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**SHAPE MEMORY ALLOY COMPOSITE FABRIC**

**PRESSURE VESSEL AND DIVING SUIT**

**STATEMENT OF GOVERNMENT INTEREST**

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

**CROSS REFERENCE TO OTHER PATENT APPLICATIONS**

[0002] None.

**BACKGROUND OF THE INVENTION**

**1) Field of the Invention**

[0003] The invention relates to pressure vessels and specifically an underwater diving suit.

**(2) Description of the Related Art**

[0004] Some diving operations require long transits at depth. Conventional gear for such long transits include diving bells and atmospheric diving suits (ADS). The use of conventional gear limits the duration of dives and diver mobility as well as requiring ancillary equipment for the dives.

[0005] A conventional ADS is a one-person articulated anthropomorphic submersible with pressure joints that allow

articulation while maintaining an internal pressure of one atmosphere. The articulatable joints in the arms and legs do not contain shape memory alloys. Conventional ADS allows the diver to descend deep underwater without the hazards associated with traditional diving methods. An example of a conventional ADS **26** is shown in the prior art view of **FIG. 1**. In the figure, the ADS **26** connects via an umbilical cable **46** to a surface vessel **48**. The umbilical cable **46** supplies breathing gas, electrical power and communications to the human being in the ADS **26**.

**[0006]** The ADS **26** includes hollow arm spaces with pressure resistant joints to carry manually-operated manipulators and hollow leg spaces that are similarly articulated for locomotion. Joint seals allow articulation while maintaining internal pressure. The ADS **26** isolates the human being occupant from the pressure of the underwater environment.

**[0007]** The conventional ADS **26** includes a plurality of articulable rotary joints on each arm portion and leg portion. In the illustrated ADS **26**, there are four articulable rotary arm joints **27, 28, 29** and **30** for a right arm portion **38**, four articulable rotary arm joints **27, 28, 29** and **30** for a left arm portion **40**, four articulable rotary leg joints **31, 32, 33** and **34** for a right leg portion **42** and four articulable rotary leg joints **31, 32, 33** and **34** for a left leg portion **44**. Other

conventional ADS may use other joints in each arm and leg portion. The arm joints or leg joints in the conventional ADS **26** do not have shape memory alloys that change from martensite to austenite or vice versa during operation of the ADS **26**.

**[0008]** While using the ADS **26**, the diver performs work as well as traveling to and from the place where the work is being done. These functions require sufficient mobility, dexterity and sensory input with the work in an ADS **26** limited by the construction of the suit.

**[0009]** Potential solutions exist, but the solutions fail to solve the challenge in an operationally effective way due to limited degrees of freedom, the requirement of constant volume, and the high complexity leading to reliability concerns. Although new bendable joints have the potential to mitigate these issues, compromises to mobility and maneuverability, still exist as long as a maneuverable and rigid exoskeleton is required. As such, a need exists for diving gear that overcomes the limitations of conventional ADS diving suits.

#### **BRIEF SUMMARY OF THE INVENTION**

**[0010]** A pressure vessel is provided for underwater use in which the vessel includes a shape memory alloy (SMA) composite fabric having a martensite phase and an austenite phase.

**[0011]** In the martensite phase, the SMA composite fabric is elastic. In the austenite phase, the SMA composite fabric is rigid to form the pressure vessel with the pressure vessel defining an interior volume large enough to contain an adult human. The shape memory alloy composite fabric can withstand ambient hydrostatic pressure at the water depth where the pressure vessel is deployed.

**[0012]** In another embodiment, a hybrid atmospheric diving suit includes an articulated anthropomorphic submersible diving suit having a plurality of joints in a right arm, a left arm, a right leg and a left leg portion of the diving suit. At least one of the joints includes a shape memory alloy composite fabric. Each of the right arm, the left arm, the right leg and the left leg portions of the suit includes one or more joints made of the shape memory alloy composite fabric.

**[0013]** The shape memory alloy composite fabric joints are rigid in an austenite phase to maintain a pressure of one atmosphere in an interior of the suit. The shape memory alloy composite fabric joints are flexible in a martensite phase to enable freedom of movement in the joints.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0014]** Other objects, features and advantages of the present invention will become apparent upon reference to the following

description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0015] **FIG. 1** is a diagram of a prior art atmospheric diving suit;

[0016] **FIG. 2** is a shape memory alloy pressure vessel in the martensite phase;

[0017] **FIG. 3** is a depiction of the pressure vessel as the pressure vessel transforms to the austenite phase;

[0018] **FIG. 4** is a flow chart for a method of use of a shape memory alloy emergency pressure vessel;

[0019] **FIG. 5** is a hybrid atmospheric diving suit with shape memory alloy composite fabric joints;

[0020] **FIG. 6** is a flow chart of a method of use for diving using a hybrid atmospheric diving suit;

[0021] **FIG. 7** is a flow chart of a method of use for emergency retrieval using the hybrid atmospheric diving suit;

[0022] **FIG. 8** is a cross-sectional view of shape memory alloy composite fabric used in the present invention;

[0023] **FIG. 9A** is a first view of the shape memory alloy composite fabric joint of the present invention;

[0024] **FIG. 9B** is a second view of the shape memory alloy composite fabric joint;

[0025] **FIG. 9C** is a third view of the shape memory alloy composite fabric joint;

[0026] **FIG. 10A** illustrates a first operational mode of a shape memory alloy composite fabric joint of the present invention;

[0027] **FIG. 10B** illustrates a second operational mode of the shape memory alloy composite fabric joint;

[0028] **FIG. 10C** illustrates a third operational mode of the shape memory alloy composite fabric joint;

[0029] **FIG. 11A** illustrates a first example of a shape memory alloy composite fabric joint of the present invention;

[0030] **FIG. 11B** illustrates a second example of a shape memory alloy composite fabric joint;

[0031] **FIG. 11C** depicts a first exemplary shape in a shape memory alloy joint;

[0032] **FIG. 11D** depicts a second exemplary shape in the shape memory alloy joint; and

[0033] **FIG. 11E** depicts a third exemplary shape in the shape memory alloy joint.

#### **DETAILED DESCRIPTION OF THE INVENTION**

[0034] Pressure vessels and diving suits may be made with SMAs (shape memory alloys). The shape memory alloys are components of a fabric used to make the pressure vessels and

diving suits. The SMA composite fabric suit prioritizes maneuverability and lightness; yet still offers a traditional atmospheric diving suit in a compact, foldable, woven hyperbaric fabric-based design.

**[0035]** The manufacture and functionality of shape memory alloys are known. Shape memory alloys exhibit a crystallographically reversible martensitic transformation. At high temperatures, the shape memory alloy exists as an austenite phase (the parent or memory phase) with a long range order. Upon cooling below a transformation temperature, the austenite transforms to a thermoelastic martensite whose structure has numerous variants, typically sheared platelets.

**[0036]** Because the martensitic structure is self-accommodating, the deformation or transformation to martensite is zero. The martensite deforms by a twinning mechanism that transforms the different variants to the variant that can accommodate maximum elongation in the direction of an applied force. The interfaces between platelets in the martensite phase slip very readily and the material deforms at low applied stresses. The austenite phase has only one possible orientation. Thus, when heated, the deformed structures of the martensite phase revert to this orientation of the austenite memory phase and the material recovers an original shape.

**[0037]** The transformation temperature is a function of the alloy type, composition and the applied thermomechanical treatments. Alloys with transformation temperatures below -100C and above 150C are known. The heating and cooling transformations do not overlap and the transformation exhibits hysteresis. The magnitude of the hysteresis varies with the alloy type and is typically in the range of 10C - 50C.

**[0038]** Examples of shape memory alloys are Nitinol, which may have a hysteresis as low as 15 degrees Centigrade; and Copper-Zinc, which may have a hysteresis as low as 10 degrees Centigrade. Other shape memory alloys include Silver-Cadmium and Gold-Cadmium.

**[0039]** Shape memory alloys change shape to a pre-set memory geometry (austenite phase) upon the application of heat, such as an electrical current or an exothermic chemical reaction. Shape memory alloys are available in thin-gauge wire form and may be interwoven into a fabric material that enables freedom of movement when the shape memory alloys are not activated (martensite phase).

**[0040]** When electrically activated (heated), the shape memory alloys fibers become rigid and conform to a pre-determined shape. This shape memory alloy composite fabric material, along with a waterproof coating, offers minimal mobility restriction

when disengaged but stiffens into a rigid pressure vessel when activated.

**[0041]** The shape memory alloys may be used to construct an emergency pressure vessel of a size to accommodate an adult human. The emergency pressure vessel may also be used as a decompression chamber. As shown in **FIG. 2**, in the elastic, martensite phase, the SMA pressure vessel **100** is foldable for storage. In one example, the folded pressure vessel **100** may be stored in an underwater vessel for emergency use.

**[0042]** As shown in **FIG. 3**, when removed from storage, the pressure vessel **100** transforms to a memory phase (austenite), such as a sphere, cylinder or another shape in which a human can fit comfortably. The hardening vessel **100** with the human inside may be ejected from the underwater vessel where the shape memory alloy fully hardens to the austenite phase. Supplemental oxygen may be included inside the vessel **100**. Because the vessel **100** is filled with air at one atmosphere pressure, the vessel floats to the surface for eventual retrieval.

**[0043]** The shape memory alloy composite fabric of the pressure vessel **100** may be in the martensite phase at a temperature below the ocean water temperature of 4 to 20 degrees Centigrade and so may be stored in a suitable cooled compartment in the underwater vessel. Then, when exposed to the ambient air in the underwater vessel and subsequently the ocean water; the

shape memory alloy in the fabric of the pressure vessel **100** transforms to the austenite or memory phase. In the austenite phase, the shape memory alloy is rigid such that the composite fabric of the pressure vessel **100** can withstand the ambient hydrostatic pressure of the ocean water.

**[0044]** Alternatively, the pressure vessel **100** may be stored at the ambient temperature in the underwater vessel and supplied with an optional heating source. The optional heating source may be a battery bank that is wired to the shape memory alloy in the pressure vessel **100** or an exothermic chemical heat source. When the pressure vessel **100** is unfolded, the shape memory alloy is heated by electrical current from the battery bank until the shape memory alloy become rigid and transforms to the austenite phase. The heating source maintains the shape memory alloy in the austenite phase as the pressure vessel **100** with the human inside floats to the water surface for retrieval.

**[0045]** As an expeditionary pressure vessel or decompression chamber, the shape memory alloy only needs to statically maintain shape so that the pressure vessel **100** can be stored at one temperature cooler than typical water temperatures (4 to 20 deg C) and transform shapes as affected by an ambient water temperature. Alternatively, the pressure vessel **100** may be stored at room temperature and deployment involves a heating system.

[0046] **FIG. 4** is a flow chart illustrating a method of using the shape memory alloy pressure vessel **100**. In step **S1**, in the martensite phase, the pressure vessel **100** is stored in folded form in an underwater vehicle. In step **S2**, the pressure vessel **100** is removed from storage and begins transformation to the austenite phase via ambient temperature or by a heating method. In step **S3**, a human enters the pressure vessel **100** at one atmosphere pressure while in the underwater vehicle. In step **S4**, the pressure vessel **100** is ejected from the underwater vehicle into water and the pressure vessel completes transformation to the austenite phase. In step **S5**, the human and the pressure vessel **100** float to the surface of the water for retrieval.

[0047] **FIG. 5** is a hybrid atmospheric diving suit **200** including shape memory alloy composite fabric joints. The hybrid atmospheric diving suit **200** has at least one joint in each of a right arm, a left arm, a right leg and a left leg portion of the diving suit. In the hybrid atmospheric diving suit **200**, one or more shape memory alloy composite fabric joints substitute for one or more of the conventional atmospheric diving suit joints.

[0048] There is at least one shape memory alloy composite fabric joint in at least one of the limb portions **202**, **204**, **206**, or **208**. There also may more than one shape memory alloy

composite fabric joint in each limb portion **202**, **204**, **206** and **208**. In the illustrated atmospheric diving suit **200**, there are three shape memory alloy composite fabric joints **210**, **212** and **210** in each arm (limb) portion **202** and **204**. There are three shape memory alloy composite fabric joints **216**, **218** and **220** in each leg (limb) portion **206** and **208**. In another embodiment, all of the joints in all of the limb portions **202**, **204**, **206** and **208** are shape memory alloy composite fabric joints.

**[0049]** The shape memory alloy composite fabric joints incorporated into the hybrid diving suit **200** offer a logistically minimalist compromise between the long-duration benefits of the conventional atmospheric diving suit **26** and the freedom of movement enjoyed by conventional ambient pressure divers at intermediate depths (25 to 185 meter depths). During long transits at depth, a diver may be held at atmospheric pressure (and temperature) by the hybrid diving suit **200**. During the long transits at depth, the shape memory alloy composite fabric joints are rigid in the austenite phase to maintain a pressure of one atmosphere in the interior of the hybrid diving suit **200** while the human being transits underwater to and from an underwater work site. The transformation of the shape memory alloy composite fabric joints from martensite to austenite are affected by heat generated by electrical current supplied to the shape memory alloy wires or threads.

**[0050]** The electrical current may be supplied by the umbilical cable **46** or a battery pack mounted on the hybrid diving suit **200**. Transformation of the shape memory alloy composite fabric joints from the austenite phase to the martensite phase are affected by reducing or eliminating the heat generated by the electrical current and subsequent cooling of the surrounding water.

**[0051]** During underwater transit to an underwater operations area or work site; the shape memory alloy joints may be in the austenite phase and the internal suit pressure at one atmosphere. Upon arrival at the work site, the shape memory alloy composite fabric joints in the hybrid diving suit **200** cool and transform from the austenite phase to the martensite phase. The internal suit pressure equalizes with the external ambient water pressure.

**[0052]** As the shape memory alloy composite fabric joints transform to the martensite phase, the joints become flexible enough to enable freedom of movement in the joints while the diver is underwater at the work site. The pressure in the hybrid diving suit **200** is equal to the ambient water pressure outside the diving suit. During transit, the diver decompresses in the same hybrid diving suit **200** by transforming the SMA composite fabric joints to the austenite phase and providing a one atmosphere pressure in the diving suit.

**[0053]** The hybrid diving suit **200** supplies heat as a byproduct of transforming shape memory alloys from martensite to austenite, which helps to warm the diver. The increased flexibility offered by the shape memory alloy joints enables a diver to swim without the need for external thrusters. The hybrid diving suit **200** may also be used as an emergency decompression system.

**[0054]** **FIG. 6** is a flow chart illustrating a method of diving using the hybrid diving suit **200**. In step **A1**, during underwater transit to underwater work site, shape memory alloy joints are in an austenite phase and internal suit pressure is one atmosphere. In step **A2**, upon arrival at the underwater work site, the shape memory alloy joints transform to the martensite phase and become flexible so that the diver can perform work at the work site. Internal suit pressure equals external water pressure. In step **A3**, after work is completed, the shape memory alloy joints transform to the austenite phase and internal suit pressure returns to one atmosphere. In step **A4**, the diver completes underwater transit back to a starting point.

**[0055]** As an emergency retrieval system, a diver may be retrieved from the working water depth by transforming the shape memory alloy composite joints to the austenite phase and maintaining a pressure inside the hybrid diving suit **200** equal to the ambient water pressure outside the diving suit at the

working depth. Then, the diver moves upward to a surface of the water and is placed in a decompression chamber.

**[0056]** **FIG. 7** is a flow chart of a method of use for emergency retrieval using the hybrid diving suit **200**. In step **B1**, upon arrival at the underwater work site, shape memory alloy joints transform to the martensite phase and become flexible so that the diver can perform work at the work site. Internal suit pressure equals external water pressure. In step **B2**, a need for emergency retrieval arises. The shape memory alloy joints transform to the austenite phase and internal suit pressure is set to match depth pressure. In step **B3**, the diver surfaces and is transported in hybrid diving suit **200** to a decompression chamber on a surface ship without a sudden pressure drop in the hybrid diving suit.

**[0057]** **FIG. 8** is a cross-sectional view of a shape memory alloy composite fabric **300**. The composite fabric **300** is used to make the pressure vessel **100** and the joints **210**, **212**, **214**, **216**, **218**, and **220**. The fabric **300** includes an internal layer or dry suit **302**, a shape memory alloy layer or pressure control layer **304** and an outer, waterproof layer **306**. The internal layer **302** may include a thermally insulating, high temperature rated, moisture wicking material such as acrylic or wool. The internal layer **302** may include breathable layers and may also include an anti-microbial layer as well as being waterproof.

[0058] The shape memory alloy layer **304** includes SMA members **308** in the form of wires, threads, etc. Space between the SMA fibers **308** may need a filler **310**. The filler **310** is a high temperature thermally insulating material such as blends of aramid fiber, novoloid fiber, fiber retardant cotton or wool serge. The outer waterproof layer **306** may be made of materials used in contemporary dry suits or immersion diving suits such as stockinette fabric covered with vulcanized rubber, nylon, polyurethane, breathable fabrics, or closed-cell foam such as neoprene. A bi-laminate or tri-laminate exterior shell may be used.

[0059] The shape memory alloy members **308** in the form of wires or threads may vary in cross-sectional diameter from 100 um to 3 millimeters. In addition, the SMA members **308** may be formed in shapes other than wires. However, it is essential that the shape memory alloy composite fabric **300** is water impermeable. The impermeability must hold against high-pressure gradients imposed by hydrostatic pressure at depth. These depths may be on the order of tens of times atmospheric or greater.

[0060] The shape memory alloy members **308** may be fitted into other fabrics, such as the filler **310** as part of the SMA layer **304**. The shape memory alloy composite fabric **300** may be nonwoven, woven or knitted. A woven fabric is a textile that is

created by interlacing warp and weft yarns. There are many different types of weaves that can be formed by differing the interlacing pattern, including the plain, twill and satin weave.

**[0061]** The shape memory alloy members **308** may be embedded in a textile structure by other methods such as stitching or knitting. The shape memory alloy members **308** may also be inserted between layers of fabric or other materials such that the members can move freely. The shape memory alloy members **308** may be sewn onto or into other layers of fabric or other materials. To increase the temperature of the shape memory alloy members **308** for transformation from martensite to austenite; the members or fibers may carry electrical current. The shape memory alloy fibers or members **308** may also be insulated to avoid overheating and increase efficiency.

**[0062]** The shape memory alloy must be trained to adapt a response to a final shape. The training may be performed before or after the integration of the shape memory alloy into the shape memory alloy members **308**. If the training is after the integration into the shape memory alloy members **308**; care must be taken that there is no damage by increases in the temperature necessary for the training.

**[0063]** The dry suit layer **302** and the waterproof layer **306** isolate the material that does not include the shape memory alloy. Strength members may be made of a variety of materials,

including the shape memory alloy. The shape memory alloy members **308** may be woven with other non-SMA fabrics in various patterns, for example, spirals, radial rings, square or diamond mesh, zig-zags, or other weave patterns. Strength members may be added to help with radial and axial loading. For example, strength members made of high performance polymers such as Kevlar may be used for tensile loads and metal strength members may be used for loads in compression.

**[0064]** Strength members may be woven into the shape memory alloy composite fabric **300** or used separately. Strength members may have a variety of forms such as rings, coils, springs, and others. Individual shape memory alloy composite fabric joints may be terminated by rings that connect the joints to adjacent rigid components of an atmospheric diving suit or other SMA composite fabric joint sections.

**[0065]** **FIG. 9A, FIG. 9B** and **FIG. 9C** are examples of SMA composite fabric joints **312, 314** and **316**. The joints **314** and **316** have the dry suit layer **302** and the waterproof layer **306** removed to show the SMA members or wires **308**. The SMA wires **308** are fixed to rings **318** at each end. The rings **318** also provide an interface for connecting to other SMA joints and/or to the conventional joints of the hybrid atmospheric diving suit **200**.

**[0066]** In **FIG. 9A**, the crisscross pattern of the SMA wires **308** in the fabric joint **312** resists tensile and compressive

forces along the longitudinal axis the fabric joint. In **FIG. 9B**, the loop pattern of the SMA wires **308** in the fabric joint **312** resist radial forces applied toward the longitudinal axis of the fabric joint. **FIG. 9C** depicts the external waterproof layer **306**.

[0067] **FIG. 10A, FIG. 10B** and **FIG. 10C** illustrate different examples of operational modes of a shape memory alloy composite fabric joint **316**. In **FIG. 10A**, the fabric joint **316** is in the austenite phase, the pressure in the hybrid atmospheric diving suit **200** would be one atmosphere and the external pressure would be ambient hydrostatic pressure. This operation mode is where the diver transits underwater to and from a work site.

[0068] In **FIG. 10B**, the fabric joint **316** has transformed through cooling to the martensite mode and the fabric joint is flexible. This is the mode where the diver is working at the work site. In **FIG. 10C**, the fabric joint **316** has transformed to the austenite phase and the diver is retrieved to the water surface. In this mode, the pressure in the diving suit **200** is equal to the hydrostatic pressure at the depth where the diver was working and the external pressure is the ambient hydrostatic pressure as the diver ascends through the water.

[0069] **FIG. 11A** and **FIG. 11B** illustrate the shape memory alloy composite fabric joint **312** that may be substituted for one or more of the conventional joints **27-30** and **31-34** in the

conventional ADS **26** of **FIG. 1**. In the figures, the example joint **312** is shown without the external waterproof layer for purposes of clarity. In the joint **312**, some of the individual shape memory alloy components or members differ in type from one another. **FIG. 11A** and **FIG. 11B** depict two different types of SMA members **312a** and **312b** although the number of different types of SMA members in a single joint may be greater than two.

[0070] The SMA members **312a** and **312b** may be wires with different diameters or lengths or wires formed in a helical shape (**FIG. 11C**), a coiled shape (**FIG. 11D**), a zig zag shape (**FIG. 11E**), or other shapes that lend better to different types of bending. The SMA members **312a** and **312b** may be combinations of wires of different diameter, material composition, and length and also SMA members that are of other shapes than wires.

[0071] By using one or more joints, the pressure in the hybrid diving suit **200** may be maintained at one atmosphere, even when a joint changes shape. This is possible because some of the SMA members remain rigid (austenite) to maintain the resistance to ambient hydrostatic pressure and some of the SMA members transform to martensite to allow the joint **312** to change shape. The SMA members in the austenite phase can tolerate some bending (under the yield strain) caused by the hydrostatic pressure.

**[0072]** The phase changes of the varying types of shape memory alloy members may be controlled by a programmed computer. The computer can be programmed to send commands to transform the various SMA members from austenite to martensite and back to austenite as needed to maintain a pressure resistant joint while simultaneously allowing the joint to change shape. The computer may be activated by voice commands from the diver and/or by encoders on the various joints (shoulder, elbow, wrist) that sense a change in the angle of the limb portion.

**[0073]** The details, materials, steps and arrangement of parts have been described and illustrated to explain the nature of the invention. It will be understood that many changes in the details, materials, steps and arrangement of parts may be made by those skilled in the art, within the principle and scope of the invention, as expressed in the appended claims and equivalents thereof.

**SHAPE MEMORY ALLOY COMPOSITE FABRIC**

**PRESSURE VESSEL AND DIVING SUIT**

**ABSTRACT OF THE DISCLOSURE**

A shape memory alloy composite fabric and a method of use is provided in underwater pressure vessels and as flexible joints in atmospheric diving suits. The atmospheric diving suit internal pressure is one atmosphere for underwater transit to and from an underwater work site. During operations at a work site, the shape memory alloy joints transform to a martensite phase and enable greater flexibility while the pressure in the atmospheric diving suit equalizes with ambient depth pressure.

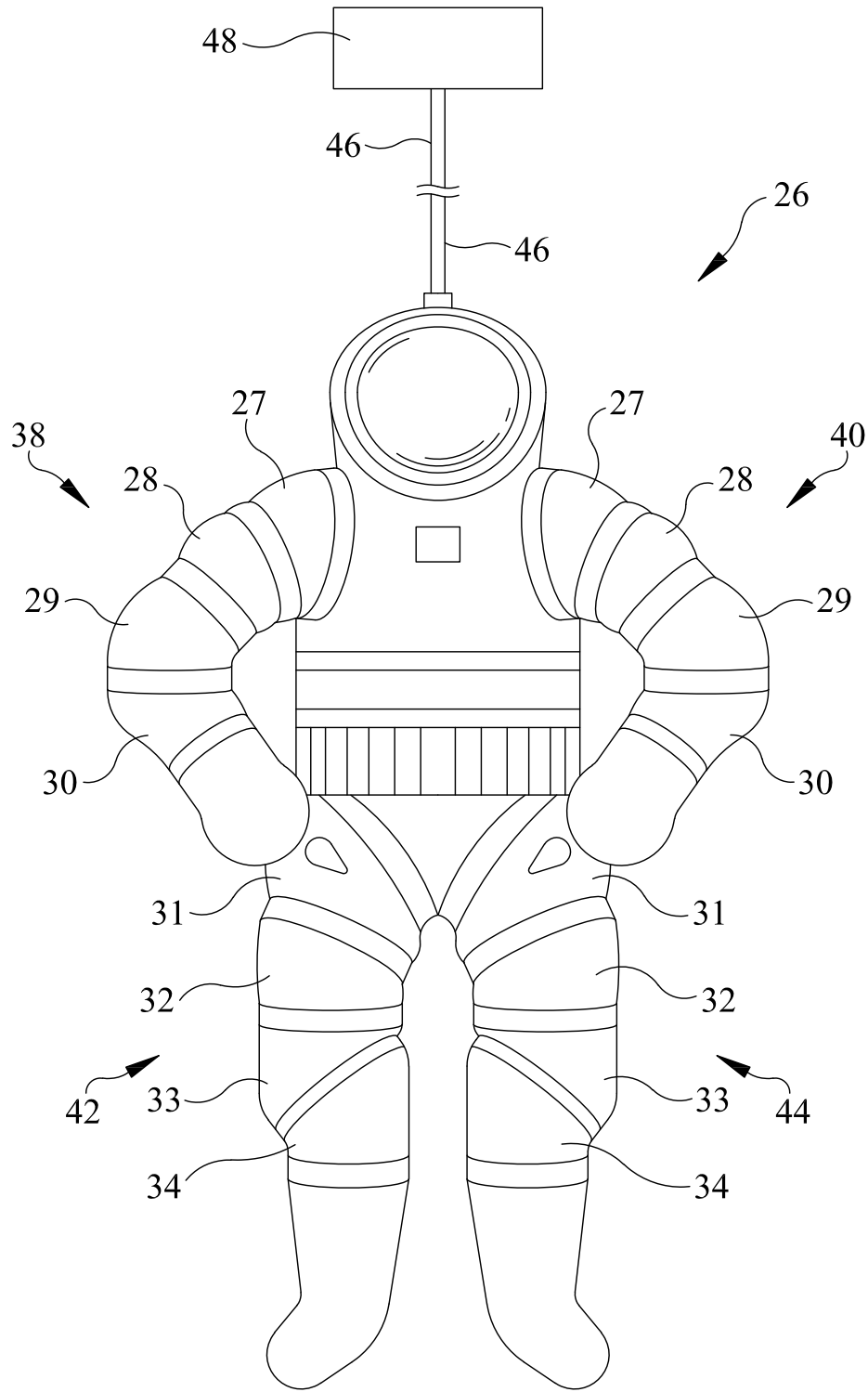


FIG. 1  
PRIOR ART

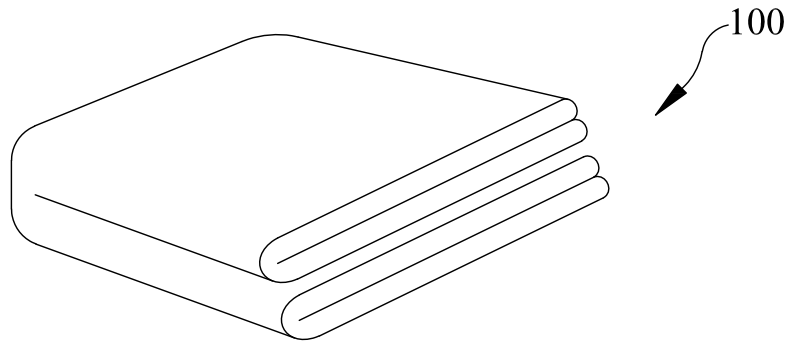


FIG. 2

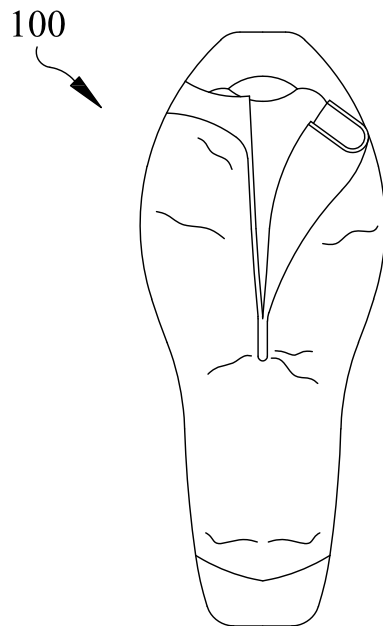


FIG. 3

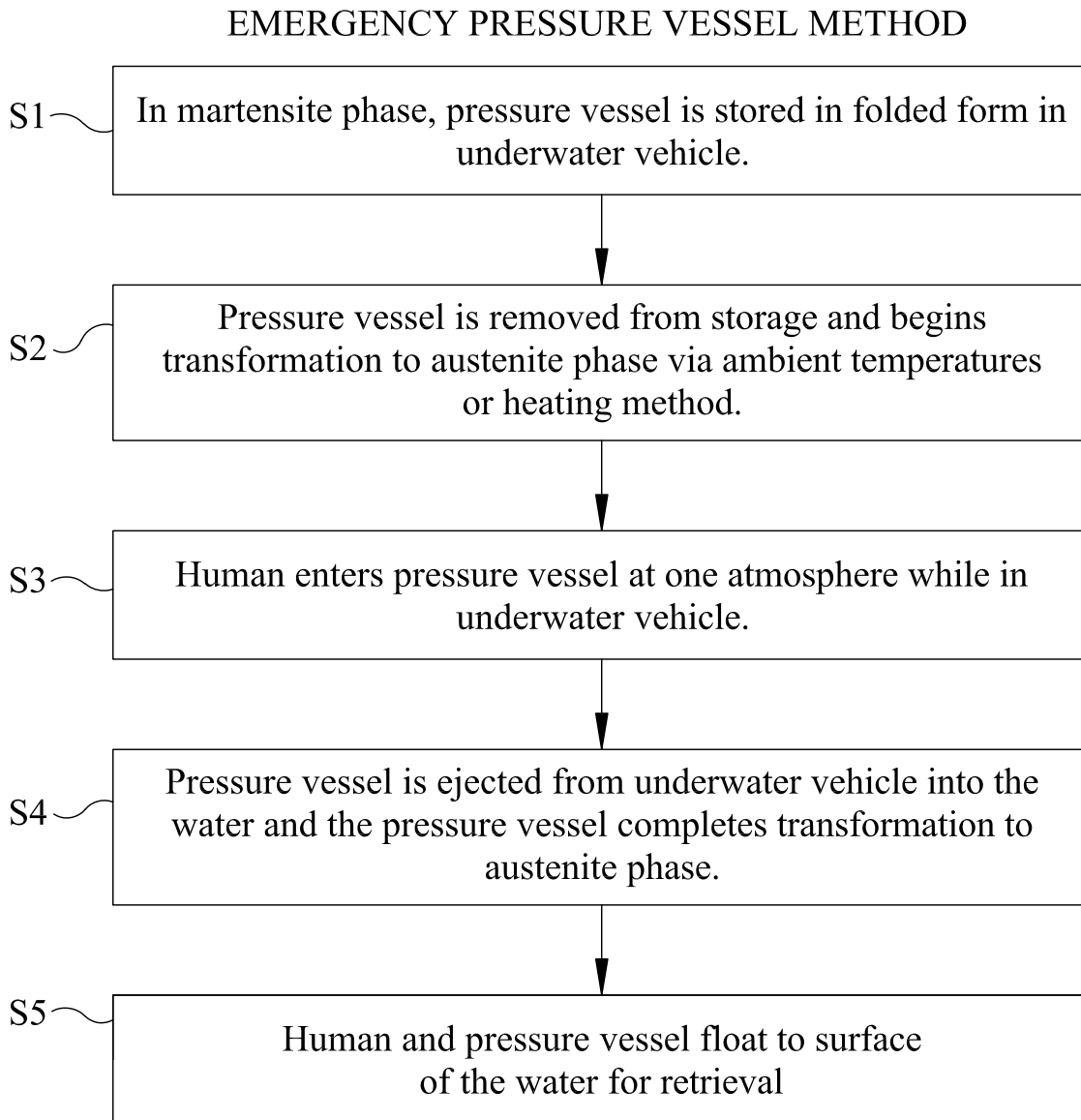


FIG. 4

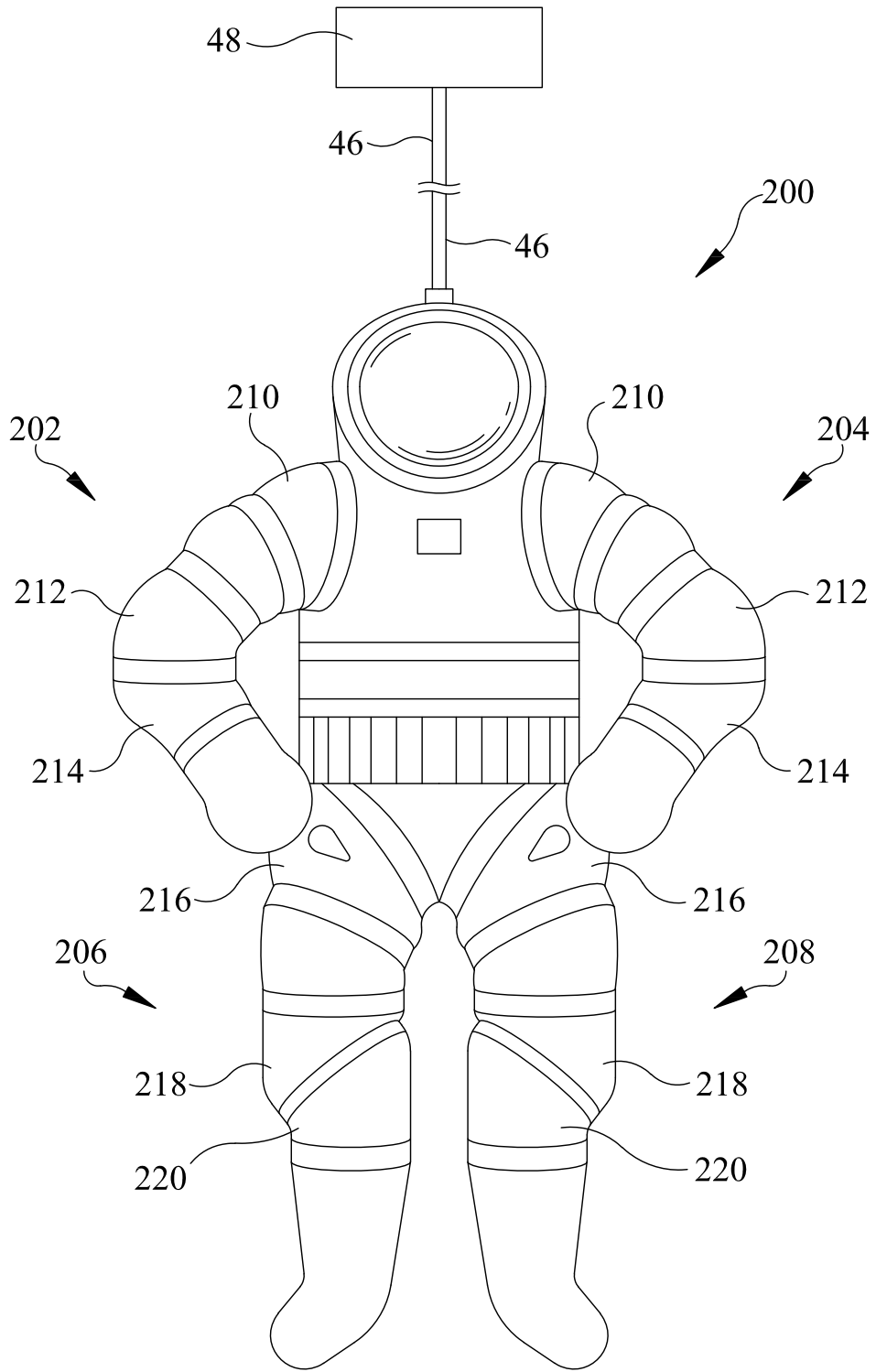


FIG. 5

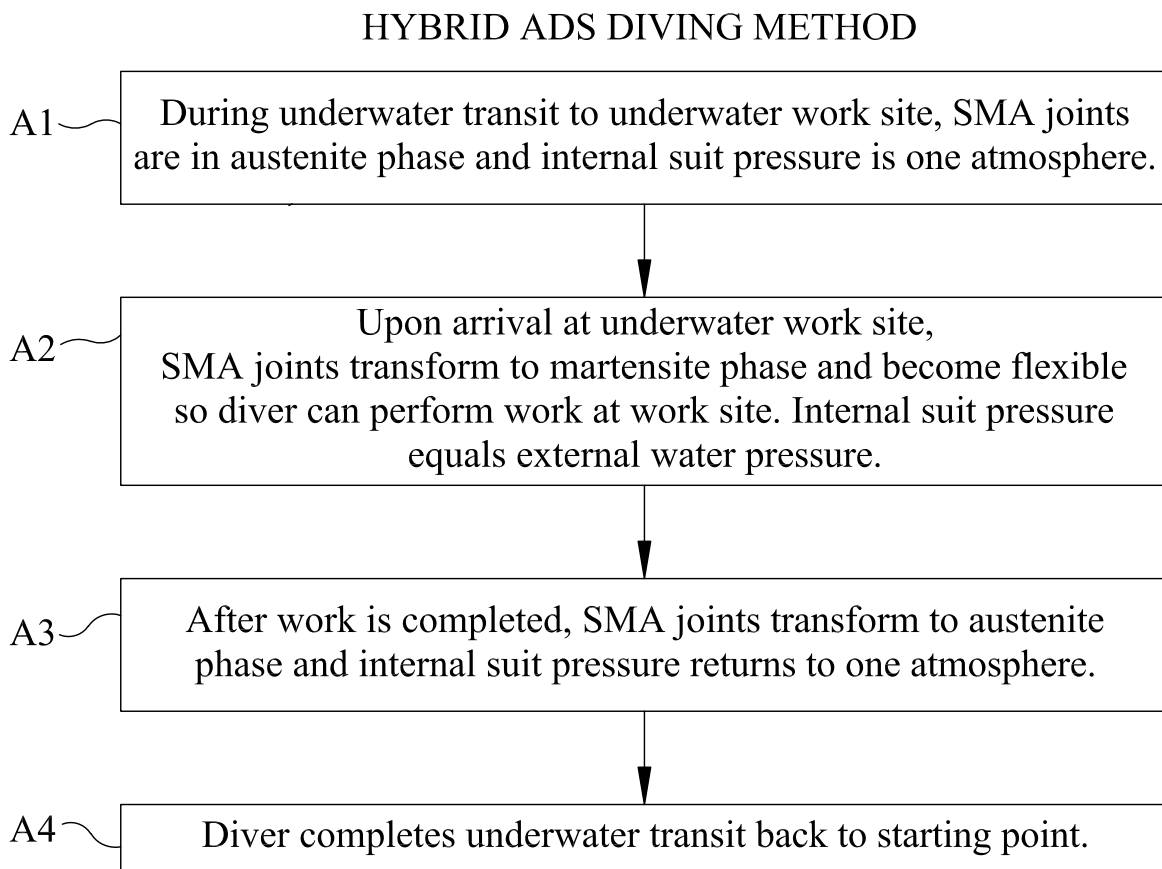


FIG. 6

HYBRID ADS -EMERGENCY RETRIEVAL METHOD

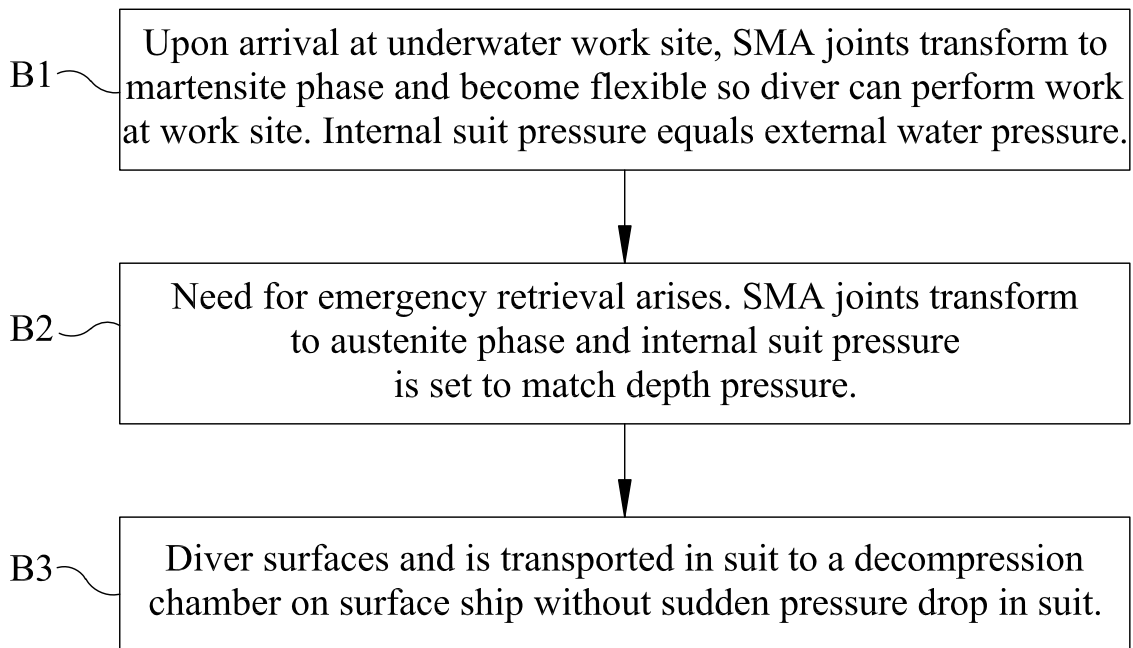


FIG. 7

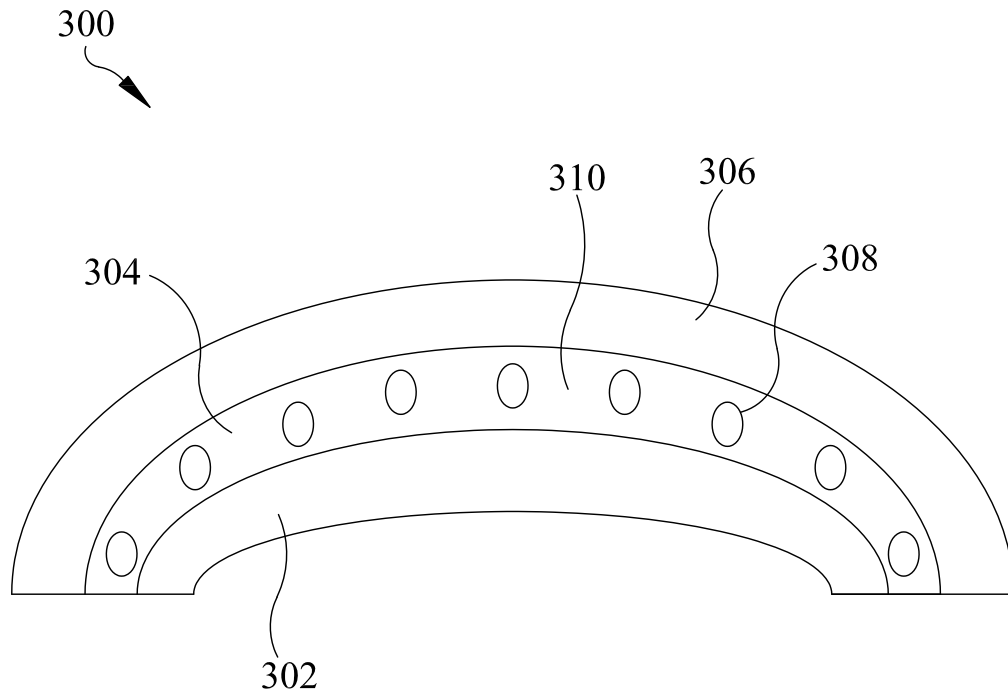


FIG. 8

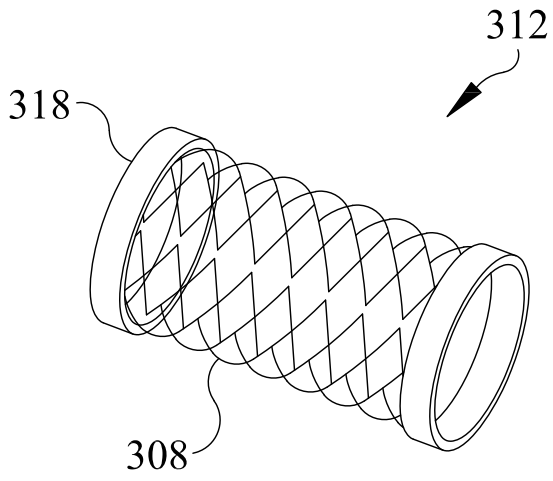


FIG. 9A

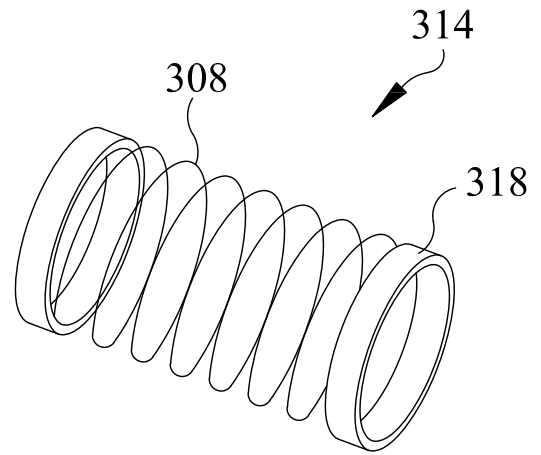


FIG. 9B

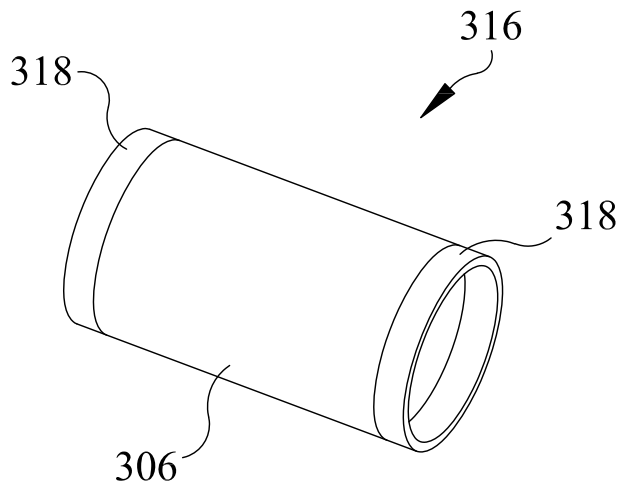
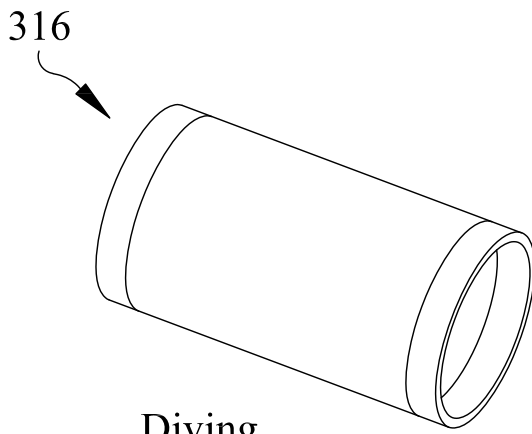
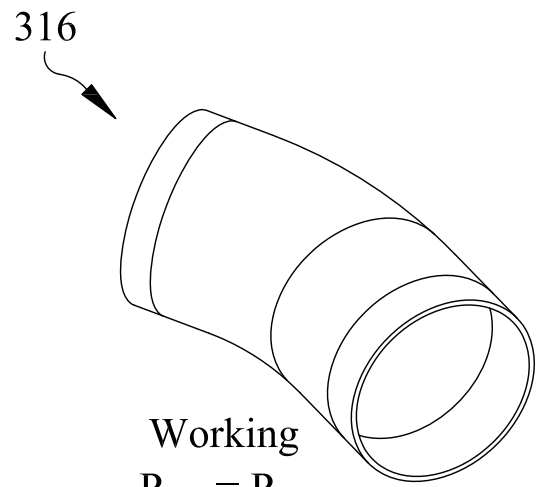


FIG. 9C



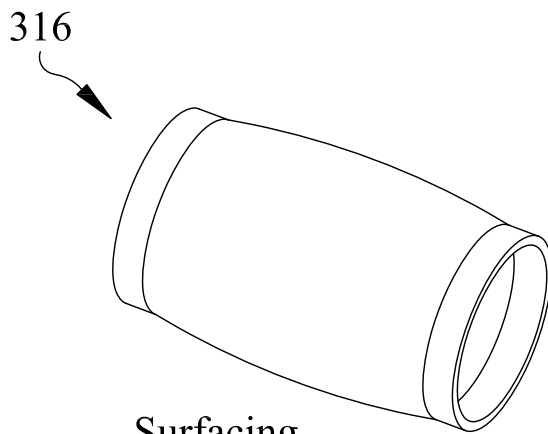
Diving  
 $P_{\text{suit}} < P_{\text{hyd}}$

FIG. 10A



Working  
 $P_{\text{suit}} = P_{\text{hyd}}$

FIG. 10B



Surfacing  
 $P_{\text{suit}} > P_{\text{hyd}}$

FIG. 10C

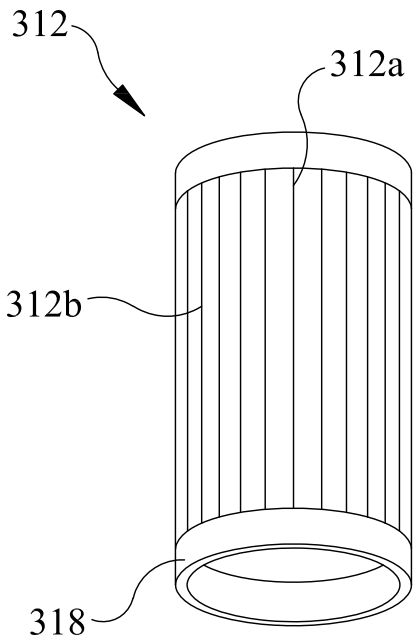


FIG. 11A

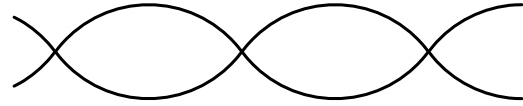


FIG. 11C

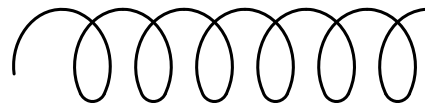


FIG. 11D

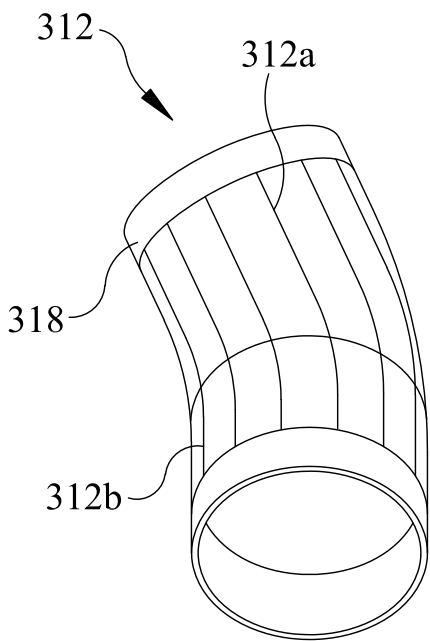


FIG. 11B



FIG. 11E