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(54) METHOD OF CONSTRUCTION FOR HIGH CYCLE FATIGUE RESISTANT PRESSURE VESSELS IN HYDROGEN SERVICE

(57) A method and system are described for a gas booster, preferably for use with hydrogen. A linear actuator can provide compression in first and second compression vessels. The liner of the compression vessels can be placed in compressive stress so that any cracks that form do not spread. Compressive stress can be applied using, at least, a shrink fit process or a wire wrapping process. The compressive stress will help the inner liner to resist fatigue and cracking due to pressure cycling and corrosion by materials being compressed in the compression vessels. This also protects the chamber jacket from wear and tear.

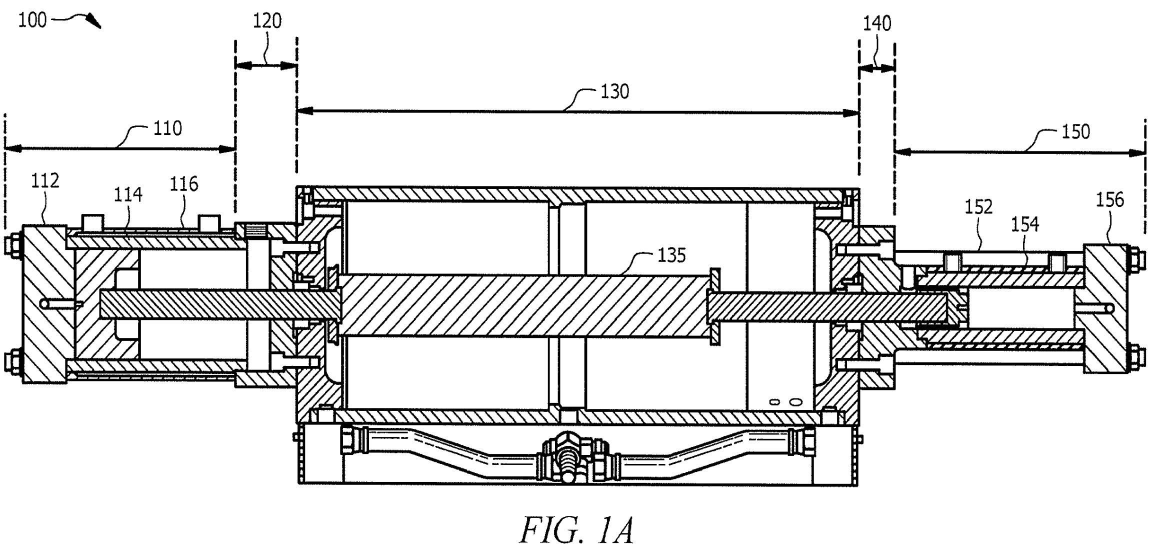

FIG. 1A

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Description

TECHNICAL FIELD

[0001] The present disclosure is directed to compressors, and more particularly to powered gas boosters.

BACKGROUND OF THE INVENTION

[0002] Gas boosters are commonly used to deliver pressurized gases for industrial processes or various manufacturing uses. Some gas boosters function with pistons or linear actuators. A retracting piston can create a low-pressure space in a barrel into which gas is drawn. A locking door may trap the gas in the barrel. Next the piston changes direction and presses down on the trapped gas, increasing the pressure of the gas which can be released to another location. The perpetual pressurization and depressurization of components, especially the barrel, in a gas booster can lead to fatigue issues. Fatigue is the weakening of a material caused by repeatedly applied loads.

[0003] In addition to fatigue, certain gas boosters that are used to compress hydrogen can suffer further problems from corrosion. Hydrogen can be particularly detrimental to certain metals used in gas booster construction. This is sometimes called the hydrogen embrittlement effect or hydrogen attack. A gas booster used for hydrogen will suffer fatigue effects that can be enhanced by the impact of hydrogen. The cycling of hydrogen in and out of a gas booster can lead to cracks which will grow due to further hydrogen flow and pressure cycling.

BRIEF SUMMARY OF THE INVENTION

[0004] One possible embodiment under the present disclosure comprises a gas booster for compressing a gas. The gas booster can comprise a compression vessel. The compression vessel can comprise an inlet configured to receive a portion of gas from a supply line and a liner surrounded by a jacket, wherein jacket and the liner have been joined by a shrink fit process. The booster can further comprise a linear actuator, the linear actuator operable to compress the portion of gas in the compression vessel when moving in a first direction and operable to draw the portion of gas into the compression vessel when moving in a second direction opposite the first direction.

[0005] Another possible embodiment under the present disclosure can comprise a barrel for use in a gas booster. The barrel can comprise an inlet configured to receive a portion of gas from a supply line; a liner surrounded by a jacket, wherein jacket and the liner have been joined by a shrink fit process; and an outlet configured to direct gas out of the compression vessel. The barrel can be configured to receive a linear actuator therein for the purpose of compressing the portion of gas.

[0006] Another possible embodiment under the present disclosure comprises a method for manufacturing a gas booster. A chamber jacket can be provided that comprises an inner diameter. Next a chamber liner can be provided that comprises an outer diameter at least as large as the inner diameter of the chamber jacket. The chamber jacket can be heated such that the inner diameter becomes larger than the outer diameter of the chamber liner and the chamber liner can be placed within the chamber jacket. The chamber jacket can then be allowed to cool such that the chamber jacket engages the chamber liner to create a barrel and such that compressive stresses are applied to the chamber liner. The barrel can then be coupled to a linear actuator.

[0007] The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGS. 1A-1B are diagrams of possible gas booster embodiments under the present disclosure;

FIGS. 2A-2B are diagrams of possible gas booster embodiments under the present disclosure;

FIGS. 3A-3B are diagrams of possible gas booster embodiments under the present disclosure;

FIGS. 4A-4B are diagrams of possible gas booster embodiments under the present disclosure;

FIG. 5 is a flow chart diagram of a possible method embodiment under the present disclosure;

FIG. 6 is a flow chart diagram of a possible method embodiment under the present disclosure;

FIG. 7 is a diagram of a possible gas booster embodiment under the present disclosure;

FIG. 8 is a diagram of a possible gas booster embodiment under the present disclosure;

FIG. 9 is a diagram of a possible gas booster embodiment under the present disclosure;

FIG. 10 is a diagram of a possible gas booster embodiment under the present disclosure;

FIG. 11 is a diagram of a possible gas booster embodiment under the present disclosure;

FIGS. 12A-12B are diagrams of a possible barrel embodiment under the present disclosure;

FIGS. 13A-13B are diagrams of a possible barrel embodiment under the present disclosure;

FIGS. 14A-14B are diagrams of a possible barrel embodiment under the present disclosure;

FIG. 15 is a flow chart diagram of a possible method embodiment under the present disclosure;

FIG. 16 is a diagram of a possible barrel embodiment under the present disclosure;

FIG. 17 is a diagram of a possible booster embodiment under the present disclosure;

FIG. 18 is a flow chart diagram of a possible method embodiment under the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0009] In compressor cylinders or other pressure vessels, the pressure can cycle between a low suction pressure and a high exhaust pressure. This cycling creates stresses, and eventually, cracks in a chamber jacket or a liner on the interior of the jacket. High pressure situations may necessitate the use of thick chamber walls, which help to also alleviate the stresses from cycling. Lower pressure use scenarios may not need thick walls, but pressure cycling can still be a threat to cause stresses and cracks. In these cases, an alternative, lower cost method, of design and construction is needed. One method that has been applied to obtain high cycle performance in high pressure vessels is to eliminate the possibility of fatigue crack propagation. This is achieved when the construction of the vessel is such that when the pressure load is applied, the crack remains closed. If the crack doesn't open, then it cannot grow and the fatigue life is then longer.

[0010] Using a gas booster for pressurizing hydrogen can cause further problems due to hydrogen's detrimental effects. Currently, pressure vessels that operate in hydrogen service and subjected to fatigue must be designed using a defect tolerant design procedure. This means that first the fracture mechanics properties of the material being considered must be measured in hydrogen at the maximum service pressure. The properties are crack propagation properties and threshold stress intensity factor for hydrogen embrittlement. With these properties, a fatigue crack propagation life can be estimated assuming an initial crack size and geometry and growing this defect to failure. The property measurements are costly and can only be performed at a few laboratories. Furthermore, the resulting lives are usually very short because of the assumed initial crack size. These factors limit the application of this design method to lower cycle or static loading applications.

[0011] Solutions under the present disclosure to the problems described above include methods and systems for placing a booster liner in a compression state. Possible embodiments for creating such a compression state include a shrink fit process for placing a jacket around a liner, and also wire wrapping around a liner. Embodiments under the present disclosure can comprise methods of design and construction of pressure vessels for high cycle use in hydrogen service at pressures preferably below 40,000 psi. A preferred embodiment of the current disclosure can be used in hydrogen service applications (though other use scenarios are contemplated).

[0012] Certain embodiments under the present disclosure can use a shrink fit system or method to place a jacket around a liner in a gas booster. Generally, for lower pressure applications the vessel or compressor head radius ratio is thin or small, while for high pressure vessels, the radius ratios are large or thick. Thick walls allow for more methods of construction to obtain the desired stress state to prevent crack growth. But for hydrogen-based systems, such thick walls are typically not used and thin walls are used because of the lower pressures in hydrogen-based systems. For example, thick walls can be made with autofrettage techniques. During autofrettage a vessel can be subjected to high pressures, such as by a compressive outer barrel, that cause internal portions of the vessel to yield plastically. Once the pressure is released there are internal compressive residual stresses. With thin walls, the use of autofrettage will usually not be practical. One goal of the present disclosure is to provide a manufacturing technique for creating thin-walled vessels with increased strength for use in gas boosters, especially hydrogen carrying gas boosters. Instead of, or in addition to, autofrettage, embodiments under the present disclosure can comprise the use of a shrink fit liner on the interior surface of a pressure vessel. In certain embodiments under the present disclosure, shrink fit construction can be used to place an inside liner in a compression cylinder in sufficient compression such that when the pressure is applied during use, any crack present would be prevented from opening and thus prevented from growing.

[0013] Referring to Figure 1A, an embodiment of a compressor (also called a gas booster) can be seen. The embodiment of Figure 1A is called a single acting two-stage booster. Booster 100 comprises a first compression stage (or barrel or vessel) 110, a first adapter plate 120, a linear actuator portion 130, a second adapter plate 140, and a second compression stage or vessel 150. Linear piston or actuator 135 moves back and forth linearly, alternating between drawing gas into and out of the first and second vessels 110, 150. For example, as actuator moves right gas can be drawn into the first vessel 110. A check valve 114 can close inlet 112 to trap gas in first vessel 110. Actuator 135 will then move left and compress the gas in first vessel 110. During or after the compression, outlet 116 can open, allowing gas to flow out of first vessel 110 and into second vessel 150 via inlet 152 (via tubing not shown). A leftward moving actuator 135 can assist in pulling gas into second vessel 150. The gas, already compressed once, enters second vessel 150 via inlet 152 and check valve 154 closes inlet 152. As the actuator 135 moves rightward again, the gas in second vessel 150 can be compressed and forced out through an outlet 156, and more gas will be pulled into first vessel 110 from a supply line. The gas leaving second vessel 150 will have been compressed twice by the gas booster 100. In preferred embodiments, the diameter of second vessel 150 will be smaller than that of first vessel 110. The process of compression described can occur continually, with each stroke of the actuator compressing gas in one vessel and drawing gas into the other vessel.

[0014] Referring to Figure 1B, an embodiment of a compressor (also called a gas booster) can be seen. The embodiment of Figure 1B is called a double acting one-stage configuration. Booster 100 preferably comprises two identical compression stages (or barrel or vessel) 110, 150, two identical adapter plates 120, 140, and a linear actuator portion 130. Linear piston or actuator 135 moves back and forth linearly, alternating between drawing gas into and out of the both stages 110, 150. For example, as actuator moves right gas can be drawn into the stage 110. A check valve 114 can close inlet 112 to trap gas in left vessel 110. Actuator 135 will then move left and compress the gas in stage 110. During or after the compression, outlet 116 can open, allowing gas to flow out of stage 110. As the actuator 135 is moving left and compressing gas in the stage 110, gas is being drawn into stage 150, which is then compressed when the actuator 135 moves right again. A difference between Figure 1B and Figure 1A is that, as seen in Figure 1B, compressed gas leaving stage 110 through outlet 116 leaves the booster through an process gas outlet and is not directed to stage 150 or inlet 152. A single process gas inlet and a single process gas outlet can serve both stages 110, 150. In preferred embodiments, the diameter of both stages 110, 150 will be of the same size. The process of compression described can occur continually, with each stroke of the actuator compressing gas in one vessel and drawing gas into the other vessel.

[0015] Figures 2A-3B show embodiments of gas boosters 100 like Figures 1A-1B. Figures 2A and 3A show single acting two-stage embodiments. Figures 2B and 3B show double acting one-stage configurations. Figures 2A-3B show first vessel 110, linear actuator portions 130, and second vessel 150. The exact location of gas inlets, check valves, linear actuator size and location, and other aspects may differ. Gas boosters that deal with hydrogen can be susceptible to unique corrosion effects within chambers 115, 155 shown in Figures 3A and 3B. Certain embodiments under the present disclosure comprise liners placed within chambers 115, 155 that will protect the chambers 115, 155 from corrosion. In this manner, chambers 115, 155 can be constructed from normally available materials, such as stainless steel.

[0016] A preferred method of combining the liners and chambers according to the concepts described herein involves a shrink fit process, wherein the chamber jacket is heated so that it expands and a liner is inserted therein. Once combined (as the chamber jacket cools), the magnitude of the resultant stress at the pressure boundary of the liner is more compressive than the magnitude of an applied pressure. The pressure on the liner operates to prevent any crack, should one initiate (or be pre-existent), from opening further. The choice of materials and the shrink fit process should produce sufficient compression in the liner. The shrink fitting can expand the jacket and place it in a condition of tension. To ensure that the jacket has sufficient life, the jacket requires a maximum threshold of linear axial indication and should be inspected and tested for integrity by means of non-destructive testing prior to assembly to ensure that there are no defects present. Threshold values for various materials under various loading conditions are found in construction codes such as ASME section VIII, Division 3, Rules for High Pressure Vessels.

[0017] Figure 4A and 4B show embodiments of gas boosters 400 comprising chamber jackets 415, 455 with liners 417, 457. Figure 4A shows a single acting two-stage embodiment. Figure 4B shows a double acting one-stage configuration. Booster 400 comprises a first compression stage (or vessel) 410 with inlet 412 and outlet 416 and a second compression stage 450 with inlet 452 and outlet 456. Linear actuator portion 430 with actuator 435 sits between the stages 410, 450. Liners 417, 457 sit within chamber jackets 415, 455. Liners 417, 457 and jackets 415, 455 are preferably combined using a shrink fit process (also known as a heat shrinking process). Other joining processes may be possible. Whatever process is used, it is preferred that the liner 417, 457 be preloaded with compressive stress before use. Preferably, first compression stage 410 has a larger diameter than second compression stage 450. But as shown in Figure 4B, they can have the same dimensions.

[0018] The material comprising a liner 417, 457 will preferably be a material resistant to corrosion or the detrimental effects of hydrogen. However, the material can vary. Some embodiments under the present disclosure may be for systems without hydrogen and may therefore use a different material than in hydrogen-based systems. Stainless steel, such as 15-5PH, is a preferred material for a chamber jacket. Stainless steel is useful because of its cost, availability, and usability in various construction techniques. Other embodiments can comprise other metals, alloys, or other appropriate materials.

[0019] Figure 5 displays a possible method embodiment 500 for constructing a portion of a booster, such as first stage 410 or second stage 450 of Figure 4. At 510, a chamber jacket is provided. At 520, a chamber liner is provided with an outer diameter larger than an inner diameter of the chamber jacket. At 530, the chamber jacket is heated to cause the inner diameter to be larger than the outer diameter of the chamber liner. At 540, the liner is inserted into the jacket to create a liner/jacket combination. Then, at 550, the liner and jacket are allowed to cool. Cooling will cause the jacket to shrink and compress the liner. The compressive stress placed on the liner will help the liner to resist tensile stress and cracks due to pressure cycling during use, or due to corrosive effects of gases or other materials within the system, such as hydrogen.

[0020] The method of Figure 5 will likely be repeated once for each of the first and second compression stages. However, some gas boosters may only comprise one compression stage, so the method will not need to be repeated for these embodiments. In addition, it may be preferable in some situations to create a single jacket/liner combination by method 500, and then cut the combination into two pieces, one for the first stage and one for the second stage.

[0021] The method of Figure 5 can be a part of creating a gas booster or compressor. A method of creating a booster can begin with method 500 of Figure 5 and then proceed to method 600 of Figure 6. At 610, first and second compression stages can be provided. A linear actuator can then be connected between the first and second stages at 620, such that the actuator can provide compression to both stages. An inlet and an outlet can be provided for the first and second stages at 630. The gas booster can then be integrated into a larger system.

[0022] Gas boosters like those described in the current disclosure have a number of uses. Uses can include: hydrogen filling stations; charging high-pressure gas cylinders and receivers; gas assisted plastic injection molding; hydraulic accumulator charging; charging air bag storage vessels; missile and satellite launch and guidance systems; component testing; laser cutting and welding; oilfield high volume gas testing; biogas charging; and more. Embodiments under the current disclosure can be implemented in any of these use scenarios.

[0023] Gas boosters like those described in the present disclosure can be coupled with different types of drives, such as a hydraulic drive, pneumatic drive, electrical drive, or can be driven using other appropriate technologies.

[0024] Sometimes gas boosters are mobile, such as the truck embodiment shown in Figure 7. Gas boosters can be coupled to other machinery, such as the power plant used to drive the booster's actuators or pistons. Figure 8 shows an example embodiment of a hydraulically driven gas booster 800. Booster 800 can comprise an actuator (or piston) portion 830 coupled to first 810 and second 850 compression stages. Hydraulic hardware 860 can supply power to the booster 800 and gauges 870 may indicate pressures or alarm conditions within the system. Figure 9 shows another example of a hydraulic gas booster 900. Actuator 930 is driven by hydraulic hardware 970, helping to compress gas in first and second compression stages 910, 950. Gauges 960 monitor the system.

[0025] Preferred embodiments of the current disclosure comprise dual-stage gas boosters. However, the teachings can be applied to single stage boosters. A possible single stage embodiment can be seen in Figure 10. Booster 1000 comprises a single compression stage 1010 with a gas inlet 1012 and outlet 1016 and a piston or actuator 1050. Compression stage 1010 comprises an inner layer 1017 and a jacket 1015 such as described in other embodiments of the present disclosure.

[0026] Figure 11 displays a further embodiment of a booster system 1100 under the present disclosure. Booster 11140 comprises first 1110 and second 1150 compression stages. First inlet 1112 can receive a gas, such as hydrogen from a supply line 1113. First stage 1110, with a jacket 1115 and liner 1117, can house the compression of the gas caused by an actuator from actuator portion 1130. Gas can then travel through first outlet 1116 to second inlet 1152 of the second compression stage 1150. After compression in the second stage 1150, the gas (now compressed twice) can travel through outlet 1156 to another component or remote location. Power plant 1170 can comprise hydraulic power, electrical power, pneumatic power, or other types. Oil reservoir 1160 can store oil used for lubrication (or possibly cooling) in the system 1100. Multiple reservoirs may be used for different purposes: lubricating oil, coolant, or more.

[0027] Dimensions of chamber jackets and liners can vary as needed in a given use scenario. Figures 12A-14B show different embodiments of possible jackets and liners with different dimensions.

[0028] Figures 12A-12B show the thinnest liner, both in absolute terms and as a ratio to the thickness of the accompanying jacket. Liner 1215 has an inner diameter of 2.480 inches and an outer diameter of 2.741 inches. Jacket 1205 has an outer diameter of 4.724 inches and an inner diameter of 2.734 inches. A shrink fit process, such as described herein, can insert liner 1215 into jacket 1205.

[0029] Figures 13A-13B show the next thinnest liner. Liner 1315 has an inner diameter of 3.543 inches and an outer diameter of 3.906 inches. Jacket 1305 has an outer diameter of 5.315 inches and an inner diameter of 3.897 inches. A shrink fit process, such as described herein, can insert liner 1315 into jacket 1305.

[0030] Figures 14A-14B show the thickest liner. Liner 1415 has an inner diameter of 5.906 inches and an outer diameter of 6.510 inches. Jacket 1405 has an outer diameter of 7.480 inches and an inner diameter of 6.499 inches. A shrink fit process, such as described herein, can insert liner 1415 into jacket 1405.

[0031] How thick to make the liner, both in absolute measurements and in comparison to a jacket, can depend on a given embodiment. Factors to consider can include the pressures that will occur during use; the type of gas/material being compressed and its corrosive relationship to a liner or jacket; space constraints; desired length of a jacket and liner; and other factors.

[0032] Both jackets and liners under the present disclosure can comprise a variety of materials. Various types of steels and steel alloys are preferred materials for both jackets and liners, though other materials are possible. Preferred jacket embodiments can use SA 564, type 630 or XM-12. Preferred liner embodiments can use SA 705 type 630 or XM-12. The jacket and liner will preferably comprise cylinder-shaped units. Other shapes are possible.

[0033] Operating conditions for compression stages or vessels under the present disclosure can vary. Typical operating pressures can be 4,500 PSIG, 9,000 PSIG, and 15,000 PSIG. Design pressures may be 14,600 PSIG, 25,500 PSIG, and 41,800 PSIG in such embodiments. Operating temperatures may range from -40 F to 400 F in such embodiments. Embodiments such as these can typically withstand nearly 80 million pressure cycles. Preloading can take the form of 410ft-1b on eight 24x3 threaded tie rods.

[0034] Figure 15 displays a possible method embodiment 1500 for the operation of a gas booster under the present disclosure. At 1510, a portion of gas is directed into a first compression vessel, the first compression vessel comprising a first liner surrounded by a first jacket, wherein the first jacket and the first liner have been joined by heating the first jacket so that the inner diameter of the first jacket becomes larger than an outer diameter of the first liner, placing the first jacket around the first liner, and allowing the first jacket to cool and apply compressive stresses to the first liner. At 1520, a first check valve is closed to lock the portion of gas in the first compression vessel. At 1530, the portion of gas is compressed by means of a linear actuator. At 1540, the portion of gas is directed through an outlet of the first compression vessel. At 1550, the portion of gas is directed into a second compression vessel, the second compression vessel comprising a second liner surrounded by a second jacket, wherein the second jacket and the second liner have been joined by heating the second jacket so that the inner diameter of the second jacket becomes larger than an outer diameter of the second liner, placing the second jacket around the second liner, and allowing the second jacket to cool and apply compressive stresses to the second liner. At 1560, the second check valve is closed to lock the portion of gas in the second compression vessel. At 1570, the portion of gas is compressed by means of the linear actuator. At 1580, the portion of gas is directed through an outlet of the second compression vessel.

[0035] In addition to embodiments using a shrink fit process, compressive forces can be applied to a liner using a wire-wrapped embodiment. An embodiment of a wire-wrapped compression stage can be seen in Figure 16. Stage or vessel 1600 comprises a liner 1620 surrounded by a wire 1650. The liner 1620 and wire 1650 help define a cavity 1640 for the reception and compression of gas as described in other embodiments hereunder. The wire 1650, preferably a metal alloy, can be wound so tight that compressive forces are applied to the liner 1620. The resulting forces can have a similar effect as described above using a shrink fit process.

[0036] Figure 17 shows a possible embodiment of a gas booster comprising wire-wrapped compression stages. Booster 1700 comprises a first stage 1710 and second stage 1750. Inlet 1712 directs gas into first stage 1710 and outlet 1716 directs compressed gas out of first stage 1710. Inlet 1752 directs gas into second stage 1750 and outlet 1756 directs compressed gas out of second stage 1750. Adapter plates 1720, 1740 couple the stages 1710, 1750 to the actuator portion 1730. Actuator 1735 can move back and forth compressing gas and drawing gas into and out of the stages 1710, 1750. In each stage 1710, 1750 wire 1760 surrounds liners 1770. Booster 1700 is shown with differently sized stages 1710, 1750, but each stage could have similar or identical dimensions. Embodiments using wire-wrapped stages, such as embodiment 1700, can comprise single acting two-stage and double acting one-stage configurations, as well as other configurations, such as a single stage booster.

[0037] Figure 18 displays a possible method embodiment for constructing a wire-wrapped compression stage and a gas booster. At 1810, a stage liner is provided. At 1820, the stage liner is wrapped with a wire to apply compressive stress to the stage liner. At 1830, a gas inlet and outlet are provided into the interior of the stage liner. At 1840, the stage liner is coupled to a linear actuator configured to compress gas in the interior of the stage liner. Steps 1810-1840 can be repeated for a second liner to add another compression stage to a booster.

[0038] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

Claims

1. A gas booster for compressing a gas, comprising:

a compression vessel comprising;

an inlet configured to receive a portion of gas from a supply line;
a liner surrounded by a jacket, wherein jacket and the liner have been joined by a shrink fit process; and

a linear actuator, the linear actuator operable to compress the portion of gas in the compression vessel when moving in a first direction and operable to draw the portion of gas into the compression vessel when moving in a second direction opposite the first direction.

2. The gas booster of claim 1 further comprising a second compression vessel, comprising:

a second compression vessel comprising;

a second inlet configured to receive the portion of gas from the compression vessel; and
a second liner surrounded by a second jacket, wherein the second jacket and the second liner have been joined by a shrink fit process;

wherein the linear actuator is operable to compress the portion of gas in the second compression vessel when moving in the second direction and to draw the portion of gas into the second compression vessel when moving in the first direction.

3. The gas booster of claim 1 wherein the portion of gas comprises hydrogen.

4. The gas booster of claim 1 wherein the linear actuator is hydraulically driven.

5. The gas booster of claim 1 wherein the linear actuator is pneumatically driven.

6. The gas booster of claim 2 wherein the compression vessel has a larger diameter than the second compression vessel.

7. The gas booster of claim 1 wherein the jacket comprises a steel alloy.

8. The gas booster of claim 1 wherein the liner comprises a steel alloy.

9. A method for manufacturing a gas booster:

provide a chamber jacket comprising an inner diameter;
provide a chamber liner, the chamber liner comprising an outer diameter at least as large as the inner diameter of the chamber jacket;
heat the chamber jacket such that the inner diameter becomes larger than the outer diameter of the chamber liner;
place the chamber liner within the chamber jacket;
allow the chamber jacket to cool such that the chamber jacket engages the chamber liner to create a barrel and such that compressive stresses are applied to the chamber liner; and
couple the barrel to a linear actuator.

10. The method of claim 9 further comprising creating a second barrel and coupling the second barrel to the linear actuator.

11. The method of claim 10 wherein the barrel and second barrel are coupled to opposite ends of the linear actuator.

12. The method of claim 9 further comprising coupling a gas outlet of the barrel to a gas inlet of the second barrel.

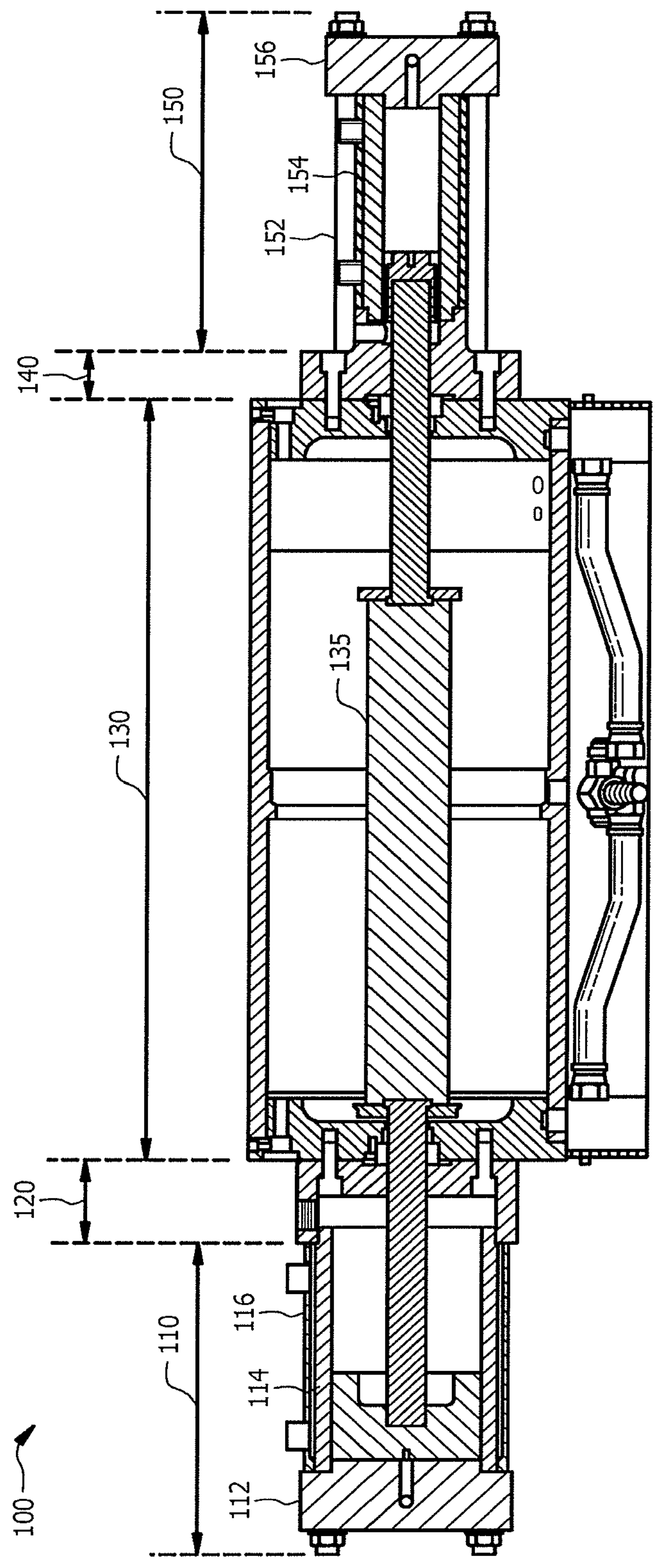

FIG. 1A

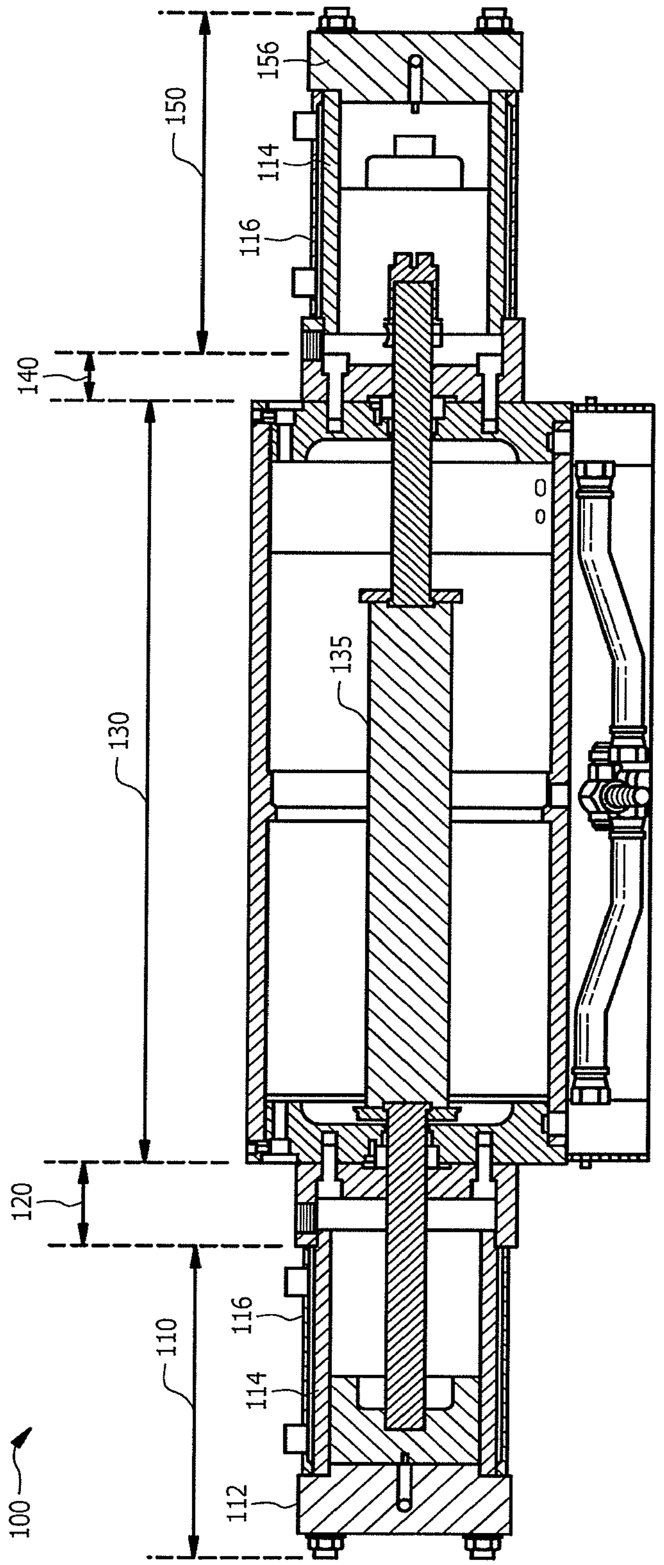

FIG. 1B

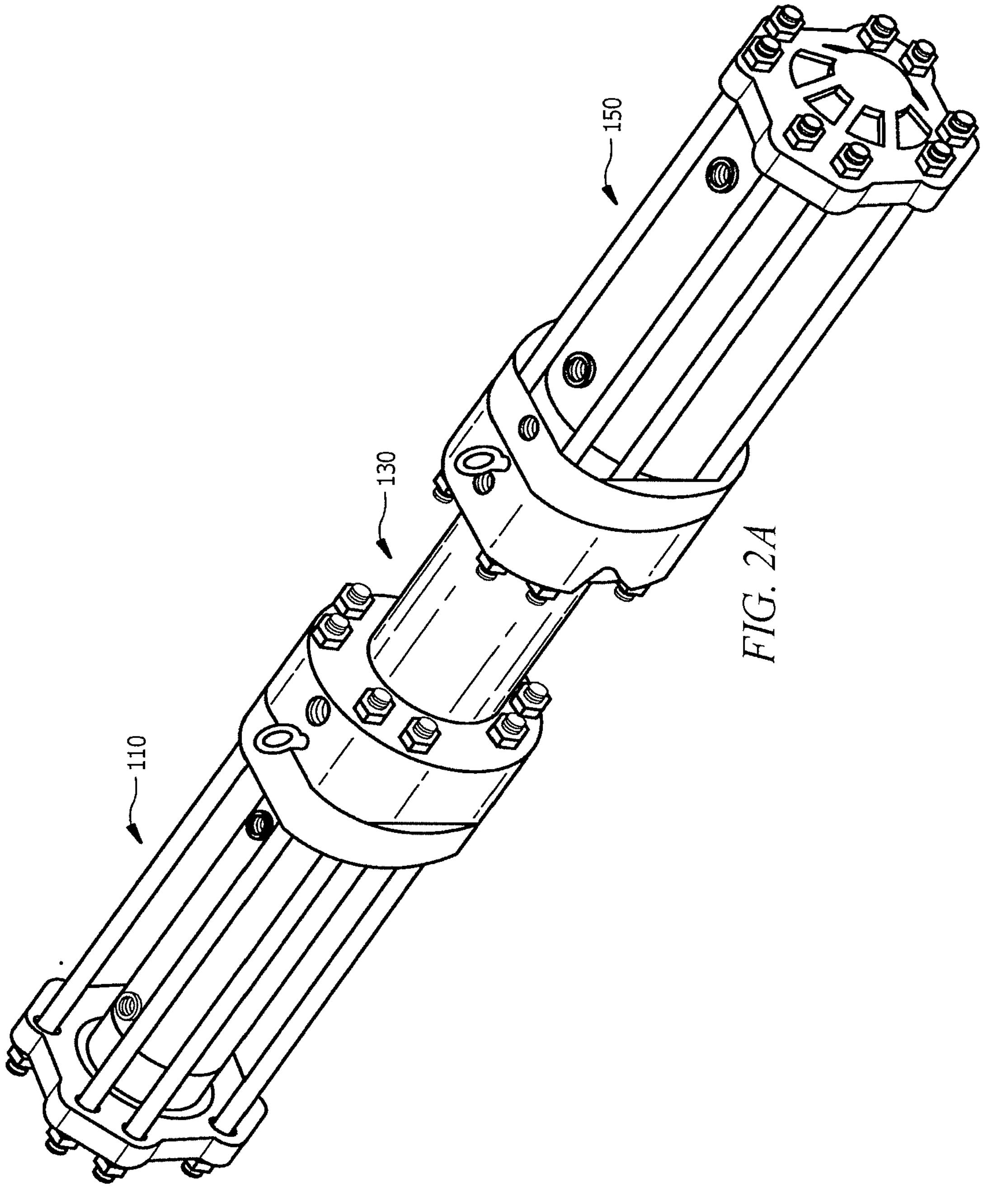

FIG. 2A

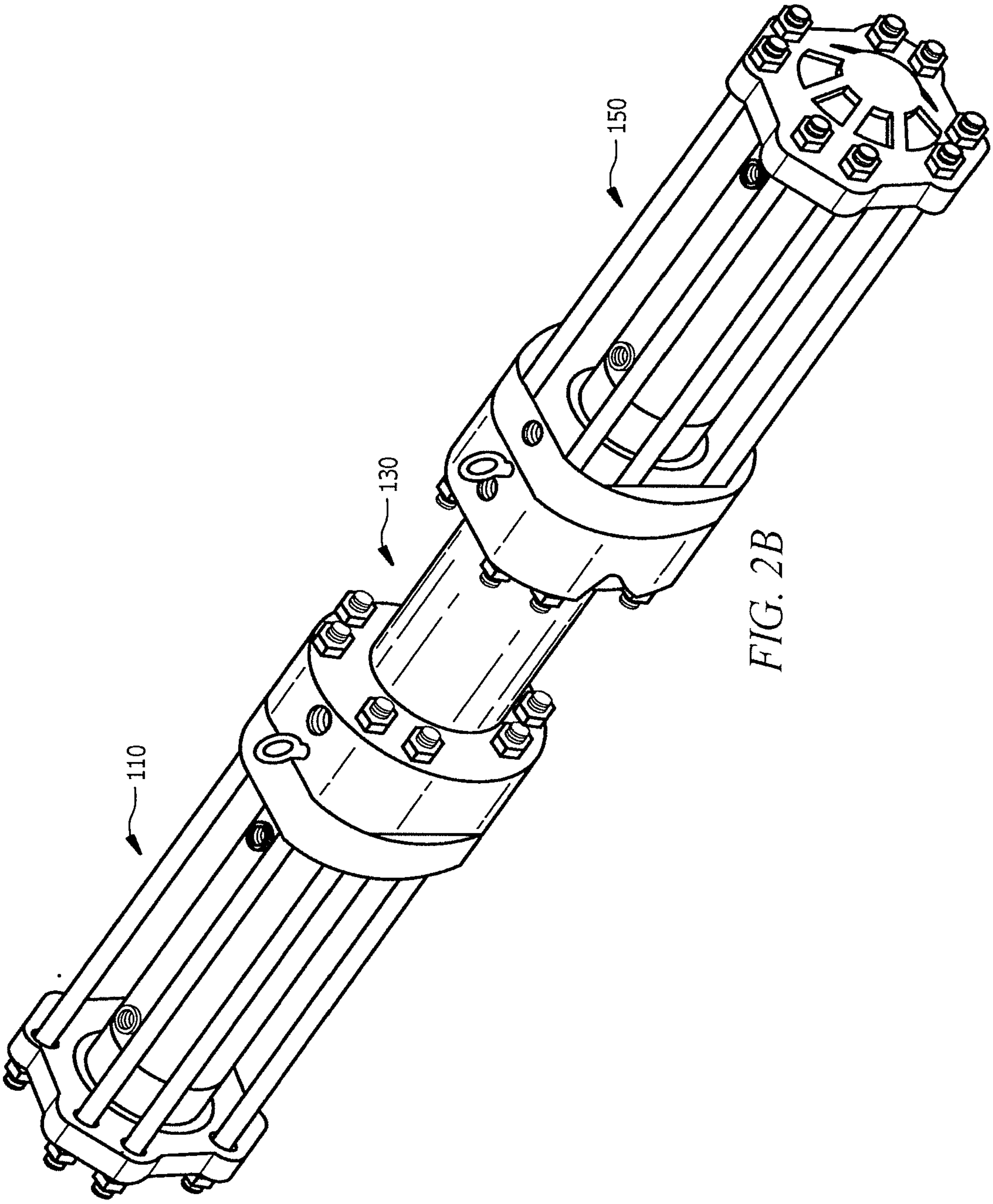

FIG. 2B

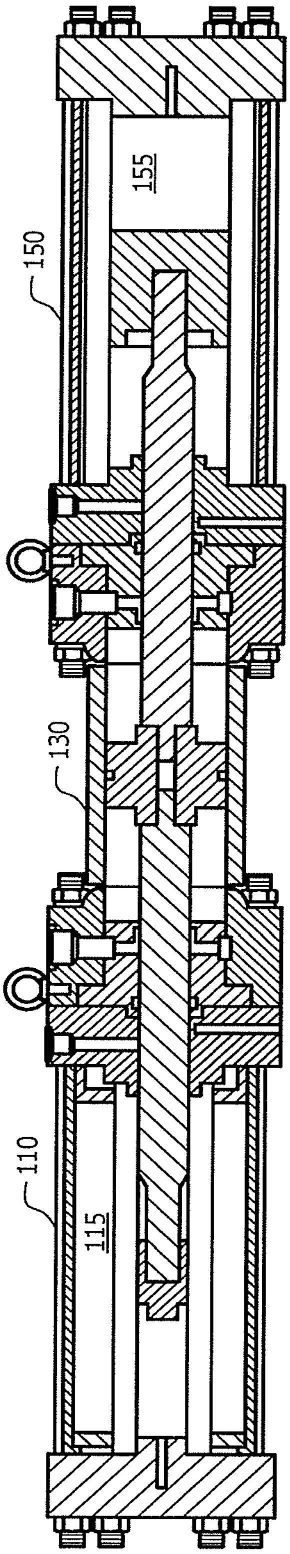

FIG. 3A

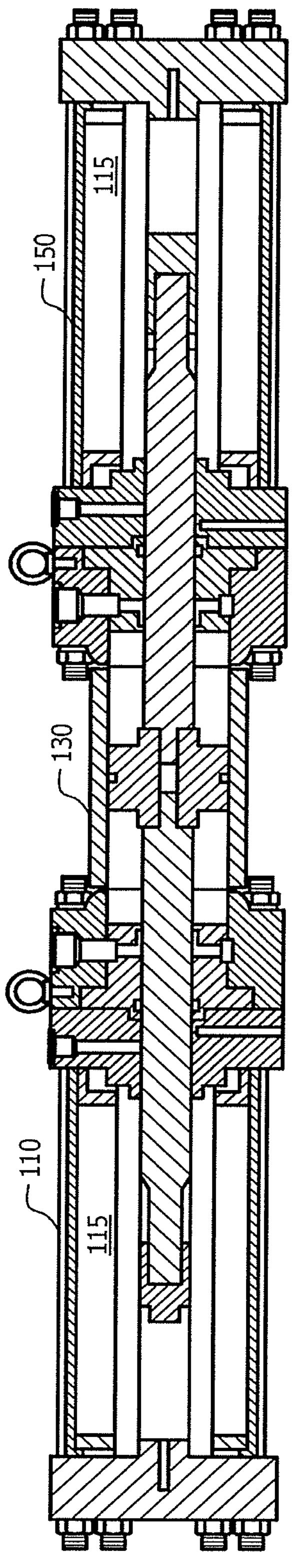

FIG. 3B

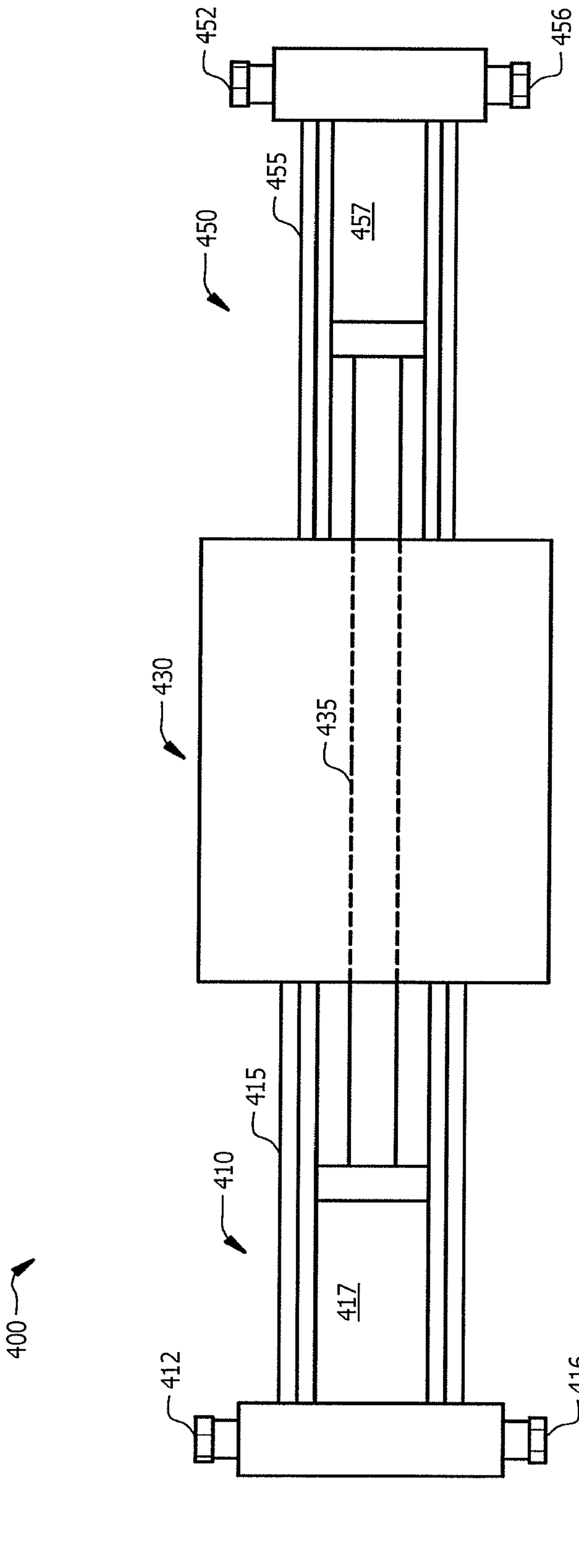

FIG. 4A

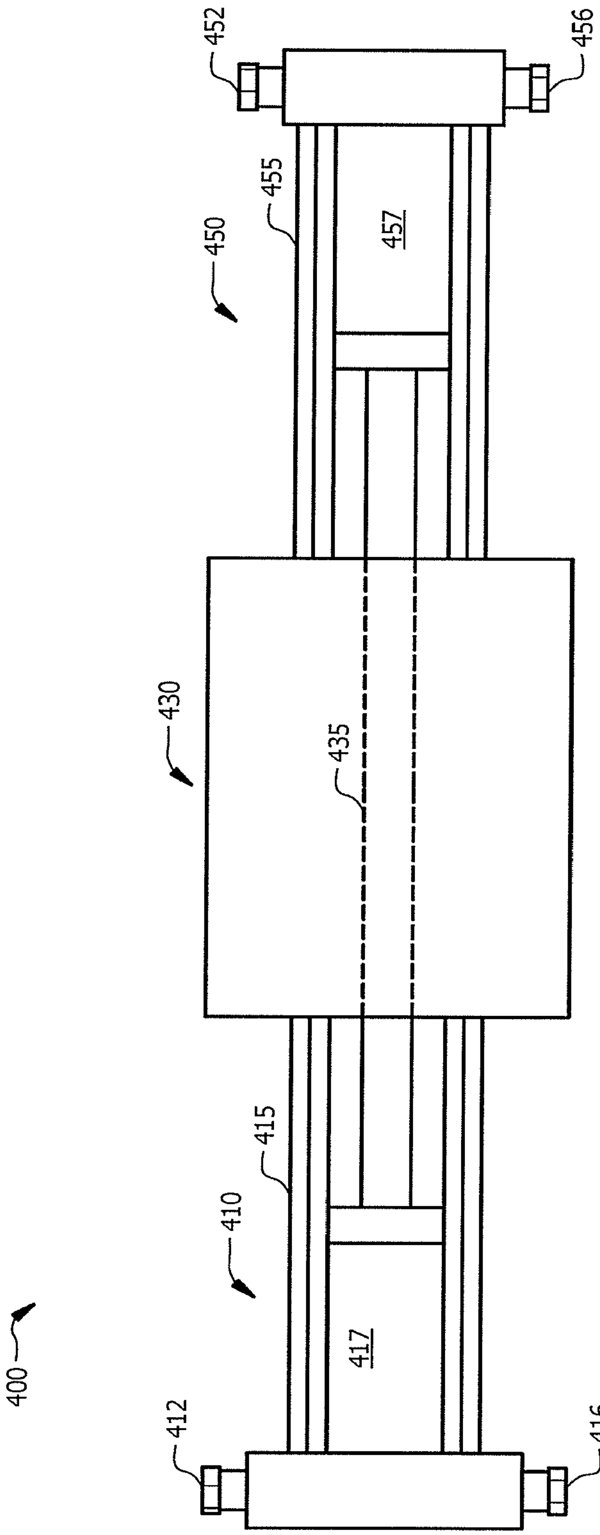

FIG. 4B

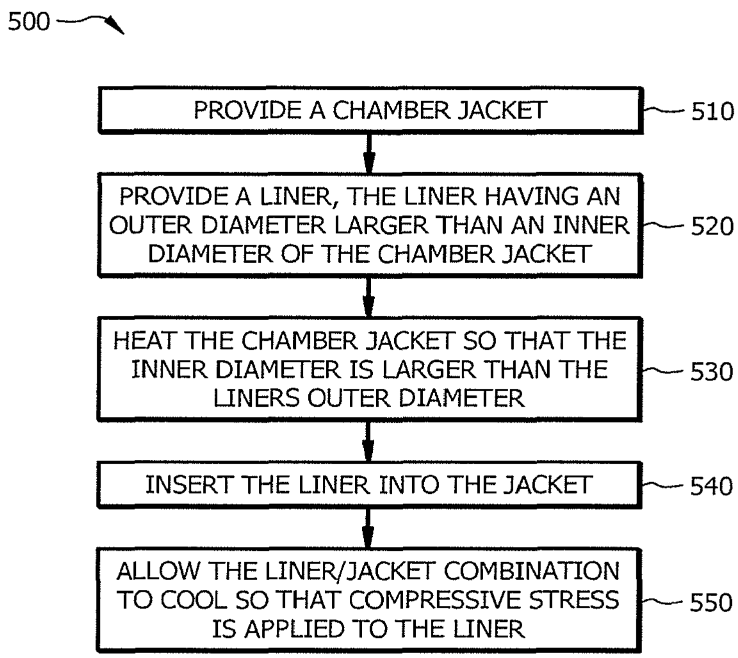
500
PROVIDE A CHAMBER JACKET
510
PROVIDE A LINER, THE LINER HAVING AN OUTER DIAMETER LARGER THAN AN INNER DIAMETER OF THE CHAMBER JACKET
520
HEAT THE CHAMBER JACKET SO THAT THE INNER DIAMETER IS LARGER THAN THE LINERS OUTER DIAMETER
530
INSERT THE LINER INTO THE JACKET
540
ALLOW THE LINER/JACKET COMBINATION TO COOL SO THAT COMPRESSIVE STRESS IS APPLIED TO THE LINER
550

FIG. 5

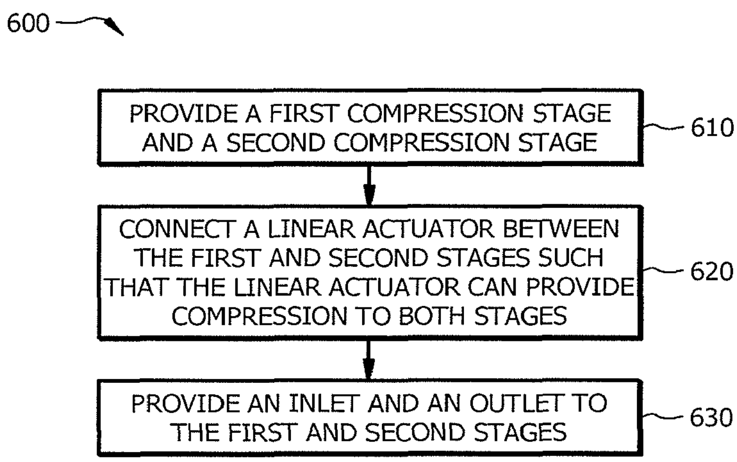
600
PROVIDE A FIRST COMPRESSION STAGE AND A SECOND COMPRESSION STAGE
610
CONNECT A LINEAR ACTUATOR BETWEEN THE FIRST AND SECOND STAGES SUCH THAT THE LINEAR ACTUATOR CAN PROVIDE COMPRESSION TO BOTH STAGES
620
PROVIDE AN INLET AND AN OUTLET TO THE FIRST AND SECOND STAGES
630

FIG. 6

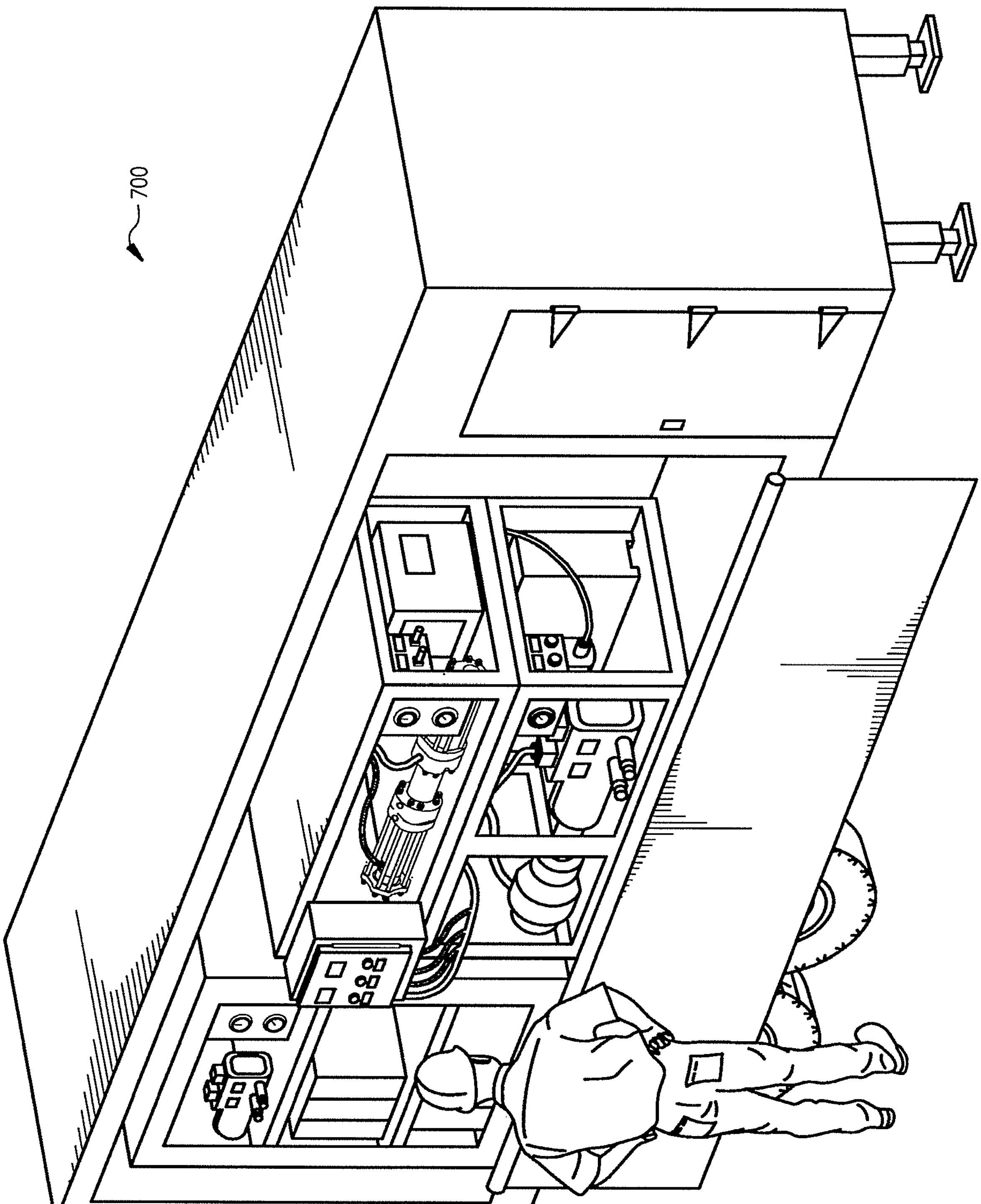

FIG. 7

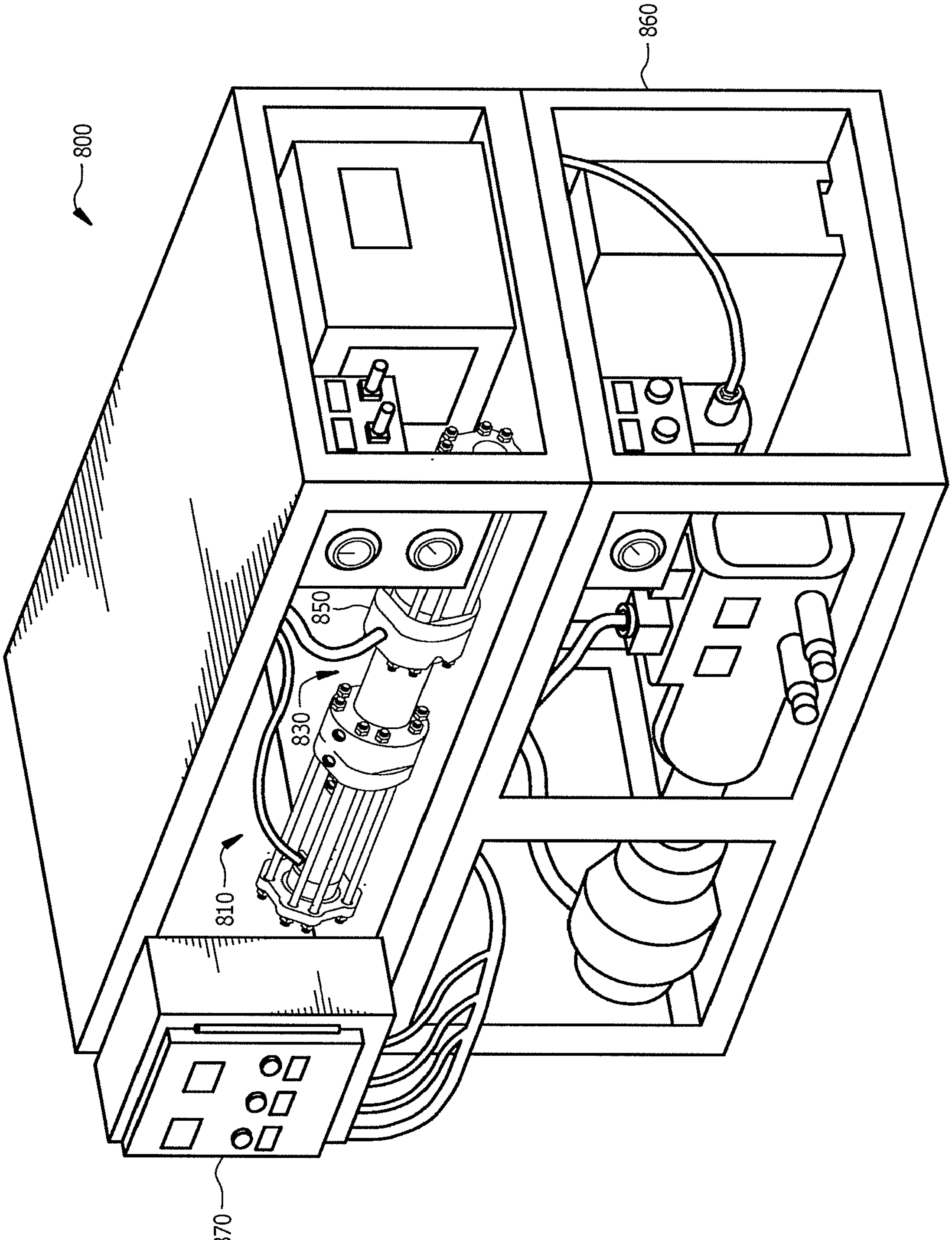

FIG. 8

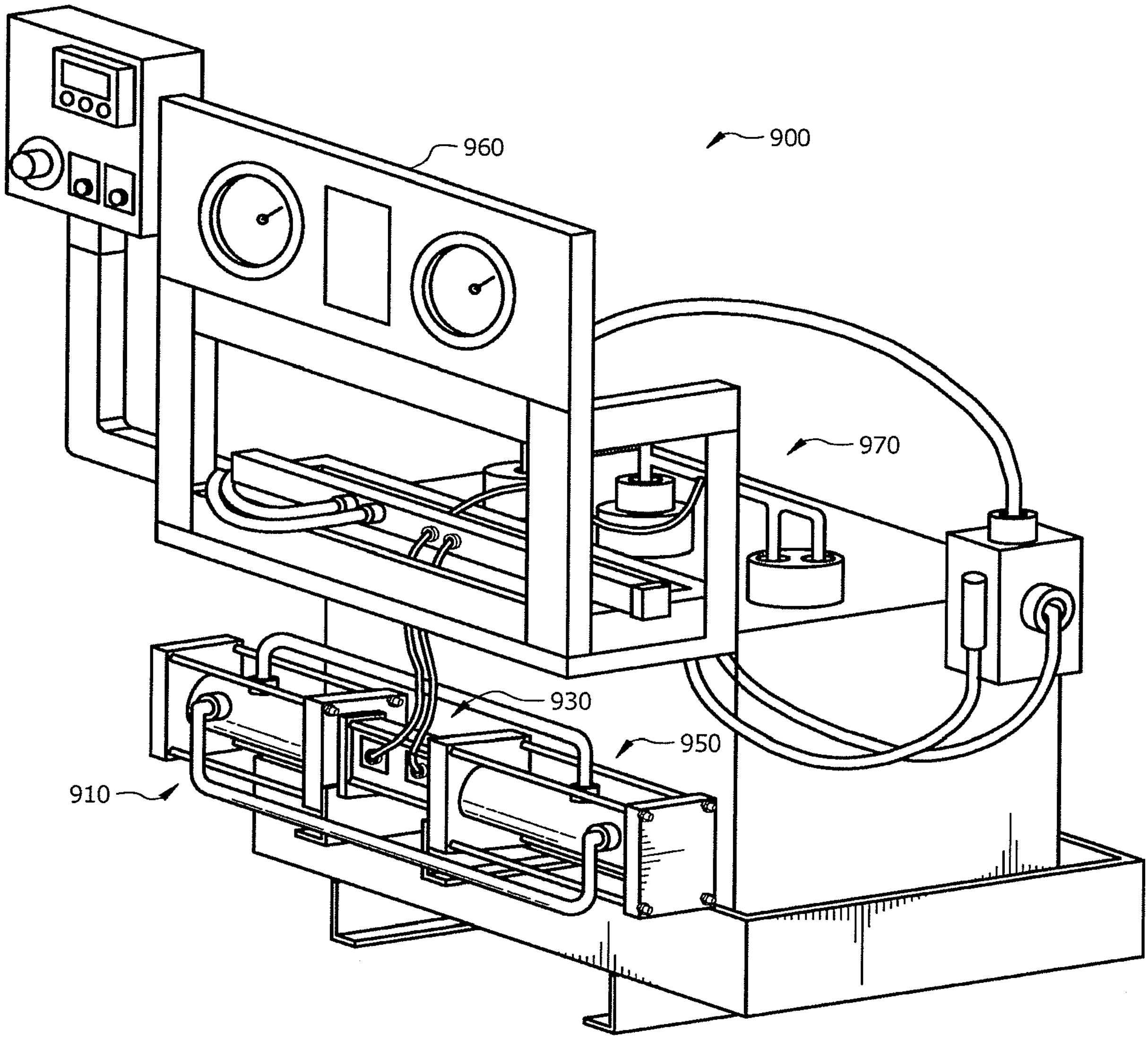

FIG. 9

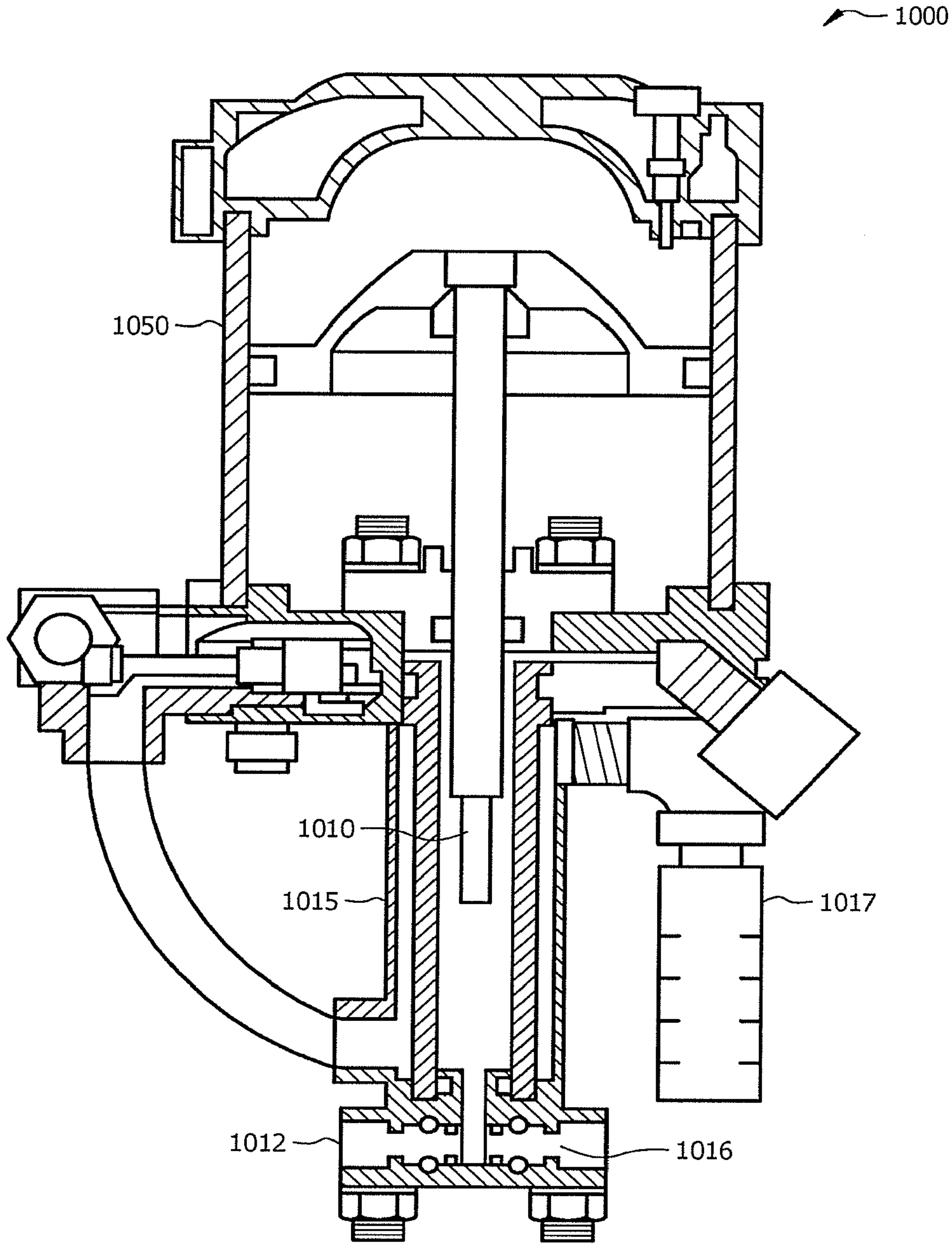

FIG. 10

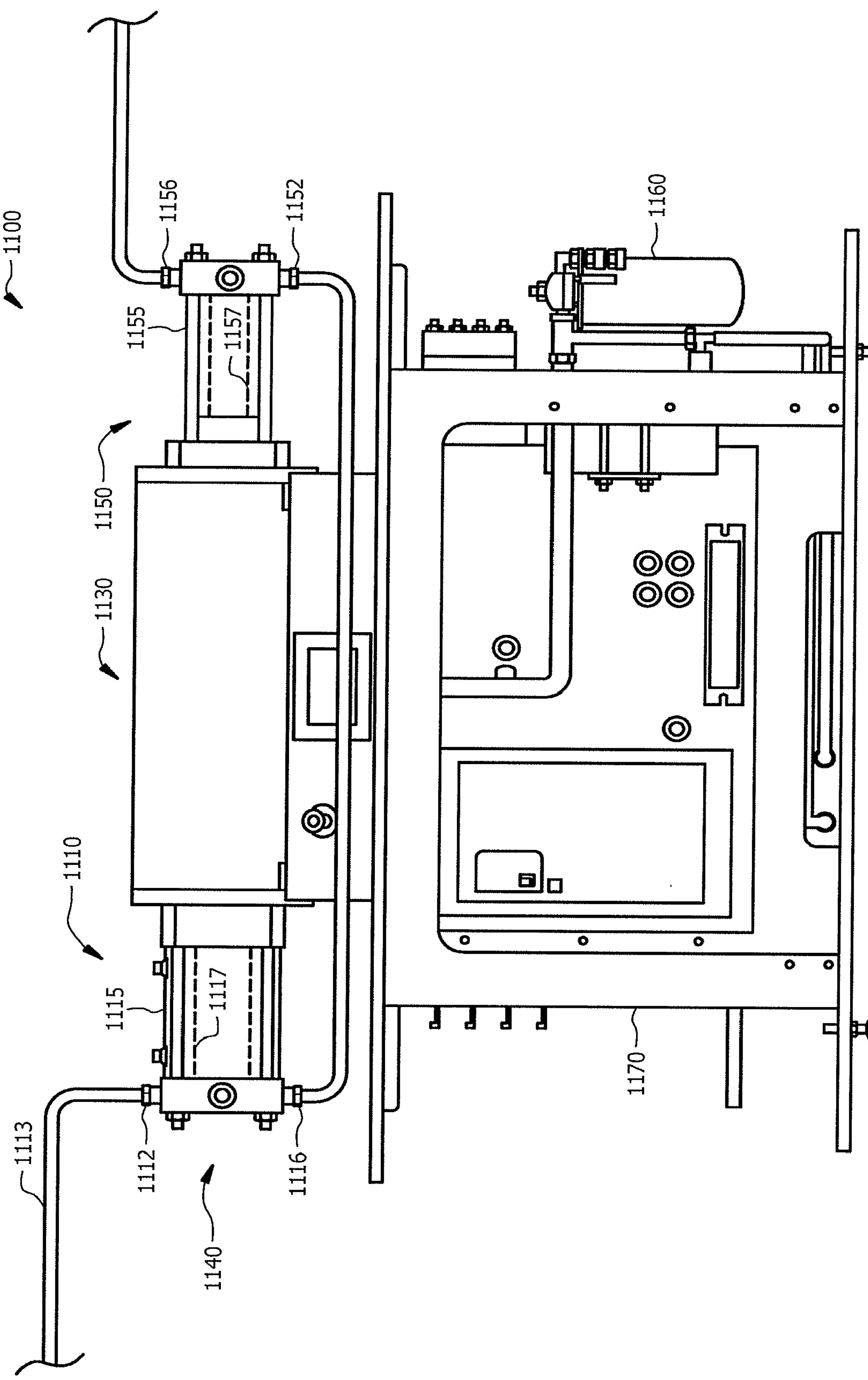
1100
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FIG. 11

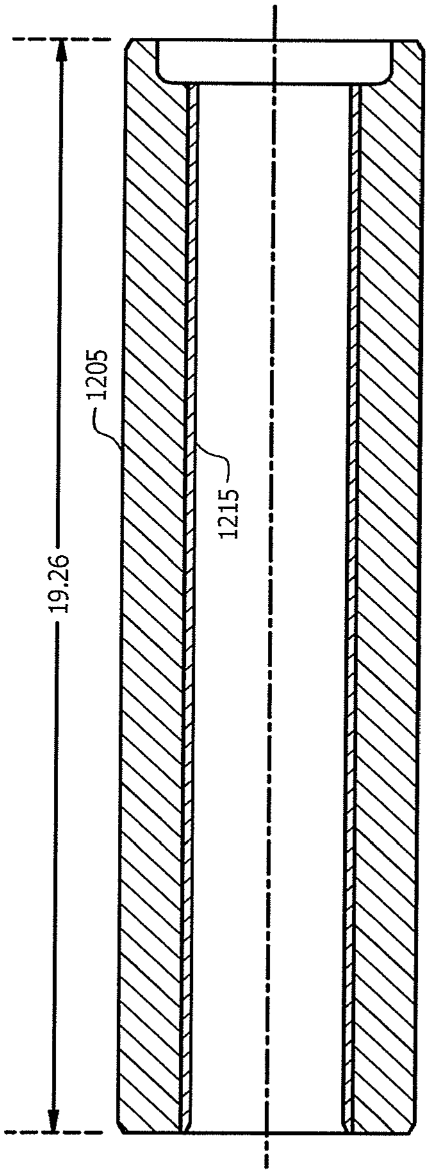

FIG. 12B

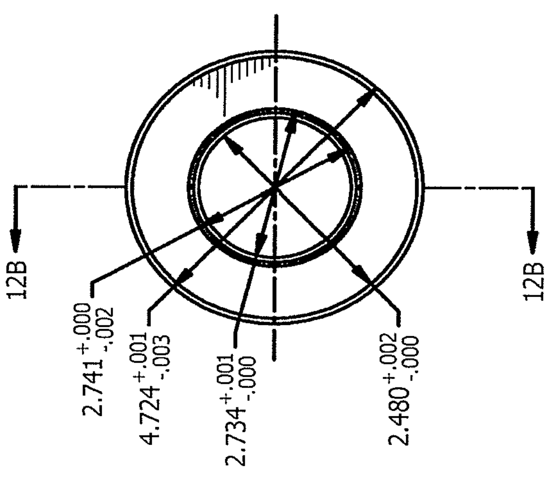

FIG. 12A

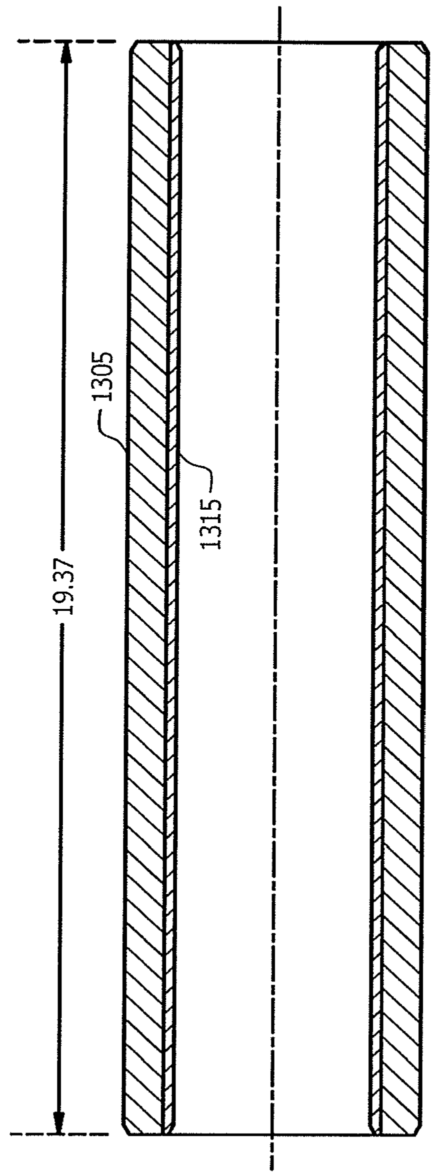

FIG. 13B

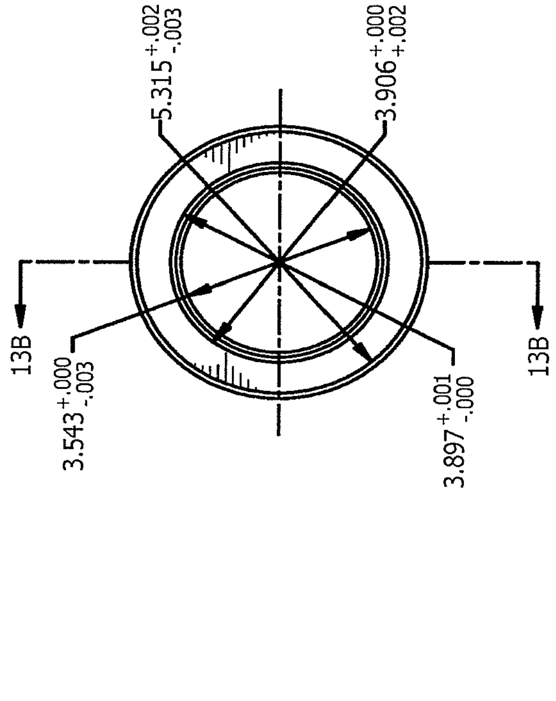

FIG. 13A

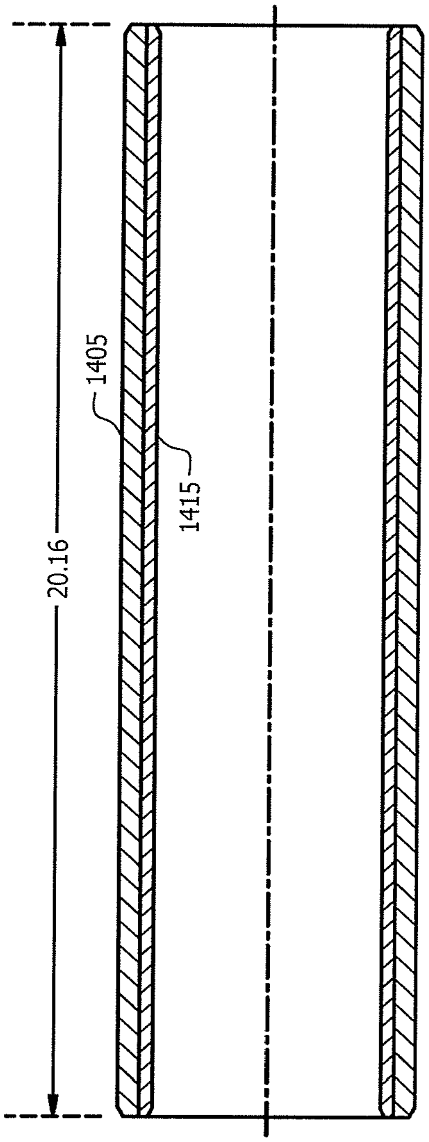

FIG. 14B

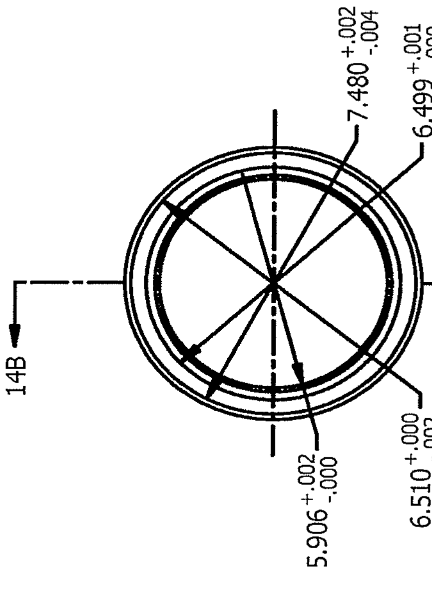

FIG. 14A

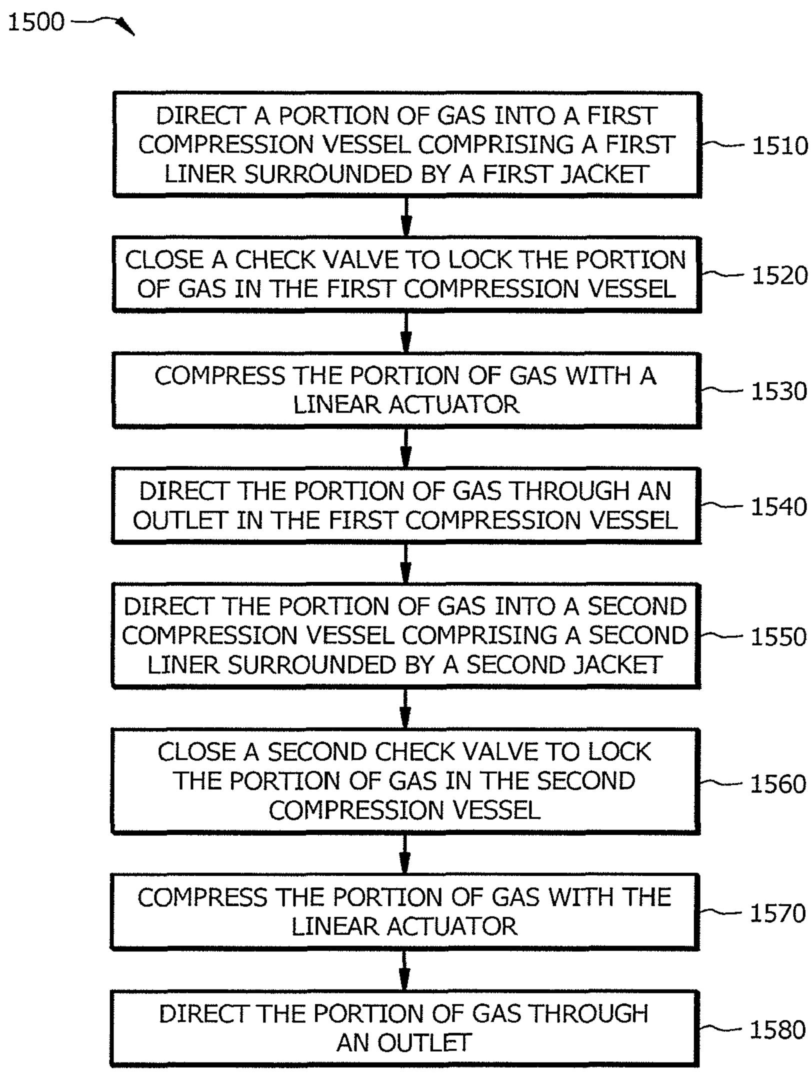
1500
DIRECT A PORTION OF GAS INTO A FIRST COMPRESSION VESSEL COMPRISING A FIRST LINER SURROUNDED BY A FIRST JACKET
1510
CLOSE A CHECK VALVE TO LOCK THE PORTION OF GAS IN THE FIRST COMPRESSION VESSEL
1520
COMPRESS THE PORTION OF GAS WITH A LINEAR ACTUATOR
1530
DIRECT THE PORTION OF GAS THROUGH AN OUTLET IN THE FIRST COMPRESSION VESSEL
1540
DIRECT THE PORTION OF GAS INTO A SECOND COMPRESSION VESSEL COMPRISING A SECOND LINER SURROUNDED BY A SECOND JACKET
1550
CLOSE A SECOND CHECK VALVE TO LOCK THE PORTION OF GAS IN THE SECOND COMPRESSION VESSEL
1560
COMPRESS THE PORTION OF GAS WITH THE LINEAR ACTUATOR
1570
DIRECT THE PORTION OF GAS THROUGH AN OUTLET
1580

FIG. 15

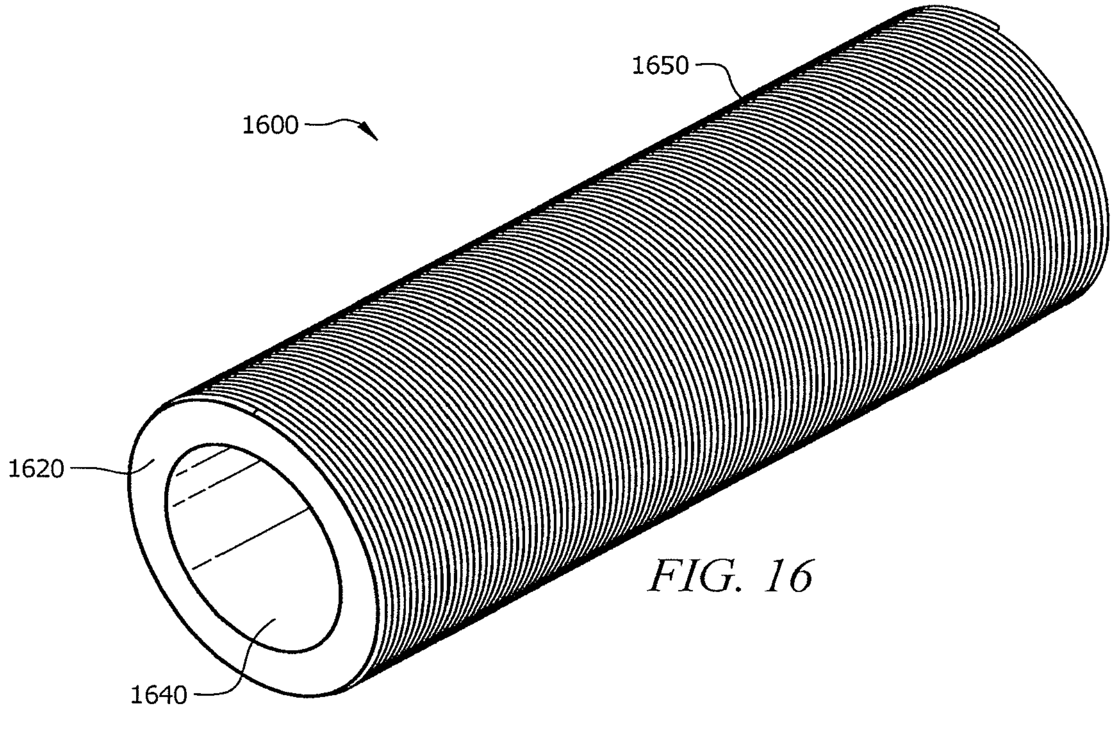

FIG. 16

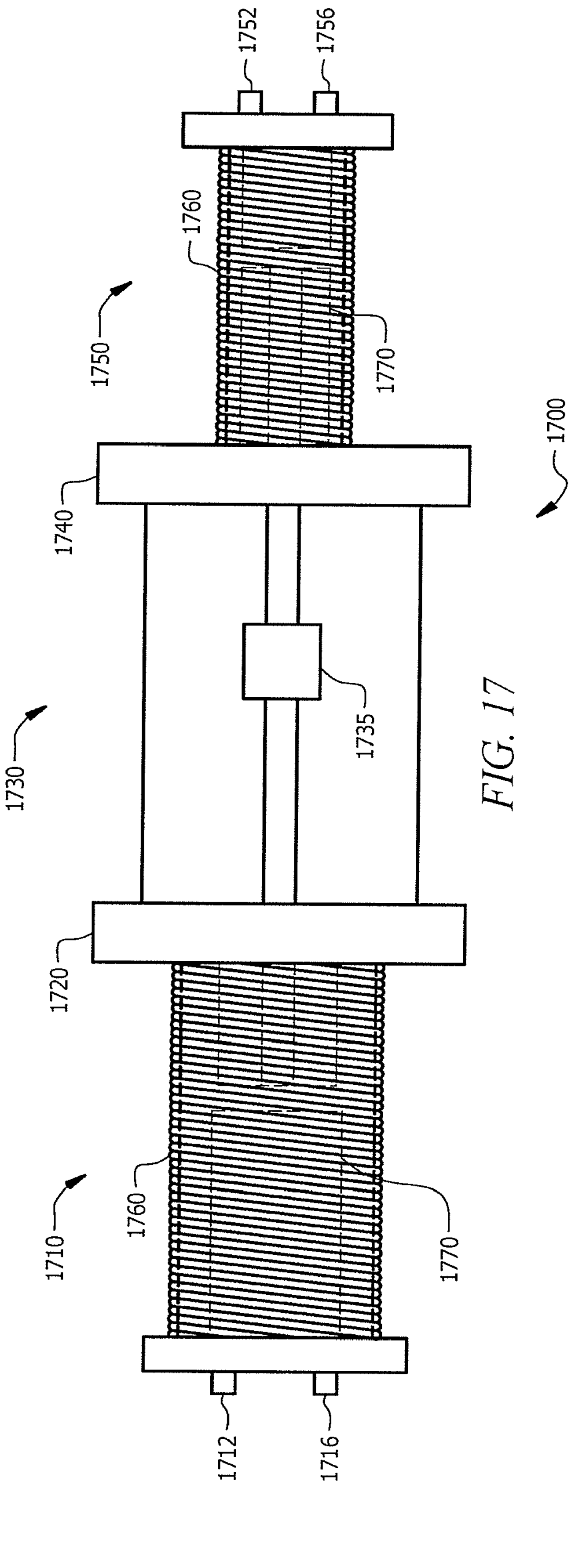
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FIG. 17

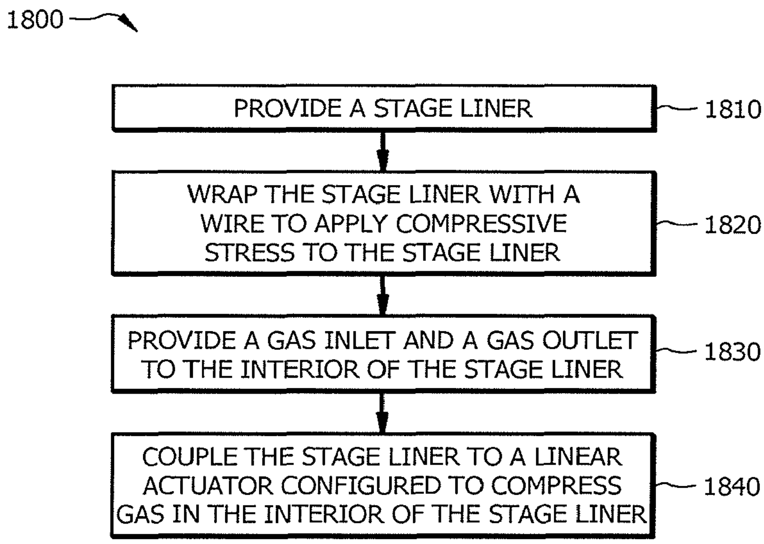
1800
PROVIDE A STAGE LINER
1810
WRAP THE STAGE LINER WITH A WIRE TO APPLY COMPRESSIVE STRESS TO THE STAGE LINER
1820
PROVIDE A GAS INLET AND A GAS OUTLET TO THE INTERIOR OF THE STAGE LINER
1830
COUPLE THE STAGE LINER TO A LINEAR ACTUATOR CONFIGURED TO COMPRESS GAS IN THE INTERIOR OF THE STAGE LINER
1840

FIG. 18

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EUROPEAN SEARCH REPORT

Application Number
EP 18 20 2301

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	DE 10 2015 001366 A1 (LINDE AG [DE]) 4 August 2016 (2016-08-04) * paragraphs [0012] - [0019]; figure 1 *	1-12 2,4, 10-12	INV. F04B37/18 F04B39/12 F04B53/16 F04B9/109 F04B9/113 F04B9/129 F04B9/133
X	US 6 086 338 A (HIGGINS BOBBY L [US]) 11 July 2000 (2000-07-11) * columns 1,2; figure 1 *	1,4,7	
X	DE 22 05 173 A1 (BOSCH GMBH ROBERT) 16 August 1973 (1973-08-16) * page 3, paragraph 3; figure 1 *	1,9	
Y	DE 10 2005 034907 A1 (LINDE AG [DE]) 1 February 2007 (2007-02-01) * paragraphs [0024] - [0029]; figure 1 *	2	
Y	US 2 991 003 A (PETERSEN ROBERT S) 4 July 1961 (1961-07-04) * figure 2 *	2,4, 10-12	TECHNICAL FIELDS SEARCHED (IPC)
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	2 April 2019	Ziegler, Hans-Jürgen

CATEGORY OF CITED DOCUMENTS

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