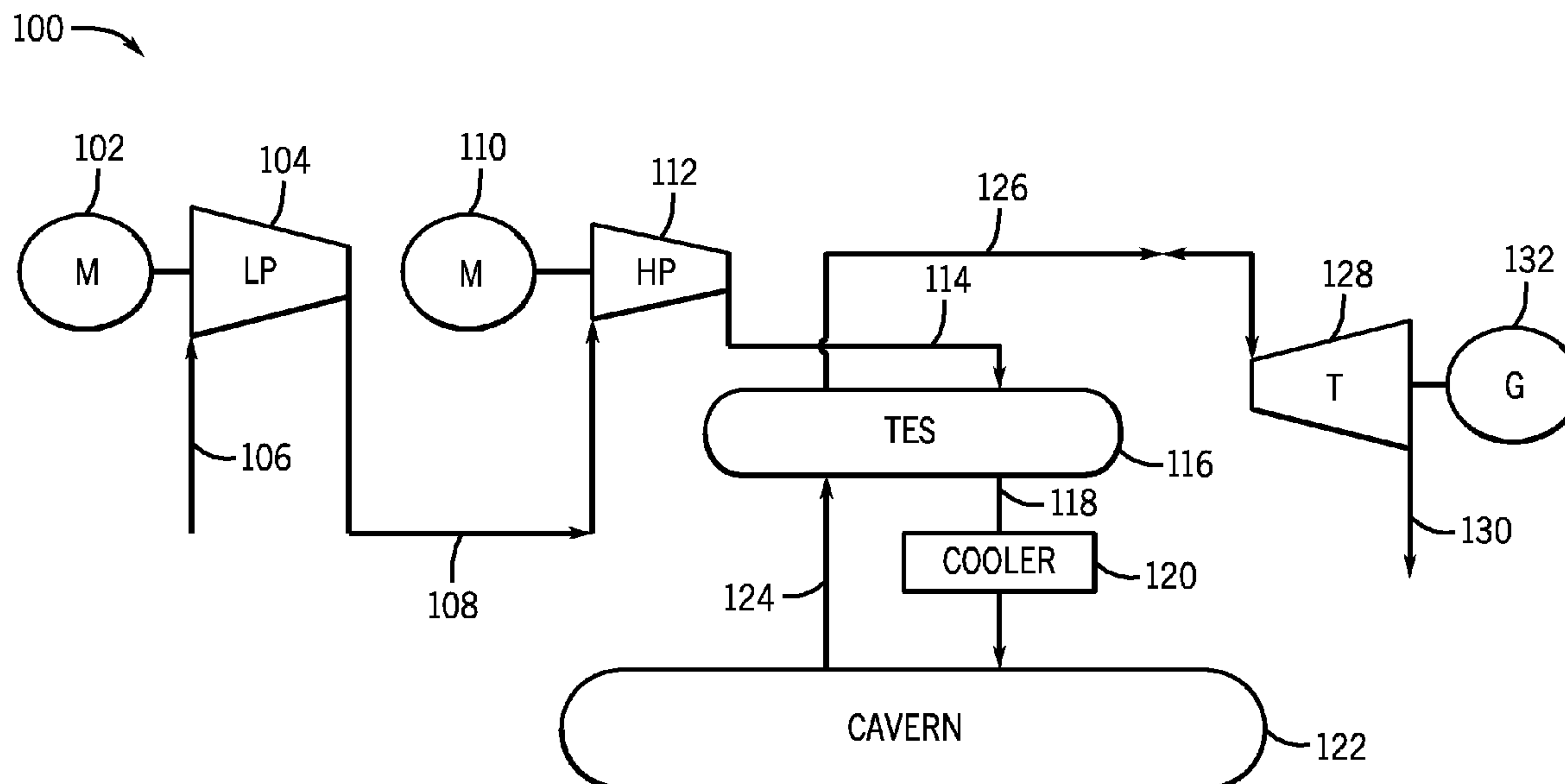


US 20110127004A1

(19) **United States**(12) **Patent Application Publication**
Freund et al.(10) **Pub. No.: US 2011/0127004 A1**(43) **Pub. Date: Jun. 2, 2011**(54) **REGENERATIVE THERMAL ENERGY
STORAGE APPARATUS FOR AN ADIABATIC
COMPRESSED AIR ENERGY STORAGE
SYSTEM****Publication Classification**(51) **Int. Cl.**
F24J 3/08 (2006.01)
(52) **U.S. Cl.** **165/45**(57) **ABSTRACT**

A system and method for a thermal energy storage system is disclosed, the thermal energy storage system comprising a plurality of pressure vessels arranged in close proximity to one another, each of the pressure vessels having a wall comprising an outer surface and an inner surface spaced from the outer surface by a respective wall thickness and surrounding an interior volume of the pressure vessel. The interior volume has a first end in fluid communication with one or more compressors and one or more turbines and a second end in fluid communication with at least one of one or more additional compressors, one or more additional turbines, and at least one compressed air storage component. The thermal energy storage system further comprises a thermal storage medium positioned in the interior volume of each of the plurality of pressure vessels.

(76) **Inventors:** **Sebastian W. Freund**, Unterföhring (DE); **Matthias Finkenrath**, Garching b. München (DE); **Cristina Botero**, Cambridge (DE); **Clarissa S.K. Belloni**, Oxford (DE); **Miguel Angel Gonzalez Salazar**, München (DE); **Stephanie Marie-Noelle Hoffmann**, München (DE)(21) **Appl. No.: 12/627,320**(22) **Filed: Nov. 30, 2009**

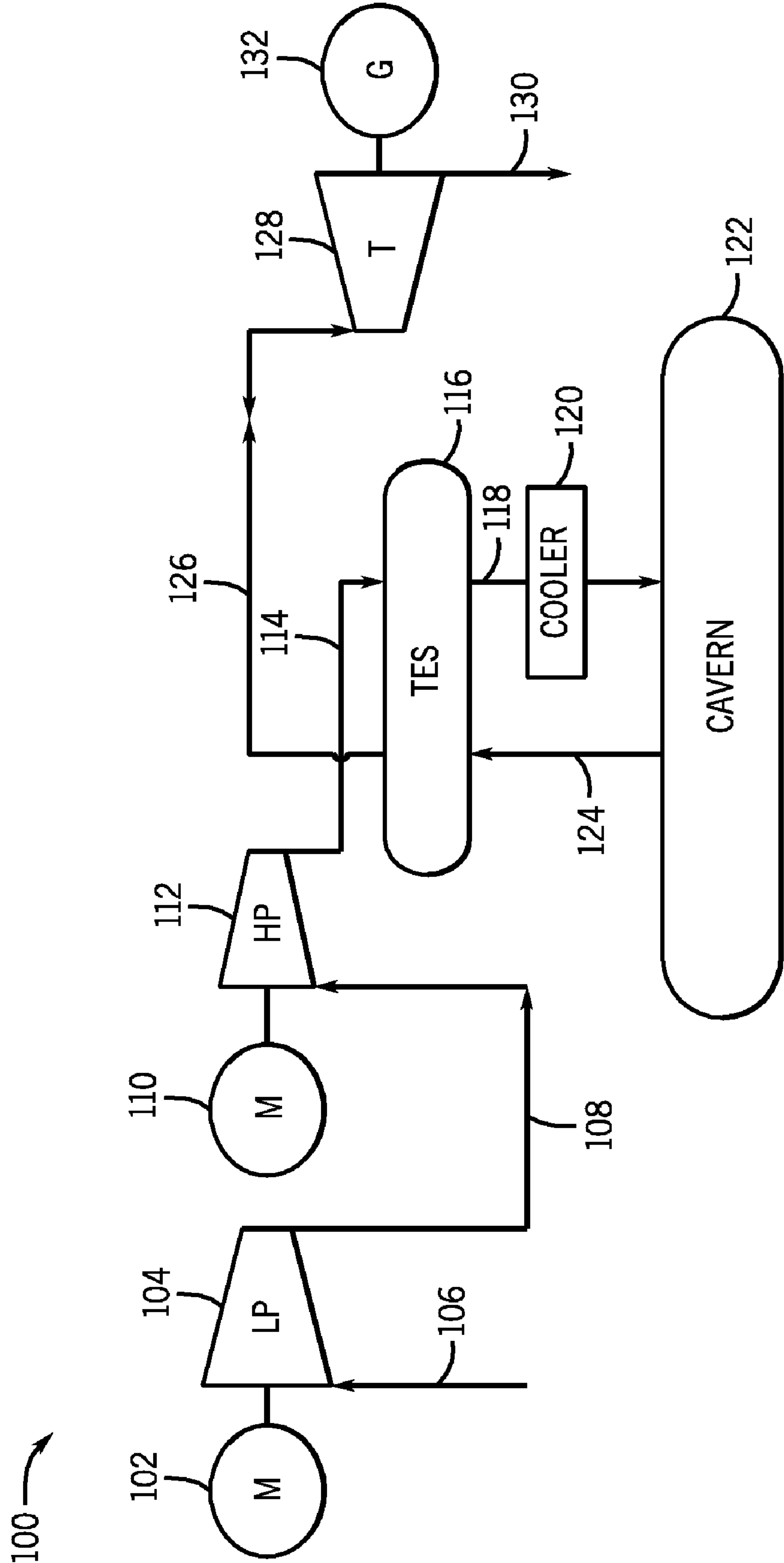
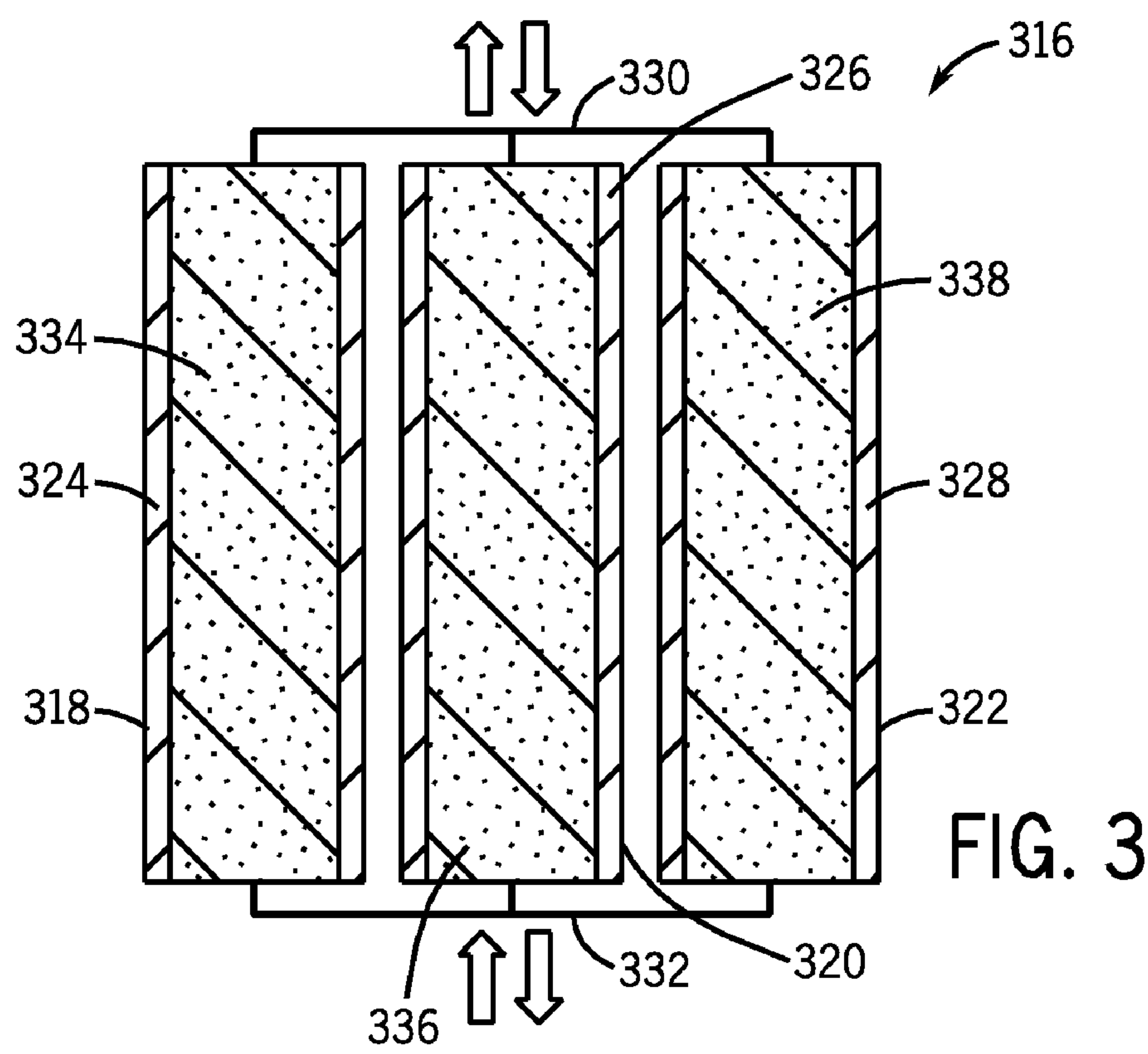
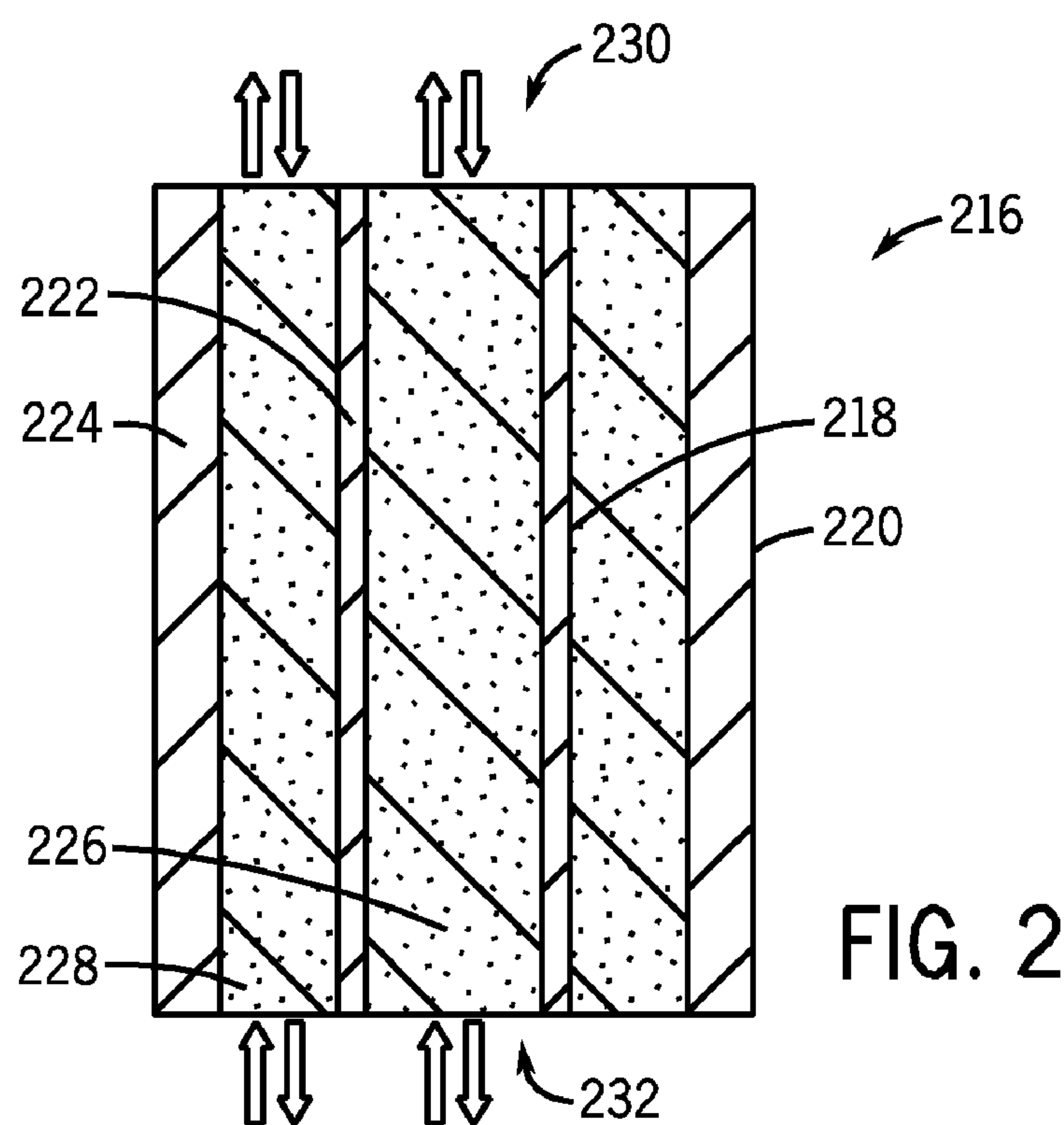


FIG. 1



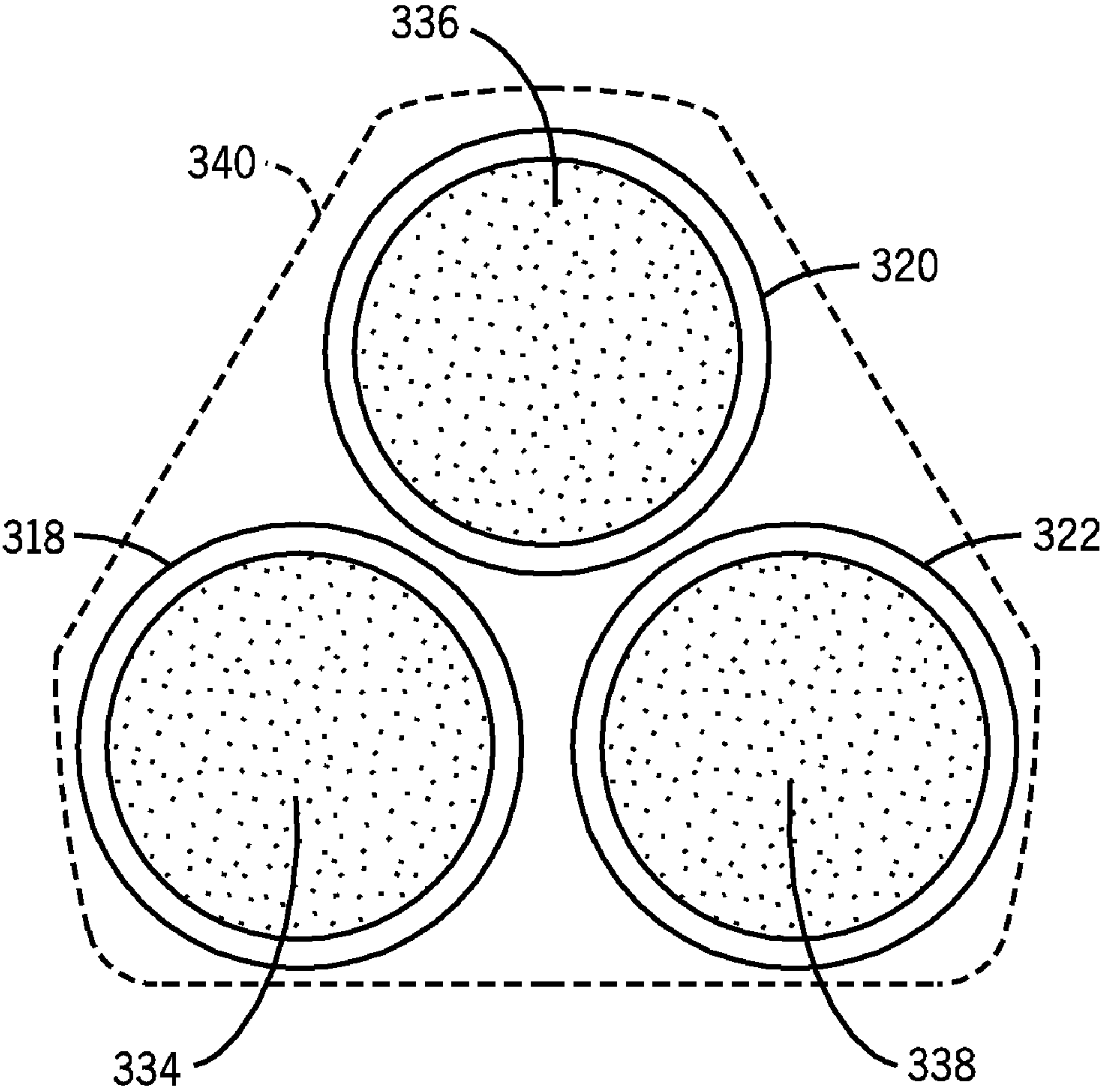
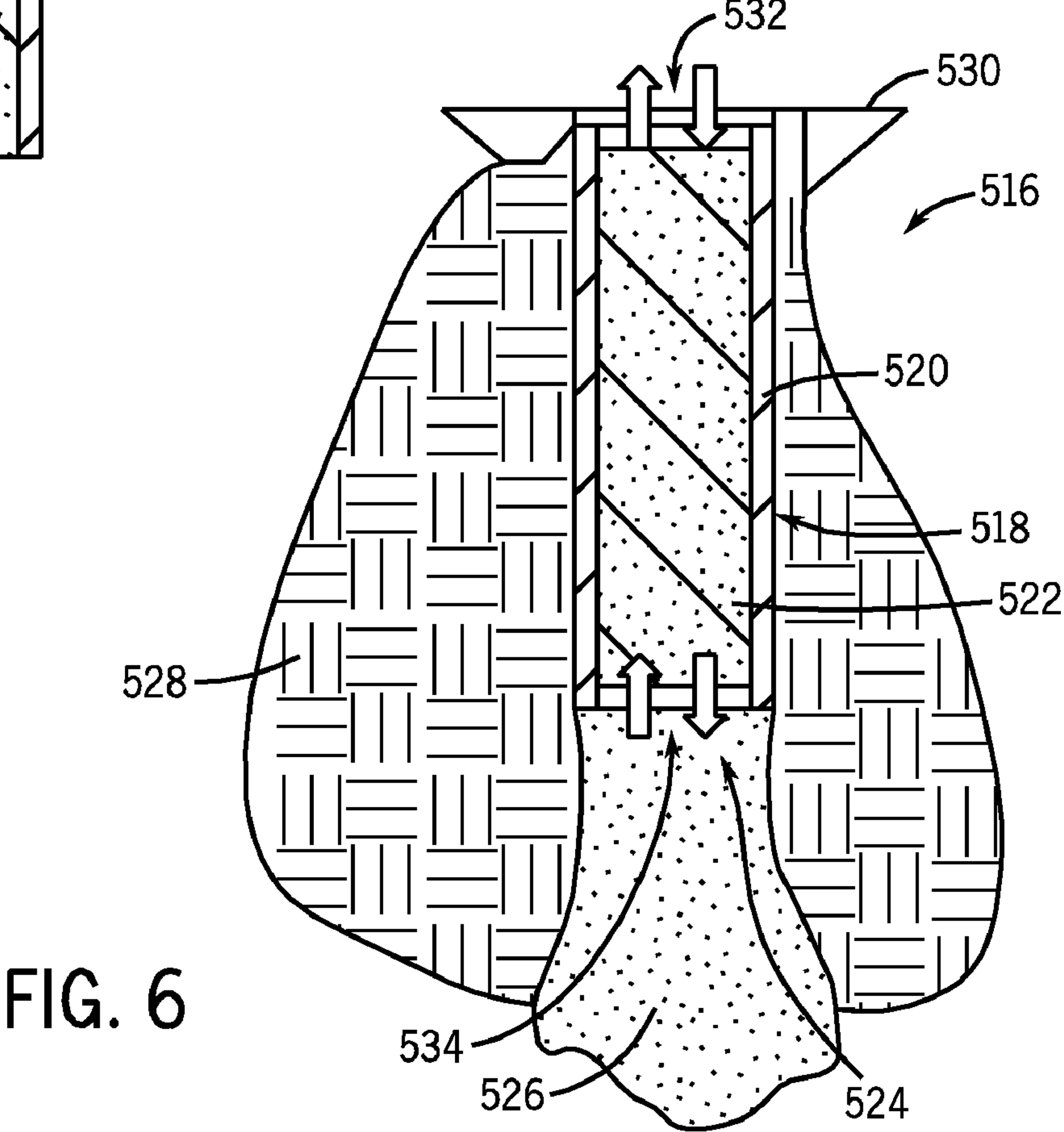
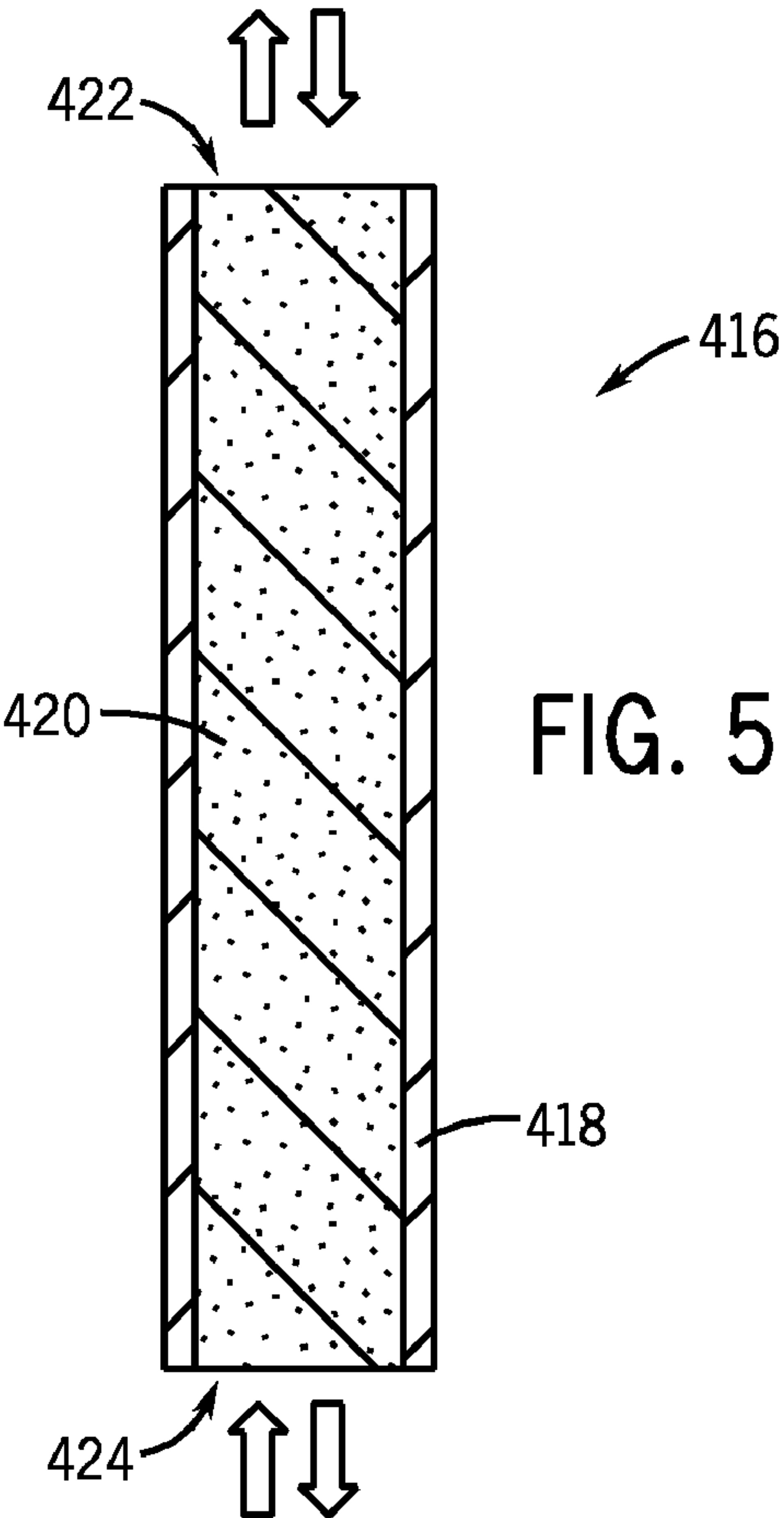


FIG. 4



**REGENERATIVE THERMAL ENERGY
STORAGE APPARATUS FOR AN ADIABATIC
COMPRESSED AIR ENERGY STORAGE
SYSTEM**

BACKGROUND OF THE INVENTION

[0001] Embodiments of the invention relate generally to compressed air energy storage (CAES) systems and, more particularly, to thermal energy storage (TES) systems in an adiabatic CAES system.

[0002] CAES systems allow for the storage of electrical energy without producing substantial emissions and/or consuming vast quantities of natural resources. CAES systems typically include a compression train having one or more compressors. The one or more compressors compress intake air in a compression stage for storage in a cavern, porous rock formation, depleted natural gas/oil field, or other compressed air storage component. The compressed air is then later used to drive turbines to produce electrical energy in an energy generation stage, which can in turn be provided to the utility grid. Often, if utility energy is used to power the compression train during the compression stage, the compression train operates during the off-peak hours of utility plants. The energy generation stage of the CAES in turn typically operates during high power demand times. Alternatively, energy from renewable sources, such as energy from wind turbines or solar panel arrays, may be used to power the compression train during the compression stage to compress and deliver air to the compressed air storage location (e.g., a cavern). In this way, the compression train may be operated during times other than off-peak hours, and existing utility energy may be preserved.

[0003] One type of CAES system is known as a diabatic-CAES system. In a diabatic-CAES system, heat generated by the compression train is typically lost to the ambient environment. That is, the heat of compression may be lost to the ambient in intercoolers and what heat is left when entering the cavern or other compressed air storage component is diminished as the compressed air mixes with the cavern air and further cools to ambient temperature during storage. Thus, when the compressed air stored in the cavern or compressed air storage component is to be used to drive one or more turbines to produce electrical energy, the compressed air is typically reheated prior to entering the turbines. This reheating step is typically performed using a natural gas-fired combustor and a recuperator positioned between the compressed air storage component and the one or more turbines. Due to this reheating step, the overall efficiency of the diabatic-CAES system is reduced, and the use of natural gas to fuel the combustor leads to carbon emissions and natural resource consumption.

[0004] Adiabatic-CAES, or ACAES, systems are capable of improving system efficiency by capturing and storing the heat of compression for later use. In such a system, one or more thermal energy storage (TES) units are positioned between the compressor and the cavern. Typically, a TES unit contains therein a medium for heat storage, such as concrete, stone, a fluid (e.g., oil), a molten salt, or a phase-change material. Hot air from the compression stage is passed through the TES unit, thereby transferring its heat of compression to the medium in the process. Thus, unlike diabatic-CAES systems, ACAES systems do not lose all of the heat generated by the compression train, but instead store some of

the heat within the TES unit or units. The compressed air then enters the cavern at or near ambient temperature.

[0005] When the compressed air stored within the cavern or other compressed air storage unit is to be withdrawn to drive the one or more turbines to produce electrical energy, the compressed air passes back through the TES unit, thereby reheating the compressed air prior to entry into the turbine or turbines. In this way, ACAES systems do not necessitate additional natural gas to reheat the compressed air exiting the cavern or other compressed air storage component. Thus, ACAES systems provide improved efficiency over diabatic-CAES systems, with fewer (if any) carbon emissions and little to no natural resource consumption.

[0006] TES units built to effectively store heat generated during the compression cycle of the compression train are constructed to withstand the high heat fluctuations and high pressure associated with ACAES systems. For example, the compressed air temperature exiting the compression train may vary from 250° C. to 750° C., while the temperature of the compressed air entering the TES unit from the cavern is near ambient temperature. Likewise, the TES units are designed to withstand pressures of 65-85 bar. To withstand such high temperatures and pressures, current proposals for TES units involve the construction of large concrete cylinders filled with a medium for heat storage. Due to their large diameter, these TES units are formed having thick, pre-stressed and steel-reinforced concrete walls, which enable the TES unit to withstand the high tension forces in the wall created by the pressure therein. However, construction of such thick concrete walls leads to substantial engineering difficulties and high costs, thereby reducing the feasibility of implementing an ACAES system as opposed to a less efficient diabatic-CAES system. Furthermore, high operating temperatures and temperature cycles induce damaging thermal stresses into the concrete walls, and these stresses are amplified as the concrete walls grow thicker.

[0007] Therefore, it would be desirable to design an apparatus and method that overcomes the aforementioned drawbacks related to TES unit construction.

BRIEF DESCRIPTION OF THE INVENTION

[0008] Aspects of the invention provide a system and method for a TES system having at least one TES unit configured to withstand high temperatures and pressures. The at least one TES unit is constructed and arranged such that the wall of the at least one TES unit has a minimal thickness.

[0009] In accordance with one aspect of the invention, a thermal energy storage system is disclosed, the thermal energy storage system comprising a plurality of pressure vessels arranged in close proximity to one another, each of the pressure vessels having a wall comprising an outer surface and an inner surface spaced from the outer surface by a respective wall thickness and surrounding an interior volume of the pressure vessel. The interior volume has a first end in fluid communication with one or more compressors and one or more turbines and a second end in fluid communication with at least one of one or more additional compressors, one or more additional turbines, and at least one compressed air storage component. The thermal energy storage system further comprises a thermal storage medium positioned in the interior volume of each of the plurality of pressure vessels.

[0010] In accordance with another aspect of the invention, a method of forming a thermal energy storage system is disclosed, the method comprising forming a first pressure

vessel, the first pressure vessel having a wall constructed to have a predetermined height and thickness, wherein an inner surface of the wall of the first pressure vessel bounds an interior volume therein, and forming a second pressure vessel, the second pressure vessel constructed to have a wall of predetermined height and thickness, wherein an inner surface of the wall of the second pressure vessel bounds an interior volume therein. The method further comprises disposing a porous thermal storage medium within the interior volume of each of the first and second pressure vessels, and arranging the first pressure vessel and the second pressure vessel in close proximity to one another. Also, the method comprises connecting a first end of each of the first and second pressure vessels to one or more compressors and to one or more turbines such that each of the first and second pressure vessels is in fluid communication with the one or more compressors and the one or more turbines, and connecting a second end of each of the first and second pressure vessels to at least one of one or more additional compressors, one or more additional turbines, and one or more compressed air storage components such that each of the first and second pressure vessels is in fluid communication with at least one of the one or more additional compressors, the one or more additional turbines, and the one or more compressed air storage components.

[0011] In accordance with yet another aspect of the invention, a thermal energy storage apparatus is disclosed, the thermal energy storage apparatus comprising a first concrete cylindrical wall bounding a first interior volume and a second concrete cylindrical wall bounding a second interior volume, wherein the second concrete cylindrical wall is arranged within the first interior volume of the first concrete cylindrical wall such that the first concrete cylindrical wall and the second concrete cylindrical wall are coaxial. The thermal energy storage apparatus further comprises a porous thermal matrix material disposed within the first interior volume of the first concrete cylindrical wall and within the second interior volume of the second concrete cylindrical wall.

[0012] Various other features and advantages will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The drawings illustrate preferred embodiments presently contemplated for carrying out the invention.

[0014] In the drawings:

[0015] FIG. 1 is a schematic arrangement of an ACAES system according to an embodiment of the present invention.

[0016] FIG. 2 is a cross-sectional view of a TES system in accordance with an embodiment of the present invention.

[0017] FIG. 3 is a cross-sectional view of a TES system in accordance with another embodiment of the present invention.

[0018] FIG. 4 is a plan view of a TES system in accordance with the embodiment of FIG. 3.

[0019] FIG. 5 is a cross-sectional view of a TES system in accordance with another embodiment of the present invention.

[0020] FIG. 6 is a cross-sectional view of a TES system placed within the shaft of a cavern in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION

[0021] According to embodiments of the invention, a system is provided that comprises at least one TES unit config-

ured to allow the at least one TES unit to withstand high pressure and temperature fluctuations while maintaining minimal wall thickness.

[0022] First, referring to FIG. 1, a schematic arrangement of the primary elements of an ACAES system is shown. ACAES system 100 comprises an electric motor 102 coupled to a low-pressure compressor 104. Electric motor 102 may be electrically powered via conventional means, i.e., the utility grid, during off-peak utility hours. Alternatively, electric motor 102 may be powered by electricity provided via wind farms, solar arrays, or other renewable sources. Electric motor 102 powers low-pressure compressor 104 such that low-pressure compressor 104 pressurizes intake air 106. Pressurized air 108 from low-pressure compressor 104 is then provided to a high-pressure compressor 112 to enable the air to undergo further compression. Similar to low-pressure compressor 104, high-pressure compressor 112 is powered by an electric motor 110. Electric motor 110 may also be powered by the utility grid or by renewable sources such as wind farms and solar arrays. While ACAES system 100 shows the use of two compressors in a "compression train", it is to be understood that more or fewer compressors could be used.

[0023] As the air passes through respective low-pressure compressor 104 and high-pressure compressor 112, the air is pressurized to a level of 65-85 bar and subsequently heated to a temperature of up to 650° C. This pressurized, heated air 114 then enters at least one thermal energy storage (TES) unit 116. The at least one TES unit 116 typically includes a porous thermal storage medium disposed therein, the porous thermal storage medium capable of retaining a substantial amount of the heat emitted by air 114 as it passes through the at least one TES unit 116. The porous thermal storage medium may be a variety of solid materials, such as natural stone (e.g., split rocks and/or pebbles), ceramics, concrete, cast iron, or a combination of ceramics and salt. Alternatively, the porous thermal storage medium may be a liquid material, such as a combination of nitrate salt and mineral oil. However, the advantage of using naturally occurring thermal storage medium materials such as split rocks and/or pebbles is that material costs can be greatly lowered, and manufacturing/transport energy can be saved, given that such naturally occurring materials are readily available. If natural stone is to be used as the porous thermal storage medium, the split rocks and/or pebbles should be of a suitable size to have a high surface-to-volume ratio and temperature resistance.

[0024] After heated air 114 passes through the at least one TES unit 116, compressed air 118 exits the at least one TES unit 116 at a lowered temperature to enable compressed air 118 to be stored in a cavern 122 or other compressed air storage component. Prior to entering cavern 122, though, compressed air 118 may need to be further cooled by an optional intercooler 120 such that compressed air 118 enters cavern 122 at a maximum temperature of approximately 50° C., for example. Cavern 122 enables air pressurized to a level of about 60-80 bar to be stored for an extended period of time without significant compression losses.

[0025] Referring still to FIG. 1, compressed air 124 may be discharged from cavern 122 when use of the stored air is desired for the generation of electricity. Compressed air 124 exits cavern 122 and re-enters the at least one TES unit 116 at a temperature of approximately 20-50° C. As the compressed air passes through the porous thermal storage medium of the at least one TES unit 116, it is reheated to a temperature of up

to 600° C., a temperature near that of heated air **114** previously discharged from high-pressure compressor **112**. This reheated compressed air **126**, which at this stage is pressurized to a level of about 55-75 bars, then enters a turbine **128**, which is powered by reheated compressed air **126**. More than one turbine **128** could be used, forming an “expansion train”. Unlike diabatic-CAES systems, compressed air **126** has been reheated within the at least one TES unit **116**, and thus there is no need for additional heat recuperation or gas firing at the steam turbine to reheat the compressed air. As turbine **128** operates, exhaust air **130** is discharged therefrom, and steam turbine **128** powers an electrical generator **132**. Electrical energy generated by generator **132** may then be provided to the utility grid for consumption. As can readily be appreciated, ACAES system **100** represents a method of generating electricity that can greatly reduce, if not eliminate, natural resource consumption and/or carbon emissions in the production of electrical energy.

[0026] Alternatively, in what is known as multi-stage ACAES systems, more than one TES unit **116** may be utilized such that only one TES unit is fluidly connected to a cavern or other compressed air storage component, while one or more intermediate TES units are disposed between the compression and/or expansion trains and the TES unit fluidly connected to the compressed air storage component. Instead of being fluidly connected to the one or more compressors and one or more turbines at one end and a compressed air storage component at another end, these intermediate TES units are fluidly connected to the one or more compressors and one or more turbines at each end thereof.

[0027] As discussed above with respect to FIG. 1, the at least one TES unit **116** may be subjected to significant pressures (65-85 bar) and temperatures (up to 650° C.) during operation of ACAES system **100**. As a result, the at least one TES unit **116** should be constructed to withstand such high pressure and temperature levels. Referring to FIG. 2, a TES system **216** in accordance with an embodiment of the invention is shown. It is to be understood that TES system **216** may be used as the at least one TES unit **116** shown in FIG. 1, whereby TES system **216** is capable of withstanding the significant pressures and temperatures associated with operation of an ACAES system.

[0028] FIG. 2 illustrates a cross-sectional view of TES system **216**. TES system **216** comprises two separate coaxial cylindrical pressure vessels **218**, **220**. Pressure vessel **218** comprises a wall **222** having a predetermined length and diameter, wherein the length of wall **222** may range from 10-30 m, while the diameter may range from 3-6 m. However, pressure vessel **218** is not limited to such length and diameter ranges, and may be larger or smaller in both length and diameter. On the other hand, pressure vessel **220** comprises a wall **224** having a predetermined length and diameter, wherein the length of wall **224** may range from 10-30 m and the diameter may range from 5-12 m. As with pressure vessel **218**, though, the length and diameter of pressure vessel **220** are not limited to the above ranges. Pressure vessels **218**, **220** are generally formed using reinforced concrete, but may be formed using any suitable material, including steel. Also, pressure vessels **218**, **220** are not limited to being cylindrical in shape, but could be formed having any suitable shape.

[0029] As is clearly illustrated in FIG. 2, pressure vessel **218** is disposed within the confines of an interior volume of pressure vessel **220**. An interior volume of pressure vessel **218** contains therein a porous thermal storage medium **226**,

while an interior volume of pressure vessel **220** contains therein a porous thermal storage medium **228**. Porous thermal storage media **226**, **228** may be composed of the same thermal storage material or, alternatively, could be composed of different thermal storage materials.

[0030] As similarly discussed above with respect to FIG. 1, TES system **216** is configured to receive compressed air from at least one compressor, whereby the compressed air enters the respective pressure vessels **218**, **220** at a first end **230** and exits respective pressure vessels **218**, **220** at a second end **232** such that the compressed air is capable of being stored in a compressed air storage unit or, alternatively, can be provided to additional compressors and/or turbines (in the case of a multi-stage ACAES system). Heat from the compressed air received from the at least one compressor may be stored in the respective porous thermal storage media **226**, **228**. In the event that the stored compressed air is to be utilized for power generation, the stored compressed air re-enters respective pressure vessels **218**, **220** at the second end **232** and is reheated as it passes through respective porous thermal storage media **226**, **228**. The reheated air then exits respective pressure vessels **218**, **220** at the first end **230**, where it is provided to one or more steam turbines to power an electrical generator.

[0031] Unlike a conventional TES system having a single pressure vessel, TES system **216** enables pressure vessels **218**, **220** to receive compressed air having differing respective pressure levels. That is, pressure vessel **218** may be configured to receive a high-pressure compressed air input from both the one or more compressors and the compressed air storage unit, while pressure vessel **220** may be configured to receive a low-pressure compressed air input from the one or more compressors and the compressed air storage unit. In one embodiment, pressure vessel **218** is configured to receive (and withstand) pressures of 40-80 bar, while pressure vessel **220** is configured to receive (and withstand) pressures of 5-20 bar. As pressure vessel **218** has a smaller diameter (and thus lower tension forces) than pressure vessel **220**, pressure vessel **218** is capable of withstanding higher pressures, even though a thickness of wall **222** could be less than a thickness of wall **224**. Also, because pressure vessel **218** is disposed within the interior volume of pressure vessel **220**, the low-pressure compressed air passing through the porous thermal storage medium **228** acts to lessen the pressure differential between the compressed air passing through pressure vessel **218** and the air outside of pressure vessel **218**. The walls of a typical single pressure vessel would be surrounded by ambient air pressure, but because pressure vessel **218** is surrounded by the low-pressure compressed air passing through pressure vessel **220**, the tension forces in wall **222** are reduced, and thus wall **222** can be constructed having a substantially reduced thickness when compared to pressure vessels used in conventional TES systems. Furthermore, because pressure vessel **220** is subjected to low-pressure compressed air, the thickness of wall **224** can also be substantially smaller than the thickness of a conventional TES pressure vessel.

[0032] Additionally, heat losses from pressure vessel **218** are also reduced when compared to conventional TES systems, as the temperature difference between the compressed air passing through pressure vessel **218** and the compressed air passing through pressure vessel **220** is much less than the temperature difference between the compressed air passing through a conventional TES unit and the surrounding ambient air. As such, even though wall **222** is thinner than a conven-

tional pressure vessel wall, heat losses are reduced due to the coaxial integrated configuration of pressure vessels **218**, **220** of TES system **216**.

[0033] Since TES system **216**, as shown in FIG. 2, is made up of a combination of pressure vessel **218** and pressure vessel **220**, the respective pressure vessels **218**, **220** can be constructed to withstand high pressures and temperatures overall, but with reduced wall thicknesses. As such, cost and complexity of constructing and transporting TES system **216** is much less than that of typical TES systems, with the added benefit of smaller pressure vessels and, thus, a smaller overall TES system footprint.

[0034] Referring now to FIG. 3, another embodiment in accordance with the present invention is illustrated. FIG. 3 schematically shows a TES system **316** comprising three separate pressure vessels **318**, **320**, **322** fluidly arranged in parallel. First pressure vessel **318** has a wall **324** surrounding a thermal storage medium **334**, second pressure vessel **320** has a wall **326** surrounding a thermal storage medium **336**, and third pressure vessel **322** has a wall **328** surrounding a thermal storage medium **338**. It is envisioned that respective pressure vessels **318**, **320**, **322** may be identically constructed, but embodiments of the present invention are not limited as such.

[0035] Pressure vessels **318**, **320**, **322** are closely arranged to enable compressed air from at least one compressor to enter the respective pressure vessels at a first end **330** of pressure vessels **318**, **320**, **322**. The compressed air travels through pressure vessels **318**, **320**, **322**, whereby heat from the compressed air is captured and stored in respective thermal storage media **334**, **336**, **338**. The compressed air then exits the respective pressure vessels at a second end **332** of pressure vessels **318**, **320**, **322**, where it is stored in a cavern or other compressed air storage device or, alternatively, is provided to additional compressors and/or turbines, as similarly described above with respect to FIG. 2. In the event that the stored compressed air is to be utilized for power generation, the stored compressed air reenters respective pressure vessels **318**, **320**, **322** at the second end **332** and is reheated as it passes through respective porous thermal storage media **334**, **336**, **338**. The reheated air then exits respective pressure vessels **318**, **320**, **322** at the first end **330**, where it is provided to one or more steam turbines to power an electrical generator.

[0036] While FIG. 3 shows three separate pressure vessels **318**, **320**, **322**, the present invention is not limited to a specific number of pressure vessels, and may comprise any number of closely arranged or packed pressure vessels. Preferably, pressure vessels **318**, **320**, **322** are arranged in a triangular array such that respective walls **324**, **326**, **328** of pressure vessels **318**, **320**, **322** are located in close proximity to one another (e.g., within centimeters, and not more than a meter apart), as is illustrated in FIG. 4. If more or fewer pressure vessels are present, other geometrical arrangements, such as a hexagonal array, can be used to ensure that the pressure vessels are closely located. With such an arrangement, an insulation layer **340** may be disposed only about the perimeter of the closely packed pressure vessels **318**, **320**, **322**, and thus heat losses, thermal stresses and/or thermal gradients within respective walls **324**, **326**, **328** may be minimized. In this manner, the design and construction of TES system **316** is simplified, since a separate insulation layer disposed about each of pressure vessels **318**, **320**, **322** is avoided.

[0037] By utilizing a plurality of closely packed pressure vessels, TES system **316** is able to effectively withstand high

temperatures and high pressures without necessitating a single TES unit having both a large diameter and substantial wall thickness requirements. As such, TES system **316** allows for effective thermal energy storage in an ACAES system with reduced system size and weight, thereby eliminating many construction and transport issues that may be associated with conventional TES systems.

[0038] FIG. 5 illustrates another embodiment in accordance with the present invention. TES unit **416** comprises a pressure vessel having a cylindrical wall **418** encompassing a thermal storage medium **420** disposed therein. TES unit **416** operates similarly to TES systems **216** and **361** described above with respect to FIGS. 2 and 3, whereby compressed air from at least one compressor enters TES unit **416** at a first end **422**. The compressed air passes through thermal storage medium **420** to allow heat from the compressed air to be captured and stored within TES unit **416**. The compressed air then exits TES unit **416** at a second end **424**, where it is stored in a cavern or other compressed air storage unit for later usage in power generation.

[0039] Cylindrical wall **418** is preferably constructed to have a high length-to-diameter ratio using a strong material having a low thickness (e.g., steel). With such a low diameter, the thickness of cylindrical wall **418** can be smaller than the reinforced concrete walls of convention TES units, while the increased length of cylindrical wall **418** still enables a sufficient amount of thermal storage medium **420** to be disposed therein to effectively capture and store the heat needed for use in an ACAES system. Furthermore, while FIG. 5 only shows a single TES unit **416**, it is envisioned that a plurality of such TES units can be arranged in parallel to form a closely packed group of TES units, as is similarly shown and discussed with respect to FIGS. 3-4. Thus, an increased compressed air volume can be handled by multiple TES units **416**, but the reduced system size and weight of each individual TES unit **416** again eliminates many construction and transport issues that may be associated with conventional TES systems.

[0040] Referring now to FIG. 6, another embodiment in accordance with the present invention is illustrated. While conventional TES units are constructed to be above-ground thermal storage units fluidly connected to a cavern or other compressed air storage unit through a network of conduits/piping, TES system **516** illustrated in FIG. 6 comprises a TES unit **518** that is configured to be disposed below ground level. Specifically, TES unit **518** comprises a wall **520** encompassing a porous thermal storage medium **522** therein. The operation of TES unit **518** is similar to that of the TES units described above with respect to FIGS. 2-5, and thus the details of the operation will not be repeated. While TES unit **518** is shown as a single unit, it is to be understood that TES unit **518** could be configured in various ways, including the arrangements described above with respect to FIGS. 2-5.

[0041] TES unit **518** is integrated into a shaft **524** of a cavern **526**, thereby surrounding wall **520** of TES unit **518** in bedrock/soil **528** such that TES unit **518** is disposed below ground level **530**. Compressed air from at least one compressor enters TES unit **518** at a first end **532** and exits TES unit **518** at a second end **534**. The compressed air is then stored in cavern **526** for eventual use in electrical power generation, as described above.

[0042] As TES unit **518** of TES system **516** is located below ground level **530**, and wall **520** is surrounded by bedrock/soil **528**, the thickness of wall **520** (and the thickness of any insulation (not shown) surrounding wall **520**) may be sub-

stantially reduced. Bedrock/soil **528** provides a natural counteraction to the high tension forces in wall **520** brought on by high pressures therein, and bedrock/soil **528** also provides natural insulation to reduce heat loss in the system. Additionally, integration of TES unit **518** in shaft **524** of cavern **526** may reduce the above-ground footprint of the ACAES plant. Furthermore, TES system **516** overcomes manufacturing and transport difficulties associated with some conventional TES systems, thereby reducing the costs and simplifying the implementation of a TES unit in an ACAES system.

[0043] Therefore, according to one embodiment of the invention, a thermal energy storage system is disclosed, the thermal energy storage system comprising a plurality of pressure vessels arranged in close proximity to one another, each of the pressure vessels having a wall comprising an outer surface and an inner surface spaced from the outer surface by a respective wall thickness and surrounding an interior volume of the pressure vessel. The interior volume has a first end in fluid communication with one or more compressors and one or more turbines and a second end in fluid communication with at least one of one or more additional compressors, one or more additional turbines, and at least one compressed air storage component. The thermal energy storage system further comprises a thermal storage medium positioned in the interior volume of each of the plurality of pressure vessels.

[0044] According to another embodiment of the invention, a method of forming a thermal energy storage system is disclosed, the method comprising forming a first pressure vessel, the first pressure vessel having a wall constructed to have a predetermined height and thickness, wherein an inner surface of the wall of the first pressure vessel bounds an interior volume therein, and forming a second pressure vessel, the second pressure vessel constructed to have a wall of predetermined height and thickness, wherein an inner surface of the wall of the second pressure vessel bounds an interior volume therein. The method further comprises disposing a porous thermal storage medium within the interior volume of each of the first and second pressure vessels, and arranging the first pressure vessel and the second pressure vessel in close proximity to one another. Also, the method comprises connecting a first end of each of the first and second pressure vessels to one or more compressors and to one or more turbines such that each of the first and second pressure vessels is in fluid communication with the one or more compressors and the one or more turbines, and connecting a second end of each of the first and second pressure vessels to at least one of one or more additional compressors, one or more additional turbines, and one or more compressed air storage components such that each of the first and second pressure vessels is in fluid communication with at least one of the one or more additional compressors, the one or more additional turbines, and the one or more compressed air storage components.

[0045] According to yet another embodiment of the invention, a thermal energy storage apparatus is disclosed, the thermal energy storage apparatus comprising a first concrete cylindrical wall bounding a first interior volume and a second concrete cylindrical wall bounding a second interior volume, wherein the second concrete cylindrical wall is arranged within the first interior volume of the first concrete cylindrical wall such that the first concrete cylindrical wall and the second concrete cylindrical wall are coaxial. The thermal energy storage apparatus further comprises a porous thermal matrix material disposed within the first interior volume of the first

concrete cylindrical wall and within the second interior volume of the second concrete cylindrical wall.

[0046] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A thermal energy storage system comprising:
 - a plurality of pressure vessels arranged in close proximity to one another, each of the pressure vessels having a wall comprising:
 - an outer surface; and
 - an inner surface spaced from the outer surface by a respective wall thickness and surrounding an interior volume of the pressure vessel, the interior volume having:
 - a first end in fluid communication with one or more compressors and one or more turbines; and
 - a second end in fluid communication with at least one of one or more additional compressors, one or more additional turbines, and at least one compressed air storage component; and
 - a thermal storage medium positioned in the interior volume of each of the plurality of pressure vessels.
2. The thermal energy storage system of claim 1 wherein the plurality of pressure vessels comprises a first pressure vessel and a second pressure vessel, the first pressure vessel arranged within the interior volume of the second pressure vessel.
3. The thermal energy storage system of claim 2 wherein the wall of the first pressure vessel has a first wall thickness and a first diameter and wherein the wall of the second pressure vessel comprises a second wall thickness and a second diameter, wherein the first diameter is less than the second diameter.
4. The thermal energy storage system of claim 2 wherein the first pressure vessel is configured to withstand a higher pressure level than the second pressure vessel.
5. The thermal energy storage system of claim 1 wherein the plurality of pressure vessels arranged in close proximity to one another are arranged according to a pattern, the pattern comprising one of a triangular pattern and a hexagonal pattern.
6. The thermal energy storage system of claim 5 further comprising an insulation layer disposed around a perimeter of the pattern of the plurality of pressure vessels.
7. The thermal energy storage system of claim 1 wherein the wall of each of the plurality of pressure vessels is formed of either steel or concrete.
8. The thermal energy storage system of claim 1 wherein the thermal storage medium is a porous thermal storage medium disposed within the interior volume of each of the plurality of pressure vessels.
9. The thermal energy storage system of claim 8 wherein the porous thermal storage medium comprises at least one natural stone material.

10. The thermal energy storage system of claim **1** wherein the plurality of pressure vessels is disposed within a cavern shaft, and wherein the cavern shaft is in fluid communication with the at least one compressed air storage component and is located below ground level.

11. The thermal energy storage system of claim **1** wherein each of the plurality of pressure vessels is cylindrical in shape.

12. A method of forming a thermal energy storage system, the method comprising:

forming a first pressure vessel, the first pressure vessel having a wall constructed to have a predetermined height and thickness, wherein an inner surface of the wall of the first pressure vessel bounds an interior volume therein;

forming a second pressure vessel, the second pressure vessel constructed to have a wall of predetermined height and thickness, wherein an inner surface of the wall of the second pressure vessel bounds an interior volume therein;

disposing a porous thermal storage medium within the interior volume of each of the first and second pressure vessels;

arranging the first pressure vessel and the second pressure vessel in close proximity to one another;

connecting a first end of each of the first and second pressure vessels to one or more compressors and to one or more turbines such that each of the first and second pressure vessels is in fluid communication with the one or more compressors and the one or more turbines; and connecting a second end of each of the first and second pressure vessels to at least one of one or more additional compressors, one or more additional turbines, and one or more compressed air storage components such that each of the first and second pressure vessels is in fluid communication with at least one of the one or more additional compressors, the one or more additional turbines, and the one or more compressed air storage components.

13. The method of claim **12** further comprising arranging the first pressure vessel to be disposed within the interior volume of the second pressure vessel.

14. The method of claim **12** further comprising forming at least one additional pressure vessel, wherein the first pressure

vessel, the second pressure vessel, and the at least one additional pressure vessel are arranged in close proximity to one another to form a grouping of pressure vessels.

15. The method of claim **14** further comprising disposing an insulating material about a perimeter of the grouping of pressure vessels.

16. A thermal energy storage apparatus comprising:

a first concrete cylindrical wall bounding a first interior volume;

a second concrete cylindrical wall bounding a second interior volume, wherein the second concrete cylindrical wall is arranged within the first interior volume of the first concrete cylindrical wall such that the first concrete cylindrical wall and the second concrete cylindrical wall are coaxial; and

a porous thermal matrix material disposed within the first interior volume of the first concrete cylindrical wall and within the second interior volume of the second concrete cylindrical wall.

17. The thermal energy storage apparatus of claim **16** wherein a diameter of the second concrete cylindrical wall is smaller than a diameter of the first concrete cylindrical wall.

18. The thermal energy storage apparatus of claim **16** wherein both the first concrete cylindrical wall and the second concrete cylindrical wall have a first end and a second end, wherein the first end is in fluid communication with one or more compressors and one or more turbines, and the second end is in fluid communication with at least one of one or more compressed air storage components, one or more additional compressors, and one or more additional turbines.

19. The thermal energy storage apparatus of claim **18** wherein the first end of the second concrete cylindrical wall receives a higher pressure input from the one or more compressors than the first end of the first concrete cylindrical wall, and the second end of the second concrete cylindrical wall receives a higher pressure input from the at least one compressed air storage component than the second end of the first concrete cylindrical wall.

20. The thermal energy storage apparatus of claim **16** wherein the porous thermal matrix material comprises at least one natural stone material.

* * * * *