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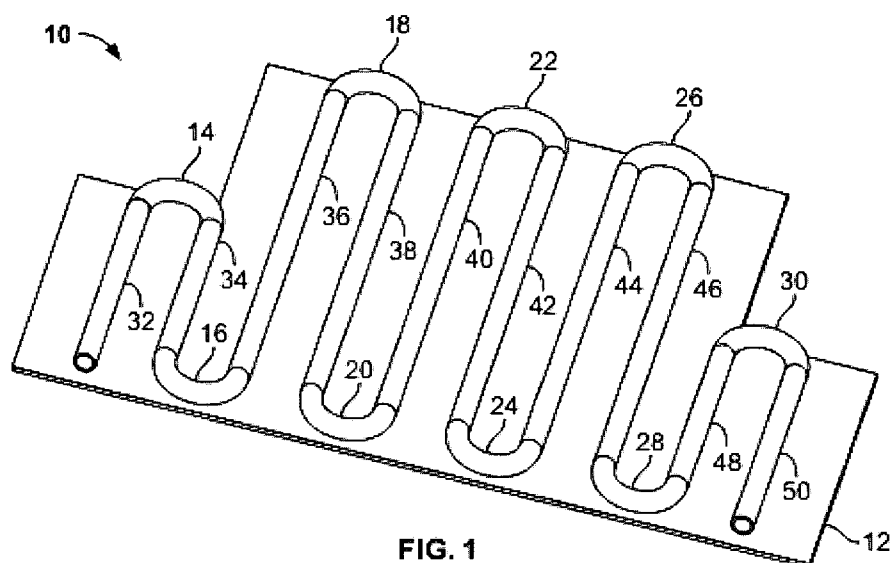


**FIG. 1**

(57) **Abstract:** A Hydrogen storage system comprising storage elements coupled to each other to form one or more containers disposed in a space having a volume  $V$  where the volume of each of the storage elements is much smaller than the volume  $V$  resulting in the storage elements experiencing reduced stress at their inner surfaces. Thus, Hydrogen can be stored at relatively high pressure within these storage elements due to the reduced stress experienced by their inner surfaces. Consequently, materials having relatively lower tensile strength and stiffness can be used to construct the storage elements of the Hydrogen storage system. Further, the storage elements can be shaped and sized to conform to a volume of space having an arbitrary shape and dimensions.



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## HYDROGEN STORAGE SYSTEM

### Background of the Invention

#### 5 Field of the Invention

The present invention generally relates to hydrogen storage systems for a defined space and more particularly relates to the architecture, size, shape and positioning of such systems for a defined space in vehicles or in storage areas.

#### 10 Description of the Related Art

Hydrogen is increasingly becoming a fuel used in all types of vehicles including bi-fuel vehicles where the other fuel is gasoline. There is however a key practical consideration associated with the use of Hydrogen as a fuel for vehicles. The key consideration is the storage of the hydrogen fuel itself; this consideration raises several issues. In particular, the size, cost of manufacture, and weight of hydrogen tanks are issues that complicate the design and practicability of such tanks. Also, the storage mass of the Hydrogen is itself a key consideration.

A first issue is the size of the tanks relative to the space allocated to them in vehicles. Current hydrogen fuel tanks store hydrogen at a typical pressure of 200-350 bars where a "bar" is a unit of pressure defined in terms of kilopascals; that is 1 bar is equal to 100 kilopascals or 100 kPa;  $1 \text{ kPa} \equiv 1000 \text{ Pa}$ ;  $1 \text{ MPa} \equiv 1,000,000 \text{ Pa}$ . The "pascal" is a well-known defined unit for the measurement of pressure, internal pressure, stress, Young's modulus (measure of stiffness of an isotropic elastic material), and tensile strength. At a pressure in the range of 200-350 bars, the amount of Hydrogen needed to be stored in a Hydrogen tank to be comparable to the energy content of a conventional gasoline tank often makes the size of the Hydrogen tank impractically large and in many cases impossible to install in the space allocated for the tank or in available space in the vehicle. Often the only available space is the trunk of an automobile and in many cases the size of a 200-350 bar tank would, for many vehicles, use virtually the entire trunk space reducing the overall usefulness of the vehicle. Typically, current hydrogen tanks have dimensions that are nearly the same as the dimensions of the space allocated to them. For example, many tanks occupy most if not the entire space of a trunk of a vehicle, which is the space that is usually allocated to such tanks.

Current Hydrogen tanks are often cylindrical in shape and thus their design considerations are based on well known laws of physics regarding the internal pressure experienced by their inner surfaces when such cylinders contain gas, liquid or other matter.

5 The effect of the internal pressure experienced by the internal surface of a cylindrical tank is expressed in terms of the stresses in the longitudinal axis of the cylinder and the stresses in the tangential directions (perpendicular to the longitudinal axis). The following equations, known as Kessel's equations, express the two types of stresses (axial stress or  $\sigma_a$  and tangential stress or  $\sigma_t$ ) in terms of  $p$  (measurable pressure),  $D$  (diameter of cylinder) and  $s$   
10 (thickness of the tank walls):

$$(1) \sigma_a = \frac{p \cdot D}{4 \cdot s} \quad (2) \sigma_t = \frac{p \cdot D}{2 \cdot s}$$

As can be clearly seen from the above equations, the stresses experienced by the internal surface of the cylinder in the axial and tangential directions are directly proportional to the inner diameter of the cylinder. Thus, for relatively large cylinders such as the 200-350  
15 bar cylinders, there is increased stress due to the relatively large diameters,  $D$ . Because of the resulting higher stresses that occur, relatively strong fibers are needed to construct these tanks. The cylindrical tanks are typically constructed using a relatively thin walled metallic cylinder reinforced with relatively strong fibers wound on the surface of the cylinder to which some type of polymer has been applied. Thus, the wound fibers are embedded in the  
20 polymer applied to the surface of the cylinder to form a FRP (Fiber Reinforced Polymer), which when cured serves as a strong shell adhered to the outer surface of the metallic cylinder so as to assist the inner metallic surface of the cylinder to withstand the resulting stresses as defined by equations (1) and (2) above.

25 The fibers used to construct the tanks are usually relatively strong fibers (such as carbon fibers), which have the requisite amount of tensile strength and stiffness to withstand the stresses resulting from relatively large diameter dimensions of the tanks. The issue with these relatively strong fibers is their cost. Such fibers although used in many industrial and commercial products are not made in the quantity necessary to provide the benefits of the economies of scale typically provided by parts manufactured en masse in relatively high  
30 quantities. Carbon fibers and other fibers with comparable physical characteristics are relatively very expensive and thus the costs of manufacture of conventional hydrogen tanks are accordingly expensive.

Further, as previously stated, the 200-350 bar tanks do not have an energy capacity comparable to gasoline tanks. Therefore, in order to increase the energy content of these tanks, the amount of hydrogen per unit volume is increased thus increasing the mass of hydrogen per unit volume and thus the energy content of the tank; this is done by increasing the internal pressure at which the Hydrogen is stored within the tank. For example, tanks having an internal pressure of 700 bars can be used. Such tanks will necessarily have more stress applied to their inner walls because of the increased pressure (See equations 1 and 2 above). With increasing pressure comes the need for strong fibers, which as described above makes the costs of such tanks relatively expensive.

A review of equations 1 and 2 above shows that one approach at reducing the stress on the inner walls of the 700 bar tanks, is to design tanks with thicker inner walls—that is, increasing  $s$  reduces  $\sigma$ . However, a tank with thicker inner walls will weigh more than the same tank with thinner inner walls. For storage tanks used in vehicles, the weight of the tank is clearly an important factor in the overall fuel efficiency of the vehicle. Also, in many cases the cost of manufacturing such thicker wall tanks increases due to the extra cost of additional wall material and modification in the manufacturing process for these tanks.

### **Brief Summary of the Invention**

The present invention provides a Hydrogen storage system comprising  $N$  storage elements coupled to each other to form one or more containers that occupy or fit within boundaries of a defined space with boundaries, dimensions, and shape resulting in a volume  $V$  where  $N$  is an integer equal to 2 or greater. Each of the storage elements has a volume that is a fraction of (or substantially less than) the volume  $V$  resulting in each storage element and the one or more containers having reduced dimensions compared to the dimensions of the defined space of volume  $V$ . A fraction of the volume  $V$  refers to a volume of space occupied by one of  $N$  storage elements such that all  $N$  storage elements fit within the boundaries of the defined space of volume  $V$ . Because each of the storage elements has a volume that is substantially less than the overall volume  $V$ , the inner surfaces of each of the storage elements experience substantially less stress compared to the stress experienced by inner surfaces of one storage tank of volume  $V$ . That is, the volume of each of the storage elements is reduced to a value that allows usage of less costly but adequately strong fibers in the construction of such storage elements. As a result, the reduced stress experienced by the inner surfaces of each of the storage elements allows the usage of fiber

material (e.g., Innegra, Basalt or other fiber having similar such properties) having relatively lower tensile strength and stiffness in the construction of each such storage element thus reducing the cost of the storage system.

5           The respective volumes of each of the storage elements are not necessarily equal to each other. For a system having N storage elements, each storage element has a volume defined by dimensions and shape that may be the same or different from the other storage elements. When all of the storage elements are coupled to each other to form one or more containers, the one or more containers have architectures defined by their shape and size  
10 and dimensions. All of the storage elements when coupled together fit in the defined space of Volume V either by conforming substantially to the shape and dimensions of the defined space or by being able to be disposed totally within the defined space of certain dimensions, boundaries and shape resulting in a volume V. The terms "conforming" or "conform" refer to the one or more containers forming a defined space that has substantially the same shape,  
15 dimensions, boundaries and volume, V of the defined space.

Each of the storage elements has an inner layer made of a Hydrogen impermeable material and an outer layer adhered to the outer surface of the inner layer. The outer layer may be a composite material made by first applying a resin (e.g., an epoxy resin) onto the  
20 outer surface of the inner layer and then winding a fiber onto the outer surface at a certain angle with respect to a defined point(s) of reference (e.g., longitudinal axis of a cylinder) thus embedding the fiber into the resin and allowing the fiber-resin combination to cure to form a relatively hard shell. Alternatively, the fiber can be wound first onto the outer surface of the inner layer and then a resin is applied; the fiber-resin combination is then allowed to cure to  
25 form a relatively hard shell. Yet further, the fiber material can be first weaved as a "sock" that is then snugly fit over the outer surface of the Hydrogen impermeable material. Resin is then applied to the fitted material and allowed to cure to form a relatively hard shell for the storage element. The process of slipping on the "sock" and then adding resin to the sock can be repeated as many times as desired. The "sock" refers to fibers weaved into the shape of a  
30 storage element so that a snug fit (i.e., a 'glove' fit) can be achieved when the "sock" is slipped on or over the outer surface of the storage element made from a Hydrogen impermeable material. Preferably, the Hydrogen impermeable material is aluminum or an aluminum alloy and the fiber is made from Basalt, Innegra, or other material with properties similar to Basalt or Innegra. Other Hydrogen impermeable materials and fiber materials that  
35 meet design requirements of the storage system of the present invention may be used. It will

be readily obvious that the storage system of this embodiment and other embodiments of the present invention are not limited to the Hydrogen impermeable material and the fiber materials mentioned above.

In a first embodiment of the storage system of the present invention, all of the storage elements may be coupled to each other to form one or more containers positioned proximate each other within the boundaries of the defined space of volume V where the containers may be different in size, shape and architecture or they may all be the same in size, shape and architecture.

In a second embodiment of the storage system of the present invention, the storage elements may be coupled to each other to form one or more containers each of which is positioned within the boundaries of the defined space of volume V. Additionally, one or more other containers—not formed from storage elements—can also be positioned within the boundaries of the defined space of volume V. The containers formed from storage elements and containers not formed from the storage elements all fit within the boundaries of the defined space of volume V.

A particular implementation which can be used for the first and/or second embodiments of the present invention comprises storage elements having two types of shapes, viz., straight cylinders and bent cylinders having equal outer diameters ( $D_o$ , where  $2 \cdot r_o = D_o$ ;  $r_o$  is the outer radius) and inner diameters ( $D_i$ , where  $2 \cdot r_i = D_i$ ;  $r_i$  is the inner radius); all of the bent cylinders have equal curve radii ( $r_c$ ). The curve radius for each of the bent cylinders is equal to  $k \cdot D_o$  (i.e.,  $r_c = k \cdot D_o$ ) where  $k$  is a real number greater than zero. Each of the bent and straight cylinders has a volume that is relatively much less than the volume V of a defined space within which these storage elements are disposed. The straight and bent cylinders are coupled to each other to form one or more serpentine cylindrical containers. Also, with the diameter having some measurable thickness so that there is an inner diameter  $D_i$  and an outer diameter  $D_o$ , the diameter value used in the Kessel equations is  $D = D_M = \frac{D_o + D_i}{2}$ .  $D_M$  is thus the mid-diameter or average diameter.

For the embodiments discussed above and any other embodiments falling within the claimed storage system of the present invention, the dimensions and shapes of the storage elements and/or containers (made and/or not made from storage elements) can be varied to construct a storage system in accordance with arbitrary design requirements. One particular

set of design requirements puts limits on the size, cost and weight of the storage system. Also, depending on the shape of the defined space, the design requirements may also dictate the shape of the storage elements and the shape of containers made or not made from the storage elements.

5

### **Brief Description of the Drawings**

The drawings shown in this application represent various embodiments of the Hydrogen storage system of the present invention. The various embodiments are not necessarily drawn to scale and are shown for illustrative purposes to further facilitate the description and explanation of Hydrogen storage system of the present invention. A brief description of the drawings is as follows:

FIG. 1 shows a serpentine cylindrical container of the Hydrogen storage system of the present invention;

FIG. 2 shows a straight cylinder section of the serpentine cylindrical container of FIG. 1;

FIG. 2A shows a cross sectional view of FIG. 2 cut along line 2A-2A and also shows the tangential and axial stress lines due to internal pressure from stored Hydrogen;

FIG. 3 shows a bent cylinder section of the serpentine cylindrical container of FIG. 1;

FIG. 4 shows the straight cylinder section of FIG. 2 with a hardened shell made of a composite material;

FIG. 5 shows the straight cylinder section of FIG. 2 with a fiber wound thereon at a particular angle;

FIG. 5A is a top view of FIG. 5 and shows the angles formed by lines tangential to the wound fiber and the longitudinal axis of the straight cylinder section of FIG. 5;

FIG. 6 depicts a graph that shows the relationships between different parameters in designing cylinders made from different fibers, having different diameters, mass and weight, and operated at different internal pressures;

FIG. 7 shows a serpentine cylindrical container with certain dimensions;

FIG. 8 shows one embodiment of the Hydrogen storage system of the present invention.

FIG. 9 shows another embodiment of the Hydrogen storage system of the present invention where the storage elements are U-shaped;

FIG. 9A shows a front view of FIG. 9 depicting the angular arrangement of the storage elements with respect to each other;

FIG. 10 shows yet another embodiment of the present invention where the storage elements are capsule shaped;

FIG. 11 shows a generalized embodiment of the storage system of the present invention having a volume of arbitrary shape and comprising three Sections where each section having  
5 three layers;

FIG. 12 shows the individual storage elements of one section of the storage system of FIG. 11;

FIG. 13 shows an exploded view of the three layers of the section depicted in FIG. 12 and all of the individual storage elements of that section; and

10 FIG. 13A shows how two adjacently positioned storage elements of the section depicted in FIG. 12 are coupled to each other.

### **Detailed Description**

15 The present invention provides a Hydrogen storage system comprising N storage elements coupled to each other to form one or more containers that occupy or fit within boundaries of a defined space with boundaries, dimensions, and shape resulting in a volume V where N is an integer equal to 2 or greater. Each of the storage elements has a volume that is a fraction of (or substantially less than) the volume V resulting in each storage  
20 element and the one or more containers having reduced dimensions compared to the dimensions of the defined space of volume V. A fraction of the volume V refers to a volume of space occupied by one of N storage elements such that all N storage elements fit within the boundaries of the defined space of volume V. Because each of the storage elements has a volume that is substantially less than the overall volume V, the inner surfaces of each  
25 of the storage elements experience substantially less stress compared to the stress experienced by inner surfaces of one storage tank of volume V. That is, the volume of each of the storage elements is reduced to a value that allows usage of less costly but adequately strong fibers in the construction of such storage elements. As a result, the reduced stress experienced by the inner surfaces of each of the storage elements allows the usage of fiber  
30 material (e.g., Innegra, Basalt or other fiber having similar such properties) having relatively lower tensile strength and stiffness in the construction of each such storage element thus reducing the cost of the storage system.

The respective volumes of each of the storage elements are not necessarily equal to  
35 each other. For a system having N storage elements, each storage element has a volume

defined by dimensions and shape that may be the same or different from the other storage elements. When all of the storage elements are coupled to each other to form one or more containers, the one or more containers have architectures defined by their shape and size and dimensions. All of the storage elements when coupled together fit in the defined space of Volume V either by conforming to substantially the shape and dimensions of the defined space or by being able to be disposed totally within the defined space of certain dimensions, boundaries and shape resulting in a volume V. The terms "conforming" or "conform" refer to the one or more containers forming a defined space that has substantially the same shape, dimensions, boundaries and volume, V of the defined space.

Each of the storage elements has an inner layer made of a Hydrogen impermeable material and an outer layer adhered to the outer surface of the inner layer. The outer layer may be a composite material made by first applying a resin (e.g., an epoxy resin) onto the outer surface of the inner layer and then winding a fiber onto the outer surface at a certain angle with respect to a defined point(s) of reference (e.g., longitudinal axis of a cylinder) thus embedding the fiber into the resin and allowing the fiber-resin combination to cure to form a relatively hard shell. Alternatively, the fiber can be wound first onto the outer surface of the inner layer and then a resin is applied; the fiber-resin combination is then allowed to cure to form a relatively hard shell. Yet further, the fiber material can be first weaved as a "sock" that is then snugly fit over the outer surface of the Hydrogen impermeable material. Resin is then applied to the fitted material and allowed to cure to form a relatively hard shell for the storage element. The process of slipping on the "sock" and then adding resin to the sock can be repeated as many times as desired. The "sock" refers to fibers weaved into the shape of a storage element so that a snug fit (i.e., a 'glove' fit) can be achieved when the "sock" is slipped on or over the outer surface of the storage element made from a Hydrogen impermeable material. Preferably, the Hydrogen impermeable material is aluminum or an aluminum alloy and the fiber is made from Basalt, Innegra, or other material with properties similar to Basalt or Innegra. Other Hydrogen impermeable materials and fiber materials that meet design requirements of the storage system of the present invention may be used. It will be readily obvious that the storage system of this embodiment and other embodiments of the present invention are not limited to the Hydrogen impermeable material and the fiber materials mentioned above.

In a first embodiment of the storage system of the present invention, all of the storage elements may be coupled to each other to form one or more containers positioned proximate

each other within the boundaries of the defined space of volume V where the containers may be different in size, shape and architecture or they may all be the same in size, shape and architecture.

5 In a second embodiment of the storage system of the present invention, the storage elements may be coupled to each other to form one or more containers each of which is positioned within the boundaries of the defined space of volume V. Additionally, one or more other containers—not formed from storage elements—can also be positioned within the boundaries of the defined space of volume V. The containers formed from storage elements  
10 and containers not formed from the storage elements all fit within the boundaries of the defined space of volume V.

A particular implementation which can be used for the first and/or second embodiments of the present invention comprises storage elements having two types of  
15 shapes, viz., straight cylinders and bent cylinders having equal outer diameters ( $D_o$ , where  $2*r_o=D_o$ ;  $r_o$  is the outer radius) and inner diameters ( $D_i$ , where  $2*r_i=D_i$ ;  $r_i$  is the inner radius); all of the bent cylinders have equal curve radii ( $r_c$ ). The curve radius for each of the bent cylinders is equal to  $k*D_o$  (i.e.,  $r_c = k*D_o$ ) where  $k$  is a real number greater than zero. Each of the bent and straight cylinders has a volume that is relatively much less than the volume V of  
20 a defined space within which these storage elements are disposed. The straight and bent cylinders are coupled to each other to form one or more serpentine cylindrical containers. Also, with the diameter having some measurable thickness so that there is an inner diameter  $D_i$  and an outer diameter  $D_o$ , the diameter value used in the Kessel equations is  $D = D_M = \frac{D_o + D_i}{2}$ .  $D_M$  is thus the mid-diameter or average diameter.

25 For the embodiments discussed above and any other embodiments falling within the claimed storage system of the present invention, the dimensions and shapes of the storage elements and/or containers (made and/or not made from storage elements) can be varied to construct a storage system in accordance with arbitrary design requirements. One particular  
30 set of design requirements puts limits on the size, cost and weight of the storage system. Also, depending on the shape of the defined space, the design requirements may also dictate the shape of the storage elements and the shape of containers made or not made from the storage elements.

Referring to FIG. 1, there is shown a particular implementation of an embodiment of the present invention wherein a serpentine cylindrical container designed to fit within the base area 12 (with corresponding volume  $V$ ) of the trunk of a 2007 Mitsubishi Evo 9, which is a bi-fuel vehicle able to operate on gasoline and/or Hydrogen. The serpentine cylindrical container design is described in the context of a trunk of a Mitsubishi Evo 9 for illustrative purposes only. It will be readily obvious that such an embodiment is not limited to the space defined by the trunk of the Evo 9 vehicle. It is clear that this embodiment and its variations can be used in different types of spaces within automobiles, or storage spaces of different environments. The boundaries of the base area of the trunk are clearly shown. In addition to the boundaries shown for the base area of the trunk are boundaries that delineate and define the volume of the trunk discussed infra. Accordingly, for ease of explanation, this embodiment of the Hydrogen storage system of the present invention will be described in the context of the trunk space of the Mitsubishi Evo 9 vehicle. The design requirements are that a Hydrogen storage system capable of storing 3 kg of Hydrogen is to be located in the trunk of the Mitsubishi Evo 9. The storage system weight, cost and size are to be as low as possible.

Continuing with the description of FIG. 1, the serpentine cylindrical container of FIG. 1 comprises six (6) long straight cylinder sections (36, 38, 40, 42, 44, 46), four (4) short straight cylinder sections (32, 34, 48, 50) and nine (9) bent cylinder sections (14, 16, 18, 20, 22, 24, 26, 28, 30). The various long, short and bent cylinder sections are arranged as shown in FIG. 1 to form serpentine cylindrical container 10 that fits within the spatial boundaries of the trunk of the Mitsubishi Evo 9. The inner diameter  $D_i$  of each of the cylinders (long, short or bent) is 36 mm. Each of the long cylinders is 736 mm in length and the short cylinders are 336 mm long. Each of the bent cylinders has an arc length of 113.1mm and a curve radius ( $r_c$ ) of 76mm and they are bent to form substantially circular arcs. The curve radius is defined with respect to the longitudinal axis 220 as mentioned in the description of FIG. 3. The serpentine storage system of FIG. 1 thus comprises three types of storage elements, viz., short cylinders, long cylinders and bent cylinders. The thickness,  $s$ , of the cylinders is 1mm for this embodiment and other embodiments discussed herein in which aluminum is used to construct the cylinders or storage elements.

Referring to FIG. 2, there is shown a perspective view of a straight (long or short) cylinder section 200 with longitudinal axis 220 having an inner radius  $r_i$  (with corresponding inner diameter  $D_i = 2 \cdot r_i$ ) and an outer radius  $r_o$  (with corresponding outer diameter  $D_o = 2 \cdot r_o$ ).

Cylinder section 200 has a thickness 240 of the Hydrogen impermeable material (e.g., aluminum) with which it is made. The geometry of cylinder 200 is the same or similar to the geometry of the long and short cylinders of FIG. 1. The cylinder 200 is formed through well-known extrusion processes or other well known cylinder forming or tube forming processes.

5

FIG. 2A shows FIG. 2 cut along lines 2A-2A of FIG. 2 to illustrate the direction of the axial stress  $\sigma_a$  and tangential stress  $\sigma_t$  forces acting on the inner surface of cylinder section 200 due to the internal pressure of stored Hydrogen gas. FIG. 3 shows a bent cylinder storage element 300 having the same inner radius ( $r_i$ ), outer radius ( $r_o$ ) and thickness 240 as the straight cylinder storage elements such as cylinder section 200. Bent cylinder storage element 300 has a curve radius  $r_c$ ; the curve radius is defined with respect to the longitudinal axis 220 as shown. The curve radius,  $r_c$ , is equal to  $k \cdot D_o$  where  $k$  is a real number greater than zero; for this embodiment  $k=2$ ; this relationship defines the degree of bending that can be performed on a cylinder. The value of  $k=2$  is currently the state of the art in aluminum bending technology. The geometry of bent cylinder storage element 300 is the same or similar to the geometry of the bent cylinder storage elements of FIG.1. Each of the storage elements (bent and straight sections) of the serpentine container is preferably an extruded aluminum section that can be made from Aluminum alloy 6xxx (for example Aluminum 6061), which has a certain strength, thickness and density.

20

The storage elements of short, long and bent cylinders depicted in FIGS. 2, 2A and 3 all have circular cross -section as they are clearly cylindrical in shape and geometry. It will be readily obvious to one skilled in this art that the present invention may also comprise storage elements of the claimed storage system having cross section profiles that are rectangular, elliptical, diamond shaped and various other cross sections that are not circular.

25

The volume  $V$  of the available trunk space of the 2009 Mitsubishi Evo 9 is 430 dm<sup>3</sup>. The formula for the volume of a cylinder (bent or straight) of length  $L$ , diameter  $D_M$  (where  $D_M = 2r_M$ ;  $r_M = \frac{r_o + r_i}{2}$ ) and thickness  $s$  has a volume  $V_{cyl} = \pi r_M^2 L$  or  $\frac{D_M^2}{4} L$ . The inner surface of a cylinder experiences stress from the pressure,  $p$ , of the stored Hydrogen in accordance with the axial and tangential stress equations (1) and (2) above which are hereby reproduced below for ease of reference:

30

$$(1) \sigma_a = \frac{p \cdot D}{4 \cdot s} \quad (2) \sigma_t = \frac{p \cdot D}{2 \cdot s}$$

Using the dimensions of the cylinders and the formula for the volume of a cylinder, the volume for each of the long cylinders is  $0.75 \text{ dm}^3$ . The volume for each of the short cylinders is  $0.34 \text{ dm}^3$  and for each of the bent cylinders is  $0.75 \text{ dm}^3$ . It is clear that the volume of the storage elements (i.e., long cylinders, short cylinders, and bent cylinders) are much smaller than the volume  $V$  of the defined space, viz., the volume of the trunk of the 2009 Mitsubishi Evo 9.

Each of the cylinder storage elements has a hardened shell adhered to its outer surface. The shell is made of a composite material, which includes fibers preferably made from Basalt ( $\text{C}^2$  fiber) or Innegra. One implementation of a cylinder storage element with a hardened shell is depicted in FIG. 4 where cylinder section 200 (made from aluminum) with thickness 240 has a hardened outer shell 280 (i.e., fiber---epoxy resin composite material allowed to cure) of thickness 260 adhered thereon. It should be noted that the thicknesses 240 and 260 of the inner cylinder section 200 and outer shell 280 respectively are not necessarily drawn to scale. The thicknesses may be equal to each other or either thickness may be greater or less than the other.

To form the hardened outer shell or outer layer for the bent and/or straight cylinder sections, an epoxy resin is first applied to the outer surfaces of the extruded aluminum sections; the resin has a certain tensile strength, stiffness and density. A fiber is then wound (at a certain angle with respect to the longitudinal axis of the bent or straight cylinder) onto the outer surface at a certain angle (preferably  $54.7^\circ$ ) with respect to the longitudinal axis 220 (or some other point of reference) of the cylinder. Alternatively, a fiber is first wound (at a certain angle—preferably  $54.7^\circ$ -- with respect to the longitudinal axis of the bent or straight cylinders) and then the epoxy resin is applied to the outer surfaces of the extruded aluminum sections. The fibers are interwoven with each other creating a thickness of fibers.

Referring to FIG. 5, there is shown cylinder section 200 with longitudinal axis 220 and with fiber 232 wound in the direction shown by curved arrow 222. The angle at which the fiber(s) is/are wound is obtained as follows. A portion of longitudinal axis 220 is projected onto the surface of cylinder section 200 resulting in a line 226 defined by at least two points A and B located at the two respective ends of cylinder section 200. Line 226 is the shortest distance between two aligned points at each end of the cylinder sections and thus, line 226 spans exactly the length of cylinder section 200. Therefore line 226 is parallel to and aligned with longitudinal axis 220. It will be readily obvious that line 226 intersects the wound fiber

232 at multiple points, some of which are indicated as intersection points 230. At intersecting points 230 tangential lines 228 are shown which represent lines drawn tangentially to the intersection points in the direction of winding (as shown by the arrows of lines 228) at those points. Each of the resulting tangential lines thus forms an angle with longitudinal axis 220.

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FIG. 5A shows a top view of FIG. 5 and fiber 232 is not shown for ease of explanation. The tangential lines 228 in relation to longitudinal axis 220 and line 226 show the angle—labeled  $\alpha$ —formed between the tangential lines 228 and longitudinal axis 220. FIG. 5 shows only one fiber 232 wound around cylinder section 200 for ease of explanation and clarity of illustration only. It will be readily understood that a plurality of fibers can be wound around cylinder section 200 to form composite material (i.e., hardened shell) 280 having a certain thickness 260 as shown in FIG. 4. As previously stated, for the serpentine cylindrical container of FIG. 1, the angle  $\alpha$  is preferably  $54.7^\circ$ .

Another method that can be used to form the hardened outer shell is to use a fiber tubing process. In this process the fiber is first weaved onto a mandrel to follow the shape and dimensions of the mandrel forming a tube or “sock” or a weaved fiber having the shape of the storage element for which a hardened shell is being constructed. The mandrel has the same shape and dimensions as the storage element. The sock (or weaved fiber shape) is then frictionally and/or snugly fit over the outer surface of the storage element. Resin is then added to the fiber. The process can then be repeated with additional layers of fiber (with the proper adjustments made for the dimensions of the weaved fiber sock or weaved fiber shape) and resin as needed or desired. The layers of fibers and resin are then allowed to cure to form the hardened shell.

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A fiber primarily made from volcanic rock such as Basalt rock is preferably used in the storage system of the present invention. For example, a Basalt fiber referred to as C<sup>2</sup> fiber having a mineralogical composition comprises at least is 52% SiO<sub>2</sub>, 17% Al<sub>2</sub>O<sub>3</sub>, 9%CaO, 5% MgO and 17% of various other substances typically found in volcanic rock. Depending on the mechanical and chemical properties of the fibers that are desirable, various adjustments can be made to the composition. The fiber can also be an Innegra fiber. By using storage elements with reduced dimensions, the need for relatively very strong and expensive fibers is eliminated. Thus, fibers not as strong as the strongest fibers (e.g., carbon, steel or silicon carbide), which have acceptable mechanical and chemical properties (such as the properties of Basalt and Innegra) and are relatively inexpensive become excellent candidates for the

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construction of the storage elements and containers used in the storage system of the present invention. A comparative look at some representative fibers and their relative properties is shown in the table below:

|                    | <b>Density<br/>[Kg/dm<sup>3</sup>]</b> | <b>Stiffness<br/>[N/mm<sup>2</sup>]</b> | <b>Tensile<br/>Strength<br/>[N/mm<sup>2</sup>]</b> | <b>Elongation<br/>[%]</b> | <b>Strength<br/>per<br/>density</b> | <b>Specific<br/>Strength<br/>per costs</b> | <b>Price<br/>[€/kg]</b> |
|--------------------|----------------------------------------|-----------------------------------------|----------------------------------------------------|---------------------------|-------------------------------------|--------------------------------------------|-------------------------|
| Innegra            | 0.84                                   | 18,000                                  | 590                                                | 5                         | 702                                 | 176                                        | 4                       |
| DP1000-<br>steel   | 7.83                                   | 210,000                                 | 1000                                               | 10                        | 128                                 | 18                                         | 7                       |
| Dyneema            | 0.97                                   | 100,000                                 | 3200                                               | 3.4                       | 3300                                | 43                                         | 77                      |
| Vectran            | 1.4                                    | 103,000                                 | 3000                                               | 3.3                       | 2143                                | 48                                         | 45                      |
| Glass              | 2.7                                    | 80,000                                  | 1800                                               | 3.5                       | 667                                 | 56                                         | 12                      |
| Basalt             | 2.7                                    | 100,000                                 | 2150                                               | 4                         | 796                                 | 159                                        | 5                       |
| Silicon<br>Carbide | 2.5                                    | 420,000                                 | 3400                                               | 0.05                      | 1360                                | 27                                         | 50                      |
| Carbon             | 1.8                                    | 400,000                                 | 4500                                               | 1                         | 2500                                | 125                                        | 20                      |
| Aramid             | 1.5                                    | 130,000                                 | 3500                                               | 2.8                       | 2333                                | 117                                        | 20                      |

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The strongest fibers listed in the table above are those with the highest stiffness and tensile strength, viz., Dyneema, Silicon carbide, and Carbon. These fibers also have some of the highest specific strengths (or strength per density) in the table. The strength per density is the ratio of tensile strength to density, which is highest for Carbon and Dyneema. However when the strength of a fiber is related to its cost, the Basalt and Innegra fibers yield the highest value for the fibers in the table (specific strength per cost for Basalt is 159 and Innegra 176); this is because Basalt and Innegra are the least expensive fibers per unit weight (4 Euros per Kg for Innegra and 5 Euros per Kg for Basalt) of any of the fibers in the table. Therefore, Basalt, Innegra and other fibers with similar strength per cost values become excellent candidates for the storage system of the present invention because the sizes of the storage elements relative to conventional Hydrogen tanks allow the use of fibers that are not as strong as Carbon or Silicon carbide.

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Various parameters related to the materials used to construct the storage elements and/or containers and the geometries of the containers and storage elements have a direct impact on the design of the storage system of the present invention. As discussed above, the three main considerations for the Hydrogen storage system of the present invention are its weight, size and cost. Some of the parameters that directly impact the weight, size and cost of the storage system of the present invention include choice of fiber material, thickness of the aluminum cylinders (or thickness of Hydrogen impermeable material), fiber fraction, (i.e., the ratio of amount of fiber to the amount of composite material made from fiber and epoxy resin) fiber angular positioning on the inner layer, the pressure at which the Hydrogen is stored and the dimension (in this case, the diameter of the cylinders) of the storage elements.

To design the storage elements and containers, one approach is to vary a dimension (say for example diameter,  $D$ ) of a storage element. Through this approach, the varying parameter will determine the value of the parameters that are related to the size, weight and cost of the storage elements. For example, varying one key parameter such as increasing the diameter of the storage elements will decrease the weight of the storage element per Hydrogen unit and increase the mass of the Hydrogen that can be stored. This is because the increase in  $D$  increases the volume in a square relationship and increases the stresses in a linear relationship. For example, if  $D$  is doubled, the stresses increase by a factor of 2, but the volume increases by a factor of  $2^2$  or 4. Thus, the volume increases much more than the stresses for the same increase in  $D$ ; keeping the amount of Hydrogen constant while increasing  $D$  results in a decrease of the weight per Hydrogen of the storage system. Clearly, however, the amount of Hydrogen that can be stored increases as  $D$  is increased. An increase in  $D$  will increase the stresses accordingly as already discussed and thus the fiber needed to withstand the resulting stress may be more expensive than what is called for by the design requirements. FIG. 6 is a chart showing the interrelationships between the diameter of cylinder storage elements, the mass of the cylinders (thus their weight) and the mass of the stored Hydrogen.

Referring to FIG. 7, there is shown the maximum length of a serpentine cylindrical container that can fit within the footprint (and also within the volume) of the trunk of the 2007 Mitsubishi Evo 9. The maximum length is obtained by decreasing the diameter of the cylindrical storage elements. Complying with the requirement that the curve radius is equal to twice the diameter ( $r_c = kD_0 = 2 \cdot r_0$ ), decreasing the diameter decreases the curve radius

thus allowing more long and short sections to be coupled to each other in the space provided which serves to increase the overall length of the serpentine cylindrical container. For a diameter of 10 mm, the container shown in FIG. 7 has eight (8) short cylinders (each 432 mm in length), 18 long cylinders (each 832 mm in length) and twenty-five (25) curved cylinders (each having a curve radius of 76 mm and a length of 75.4 mm). For cylinders having diameters of 5mm or less, no hardened outer shell is used. Generally, for storage elements in which the volume of such an element is relatively small, no outer shell is used.

A modified version of the already discussed design approach for the storage system of the present invention is to define ranges for an acceptable minimal mass of Hydrogen and a maximum weight of the storage system. The diameter of the storage elements can then be calculated or determined to meet these design requirements. It is easily seen that the value of the diameter will determine the weight of the storage system, the size of the storage system. Further, the diameter value will determine the stress and thus the choice of fiber for the storage elements, which is a significant factor in the overall cost of the storage system.

Referring now to FIG. 8, there is shown an embodiment in which one container is made from the coupling of storage elements (i.e., straight cylinders and bent cylinders) to each other to form a serpentine cylindrical container 600 and the other two containers 602, 604 are spherical containers not formed from storage elements. The three containers are positioned proximate each other and are disposed within the boundaries a space 606 of volume  $V = 430 \text{ dm}^3$  defined by the boundaries of the trunk of the 2007 Mitsubishi Evo 9.

The storage elements are not necessarily limited to cylinders or elements having circular profiles. Storage elements having rectangular, square, triangular, elliptical, arbitrarily configured profiles and other profiles can be considered as tubes (of various lengths) which can be coupled to each other to form containers that conform to the particular shape and contours of a defined space (with defined boundaries) having a volume  $V$  and which fit within the boundaries of the defined space. These tubes may be bent or shaped in various ways so that they fit within a particular defined space delineated by boundaries.

Referring now to FIG. 9, there is shown another embodiment 700 of the storage system of the present invention where each of the storage elements is a U-shaped element 702 that is constructed using a bent cylinder section as in FIG. 3 and two short cylinder sections (similar to FIG. 4) or constructed with an integral one-piece U-shaped section.

Whether constructed as a one piece storage element or a three piece storage element, the cylindrical sections are manufactured in the same or similar fashion (and made with the same materials) as the cylindrical sections described with respect to FIGS. 2-5A. Each of the U-shaped storage elements 702 has the same shape and dimensions. However, one can easily conceive a storage system where all of the storage elements are U-shaped but some or all are of different sizes. Each of the U-shaped storage elements 702 is connected to a common distribution conduit 704 (which may be a cylinder or a pipe or other shape), which serves as a coupling member to all of the U-shaped storage elements 702. Thus, all of the storage elements are coupled to each other via this common conduit. Another conduit 706 is coupled to the distribution conduit 704 as shown. Conduit 706 (similar to conduit 704) can be made and/or manufactured with the same materials and in the same or similar fashion as the storage elements described with respect to FIGS. 2-5A. Conduits 704 and 706 can also be made from any appropriate Hydrogen impervious material; preferably conduits 704 and 706 can be made from stainless steel or the hydrogen impervious material and composite material shell described with respect to the serpentine containers discussed above. The conduits 704 and 706 may be coupled to each other via a threaded T-connector or other well known threaded connector.

FIG. 9A shows a front view of the storage system of FIG. 9 positioned on or adhered to a flat surface 705. Each of the storage elements 702 defines a plane 703 with its U-shape geometry. Thus, each of the storage elements forms an angle  $\theta$  defined by plane 703 and surface 705. The particular value of  $\theta$  will depend on any number of factors including volume V within which the resulting container (comprising a plurality of U-shaped containers coupled to each other via conduit 704) is disposed.

The embodiment shown in FIGS. 9 and 9A is an example of what is referred to as a "straight pipe" design where each of the storage elements is coupled to a common conduit (e.g., a pipe) through which Hydrogen gas is delivered to the various storage elements. Such an arrangement or configuration is relatively more conducive to automated manufacturing and assembly. In particular, each of the storage elements and the common conduit can be made from material similar to the storage elements used in the serpentine containers discussed above. Further, the assembly of the individual storage elements to the common conduit can also be achieved in an automated fashion making the manufacture of such straight pipe designs more efficient and thus relatively less costly than other types of designs. Also, the "straight pipe" design is a modular design approach because one set of

storage elements coupled to a common conduit can be coupled to another similar set. For example, for a given space of volume  $V$ , the embodiment shown in FIG. 9 can be replicated  $K$  times ( $K$  is an integer equal to 2 or greater) and each of the  $K$  straight pipe designs can be coupled to another similarly configured straight pipe design forming a modularized embodiment of the storage system of the present invention. Further, different types of “straight pipe” designs can be coupled to each other to form yet another type of modularized embodiment of the storage system of the present invention.

FIG. 10 shows another straight pipe embodiment of the storage system of the present invention where the storage elements 802 are shaped as capsules and are coupled to a conduit 804 via straight connectors 810. In the example depicted by FIG. 10, there are 16 capsule storage elements. It will be readily understood that the storage system may contain any number of capsules as necessary to meet a particular design requirement. At the ends of the conduit 804, the storage elements are coupled to conduit 804 via right-angled connectors 808. Each of the storage elements is shaped as a capsule; that is, each element is cylindrical in form, but the ends of the cylinder are semi-spherical in shape. Another conduit 812 is coupled to conduit 804 with the use of a T-connector 806 as shown. Conduit 804, straight connector 810, right angle connector 808 and T-connector 806 can all be made from stainless steel or other appropriate Hydrogen impermeable material; these parts can also be made from the same materials used to construct the serpentine containers discussed above.

The storage system shown in FIGS. 9 and 10 are referred to as “straight pipe” systems because each such system has a conduit (704 in FIG. 9 and 804 in FIG. 10) to which the storage elements are coupled. Such an arrangement or configuration of storage elements is more conducive to automated assembly. Further, storage systems using the “straight pipe” configuration or arrangement can be modified more quickly.

The various embodiments described above all comprise storage elements that are cylindrical in shape and appropriately sized and dimensioned such that their relatively small volumes allow the use of relatively inexpensive materials having relatively lower tensile strength and stiffness to construct them. The following embodiment depicts a storage system in which the storage elements are not cylindrical but are arbitrary in shape and dimension and but they have relatively small volumes that allow the use of inexpensive materials in their construction. Thus, for the embodiments described above and the

embodiment to be discussed below (FIGS. 11-13A) Hydrogen of pressure equal to 700 bars or greater can be stored in such storage systems.

FIG. 11 shows a storage system 900 of the present invention having a volume  $V$  of arbitrary shape and dimensions divided into  $N$  different storage elements, which when coupled to each other as shown form the storage system shown in FIG. 11. Arbitrary shape and dimensions mean any space of volume  $V$ , which can be defined by a particular shape with particular dimensions where such shape and dimensions are created in arbitrary fashion or are created for any conceivable purpose. Each of the storage elements has a volume  $V_i \leq \frac{V}{N}$ ; with  $i = 2, 3, 4, 5, \dots, N$  and where each such volume  $V_i$  is relatively small (compared to  $V$ ; i.e.,  $V_i \ll V$ ) such that the materials and techniques used in constructing the storage elements described with respect to FIGS. 1-5A can also be used to construct these storage elements. That is, the storage system of FIG. 11 comprises  $N$  storage elements ( $N$  is an integer equal to 2 or greater) each having a volume  $V_i$  which allows the use of a Hydrogen impermeable material (such as Aluminum) with a fiber-resin shell where the fiber can be made from such materials as Innegra, Basalt or materials with properties similar to those of Innegra and Basalt. When these storage elements are coupled together as shown, they form the storage system of the present invention, viz., a container having a particular shape and volume. The winding of the fiber process or the fiber tubing process described above with respect to the construction of the hardened outer shell for cylindrical storage elements can be used to construct the fiber hardened outer shells of the storage elements for the storage system of FIG. 11.

The particular embodiment shown in FIG. 11 has a shape that conforms to the shape of the volume  $V$  within which this storage system is disposed; that is, the storage system of the present invention has substantially the same or similar shape and has substantially the same dimensions as the available space of volume  $V$  so that the storage system can fit within the defined space or the storage system defines a space that is similar to or is exactly the shape and dimensions of the defined space. Because this embodiment of the storage system of the present invention conforms to the shape of the volume within which it occupies, an efficient use of the volume space can be achieved. The various storage elements are shaped and dimensioned such that when they are all coupled to each other and positioned as shown, the resulting storage system conforms to the shape of the available volume  $V$ . Thus, such an embodiment can be used to replace previous tanks having arbitrary shapes that were used to contain other fuels such as natural gas, gasoline,

liquid fuels and/or other matter. Further, the same space can now be used to store Hydrogen at relatively high pressures (e.g., 700 bars or higher) for various applications such as a vehicle storage system, storage system for generating electricity, storage system for home heating, storage system for industrial applications, storage systems used to transport Hydrogen and other types of storage systems. This particular embodiment of the storage system of the present invention can take on the exact shape or a similar shape of the tanks used to store these various fuels. The storage system shown in FIG. 11 can be described as having three layers  $L_1$ ,  $L_2$ , and  $L_3$  and three sections  $S_1$ ,  $S_2$  and  $S_3$  as shown. Thus, the storage elements are coupled to each other to form a container comprising one or more sections.

Referring now to FIG. 12, the storage system of FIG. 11 is shown with a detailed depiction of section  $S_1$ . As with the other sections, Section  $S_1$  comprises three layers 902, 904 and 906, which are portions of layers  $L_1$ ,  $L_2$ , and  $L_3$  respectively. As shown for this specific storage system, each of the layers (902, 904 or 906) comprises seven (7) storage elements coupled together via openings in the same or similar manner as the storage elements of the serpentine storage elements discussed above. Layer 902 of section  $S_1$  comprises storage elements 902A, 902B, 902C, 902D, 902E, 902F and 902G. Layer 904 of section  $S_1$  comprises storage elements 904A, 904B, 904C, 904D, 904E, 904F and 904G. Layer 906 of section  $S_1$  comprises storage elements 906A, 906B, 906C, 906D, 906E, 906F and 906G.

Referring now to FIG. 13, an exploded perspective view of section  $S_1$  is shown. More particularly, FIG. 13 illustrates how each of the layers forms a portion of section  $S_1$ . Referring temporarily to FIG. 13A, there is shown how storage element 902A is coupled to 902B via openings 903A and 903B. The openings at which the storage elements 902A and 902B are coupled can be tapered in complementary fashion (not shown) to promote coupling. Another embodiment of this storage system may have a circular opening (not shown) at the side where openings 903A and 903B are located and a cylindrical tube can then be used to couple the two storage elements 902A and 902B together. Various other methods and techniques can be used to properly couple the storage elements to each other. The methods and techniques shown and discussed do not at all represent the entire set of techniques and methods that can be used to couple the storage elements of the storage system of the present invention to each other. It should be noted that sections of storage elements or individual storage elements are said to be "coupled" to each other when their openings align with each other to define a container for Hydrogen with virtually no leakage.

However, storage elements which are attached to each other or which are positioned in relatively close proximity to each other mean storage elements that are placed physically sufficiently close to each other but are not necessarily "coupled" to each other.

Referring back to FIG. 13, each of the storage elements of each layer has at least one opening to allow the coupling of each such storage element to adjacently positioned storage elements of that layer. It will be clear from a review of FIGS. 12 and 13 that except for storage element 902A, each of the storage elements 902B-902G has two openings. Further, storage element 902G couples to storage elements of different layers and is thus a layer coupling storage element as its opening 1000A aligns with an opening 1000B of storage element 904G of layer 904. Layer 904 comprises storage elements 904A-904G. Similar to layer 902, each of the storage elements of layer 904 has two openings. Storage element 904A, however, is also a layer coupling storage element as its opening 2000A is aligned with opening 2000B of storage element 906A of layer 906. Layer 906 comprises storage elements 906A-906G. When the three layers 902, 904 and 906 are coupled to each other via the layer coupling storage elements as discussed, they define a space or section  $S_1$ . A similar arrangement can be constructed in sections  $S_2$  and  $S_3$  and all three sections can be coupled ( $S_1$  to  $S_2$  and  $S_2$  to  $S_3$ ) to define the overall space of this embodiment of the storage system of the present invention. For example, section  $S_1$  can be coupled to section  $S_2$  via openings (not shown) at particular adjacently positioned storage elements from sections  $S_1$  and  $S_2$ . Further, section  $S_2$  can then be coupled to section  $S_3$  also via openings (not shown) at particular adjacently positioned storage elements from these two sections. The three sections can be coupled as described above and positioned in close proximity to each other (or attached to each other) to form the storage system of the present invention as depicted in FIG. 11. Thus a plurality of the  $N$  storage elements are coupled to each other to form one or more sections each of which is coupled to another section and can be attached or positioned in relatively close proximity to each other so that all the sections fit within the space of volume  $V$  having an arbitrary shape and dimensions that conform to the shape of the embodiment of the storage system of the present invention as shown in FIG. 11. The coupled sections  $S_1$ ,  $S_2$ , and  $S_3$ , form a container, which conforms to the shape and dimensions of the defined space of volume  $V$ . The coupled sections may form more than one container all of which when coupled together may conform to the shape and dimensions of the defined space of volume  $V$  and/or may fit within the boundaries of the defined space of volume  $V$ .

The storage system of the present invention has been described in terms of storage elements that are coupled to each other to form containers within which Hydrogen is stored to power vehicles. It will be readily obvious however that the Hydrogen storage system of the present invention can be used for storage systems for various other applications such as storage systems for vehicles used to distribute Hydrogen to refill stations. These vehicles transport large amounts of Hydrogen in large tanks; the storage system of the present invention can be used to replace these large tanks. The transported Hydrogen is delivered to refill stations for vehicles and is stored in storage tanks at those locations. Further the transported Hydrogen can be delivered to households or places of business, which use the delivered Hydrogen for heating systems and electricity generating systems. The storage system of the present invention can thus be used to transport Hydrogen to distribute the Hydrogen to refill stations. The present invention can be used to store Hydrogen at the refill stations. Further, the storage system of the present invention can be used to store Hydrogen in households or commercial buildings for heating or for generating electricity. Yet further, containers built in accordance with the storage system of the present invention and which are located at power stations can be used to generate electricity.

The storage system of the present invention has been described in terms of the various embodiments disclosed herein. It will be readily understood that the various embodiments discussed do not at all limit the scope of the present invention. One of ordinary skill to which the present invention belongs can, after reading this specification and the claims, implement the storage system of the present invention using other embodiments and implementations that are different from those disclosed herein but which are well within the scope of the claimed hydrogen storage system of the present invention.

**CLAIMS**

1. A Hydrogen storage system to be disposed within a defined space of volume  $V$ , the hydrogen storage system comprising:

5         $N$  storage elements coupled to each other to form one or more containers that fit within the defined space where each storage element has a volume equal to a fraction of the volume  $V$  and  $N$  is an integer equal to 1 or greater.

2. The Hydrogen storage system of claim 1 where each of the storage elements has a  
10        volume and shape that are the same as other storage elements.

3. The Hydrogen storage system of claim 1 where some or all of the storage elements have different volumes and shapes.

4. The Hydrogen storage system of claim 1 where each of the storage elements has an  
15        inner layer made of hydrogen impermeable material and an outer layer made from a composite material.

5. The Hydrogen storage system of claim 1 further comprising one or more other containers  
20        not made from coupled storage elements and the one or more other containers are positioned proximate the one or more containers such that both types of containers fit within the defined space of volume  $V$ .

6. The Hydrogen storage system of claim 1 where the storage elements comprise long  
25        cylinders, short cylinders and bent cylinders all of which have an inner layer with equal inner and outer diameters and with corresponding inner and outer surfaces and where such inner layer is made from aluminum of a certain thickness.

7. The Hydrogen storage system of claim 6 where the bent cylinders are curved cylinders  
30        with a curve radius equal to  $k \cdot D_o$  where  $k$  is an integer equal to a real number greater than zero and  $D_o$  is the outer diameter of the bent cylinder.

8. The Hydrogen storage system of claim 7 where  $k$  is equal to 2.

9. The Hydrogen storage system of claim 6 where the long cylinders, short cylinders and bent cylinders are coupled to form a serpentine cylindrical container having the inner layer and an outer layer made of a composite material adhered to the outer surface of the inner layer.

5 10. The Hydrogen storage system of claim 9 where the outer layer comprises resin applied to the outer surfaces of the inner layer and Basalt fibers wound onto the resin applied to the outer surfaces of the inner layer at a 45 degree angle with respect to a longitudinal axis of each of the coupled storage elements.

10 11. The Hydrogen storage system of claim 9 where the outer layer comprises resin applied to the outer surfaces of the inner layer and Innegra fibers wound onto the resin applied to the outer surfaces of the inner layer at a 45 degree angle with respect to a longitudinal axis of each of the coupled storage elements.

12. The Hydrogen storage system of claim 9 comprising a plurality of serpentine containers positioned proximate each other to fit within the defined space of volume V.

15 13. The Hydrogen storage system of claim 6 where the long cylinders, short cylinders and bent cylinders are coupled to form one or more serpentine cylindrical containers and one or more other containers not formed from the long cylinders, short cylinders and bent cylinders and all of the containers are positioned proximate each other to fit within the defined space of volume V.

20 14. The Hydrogen storage system of claim 13 where the one or more other containers are spherical containers.

15. The Hydrogen storage system of claim 6 where each of the storage elements has a circular cross section profile.

25 16. The Hydrogen storage system of claim 6 where the storage elements have different cross section profiles.

17. The Hydrogen storage system of claim 1 where the storage elements are coupled to each other via a common distribution conduit.

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18. The Hydrogen storage system of claim 17 where the storage elements are U-shaped cylinders.

19. The Hydrogen storage system of claim 17 where the storage elements are capsules.

20. A Hydrogen storage system to be disposed within a defined space of volume V having an arbitrary shape and dimensions, the hydrogen storage system comprising:

N storage elements each having a volume equal to or less than  $\frac{V}{N}$  where N is an integer equal to 2 or greater and the storage elements are coupled to each other to form a container that conforms to the shape and dimensions of the defined space.

21. The Hydrogen storage system of claim 20 where the container comprises one or more sections coupled to each other and positioned in relatively close proximity to each other or are attached to each other.

22. The Hydrogen storage system of claim 21 where each of the sections comprises a plurality of the N storage elements coupled together.

23. The Hydrogen storage system of claim 20 where each of the storage elements is made from a Hydrogen impermeable material having an outer surface to which a composite material is adhered.

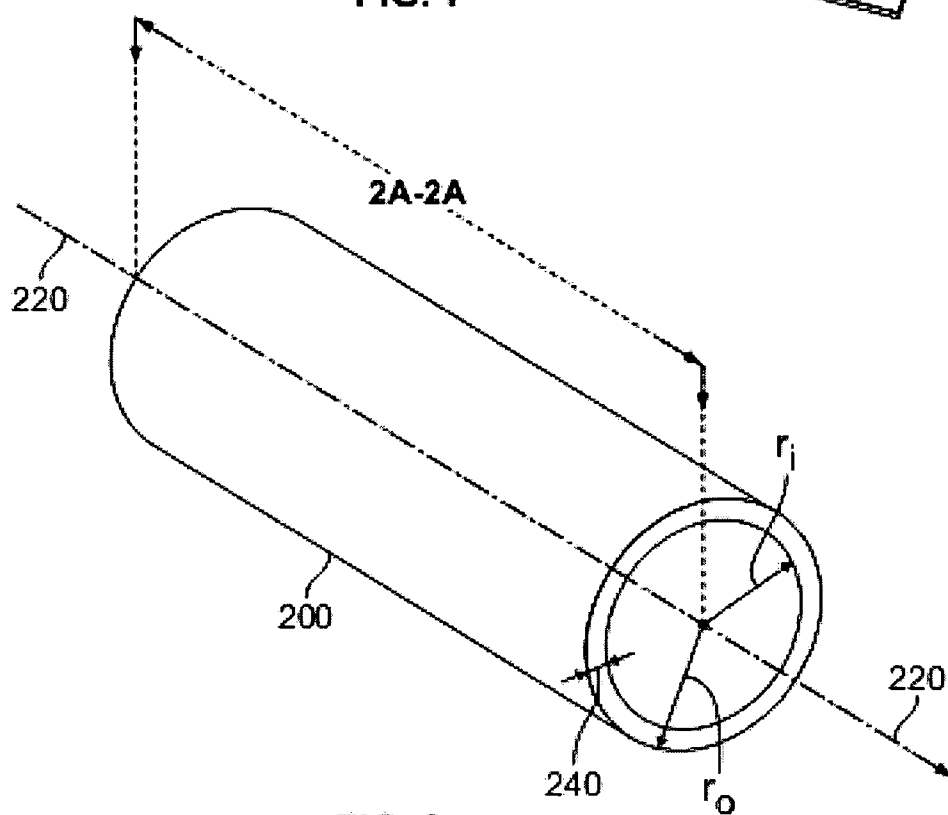
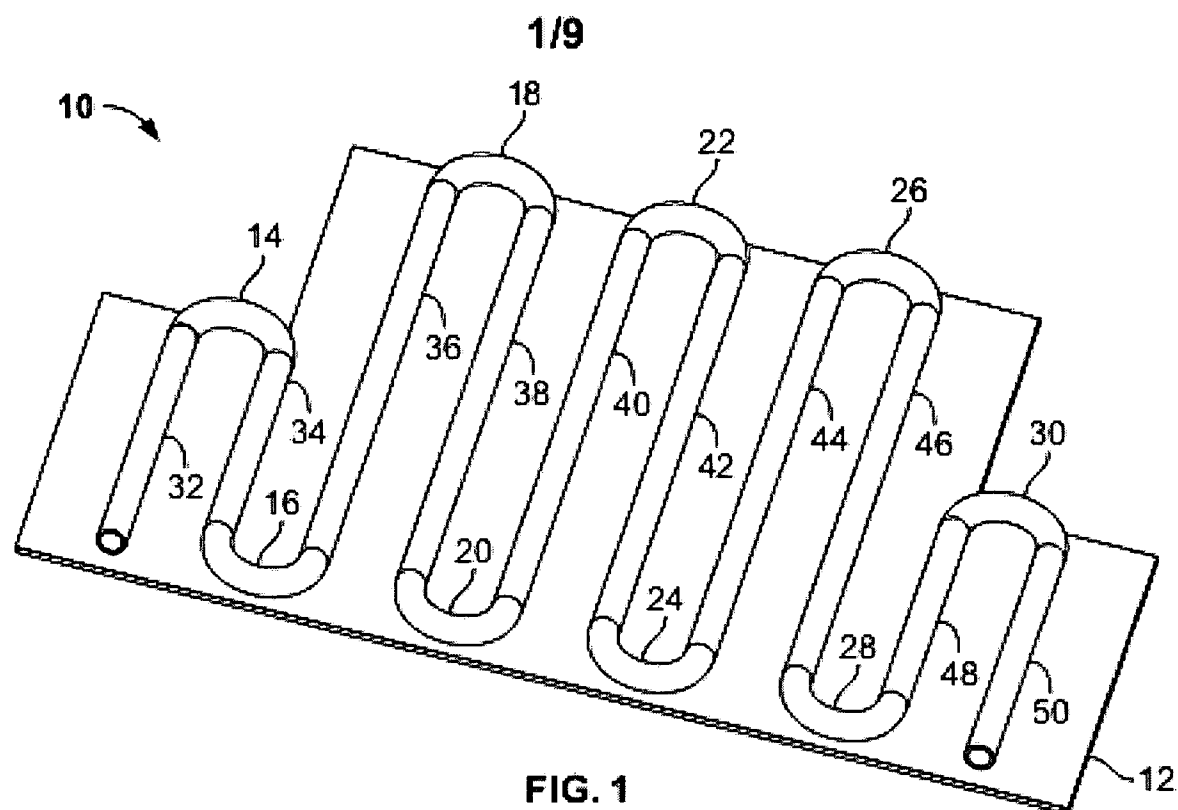
24. The Hydrogen storage system of claim 23 where the composite material comprises resin and fibers made from Basalt rock.

25. The Hydrogen storage system of claim 23 where the composite material comprises resin and fibers made from Innegra.

26. A Hydrogen storage system to be disposed within a defined space of volume V having an arbitrary shape and dimensions, the hydrogen storage system comprising:

N storage elements each having a volume equal to or less than  $\frac{V}{N}$  where N is an integer equal to 2 or greater and the storage elements are coupled to each other to form one or more containers that fit within the defined space.

27. The Hydrogen storage system of claim 26 where the one or more containers are coupled to each other.



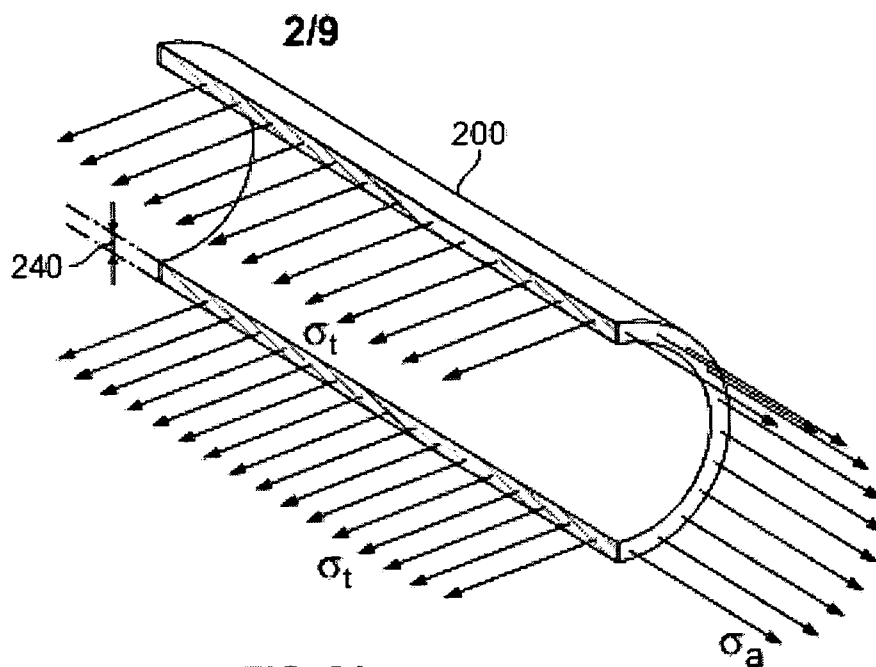


FIG. 2A

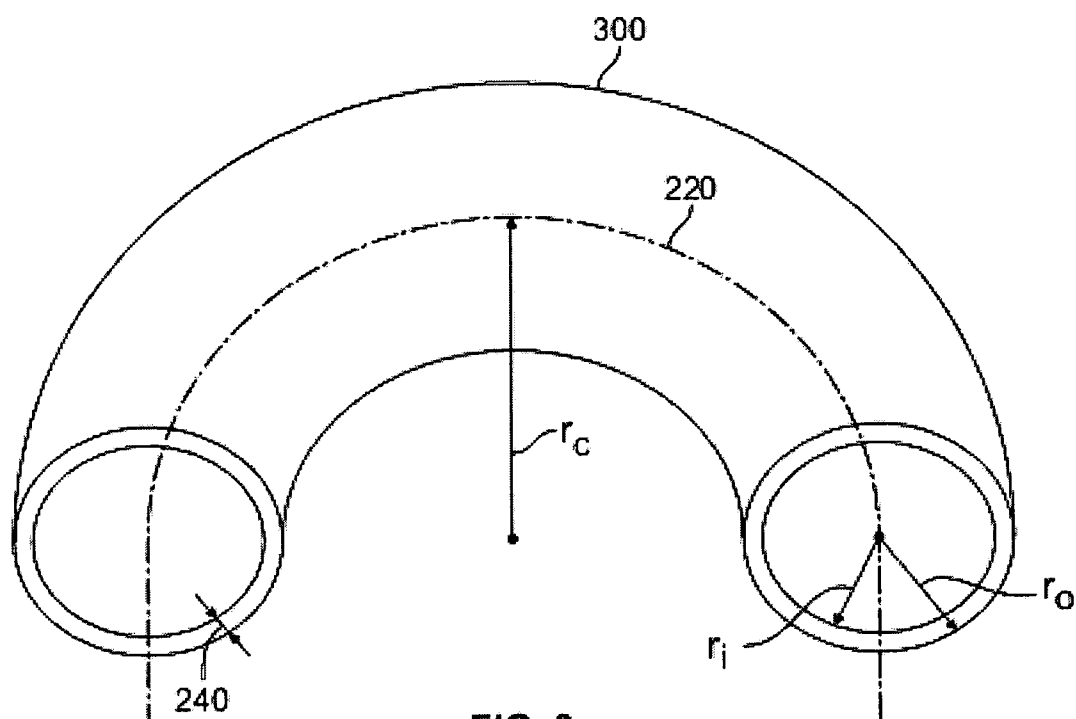


FIG. 3

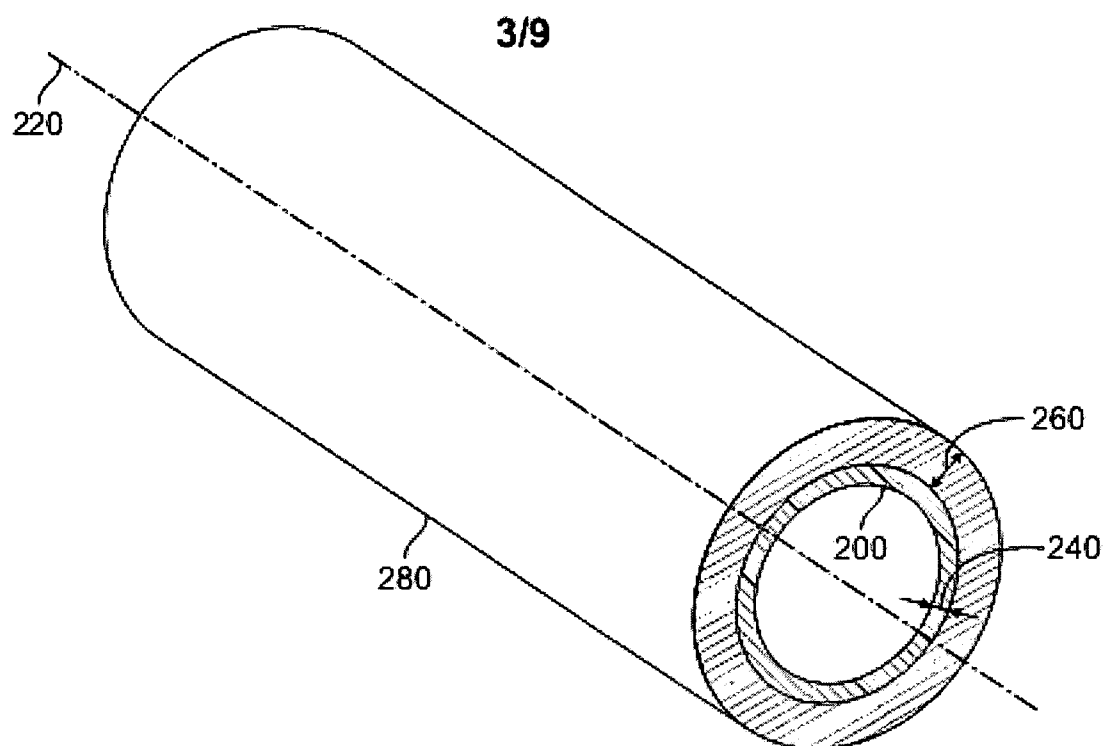


FIG. 4

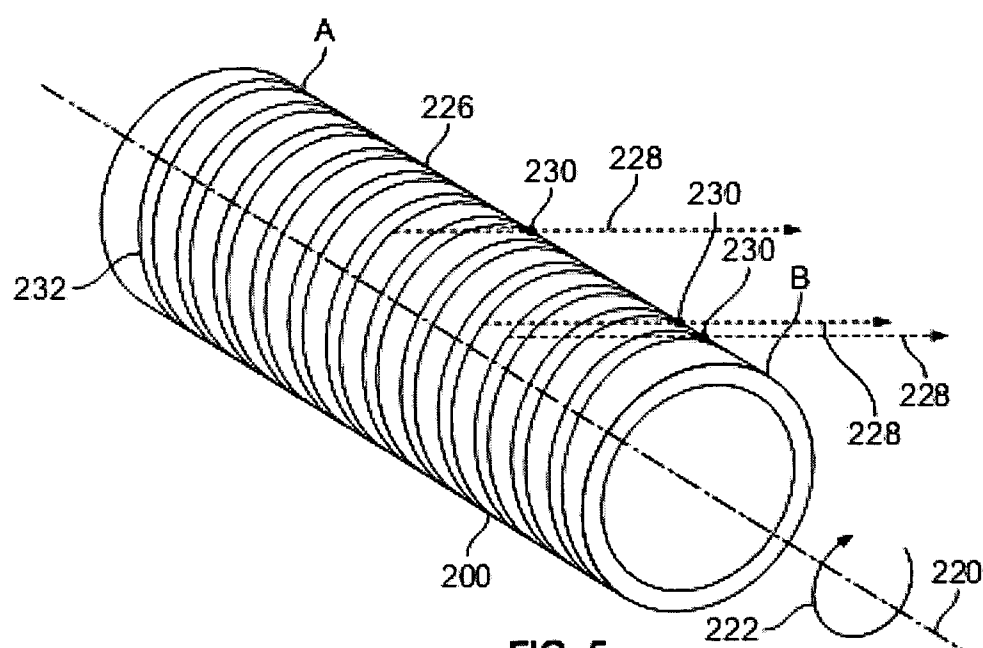
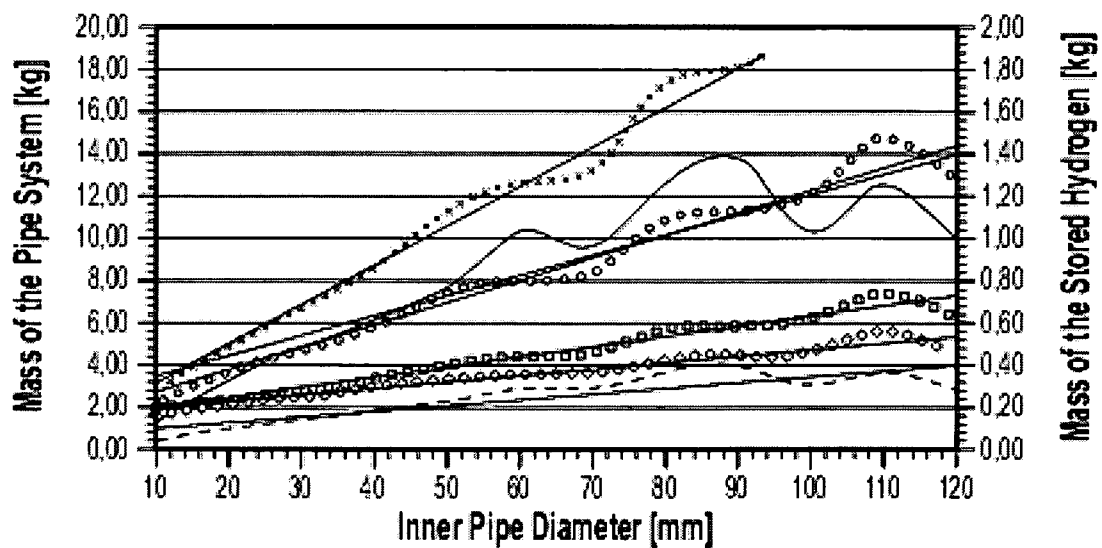
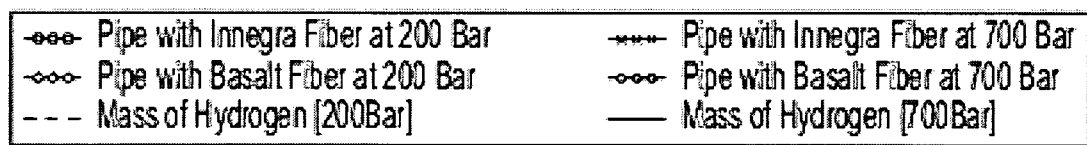
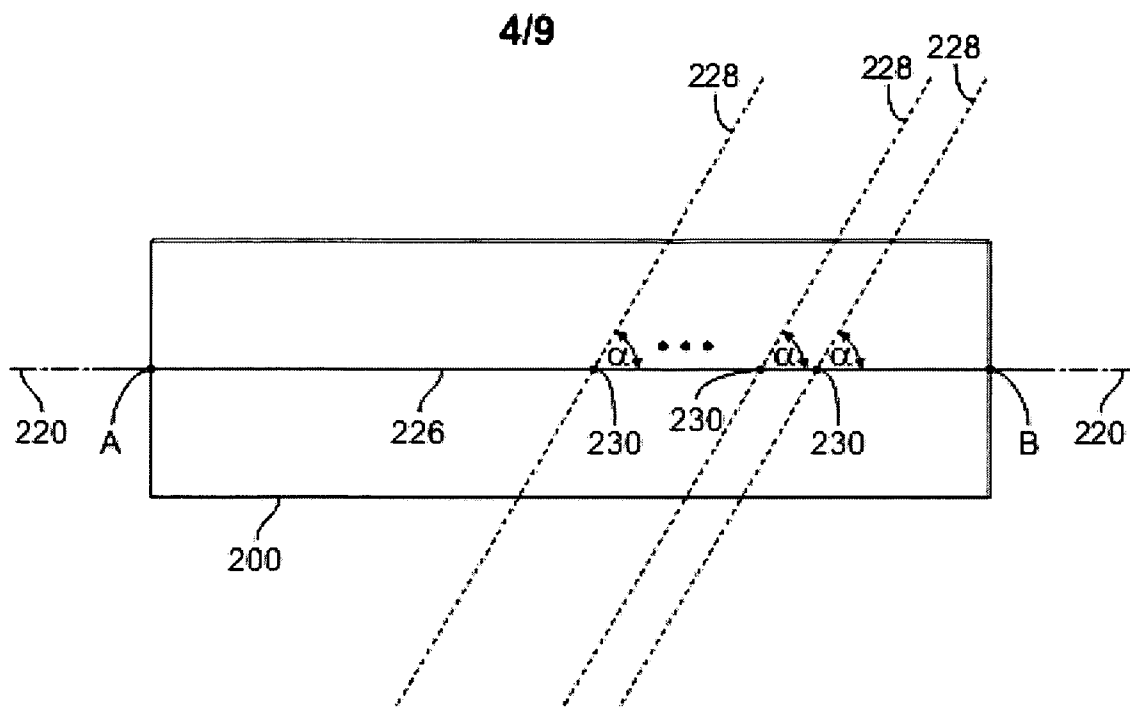


FIG. 5



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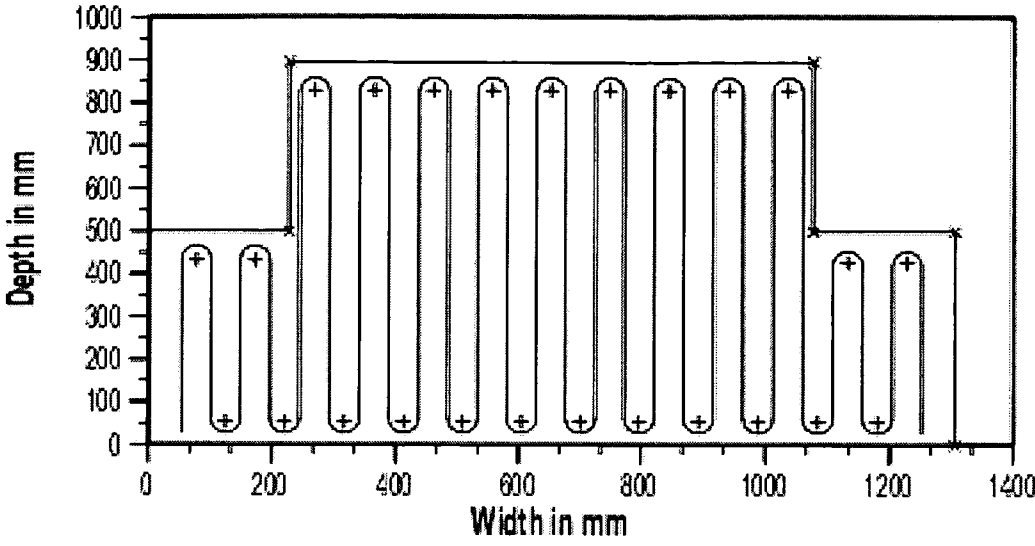


FIG. 7

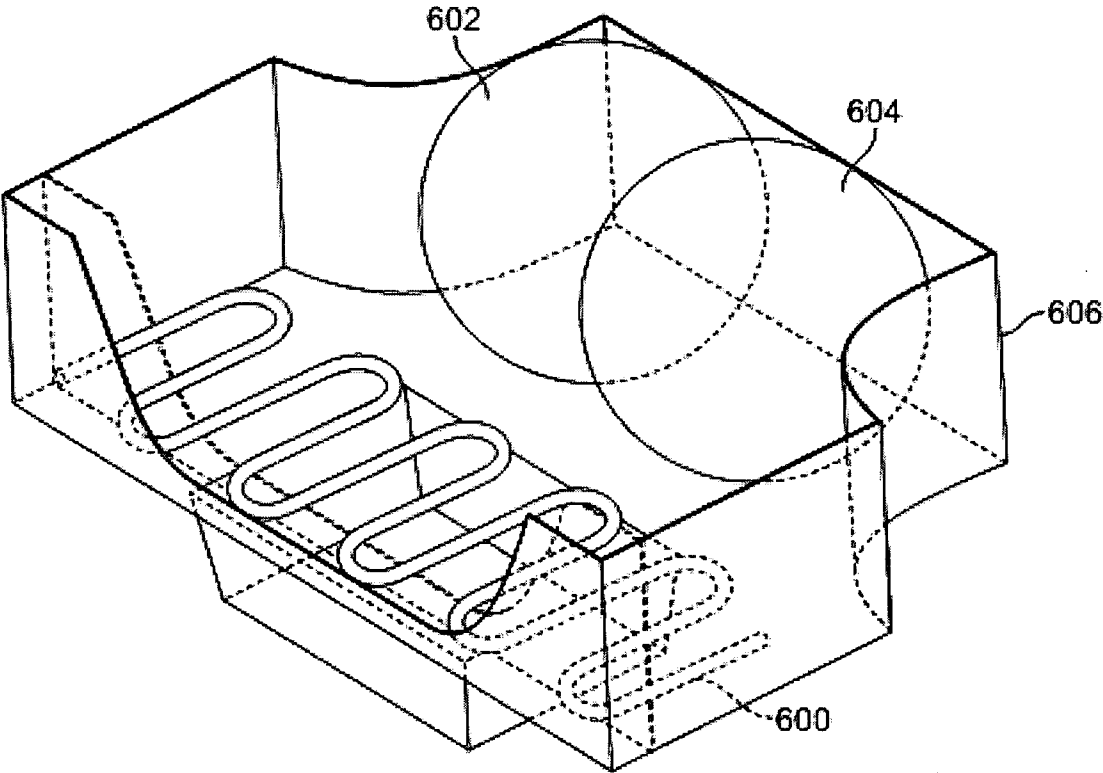


FIG. 8

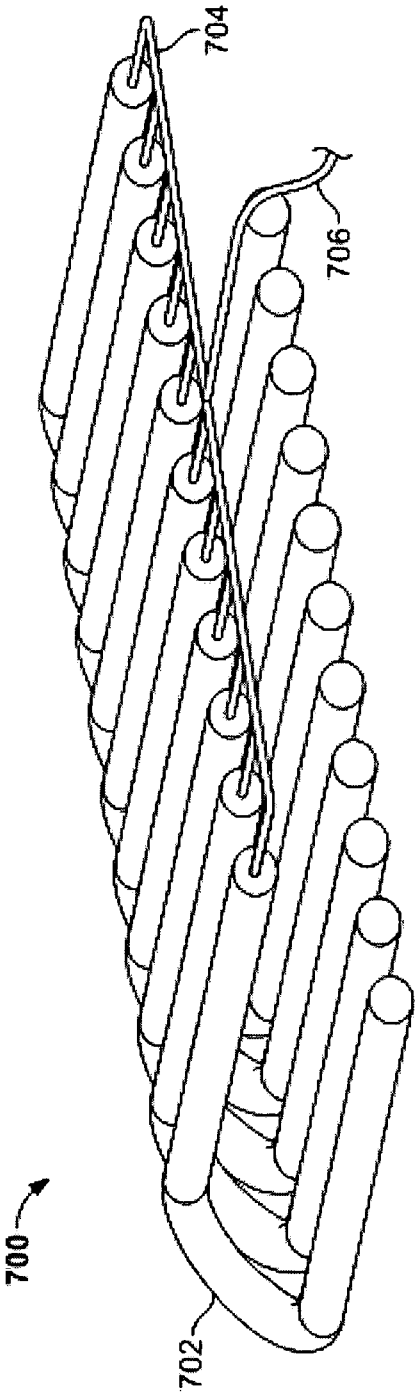


FIG. 9

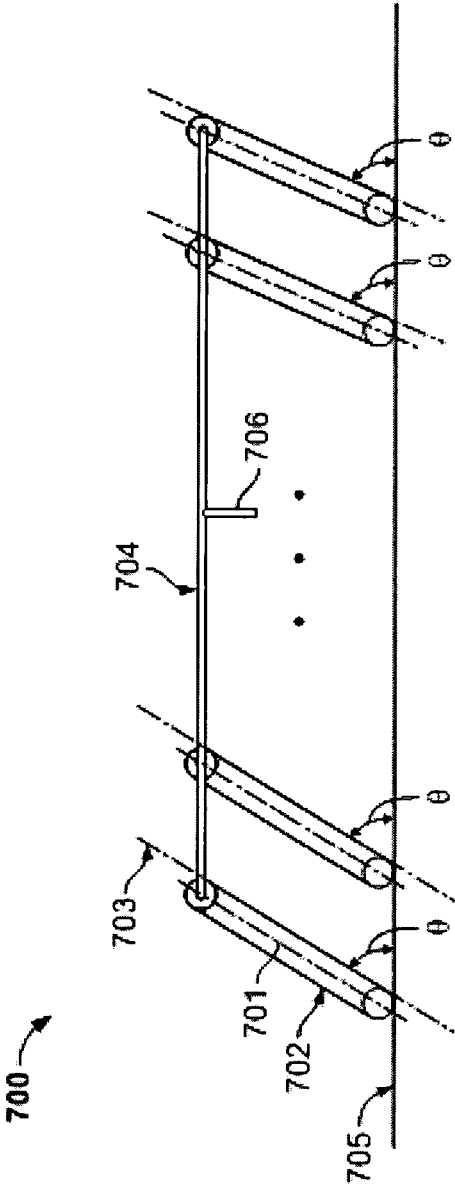
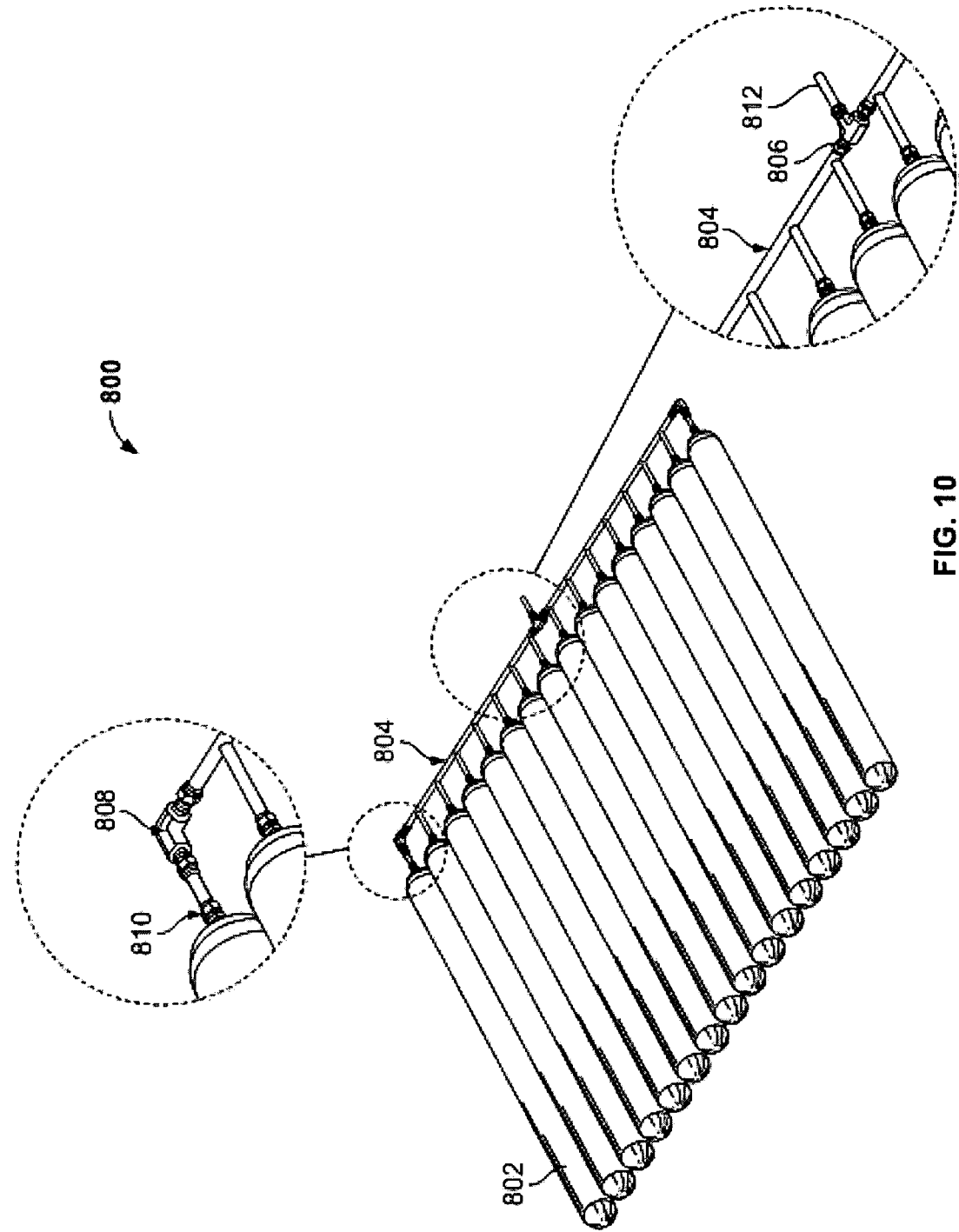


FIG. 9A



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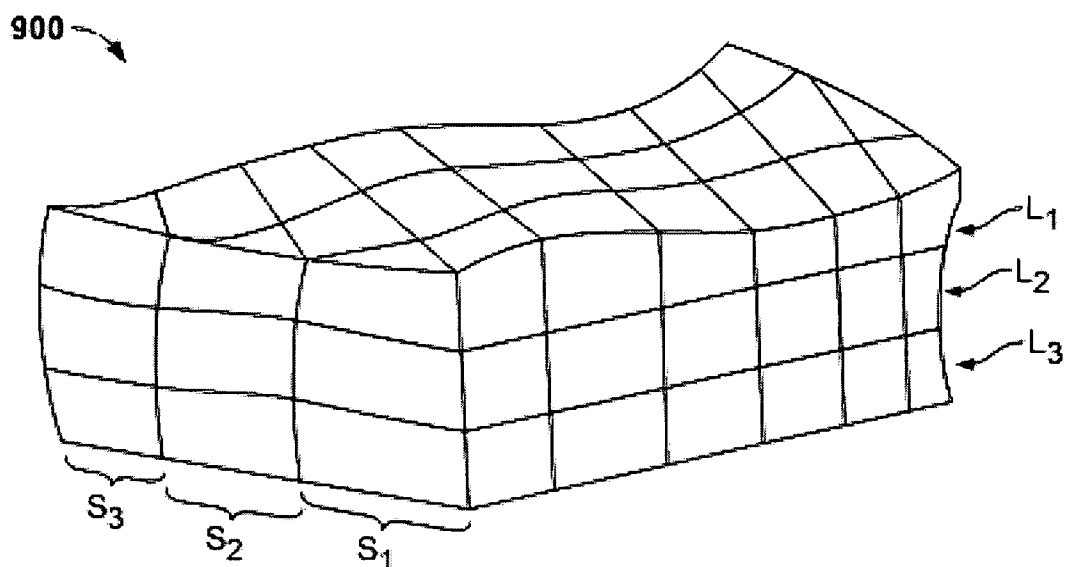


FIG. 11

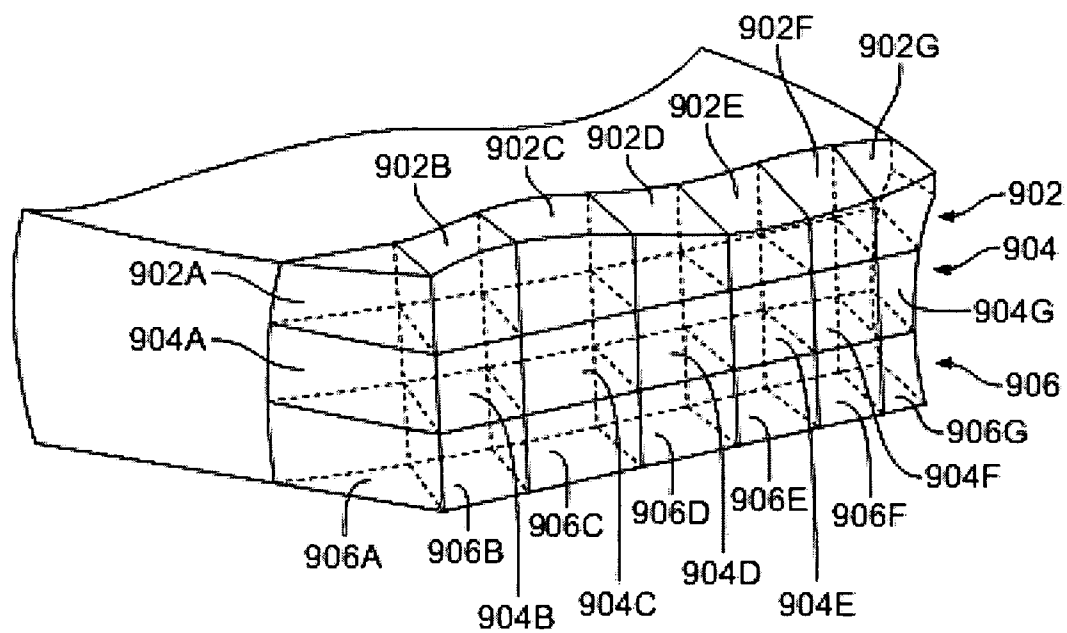


FIG. 12

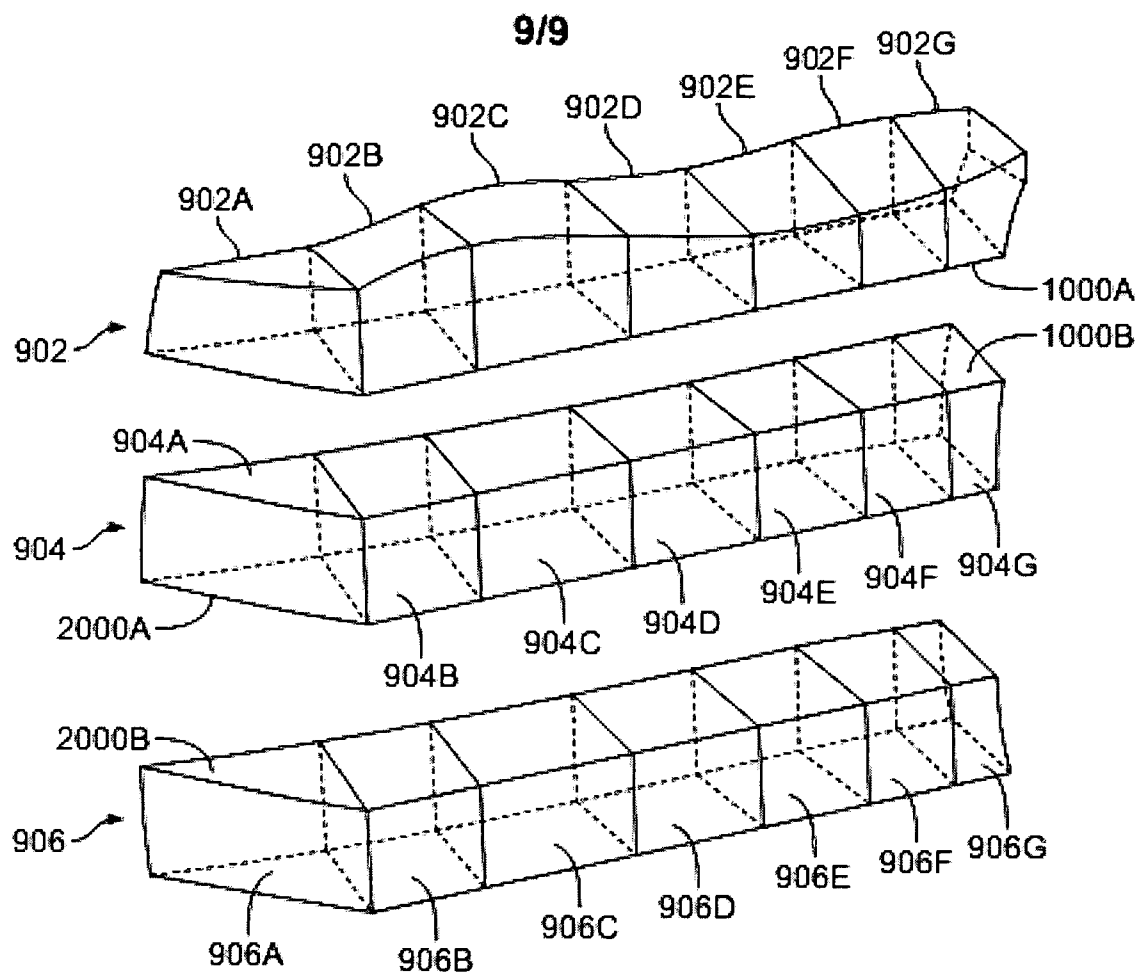


**FIG. 13**

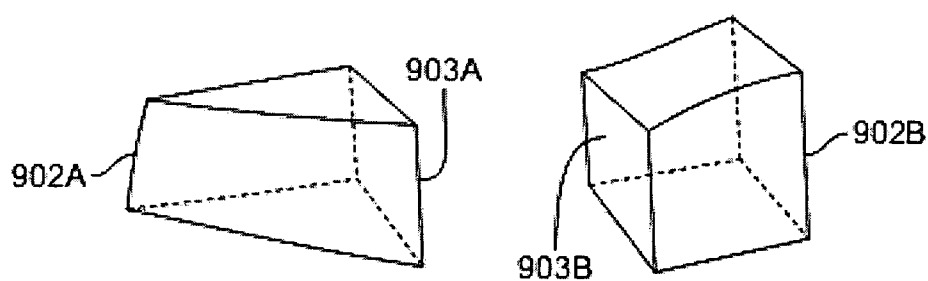


**FIG. 13A**