of the second valve is in the second position, the first chamber is coupled to the fluid supply and the second chamber is coupled to atmosphere;

when the spool of the first valve is in the third position and the spool of the second valve is in the second position, the first chamber is coupled to the fluid reservoir and the second chamber is coupled to atmosphere;

when the spool of the first valve is in the second position and the spool of the second valve is in the second position, the first chamber is coupled to atmosphere and the second chamber is coupled to atmosphere; and

when the spool of the first valve is in the second position and the spool of the second valve is in the third position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid reservoir.

39. The system of claim 38 wherein:

when the spool of the first valve is in the second position and the spool of the second valve is in the first position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid supply;

when the spool of the first valve is in the second position and the spool of the second valve is in the third position, the first chamber is coupled to atmosphere and the second chamber is coupled to the fluid reservoir;

when the spool of the first valve is in the second position and the spool of the second valve is in the second position, the first chamber is coupled to atmosphere and the second chamber is coupled to atmosphere; and

when the spool of the first valve is in the third position and the spool of the second valve is in the second position, the first chamber is coupled to the fluid reservoir and the second chamber is coupled to atmosphere.

40. The system of claim 39 wherein:

the valve body of each of the first and second valves comprises:

a supply port, a first outlet port, a second outlet port and one or more exhaust ports wherein:

a) when the spool is in the first position, the supply port and the first outlet port are in fluid communication with each other and the one or more exhaust ports and second outlet port are in fluid isolation;

b) when the spool is in the second position, the first outlet port and one of the one or more exhaust ports are in fluid communication with each other and the supply port and the second outlet port are in fluid isolation; and

c) when the spool is in the third position, the first outlet port and the second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in fluid isolation.

41 The system of claim 40 wherein:

the one or more exhaust ports number two exhaust ports, the two exhaust ports comprising a first exhaust port and a second exhaust port; and

the first exhaust port, the supply port, the first outlet port, the second outlet port and the second exhaust port are arranged sequentially between the first end of the body and the second end of the body; and

when the spool is in the first position, the first outlet port and the supply port are in fluid communication with each other and the second outlet port and the one or more exhaust ports are in respective fluid isolation;

when the spool is in the second position, the first outlet port and the first exhaust port are in fluid communication with each other and the supply port, the second exhaust port, and second outlet port are in respective fluid isolation; and

when the valve spool is in the third position, the first outlet port and second outlet port are in fluid communication with each other and the supply port and the one or more exhaust ports are in respective fluid isolation.

42. A method of charging and discharging a pneumatic pressure vessel, the method comprising:

A. providing the valve of Claim 2;

B. fluidly connecting the valve to a fluid supply, a reservoir and the pressure vessel;

C. configuring the spool into the first position and thereby causing fluid to flow from the fluid supply into the pressure vessel;

D. configuring the spool into the third position and thereby causing the flow of fluid from the pressure vessel into the reservoir;

E. maintaining the spool in the third position until such time as the pressures in the pressure vessel and reservoir arrive at a common equilibrium pressure;

F. configuring the spool into the second position and thereby causing the flow of fluid from the pressure vessel to atmosphere;

G. configuring the spool into the third position and thereby causing the flow of fluid from the reservoir to the pressure vessel;

H. maintaining the spool in the third position until such time as the pressures in the pressure vessel and reservoir arrive at a common equilibrium pressure; and

I. configuring the spool into the first position and thereby causing the flow of fluid from the fluid supply into the pressure vessel.

43. The method of claim 42 wherein the pressure vessel is the fluid chamber of a single-acting actuator and:

the single-acting actuator is placed in a first actuator position when the valve is configured in accordance with paragraph C and a second actuator position when the valve is configured in accordance with paragraph F.

44. A method of charging and discharging a pneumatic pressure vessel, the method comprising:

A. providing the valve of Claim 3;

B. fluidly connecting the valve to a fluid supply, a reservoir and the pressure vessel;

C. configuring the spool into the first position and thereby causing the flow of fluid from the fluid supply into the pressure vessel;

D. configuring the spool into the third position and thereby causing the flow of fluid from the pressure vessel into the reservoir;

E. maintaining the spool in the third position until such time as the pressures in the pressure vessel and reservoir arrive at a common equilibrium pressure;

F. configuring the spool into the second position and thereby causing the flow of fluid from the pressure vessel to atmosphere;

G. configuring the spool into the third position and thereby causing the flow of fluid from the reservoir to the pressure vessel;

H. maintaining the spool in the third position until such time as the pressures in the pressure vessel and reservoir arrive at a common equilibrium pressure; and

I. configuring the spool into the first position and thereby causing the flow of fluid from the fluid supply into the pressure vessel.

45. The method of claim 44 wherein the pressure vessel is the fluid chamber of a single-acting actuator and:

the single-acting actuator is placed in a first actuator position when the valve is configured in accordance with paragraph C and a second actuator position when the valve is configured in accordance with paragraph F.

46. A method for pneumatically actuating a double-acting actuator having a first chamber and a second chamber, the method comprising:

providing two valves, a first valve and a second valve, according to claim 2;

fluidly connecting: the supply ports of the first and second valves to a fluid supply; the one or more exhaust ports of the first and second valves to exhaust; the first outlet port of the first valve to the first chamber; the first outlet port of the second valve to the second chamber; the second outlet port of the first valve to the reservoir; and the second outlet port of the second valve to the reservoir;

C. configuring the spool of the first valve into the first position and the spool of the second valve into the second position thereby causing the flow of fluid from the fluid supply into the first chamber;

D. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the third position and thereby causing the flow of fluid from the first chamber into the reservoir;

E. maintaining the spools of the first and second valves in the configurations of step D until such time as the pressures in the first chamber and reservoir arrive at a common equilibrium pressure;

F. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the second position and thereby causing the flow of fluid from the first chamber to atmosphere;

G. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the third position and thereby causing the flow of fluid from the reservoir to the second chamber;

H. maintaining the spools of the first valve and second valve in the configurations of step G until such time as the pressures in the second chamber and reservoir arrive at a common equilibrium pressure;

I. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the first position and thereby causing the flow of fluid from the fluid supply into the second chamber;

J. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the third position and thereby causing the flow of fluid from the second chamber into the reservoir;

K. maintaining the spools of the first valve and second valve in the configurations of step J until such time as the pressures in the second chamber and reservoir arrive at a common equilibrium pressure;

L. maintaining the spool of the first valve in the second position and configuring the second valve into the second position and thereby causing the flow of fluid from the second chamber to exhaust;

M. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the third position and thereby causing the flow of fluid from the reservoir into the first chamber; and

N. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the first position and thereby causing the flow of fluid from the fluid supply into the first chamber.

47. A method for pneumatically actuating a double-acting actuator having a first chamber and a second chamber, the method comprising:

providing two valves, a first valve and a second valve, according to claim 3;

fluidly connecting: the supply ports of the first and second valves to a fluid supply; the one or more exhaust ports of the first and second valves to exhaust; the first outlet port of the first valve to the first chamber; the first outlet port of the second valve to the second chamber; the second outlet port of the first valve to the reservoir; and the second outlet port of the second valve to the reservoir;

C. configuring the spool of the first valve into the first position and the spool of the second valve into the second position thereby causing the flow of fluid from the fluid supply into the first chamber;

D. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the third position and thereby causing the flow of fluid from the first chamber into the reservoir;

E. maintaining the spools of the first and second valves in the configurations of step D until such time as the pressures in the first chamber and reservoir arrive at a common equilibrium pressure;

F. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the second position and thereby causing the flow of fluid from the first chamber to atmosphere;

G. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the third position and thereby causing the flow of fluid from the reservoir to the second chamber;

H. maintaining the spools of the first valve and second valve in the configurations of step G until such time as the pressures in the second chamber and reservoir arrive at a common equilibrium pressure;

I. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the first position and thereby causing the flow of fluid from the fluid supply into the second chamber;

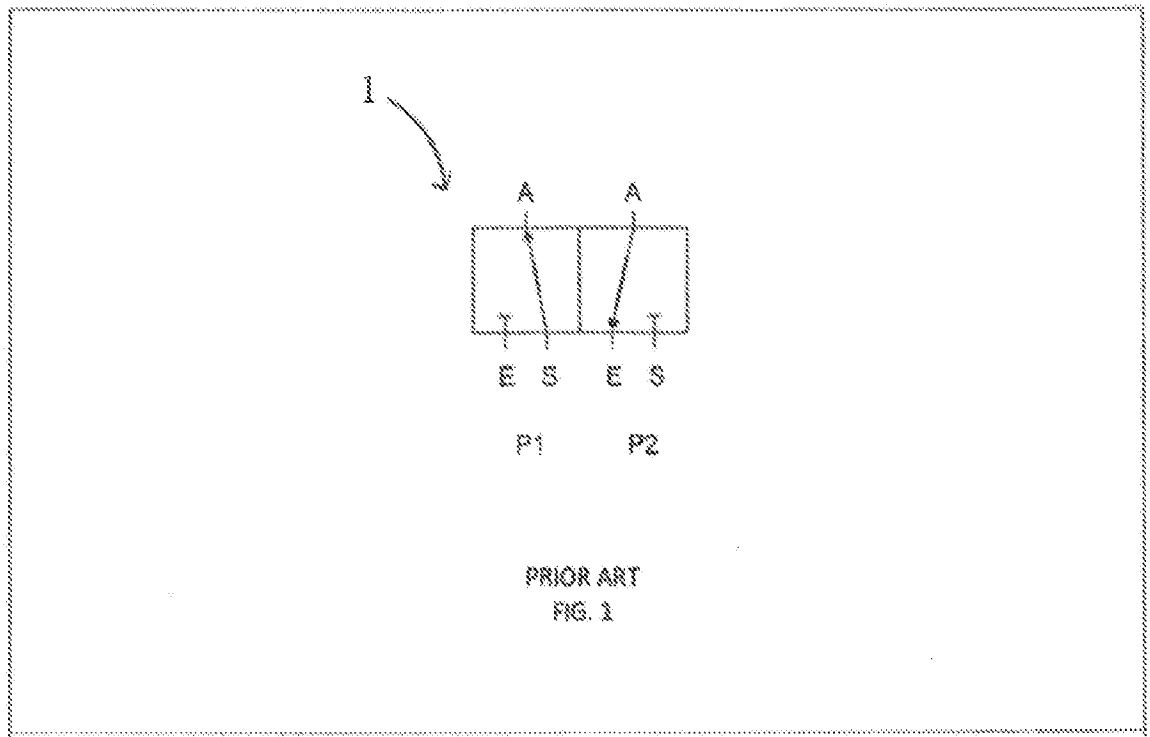
J. maintaining the spool of the first valve in the second position and configuring the spool of the second valve into the third position and thereby causing the flow of fluid from the second chamber into the reservoir;

K. maintaining the spools of the first valve and second valve in the configurations of step J until such time as the pressures in the second chamber and reservoir arrive at a common equilibrium pressure;

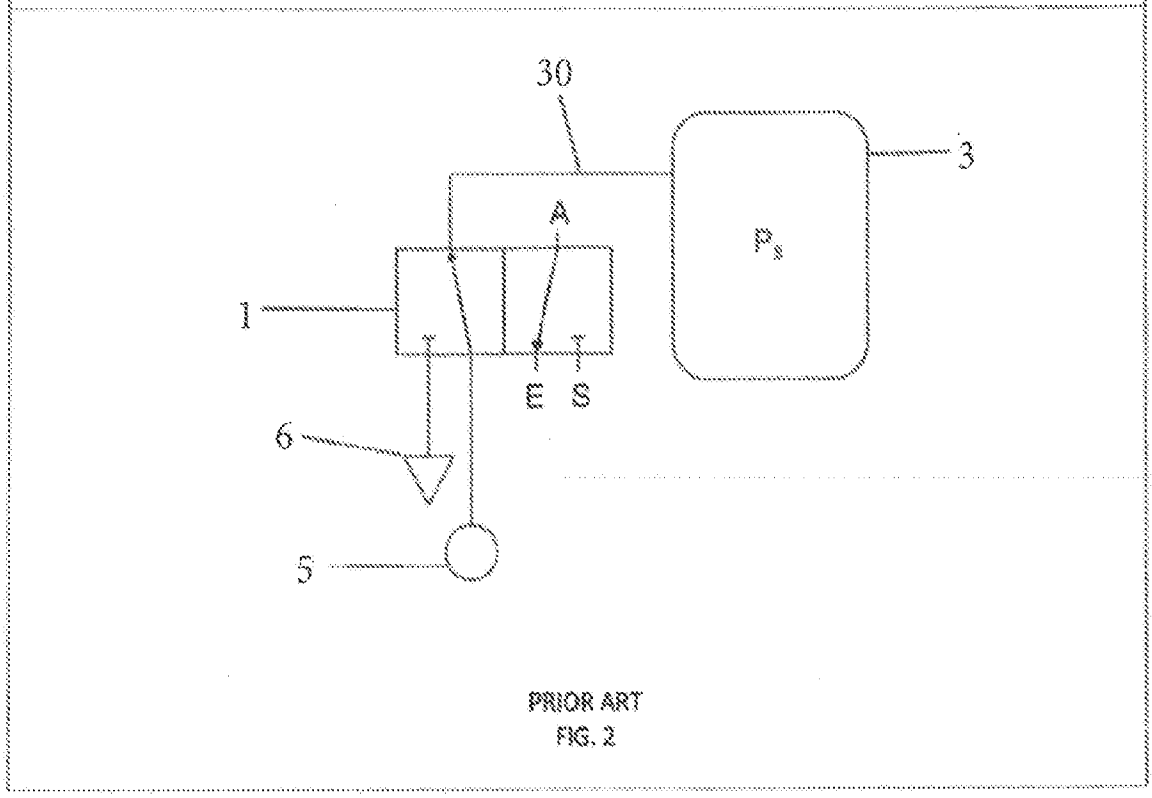
L. maintaining the spool of the first valve in the second position and configuring the second valve into the second position and thereby causing the flow of fluid from the second chamber to exhaust;

M. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the third position and thereby causing the flow of fluid from the reservoir into the first chamber; and

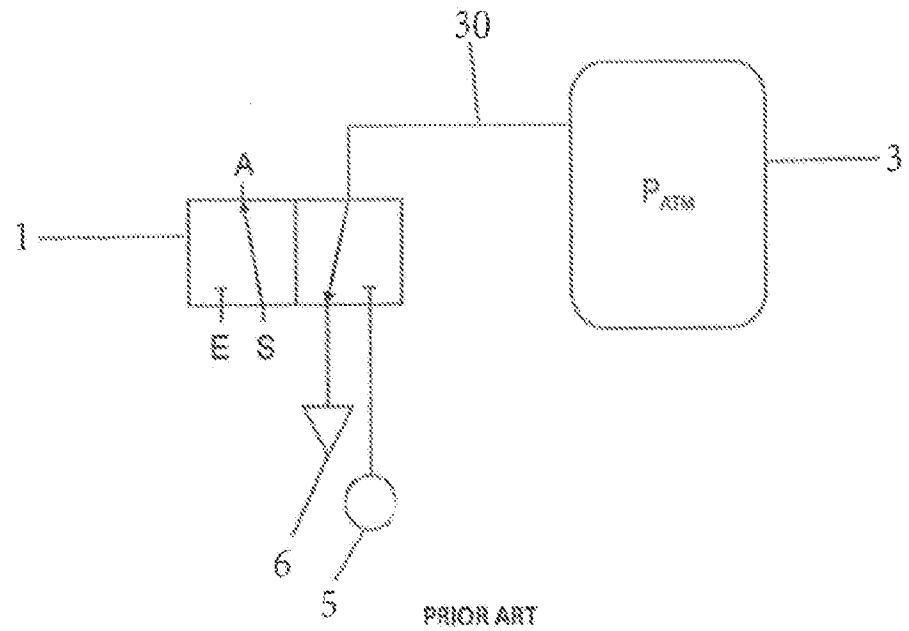
N. maintaining the spool of the second valve in the second position and configuring the spool of the first valve into the first position and thereby causing the flow of fluid from the fluid supply into the first chamber.



PRIOR ART
FIG. 1



PRIOR ART
FIG. 2



PRIOR ART
FIG. 3

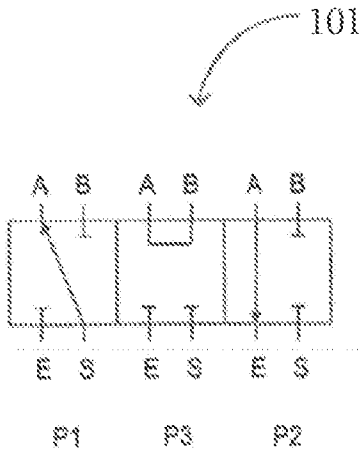


FIG. 4

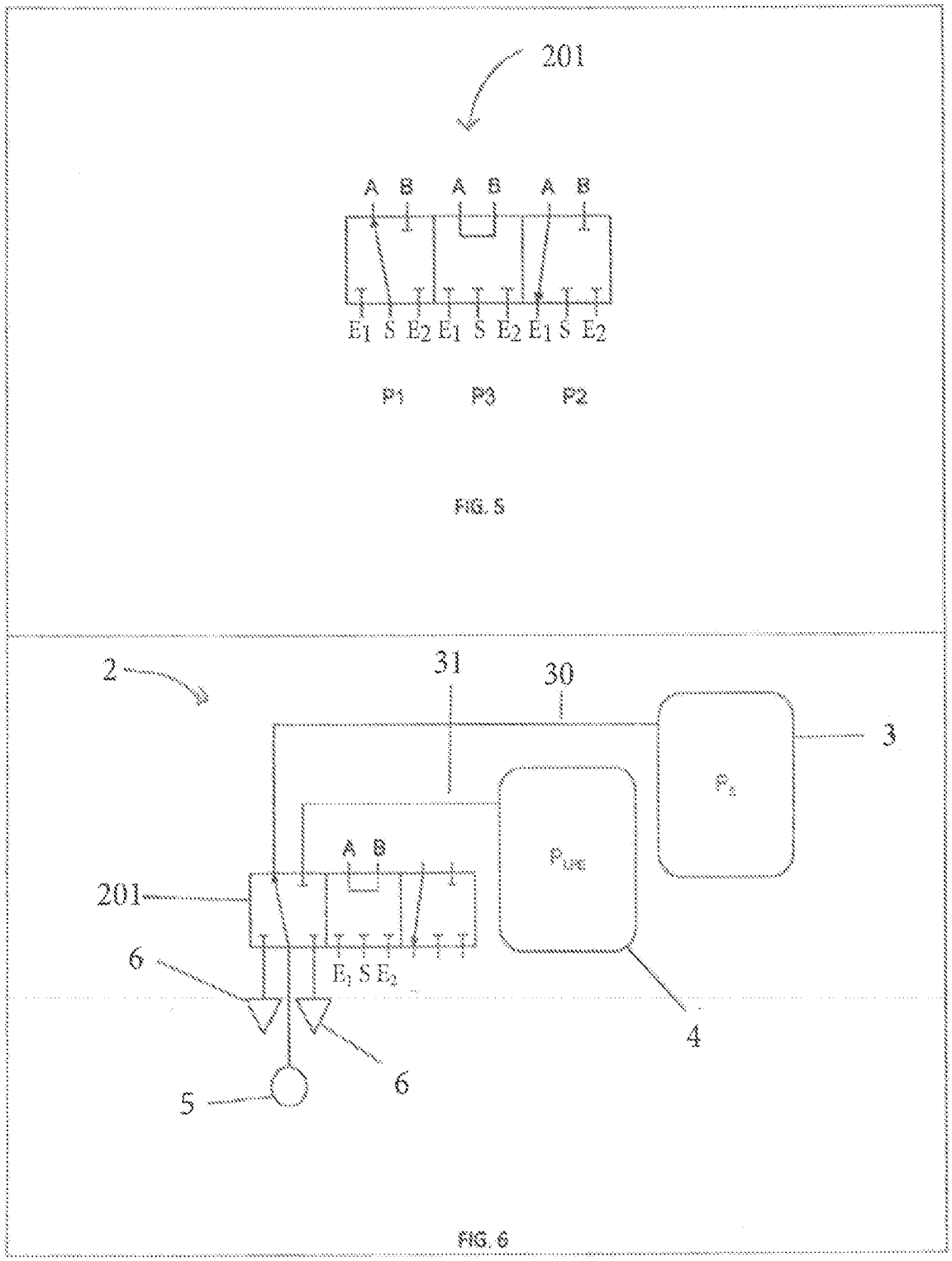

201
A B A B A B
E1 S E2 E1 S E2 E1 S E2
P1 P3 P2
2
31
30
3
A B
201
6
E1 S E2
4
5
6

FIG. 5

FIG. 6

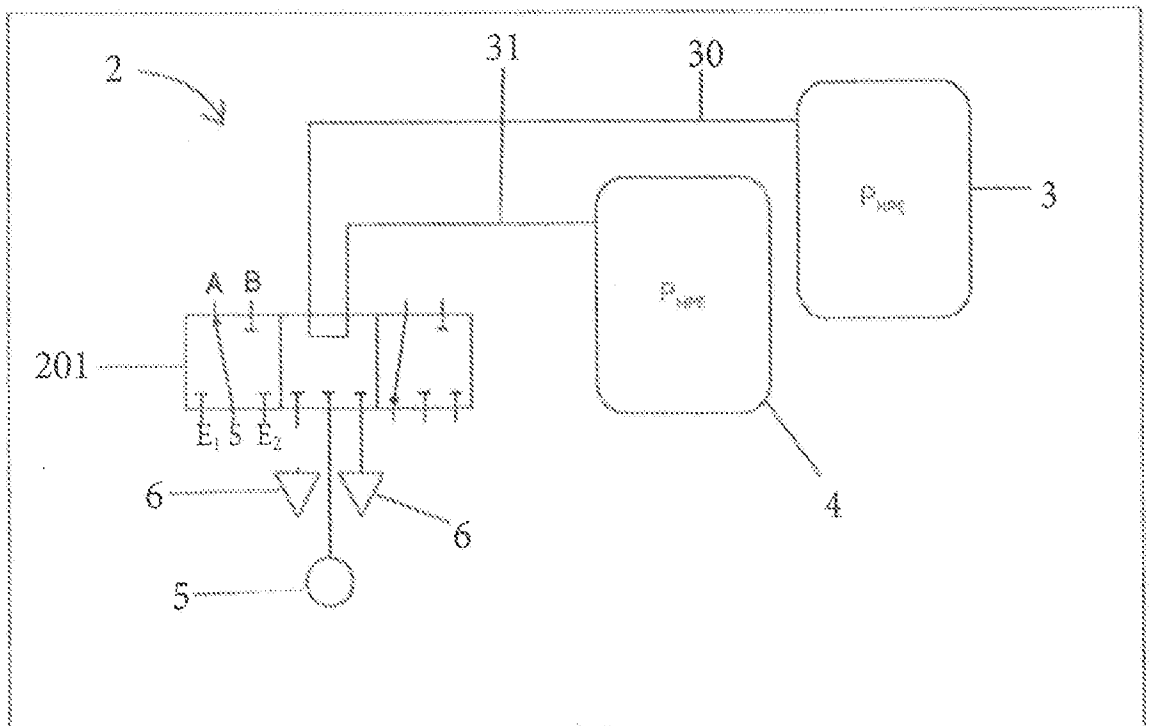


FIG. 7

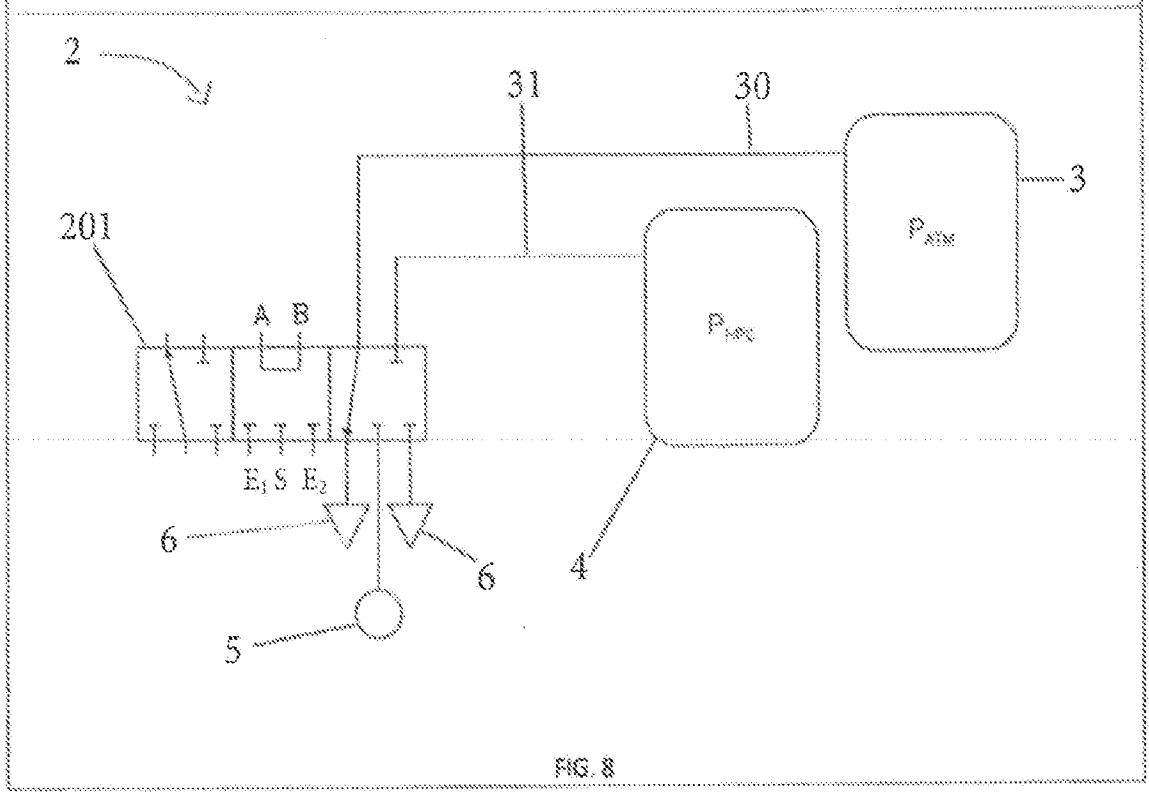


FIG. 8

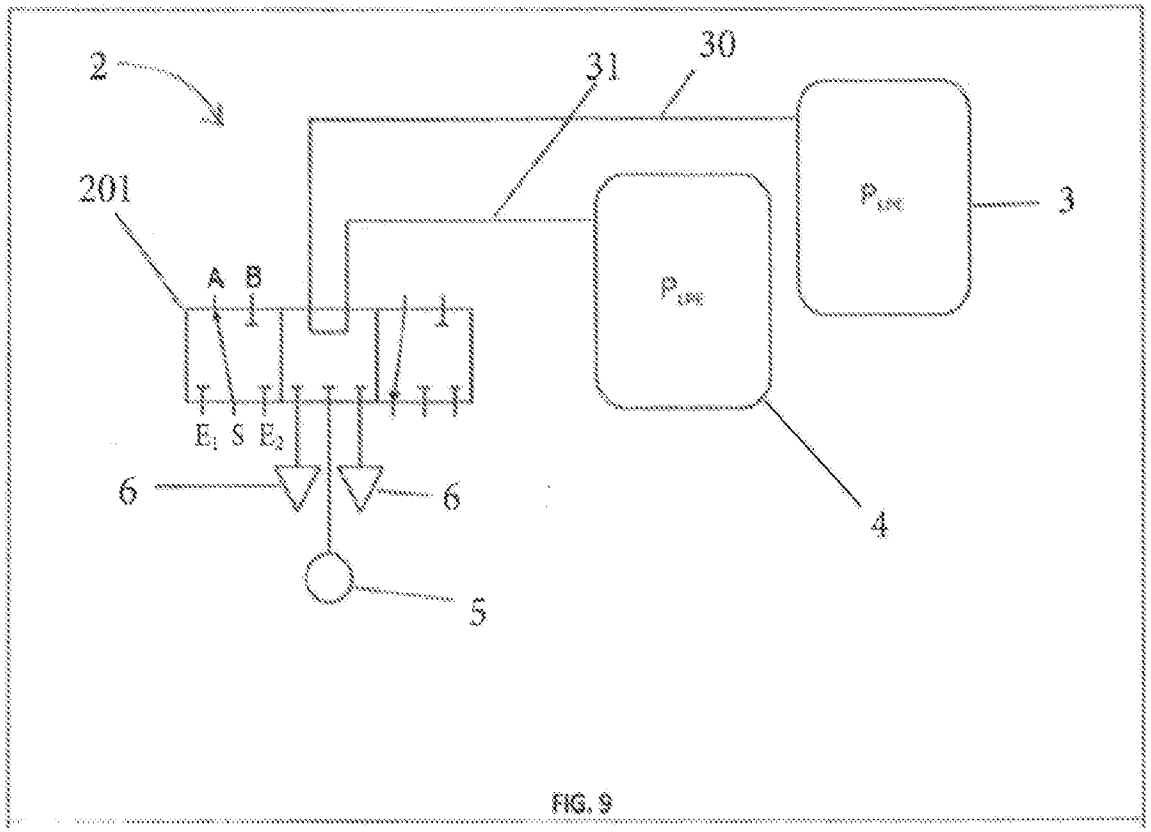
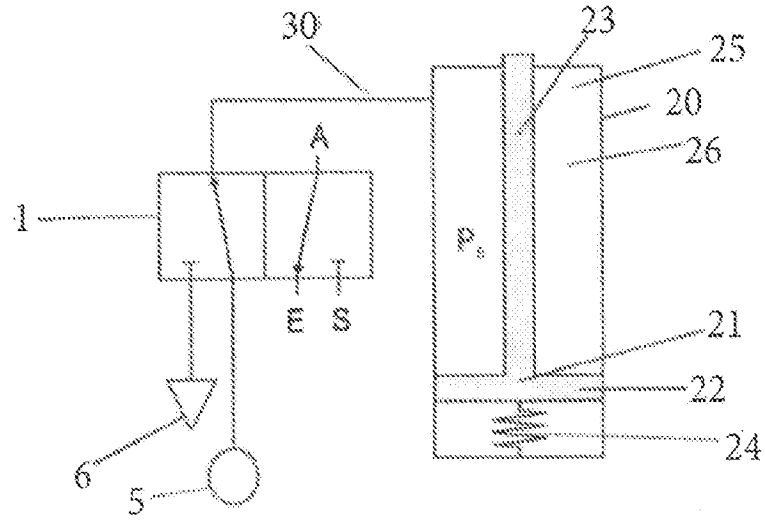
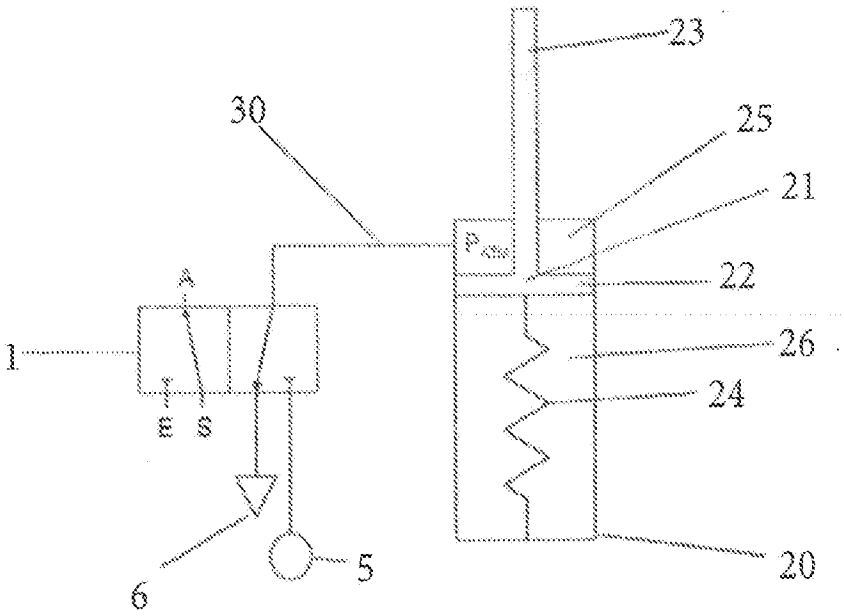


FIG. 9



PRIOR ART
FIG. 10



PRIOR ART
FIG. 11

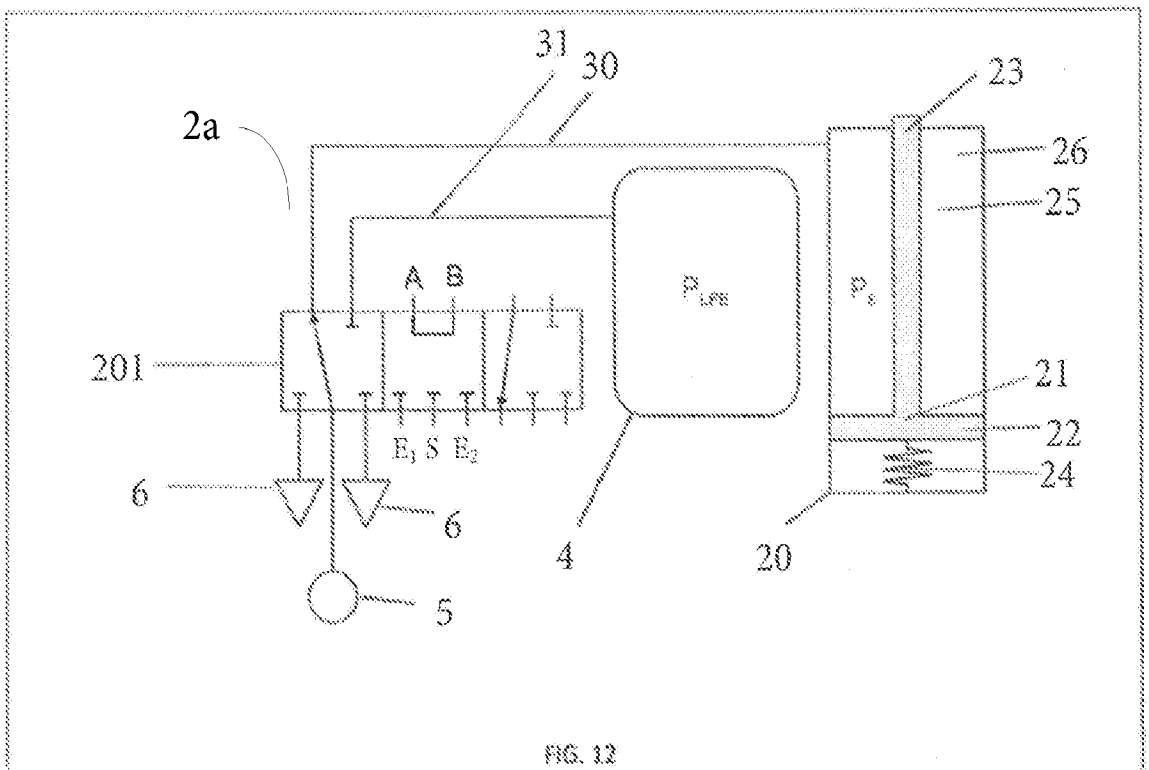

31
30
2a
23
26
25
A B
201
21
22
E1 S E2
24
6
6
4
20
5

FIG. 12

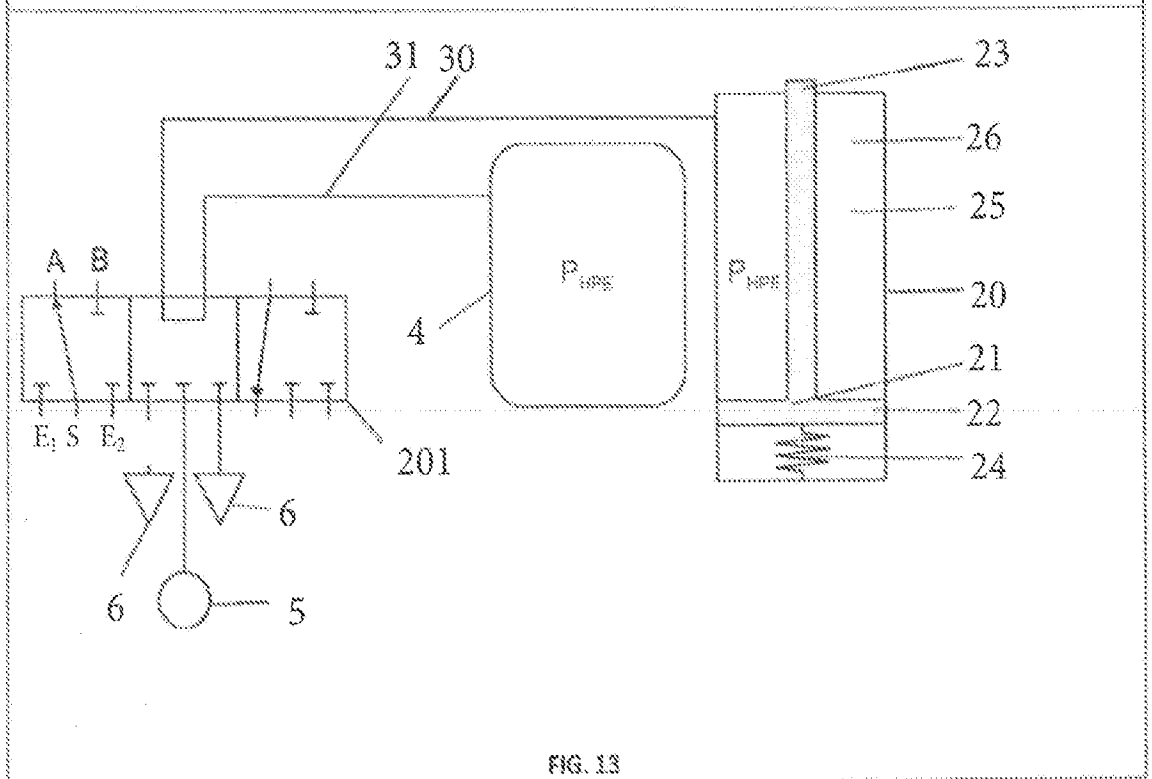

31 30
23
26
25
A B
20
4
21
22
E1 S E2
201
24
6
6
5

FIG. 13

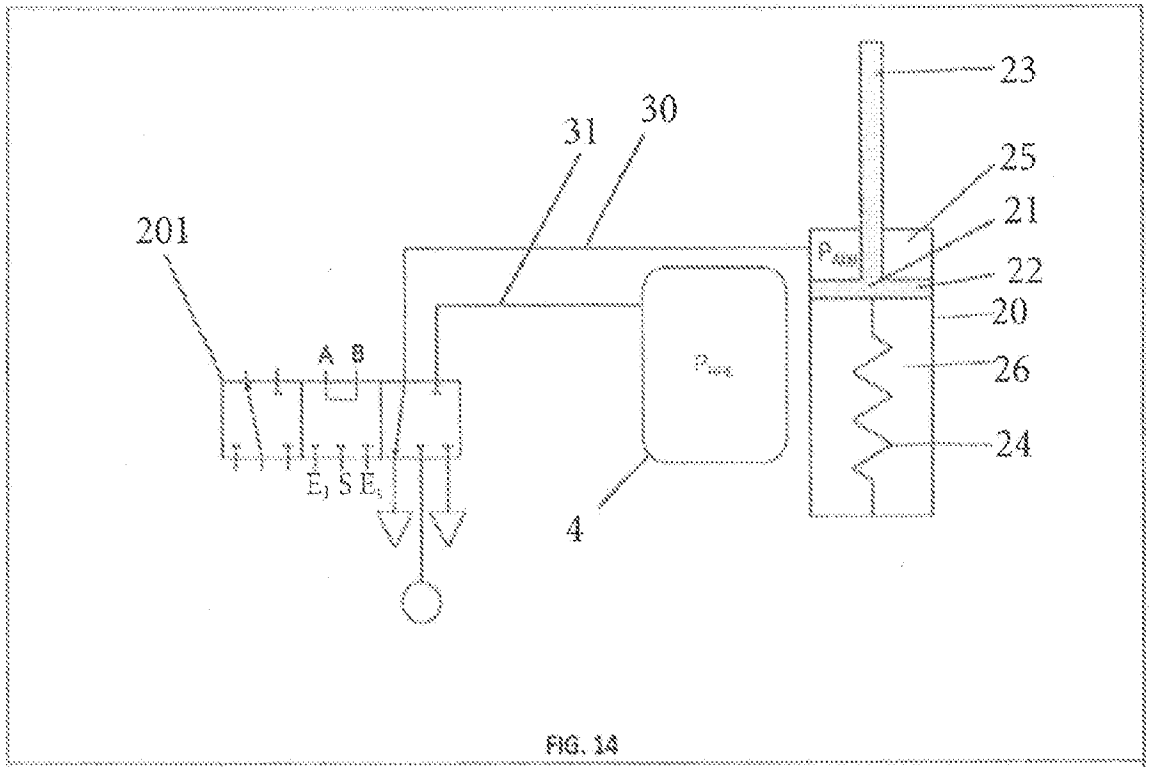

23
31
30
25
21
201
22
20
A B
26
24
E1 S E2
4

FIG. 14

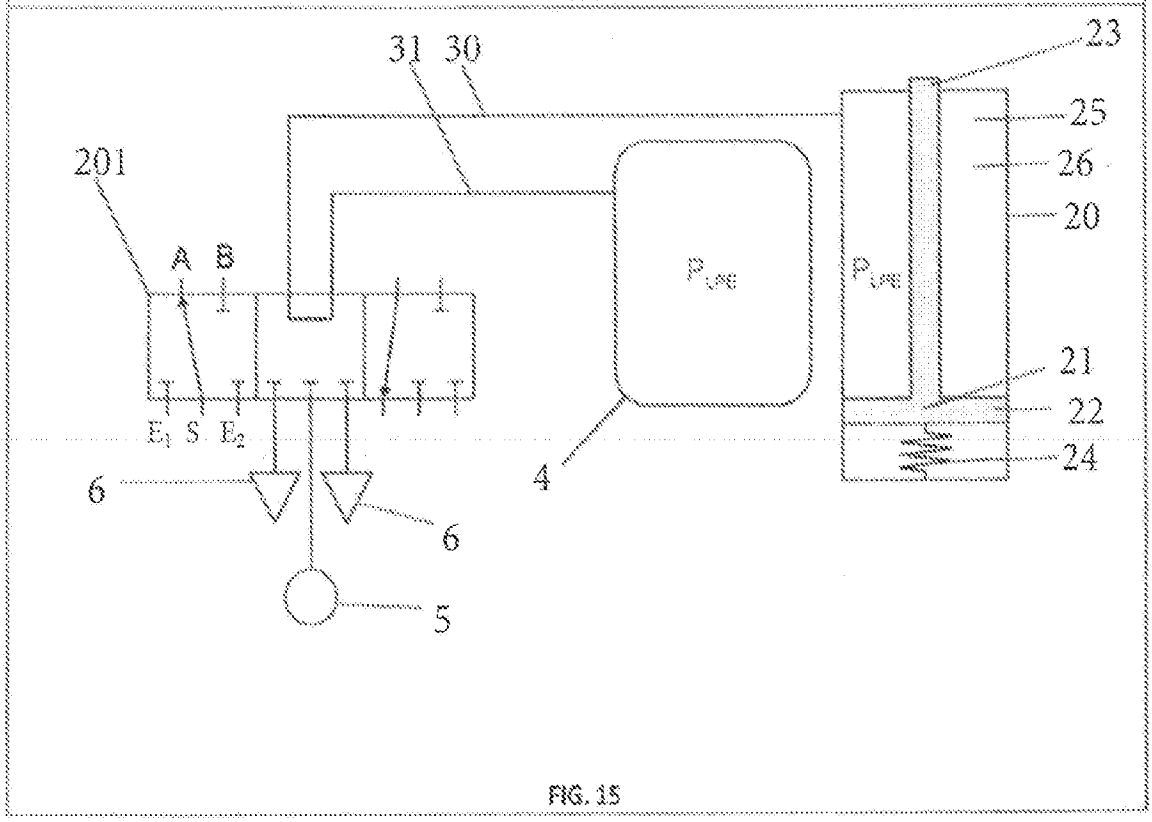

31 30
23
25
201
26
20
A B
21
22
E1 S E2
24
6
6
5
4

FIG. 15

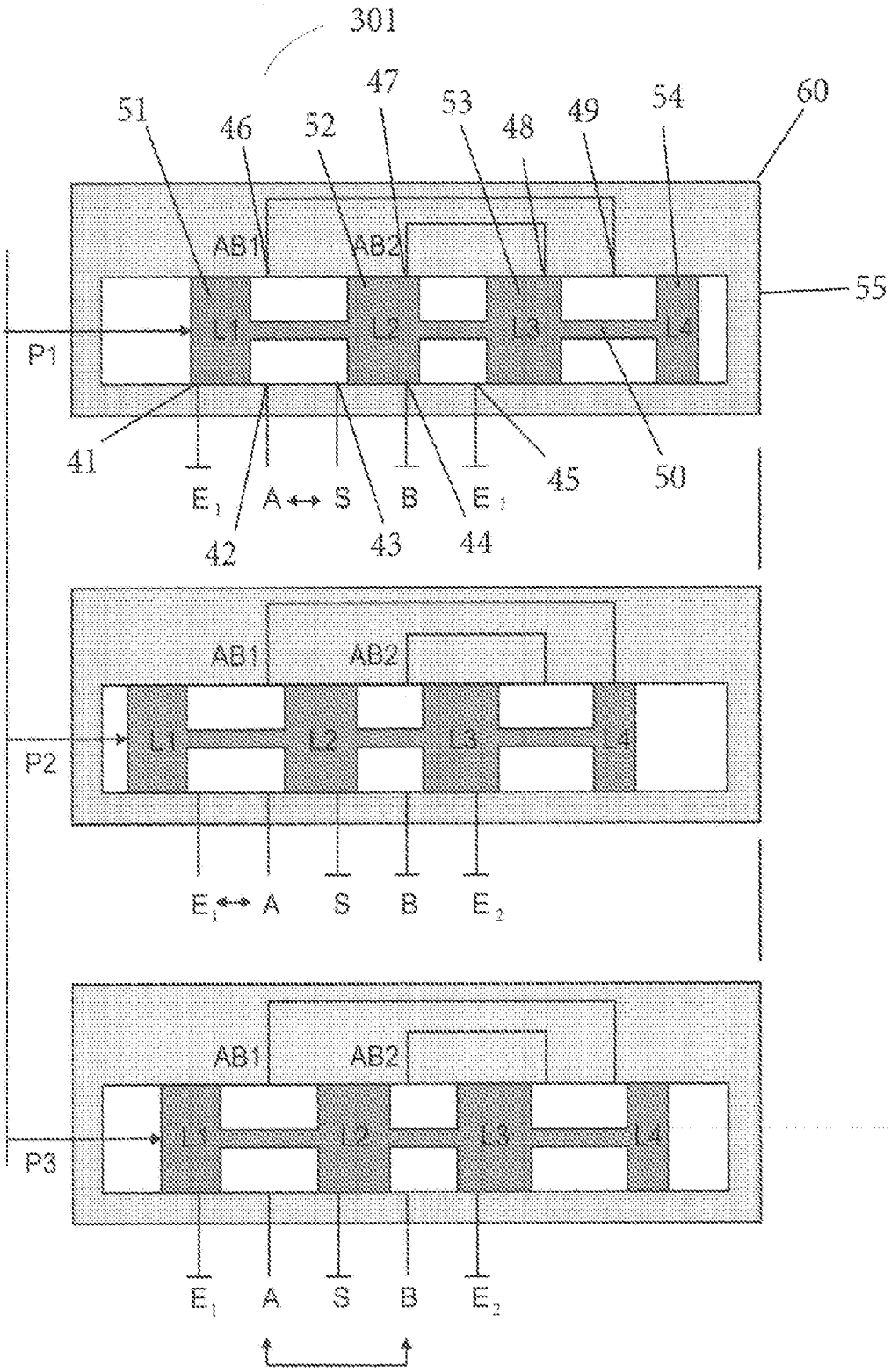

301
51
46
52
47
53
48
49
54
60
55
AB1
AB2
L1
L2
L3
L4
P1
P2
P3
41
42
43
44
45
50
E1
A
S
B
E2

Fig. 16

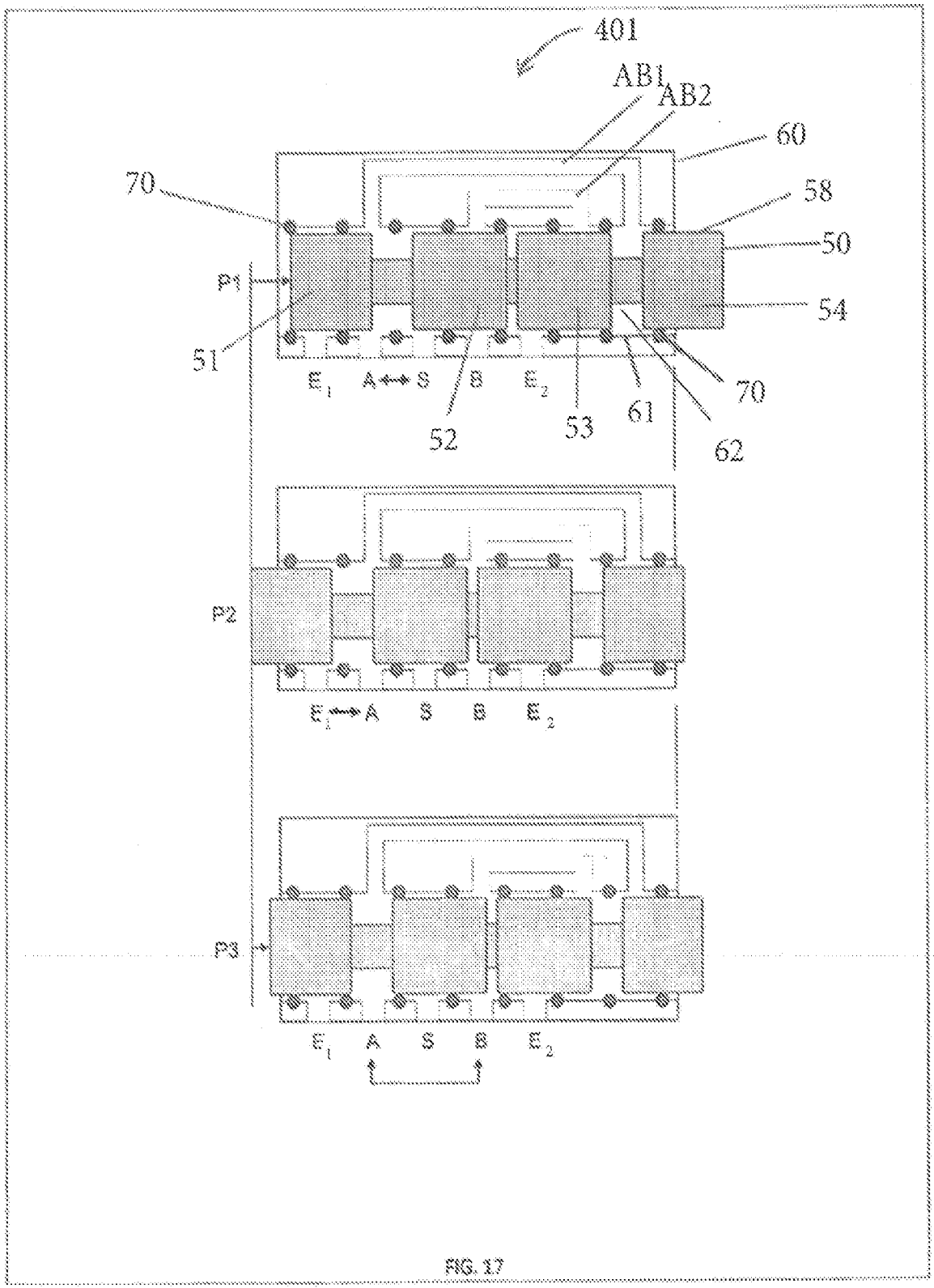

401
AB1
AB2
60
70
58
50
54
P1
51
E1 A S B E2
52
53
61
70
62
P2
E1 A S B E2
P3
E1 A S B E2

FIG. 17

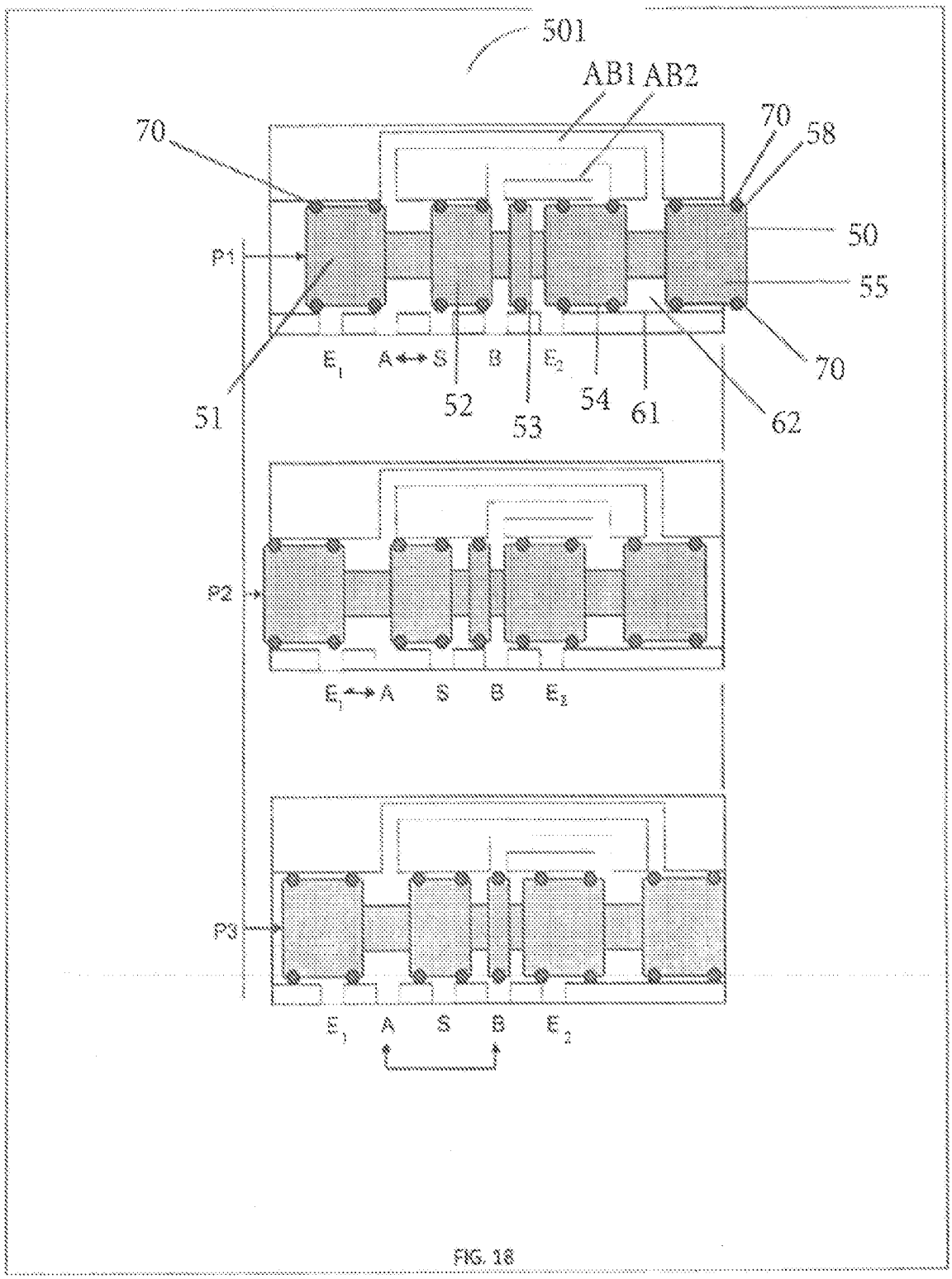


FIG. 18

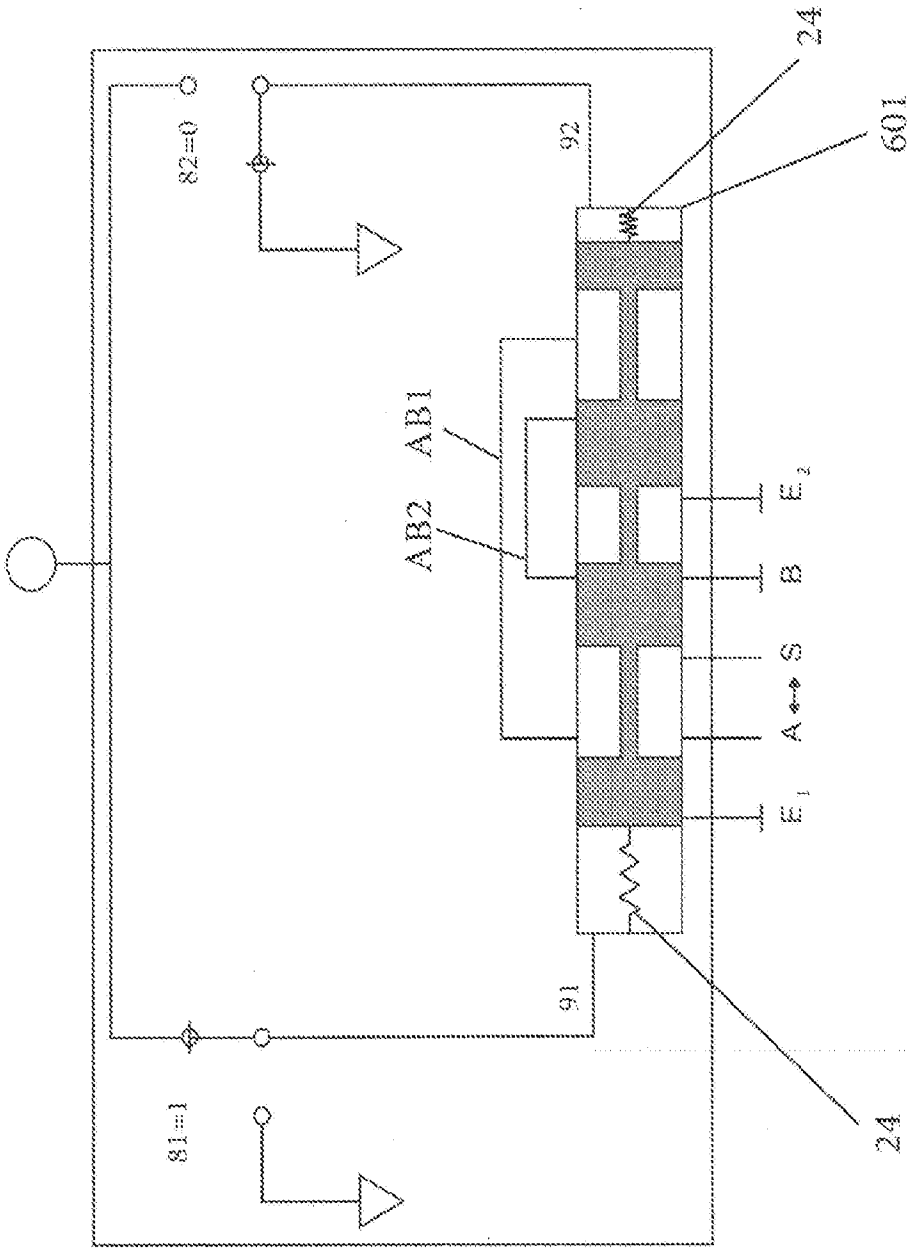


Fig. 19

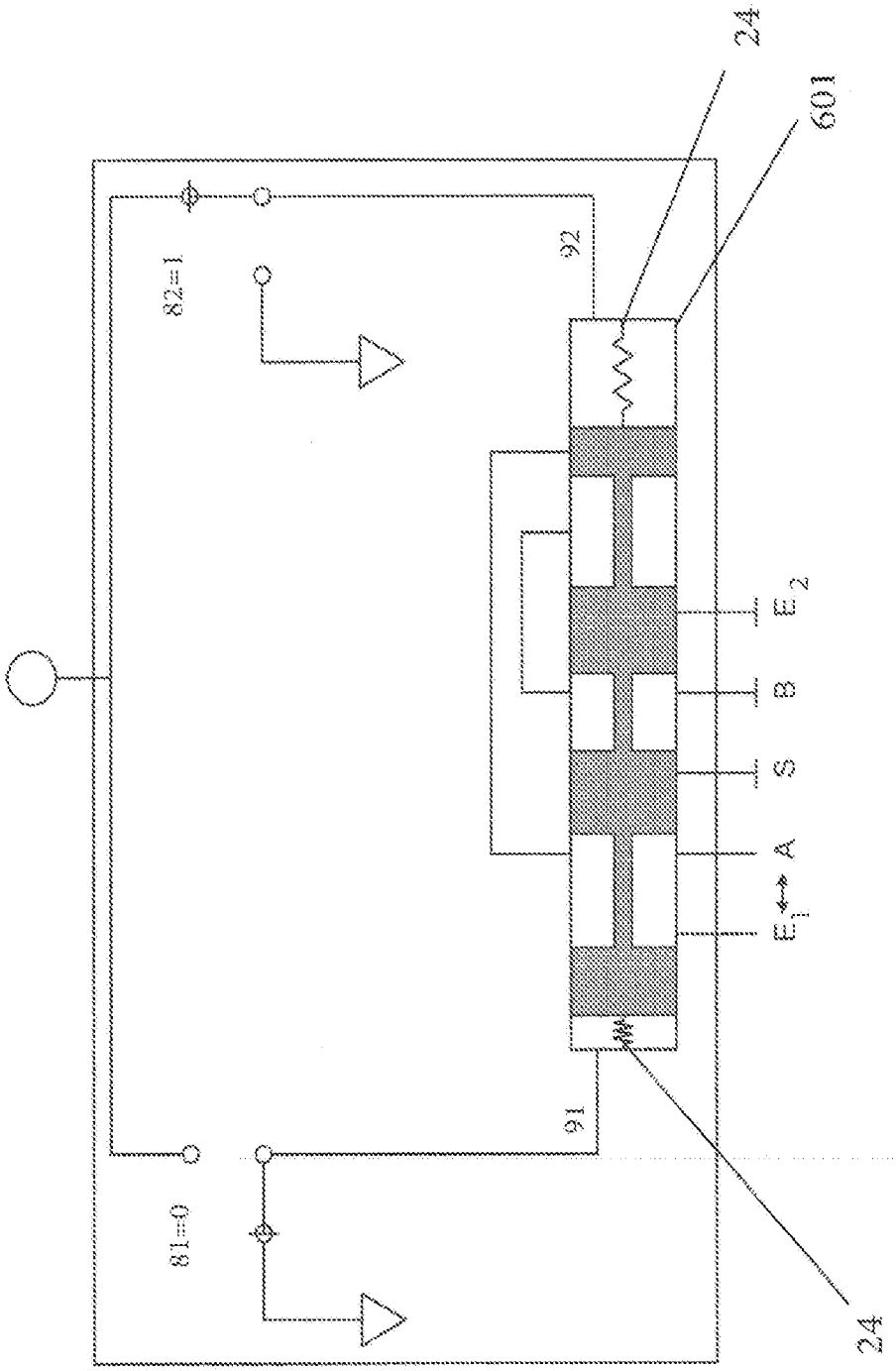


Fig. 20

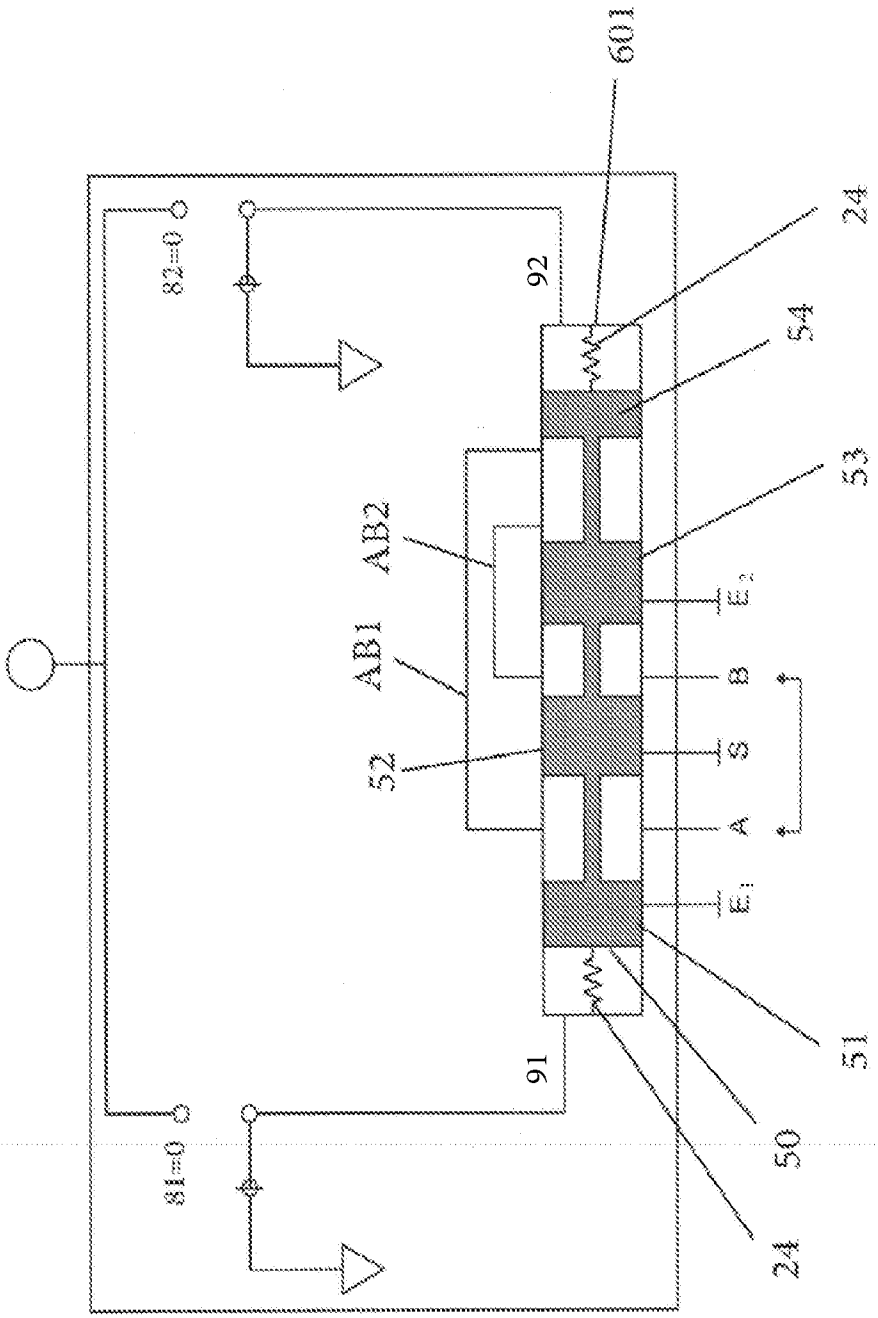


Fig. 21

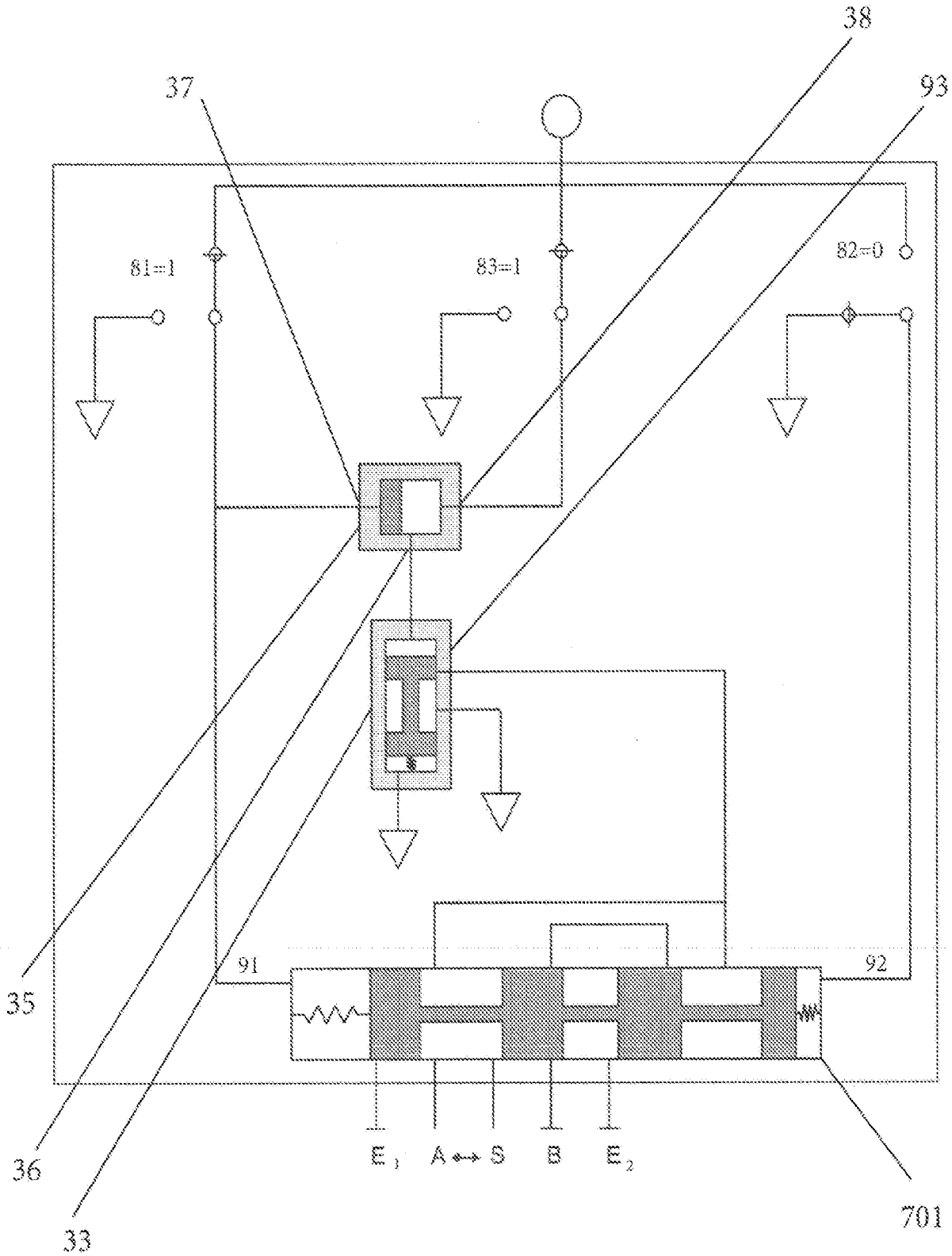


Fig. 22

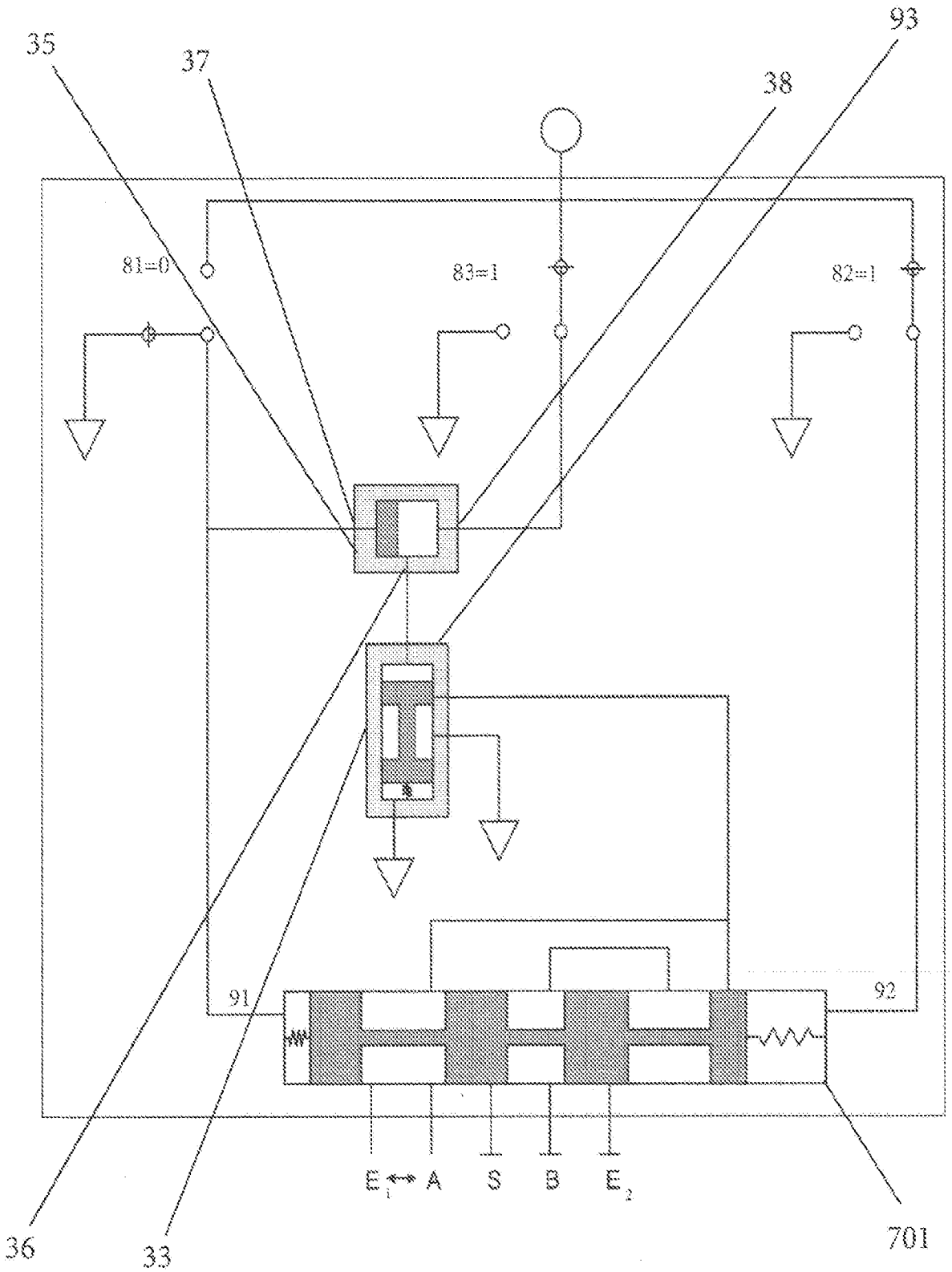


Fig. 23

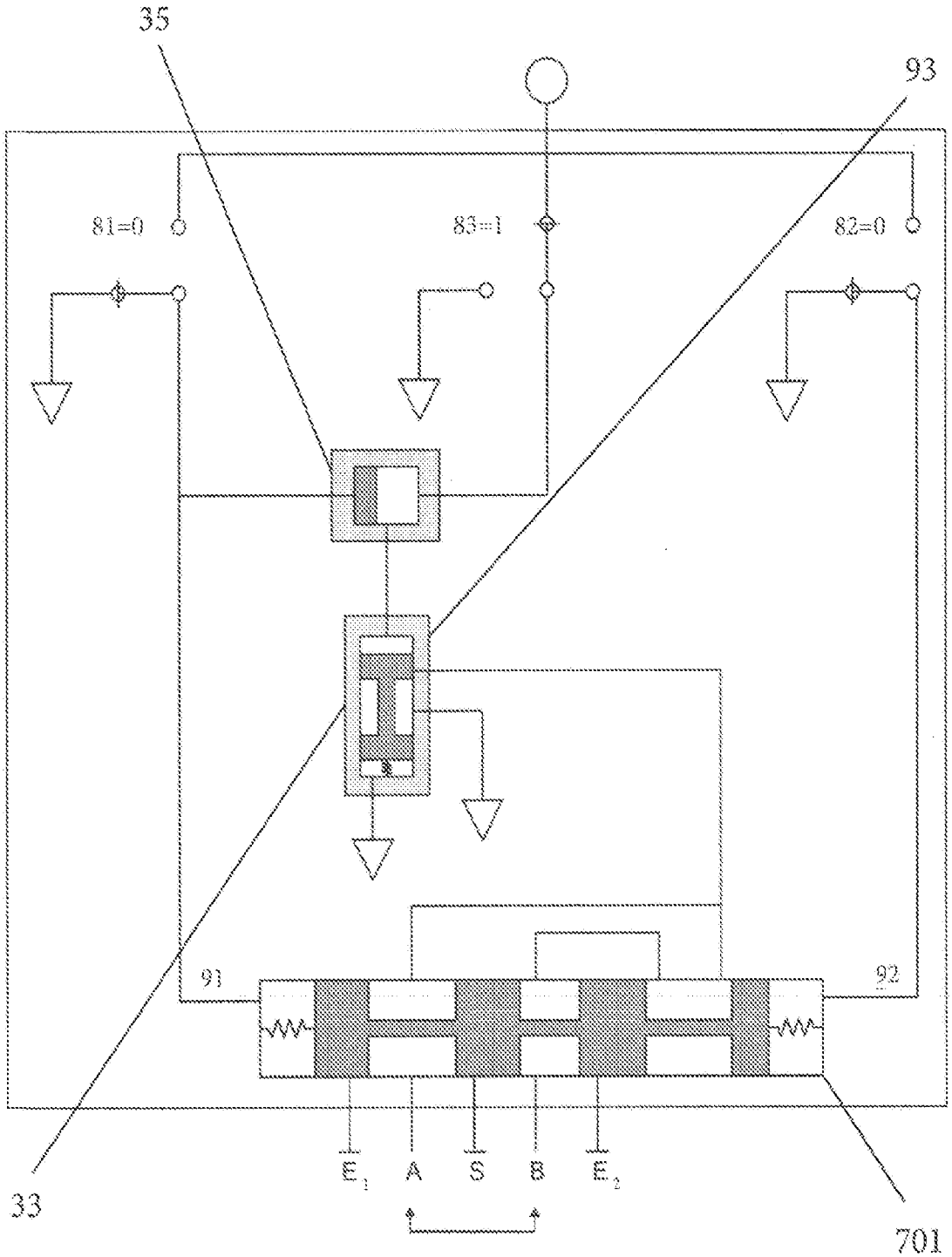


Fig. 24

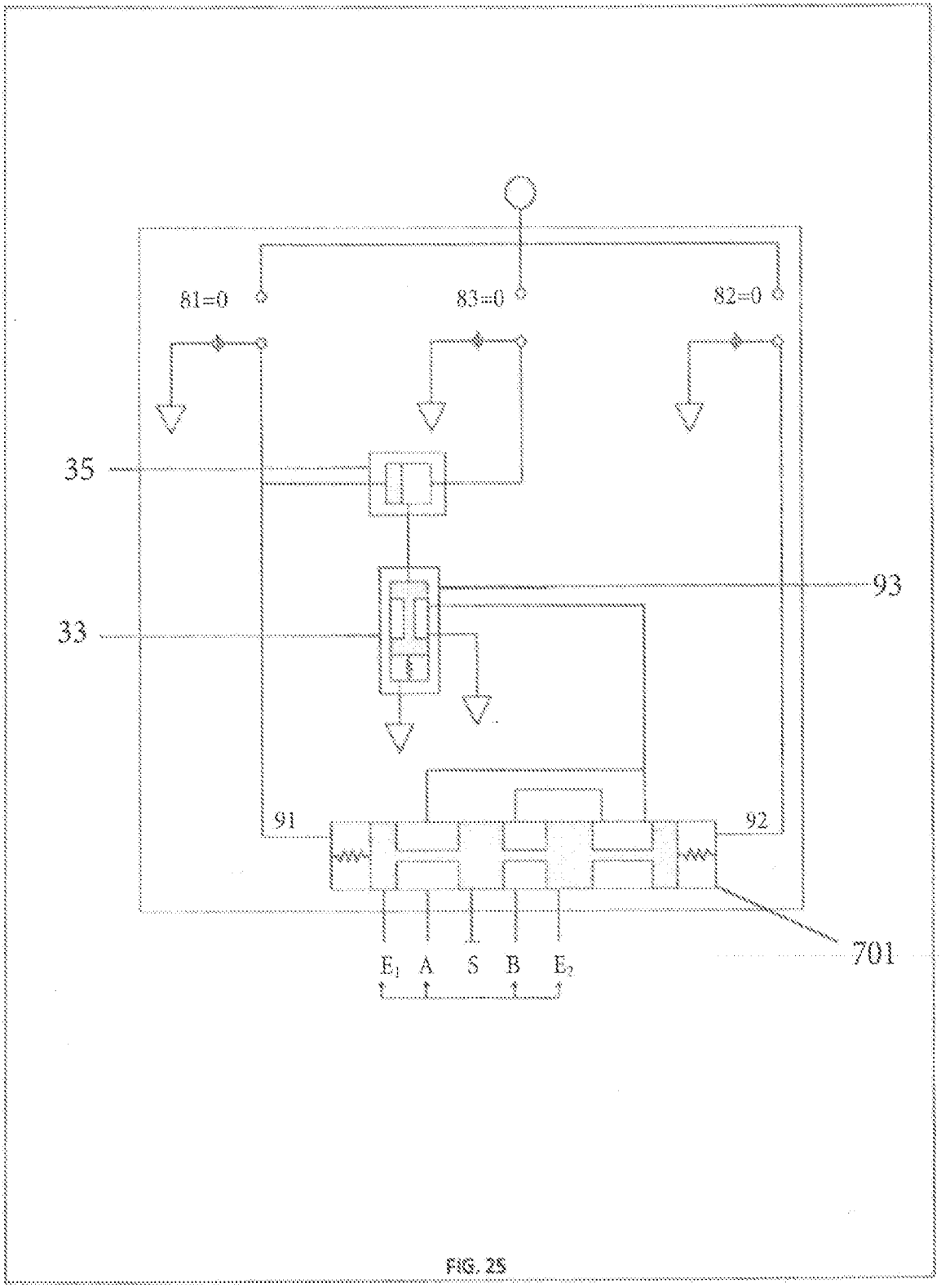


FIG. 2S

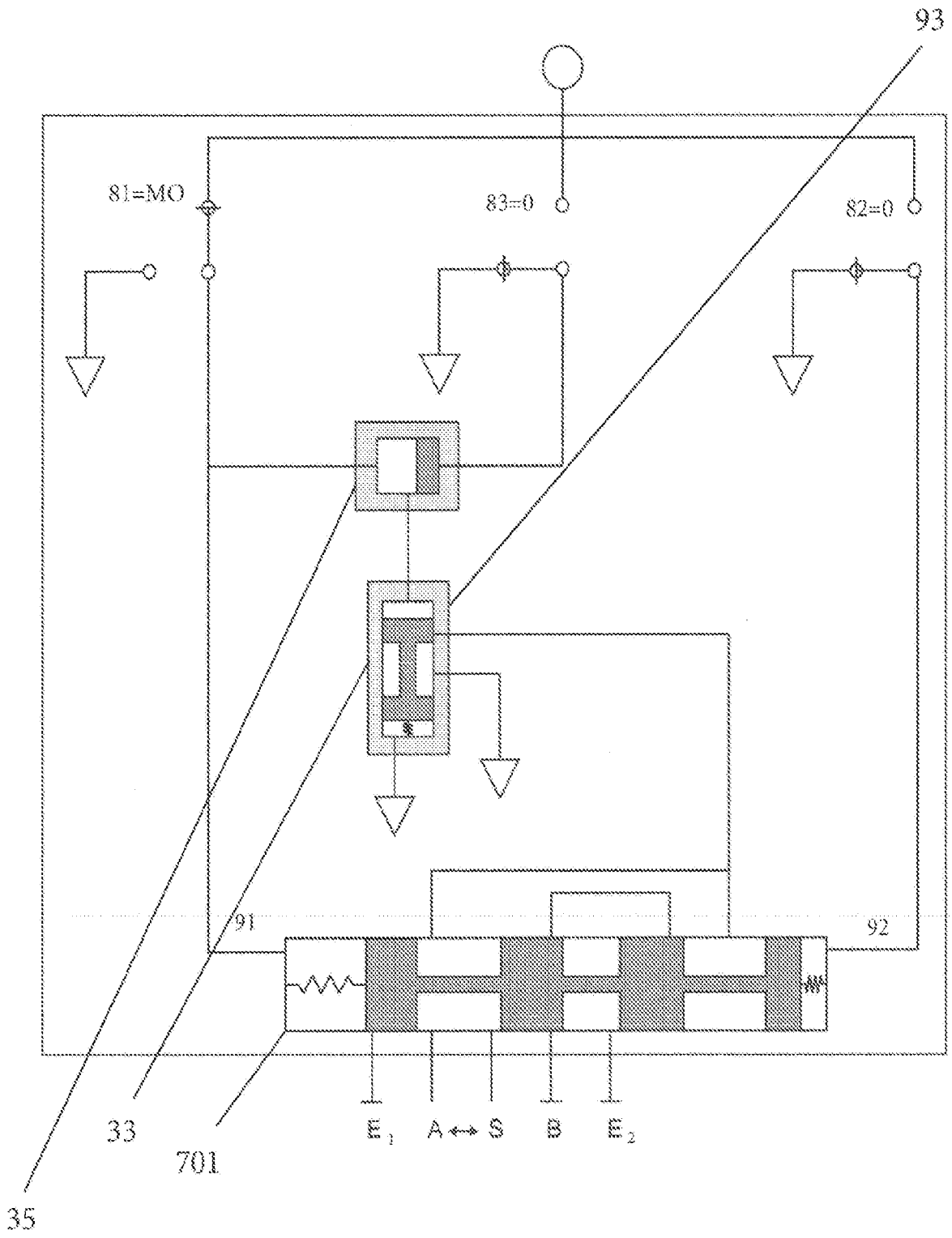


Fig. 26

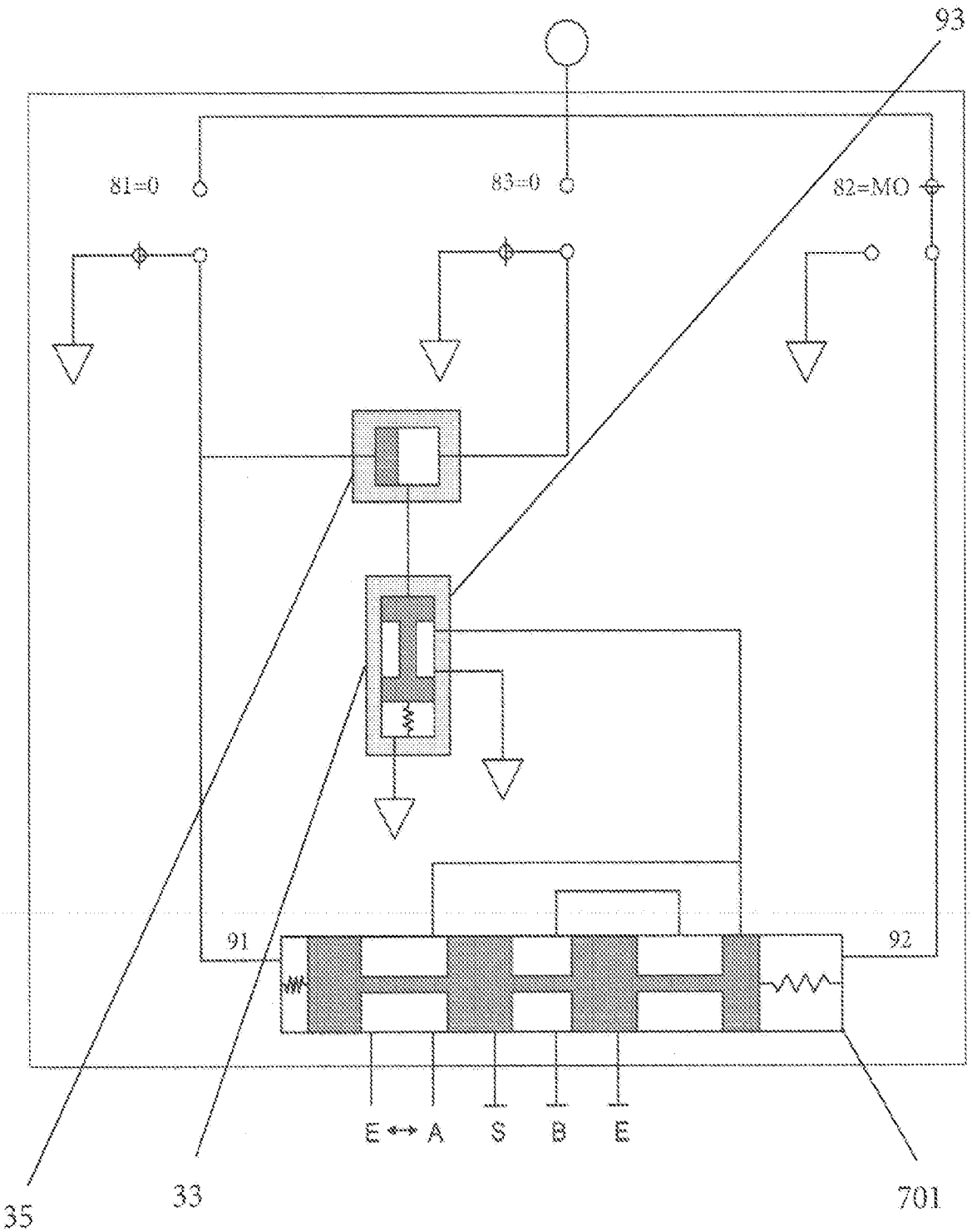


Fig. 27

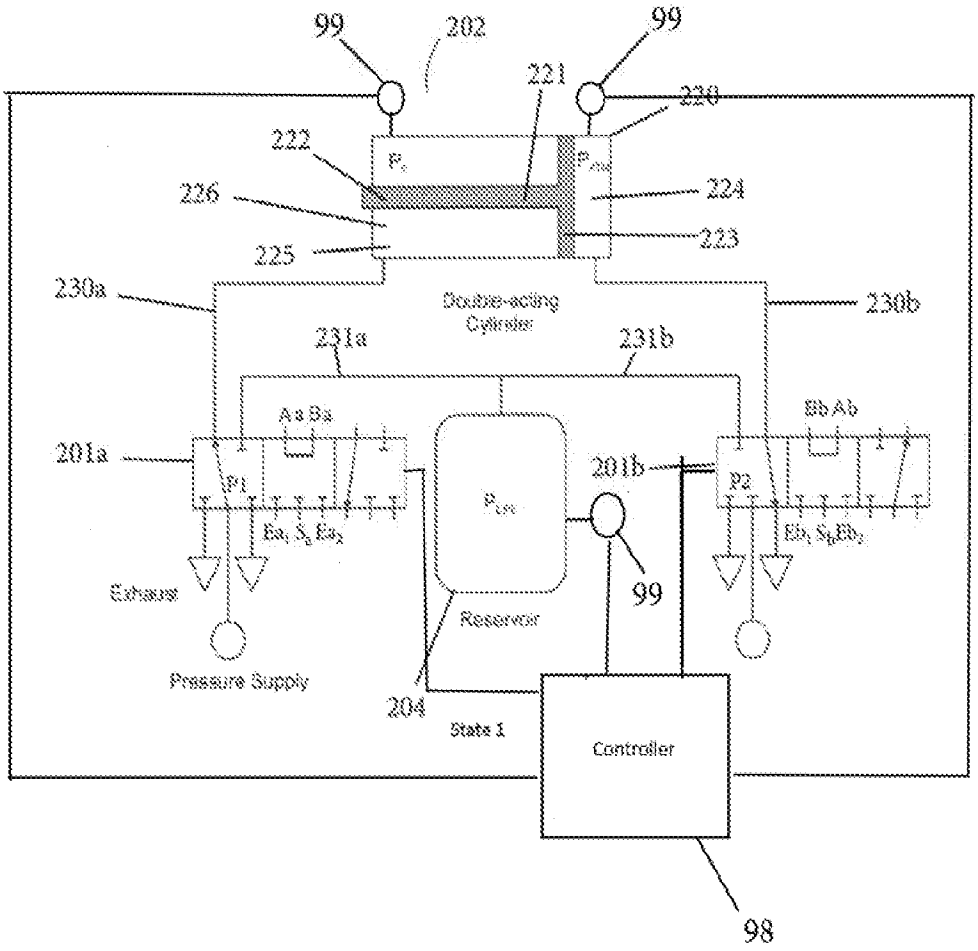

99
202
99
221
220
222
226
224
225
223
230a
230b
Double-acting Cylinder
231a
231b
201a
201b
Exhaust
Pressure Supply
Reservoir
99
204
State 1
Controller
98

Fig. 28

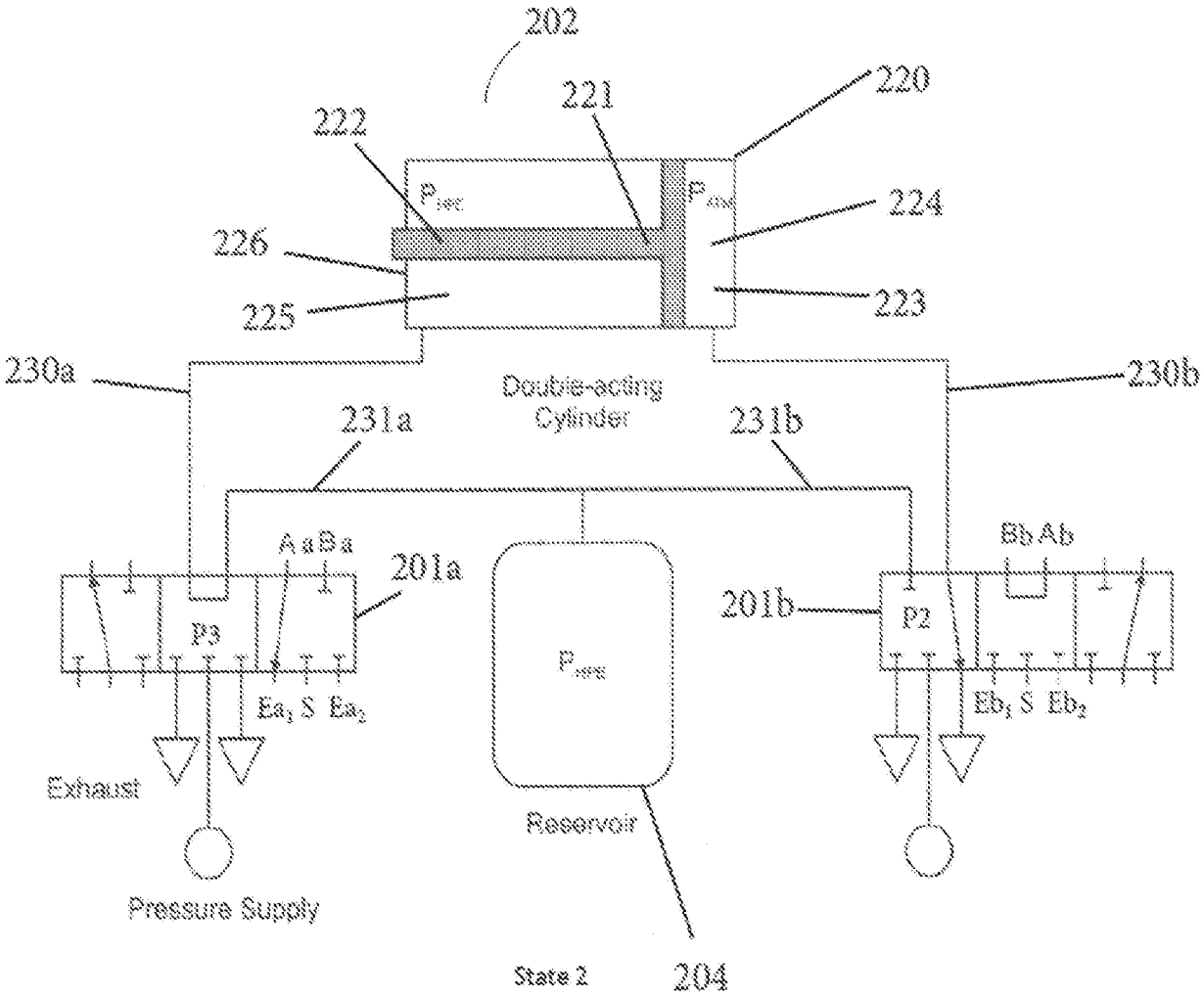

202
221
220
222
224
226
225
223
230a
230b
Double-acting Cylinder
231a
231b
AaBa
201a
BbAb
201b
P3
P2
Exhaust
Reservoir
Pressure Supply
State 2
204

Fig. 29

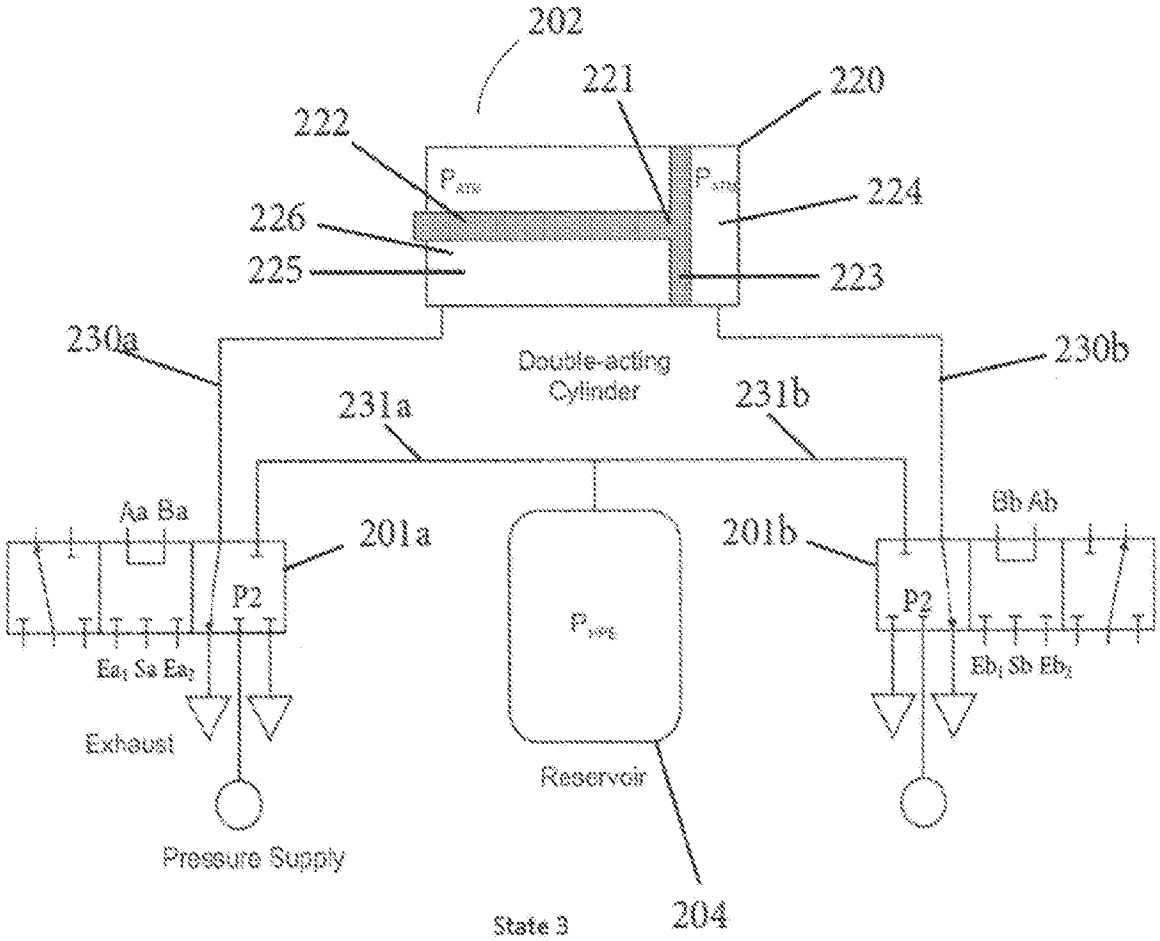

202
221
220
222
224
226
225
223
230a
230b
Double-acting Cylinder
231a
231b
Aa Ba
201a
201b
Bb Ab
P2
P2
Ea1 Sa Ea2
Eb1 Sb Eb2
Exhaust
Reservoir
Pressure Supply
204
State 3

Fig. 30

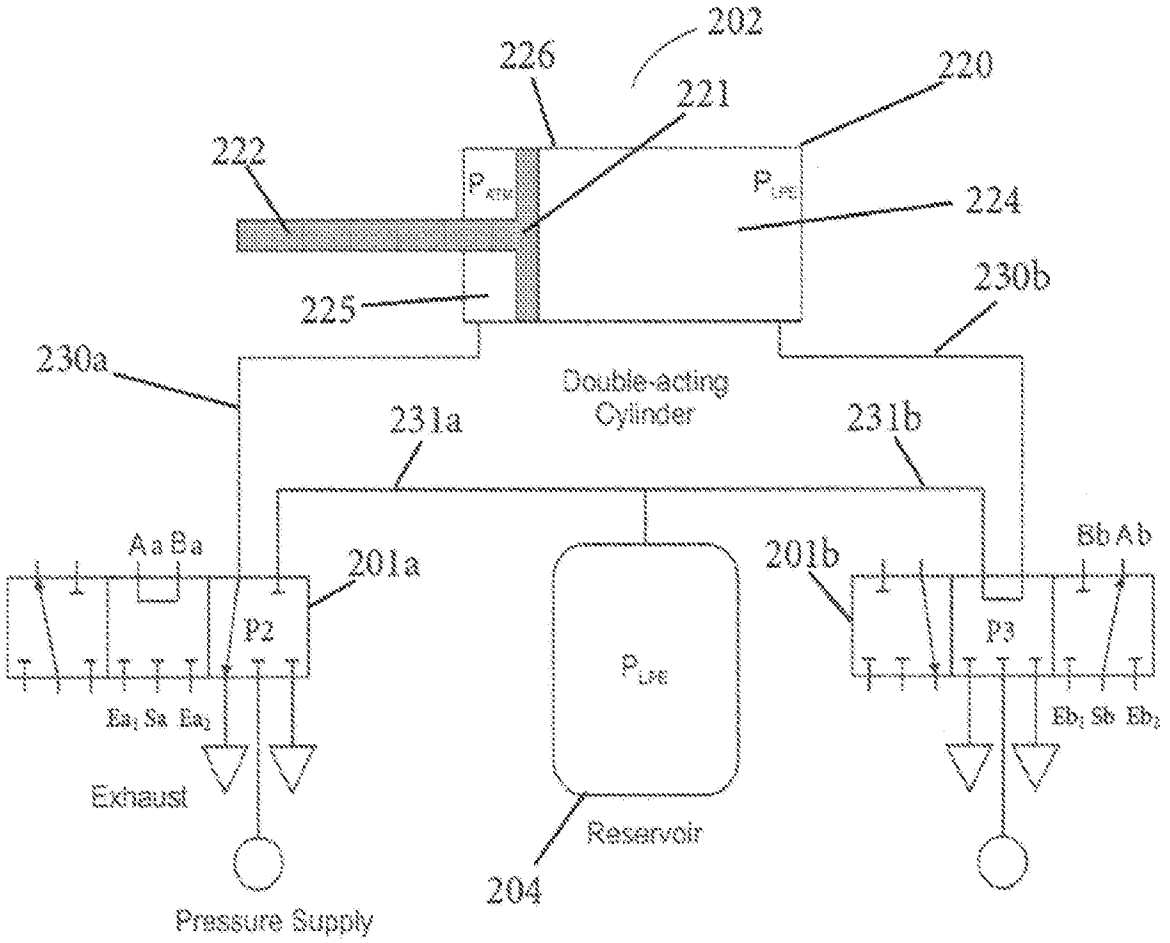

202
226
221
220
222
224
225
230b
230a
Double-acting
Cylinder
231a
231b
Aa Ba
201a
201b
Bb Ab
P2
P3
Ea1 Sa Ea2
Eb1 Sb Eb2
Exhaust
Reservoir
204
Pressure Supply
State 4

Fig. 31

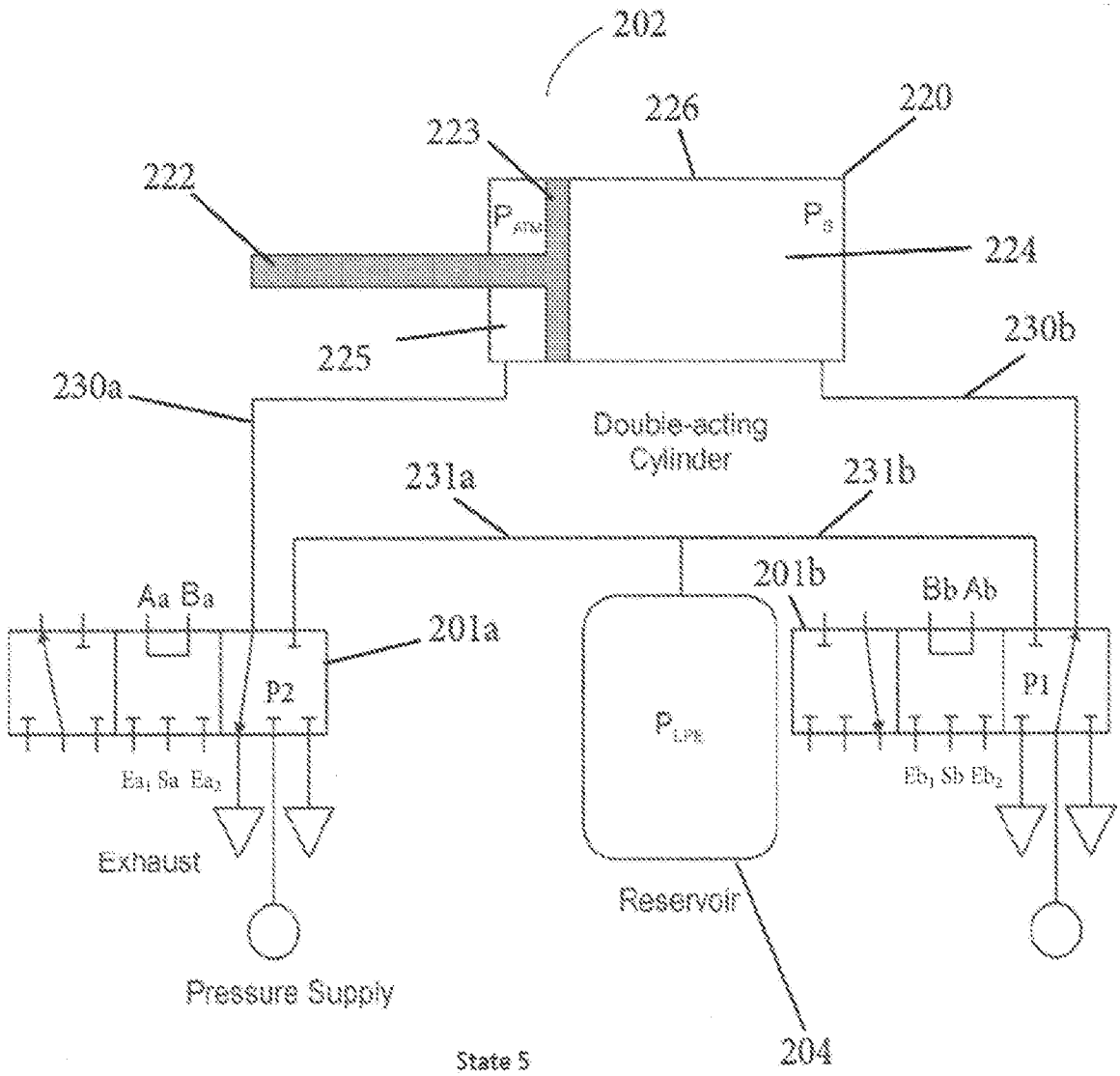

202
223
226
220
222
224
225
230b
230a
Double-acting
Cylinder
231a
231b
201b
Aa Ba
Bb Ab
201a
P2
P1
Ea1 Sa Ea2
Eb1 Sb Eb2
Exhaust
Reservoir
Pressure Supply
204
State 5

Fig. 32

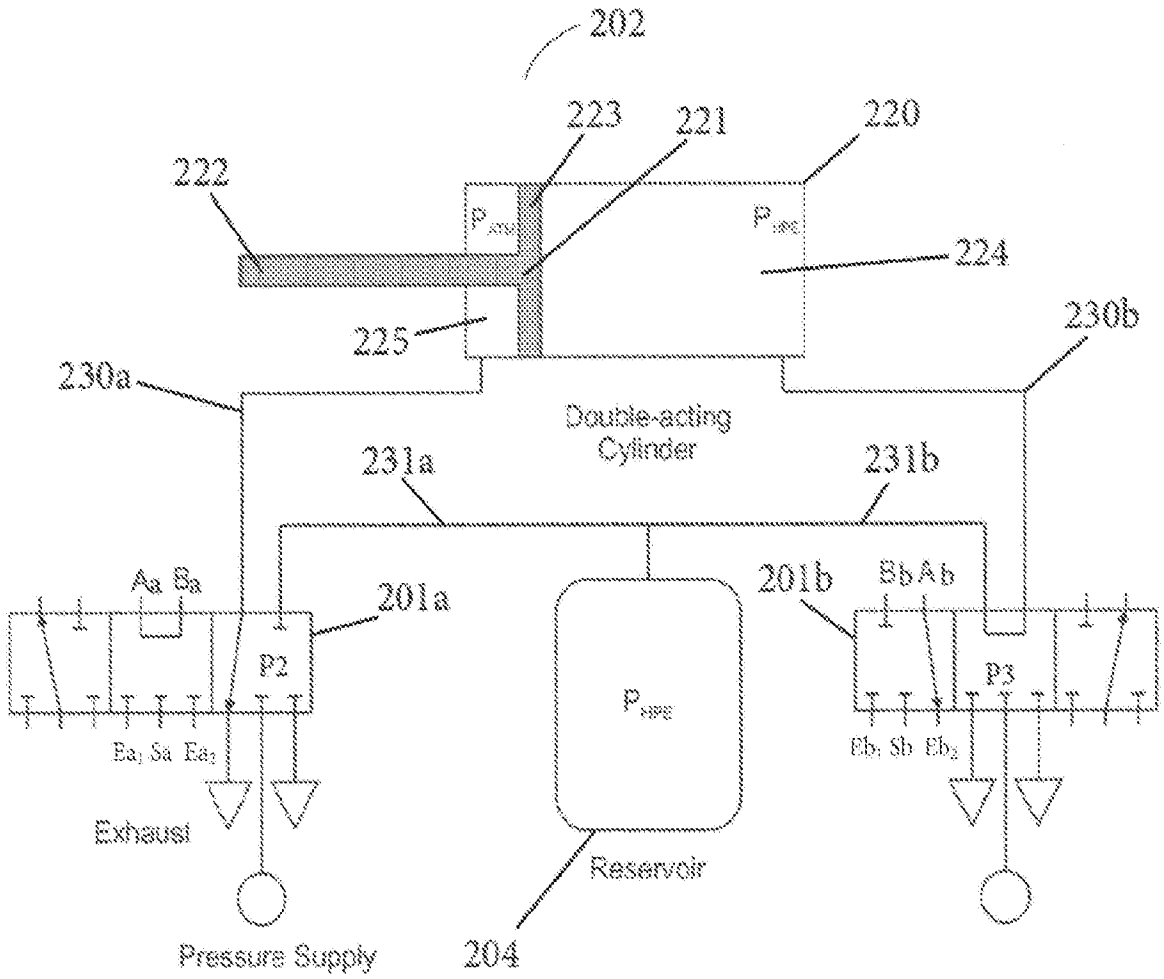

202
223
221
220
222
224
225
230b
230a
Double-acting
Cylinder
231a
231b
201a
201b
P2
P3
Exhaust
Reservoir
Pressure Supply
204
State 6

Fig. 33

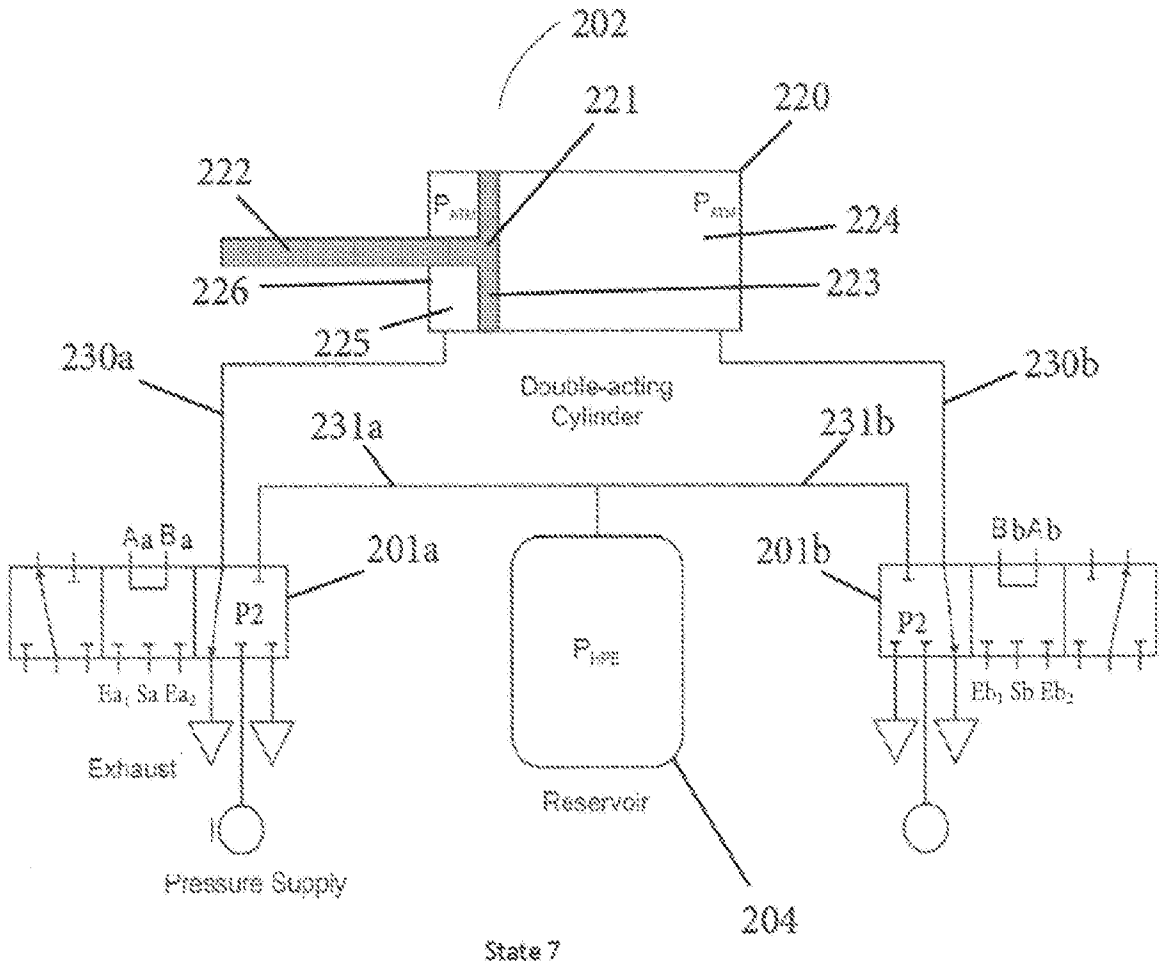

202
221
220
222
224
226
223
225
230a
230b
Double-acting Cylinder
231a
231b
Aa Ba
201a
201b
BbAb
P2
P2
Ea1 Sa Ea2
Eb1 Sb Eb2
Exhaust
Reservoir
Pressure Supply
204
State 7

Fig. 34

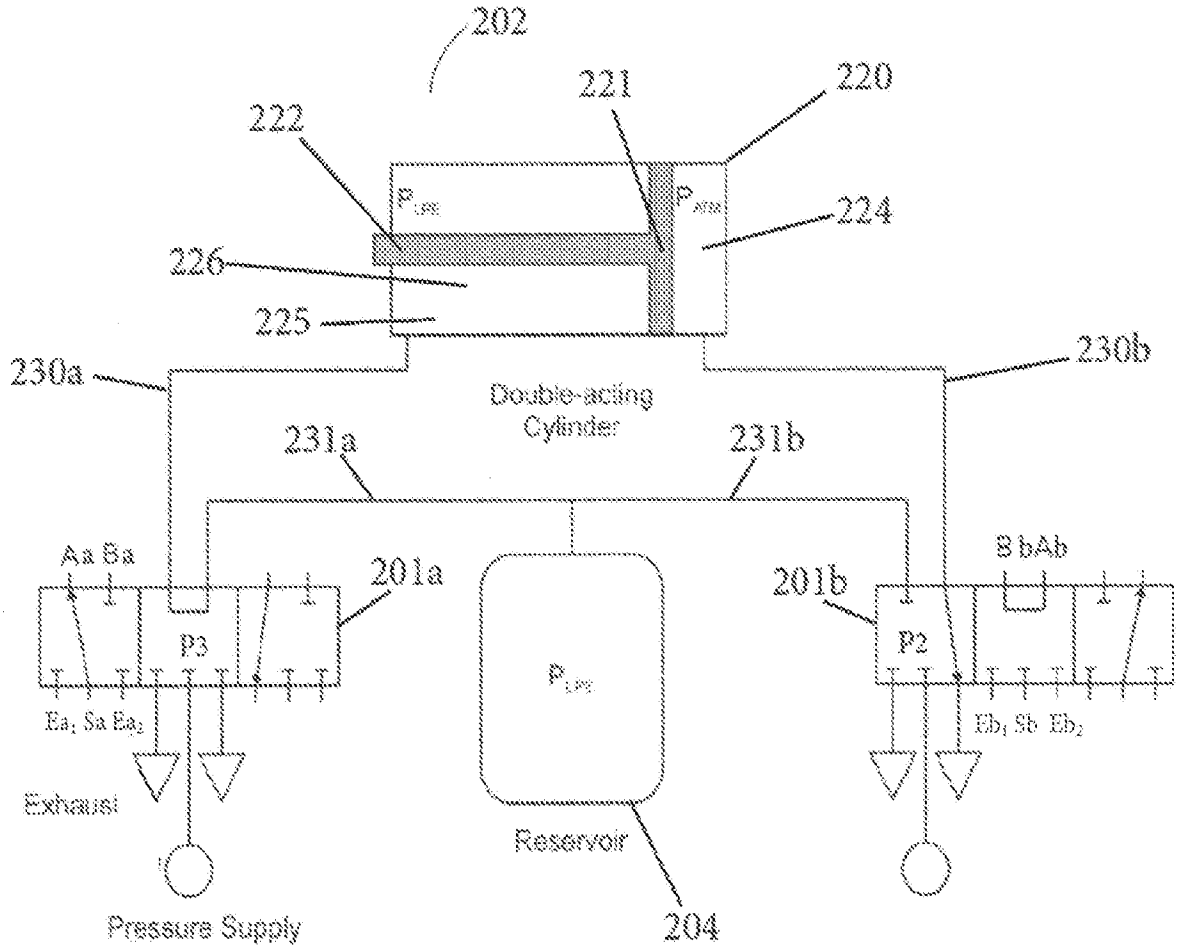

202
221
220
222
224
226
225
230a
230b
Double-acting Cylinder
231a
231b
Aa Ba
201a
P3
Ea1 Sa Ea2
Exhaust
Pressure Supply
Reservoir
204
201b
P2
Bb Ab
Eb1 Sb Eb2
State 8

Fig. 35

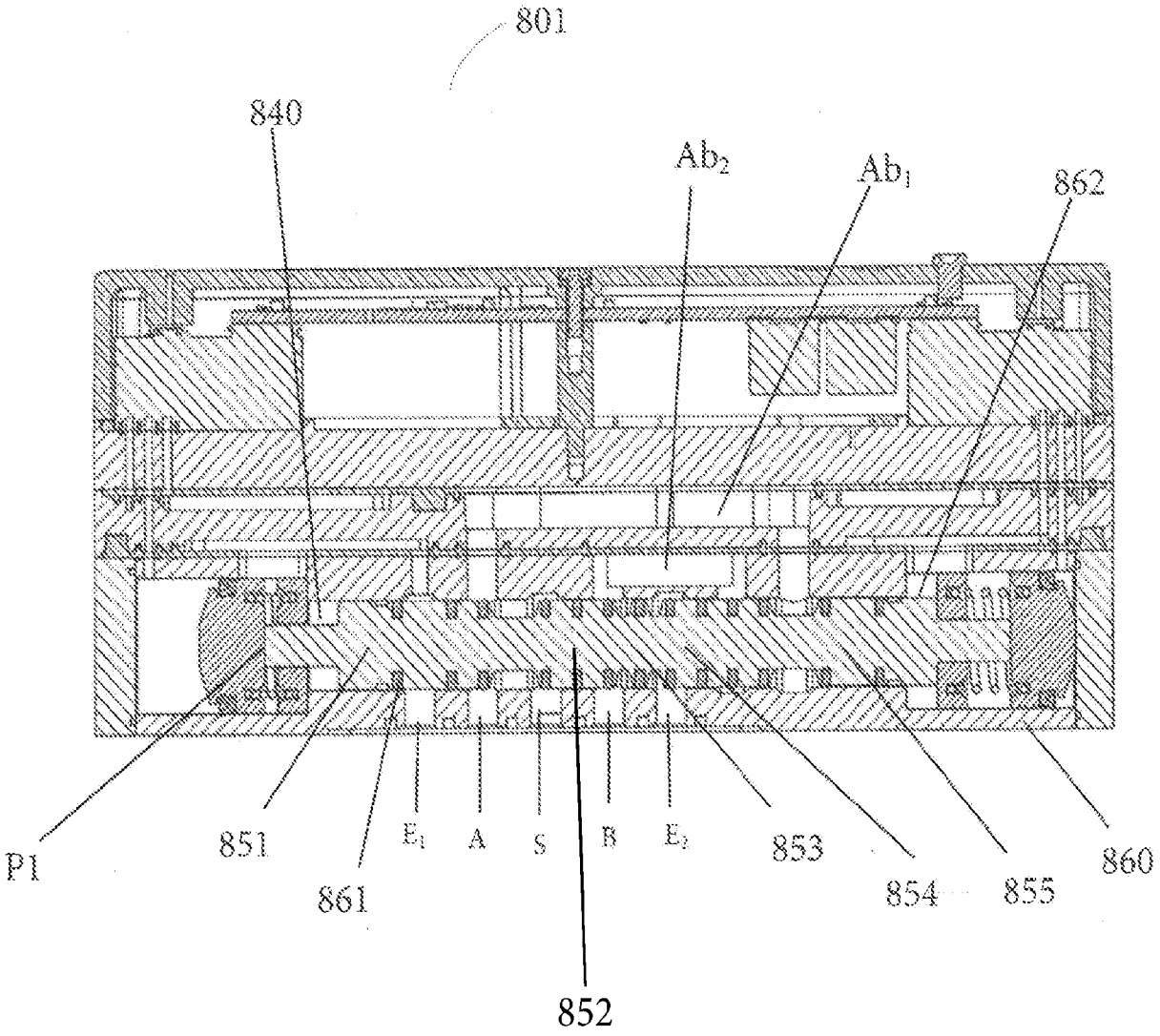


Fig. 36

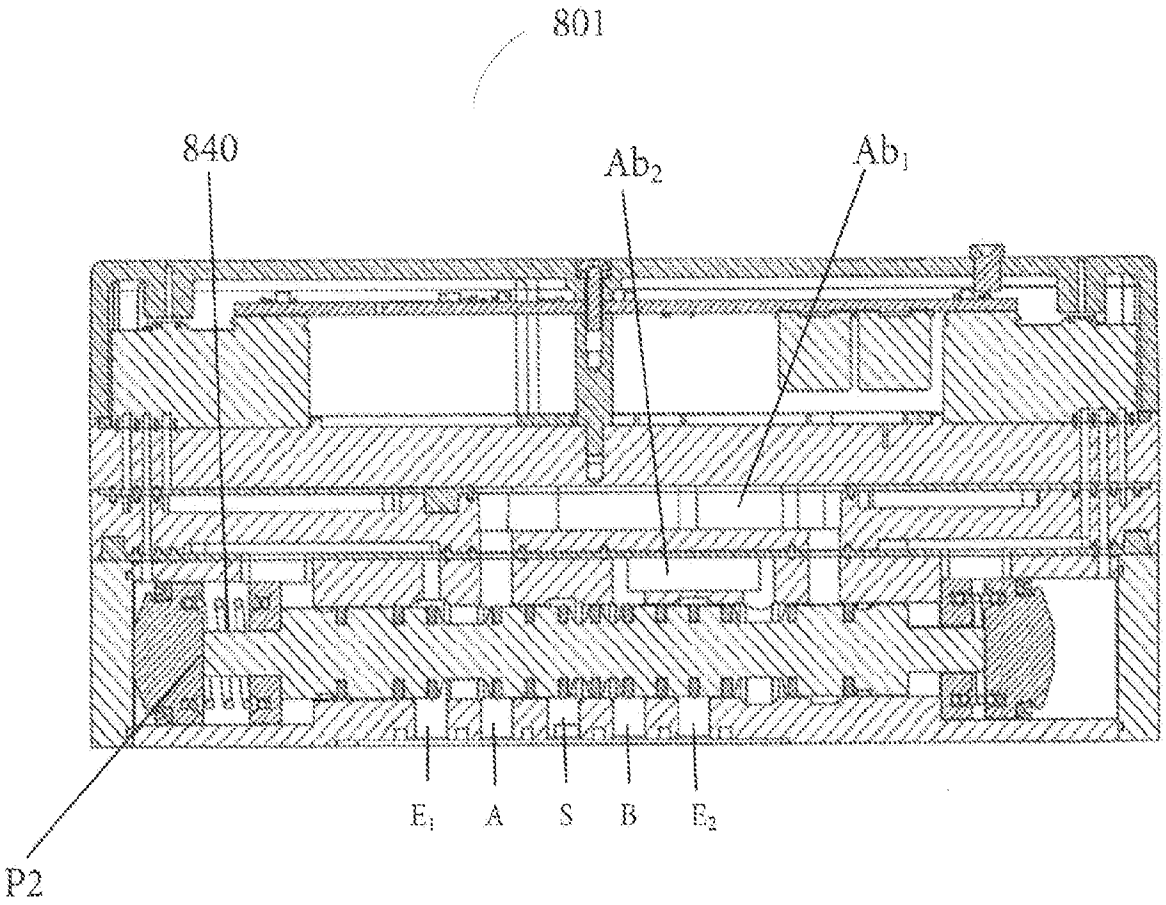


Fig. 37

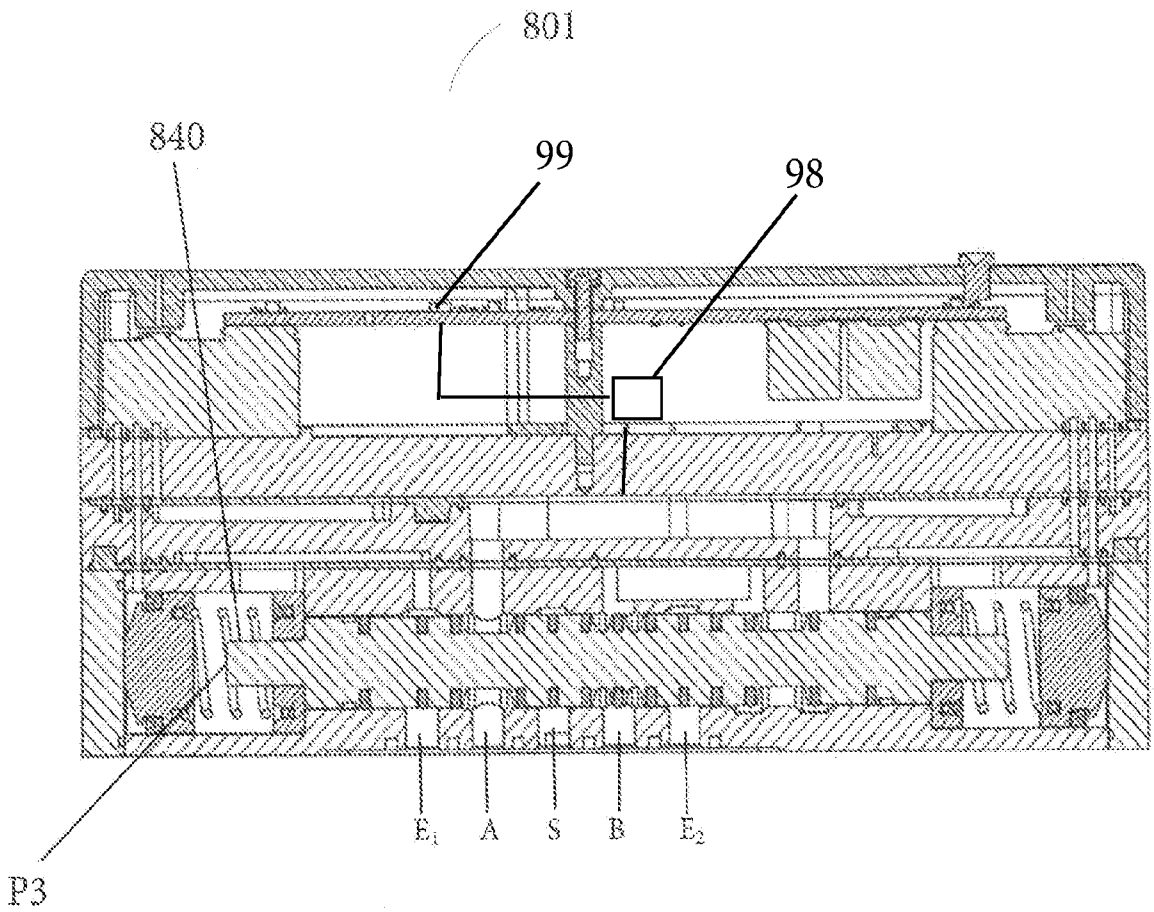


Fig. 38

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/014337

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F15B 15/00; F15B 1/02; F15B 1/04; F15B 1/26; F15B 11/024; F15B 11/042 (2017.01)

CPC - F15B 15/00; F15B 1/02; F15B 1/04; F15B 1/26; F15B 11/024; F15B 11/042; F15B 11/044; F15B 13/00; F15B 13/0402; F15B 2013/0412; F15B 15/04; F15B 2211/00; F15B 2211/212; F16K 11/07; F16K 27/04; F16K 27/041 (2017.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

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

USPC - 91/462; 91/465; 92/163; 137/596; 137/625 (keyword delimited)

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

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/0211476 A1 (HAGER) 28 October 2004 (28.10.2004) entire document	1-47
A	US 2004/0011192 A1 (FREDIANI et al) 22 January 2004 (22.01.2004) entire document	1-47
A	US 2011/0258996 A1 (INGERSOLL et al) 27 October 2011 (27.10.2011) entire document	1-47
A	US 2014/0047825 A1 (MCBRIDE et al) 20 February 2014 (20.02.2014) entire document	1-47
A	US 2006/0037466 A1 (YAJIMA et al) 23 February 2006 (23.02.2006) entire document	1-47

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"I" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 March 2017	31 MAR 2017
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774