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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 June 2013 (13.06.2013)

(10) International Publication Number
WO 2013/083662 A2

(51) International Patent Classification:
F17C 1/14 (2006.01)

(21) International Application Number:
PCT/EP2012/074573

(22) International Filing Date:
5 December 2012 (05.12.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PCT/EP201 1/071793 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071797 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071805 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071794 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071789 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071799 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071788 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071786 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071810 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071809 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071808 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071800 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/07181 1 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071812 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071815 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071813 5 December 201 1 (05. 12.201 1) EP
PCT/EP201 1/071814 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071807 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071801 5 December 201 1 (05. 12.201 1) EP
PCT/EP20 11/071818 5 December 201 1 (05. 12.201 1) EP

(71) Applicant: BLUE WAVE CO S.A. [LU/LU]; 4, rue de la Greve, L-1643 Luxembourg (LU).

(72) Inventors: NETTIS, Francesco; Flat A, 14, Chesham Place, London SW1X 8HN (GB). **SPENCER, Brian;** 4550 Pell Drive, Sacramento, California 95838 (US). **SPENCER, Zachary;** 4550 Pell Drive, Sacramento, California 95838 (US). **BERGAMIN, Giuseppe;** 23 Via Cesare Pavese, 1-10017 Montanaro (TO) (IT). **CARINI, Giulio;** 239 Route d'Esch, L-1471 Luxembourg (LU). **D'AMELJ, Daniele;** 9 via Assisi, 1-6089 Torgiano (PG) (IT). **NISO, Gianfranco;** 63-65 rue de Merl, L-2146 Luxembourg (LU). **REDONDI, Paolo;** 18 via Turati, 1-24020 Gorle (BG) (IT). **TOMASELLI, Vanni Neri;** 46 rue d'Anvers, L-l 130 Luxembourg (LU).

(74) Agent: WATTERSON, Peer Marten John; B.P. 1775, L-1017 Luxembourg (LU).

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available):* ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: ULTRA-HIGH OPERATING PRESSURE VESSEL

(57) Abstract: The present invention relates to a high pressure vessel for containing or transporting gas at ultra-high pressures. More particularly it relates to such vessels for containing or transporting compressed natural gas at these pressures and methods of manufacturing them. The present invention also relates to a method of storing or transporting gas onshore or offshore.

ULTRA-HIGH OPERATING PRESSURE VESSEL

Field of the invention

The present invention relates to high pressure vessels for containing or transporting pressurized gas or fuel in a ship. More particularly it relates to such vessels for containing or transporting compressed natural gas (CNG).

The present invention also relates to a method of storing or transporting gas onshore or offshore. Moreover, the present invention relates to a vehicle for transporting gas, in particular compressed natural gas.

The present application claims priority from PCT/EP201 1/071793, PCT/EP201 1/071797, PCT/EP201 1/071805, PCT/EP201 1/071794, PCT/EP201 1/071789, PCT/EP201 1/071799, PCT/EP201 1/071788, PCT/EP201 1/071786, PCT/EP201 1/071810, PCT/EP201 1/071809, PCT/EP201 1/071808, PCT/EP201 1/071800, PCT/EP201 1/071811, PCT/EP201 1/071812, PCT/EP201 1/071815, PCT/EP201 1/071813, PCT/EP201 1/071814, PCT/EP201 1/071807, PCT/EP201 1/071801 and PCT/EP201 1/071818, all of which are incorporated herein in full by way of reference. The features of the pressure vessels disclosed in those prior filings are relevant to the present invention in that they can provide the structure of suitable storage means for storing the fluid at the required pressure.

The increased capacity and efficiency requests in the field of fuel, and in particular Compressed Natural Gas (CNG) transportation and the most common use of steel-based cylinders has led to the development of thicker structures, which usually require stricter quality control over defects and structural irregularities, especially in corrosive environments. The exploitation of stranded gas reserves leads to the necessity of reducing facilities and treatments at remote loading and offloading sites. The down side of this requirement is the possible presence of condensates and hydrates in the transported fluid, making the containment materials requirements higher in terms of corrosion and damage resistance.

Furthermore, in the case of large reserves the use of CNG is penalized due to the relatively lower density compared to the one of Liquified Natural Gas (LNG): approximately 0.2 kg/cm3 for CNG at 200 bar and ambient temperature vs. 0.4 kg/cm3 for LNG at -162 °C (cryogenic liquid). There are different methods to achieve higher gas densities and therefore improve the amount of transported gas with a given volume, but only one of these excludes the complex implementation of process facilities to refrigerate and possibly liquefying the fluid: increasing storage and transportation pressure at ambient temperature. This method requires thicker and heavier containment structures.

CNG loading and offloading procedures and facilities depend on several factors linked to the locations of gas sources and the composition of the gas concerned.

With respect to facilities for connecting to ships (buoys, platform, jetty, etc..) it is desirable to increase flexibility and minimize infrastructure costs. Typically, the selection of which facility to use is made taking the following criteria into consideration:

- safety;
- reliability and regularity;
- water depth and movement characteristics; and
- ship operation: proximity and maneuvering.

A typical platform comprises an infrastructure for collecting the gas which is connected with the seabed.

A jetty is another typical solution for connecting to ships (loading or offloading) which finds application when the gas source is onshore. From a treatment plant, where gas is treated and compressed to suitable loading pressure as CNG, a gas pipeline extends to the jetty and is used for loading and offloading operations. A mechanical arm extends from the jetty to a ship.

Jetties are a relatively well-established solution. However, building a new jetty is expensive and time-intensive. Jetties also require a significant amount of space and have a relatively high environmental impact, specifically in protected areas and for marine traffic.

Solutions utilizing buoys can be categorized as follows:

- CALM buoy;
- STL system;
- SLS system; and
- SAL system.

The Catenary Anchor Leg Mooring (CALM) buoy is particularly suitable for shallow water. The system is based on having the ship moor to a buoy floating on the surface of the water. The main components of the system are: a buoy with an integrated turret, a swivel, piping, utilities, one or more hoses, hawsers for connecting to the ship, a mooring system including chains and anchors connecting to the seabed. The system also comprises a flexible riser connected to the seabed. This type of buoy requires the support of an auxiliary/service vessel for connecting the hawser and piping to the ship.

The Submerged Turret Loading System (STL) comprises a connection and disconnection device for rough sea conditions. The system is based on a floating buoy moored to the seabed (the buoy will float in an equilibrium position below the sea surface ready for the connection). When connecting to a ship, the buoy is pulled up and secured to a mating cone inside the ship. The connection allows free rotation of the ship hull around the buoy turret. The system also comprises a flexible riser connected to the seabed, but requires dedicated spaces inside the ship to allow the connection.

The Submerged Loading System (SLS) consists of a seabed mounted swivel system connected to a loading/offloading riser and acoustic transponders. The connection of the floating hose can be performed easily without a support vessel. By means of a pick up rope the flexible riser can be lifted and then connected to a corresponding connector on the ship.

The Single Anchor Loading (SAL) comprises a mooring and a fluid swivel with a single mooring line, a flexible riser for fluid transfer and a single anchor for anchoring to the seabed. A tanker is connected to the system by pulling the mooring line and the riser together from the seabed and up towards the vessel. Then the mooring line is secured and the riser is connected to the vessel.

Increased capacity and efficiency requests in the field of CNG transportation, and the common use of steel-based cylinders therefor, has led to the development of steel-based cylinders with a thicker structure, which usually results in a heavy device or a device with a lower mass ratio of transported gas to containment system. This effect can be overcome with the use of advanced and lighter materials such as composite structures.

Some existing solutions therefore already use composite structures in order to reduce the weight of the device, but the size and configuration of the composite structures are not optimized, for example due to the limitations of the materials used. For example, the use of small cylinders or non-traditional shapes of vessel often leads to a lower efficiency in terms of transported gas (smaller vessels can lead to higher non-occupied space ratios) and a more difficult inspection of the inside of the vessels. Further, the use of partial wrapping (e.g. hoop-wrapped cylinders) for covering only the cylindrical part of the vessel, but not the ends of it, leads to an interface existing between the wrapped portion of the vessel and the end of the vessel where only the metal shell is exposed. That too can lead to problems, such as corrosion.

Also, transitions between materials in a continuous structural part usually constitute weaker areas, and hence the points in which failures are more likely to occur.

Pressure vessels for the carriage or transport of compressed fluids presently constitute four regulatory agency approved classes or types, all of which are cylindrical with one or two domed ends:

Type I. Consists of an all metal, usually aluminum or steel, construct. This type of vessel is inexpensive but is very heavy in relation to the other classes of vessels. The entire vessel is of sufficient strength to withstand the intended pressure exerted on the vessel by a contained compressed fluid and therefore does not require any manner of strength-enhancing over-wrap, including the dry filamentous over-wrap of this invention. Type I pressure vessels currently comprise a large portion of the containers used to ship compressed fluids by sea, their use in marine transport incurs very tight economic constraints.

Type II. Consists of a thinner metal cylindrical center section with standard thickness metal end domes such that only the cylindrical portion need be reinforced, currently with a composite over-wrap. The composite wrap generally constitutes glass or carbon filament impregnated with a polymer matrix. The composite is usually "hoop wrapped" around the middle of the vessel. The domes at one or both ends of the vessel are of sufficient strength to withstand the pressures developed in the vessel under normal use and are not composite wrapped. In type II pressure vessels, the metal liner carries about 50% of the stress and the composite carries about 50% of the stress resulting from the internal pressure of the contained compressed fluid. Type II vessels are lighter than type I vessels but are more expensive.

Type III. Consists of a thin metal liner that comprises the entire structure, that is, the cylindrical center section and the end dome(s). Thus, the liner is currently reinforced with a filamentous composite wrap around entire vessel. The stress in Type III vessels is shifted virtually entirely to the filamentous material of the composite wrap; the liner need only withstand a small portion of the stress. Type III vessels are much lighter than type I or II vessels but are substantially more expensive.

Type IV. Consists of a polymeric, essentially gas-tight liner that comprises both the cylindrical center section and the dome(s), all of which is currently fully wrapped with a filamentous composite. The composite wrap provides the entire strength of the vessel. Type IV vessels are by far the lightest of the four approved classes of pressure vessels but are also the most expensive.

As noted above, Type II, III and IV pressure vessel currently require a composite overwrap over a vessel liner to give them the necessary strength to withstand the intended pressure exerted by a compressed fluid contained in the vessel.

The present invention concerns the adaptation of these pressure vessels and fabrication of further types of pressure vessel which are suitable for high pressure (up to 1000 bar) applications

The present invention therefore aims at overcoming or alleviating at least one of the disadvantages of the known pressure vessels.

In particular, an object of the present invention is to provide high pressure vessels which are capable of withstanding substantially higher pressures than current designs. This allows higher gas densities to be achieved, thus increasing transportation efficiency. In addition, the high pressure vessels of the current invention must be light in weight since a lighter vessel allows a greater volume of gas/fluid to be transported on a seafaring vehicle, such as a ship, without exceeding the vehicle's load bearing capacity - less of the carried weight (i.e. a smaller percentage) will be attributed to the physical vessels, as opposed to the contents of those vessels (i.e. the pressurized gas or the transported fluid). Finally, the vessels must be highly corrosion and damage resistant to enable containment with minimal facilities and treatments located at the sight of the reserve.

The first containment system solution mentioned in this patent is made of composite materials for carrying the loads generated by the internal pressure and at least one polymeric coating made out of non-metallic materials that have no structural aims, during CNG transportation, loading and offloading phases, usually called "liner". The use of composite storage tanks mitigates the effect of having thicker structures with the implementation of materials with higher specific properties (mechanical property/density of material) as compared to traditional and high-strength steel alloys.

The innovation of these corrosion-proof tanks relies in the method for having thicker composite layer assuring efficiency of design and load conditions.

The non-metallic coating should be corrosion-proof and capable of carrying non-treated or unprocessed gases. In case of thermoplastic polymers is foreseen the use of a polyethylene or similar capable of hydrocarbon corrosion resistance. In case of thermoset resins is foreseen the use of a polyester, an epoxy, a resin based on poly-dicyclopentadiene or similar capable of hydrocarbon corrosion resistance. Particularly, poly-dicyclopentadiene resins have showed lower diffusion rates at high pressures compared to the one of high-density polyethylene, and are deemed to be the best fit for these ultra-high pressure CNG applications.

Due to the high-compressive stresses, it is required that the polar fittings of these composite pressure tanks are made out of metal alloys, e.g. with stainless steel to withstand compressive stresses, being non-corrosion susceptible as well as avoiding galvanic coupling with the composite materials, if carbon fiber-reinforced.

A first aspect of the present invention relates to a high pressure vessel for fuel containment or transport at a pressure in excess of 200 bar, the high pressure vessel (10) comprising:

at least one opening for gas loading and offloading and for liquid evacuation;
a liner; and
at least one external fiber layer provided on the outside of the liner.

Preferably the fuel is compressed natural gas.

Preferably the liner is non-metallic.

Preferably the high pressure vessel is suitable for storing and transporting the fuel at a pressure in excess of 350 bar, 700 bar or more preferably up to 1000 bar. Vessels suitable for storing fuel at pressures in excess of 1000 bar are also envisaged as being possible using the method disclosed herein. However, it is envisioned that certification of pressure vessels for pressures in excess of 1034 bar will be difficult using current certification approaches. Nevertheless, capabilities in excess of that are achievable using the approaches disclosed herein.

The liner may be substantially chemically inert.

The liner may have a corrosion resistance of at least that of stainless steel. Preferably the resistance is in relation to hydrocarbons or CNG or other such fuels, and impurities in such fluids, such as H_2S and $C0_2$.

The non-metallic liner may have a corrosion resistance of at least that of stainless steel, e.g. an AISI 316 stainless steel, e.g. in relation to hydrocarbons or CNG, or impurities in such fluids, such as H_2S and $C0_2$. For example, the liner may be essentially, preferably or substantially H_2S resistant, for example in accordance with IS015156.

The internal surface of the liner may be further protected in order to offer additional permeability and corrosion limits. The internal protection of the liner can be either an additional thin layer of resin with specific low permeability properties or a thin metallic layer. The deposition of the thin protective layer in the case of metals should involve a catalyst able to provide chemical bonding between the organic (polymeric) substrate and the selected low-permeability metal.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state.

The liner may be selected from the group comprising: high-density polyethylene, high-purity poly-dicyclopentadiene, high-purity poly-cyclopentadiene resins based on poly-dicyclopentadiene, epoxy resins, polyvinyl chloride, or other polymers known to be impermeable to hydro-carbon gases, especially compressed natural gas polymers - the liner is desirably capable of hydraulic containment of raw gases, such as hydrocarbons and natural gas mixtures. The liner is also preferably inert to attack from such gases.

The fiber layer may be made of fiber wound about the liner.

The fibers in the fiber layer may be selected from the group of carbon fibers, graphite fibers, E-glass fibers, or S-glass fibers. Preferably the fibers are carbon fibers.

The fibers may be coated with a thermoplastic or thermoset resin, forming a composite layer. Preferably the fibers are coated with a thermoset resin. Preferably the carbon fibers are impregnated with the thermoset or thermoplastic resin prior to being applied to the liner. Preferably the fibers are wound around the liner after being impregnated with resin.

The thermoset resin may be selected from the group comprising epoxy-based or high-purity poly-dicyclopentadiene-based resins.

Preferably the resin-impregnated fibers or the impregnating resin are heated, prior to being applied to the outside of the liner. The reason for this is that high pressure vessels require thick composite walls. As the thickness of the sidewall increases, curing of the composite does not happen at a uniform rate, with the surfaces of the wall curing at a different rate to the centre of the wall. This results in different thermomechanical behaviour between adjacent parts of the wall, and thus internal thermal stresses are built up. These can then result in residual internal thermal stresses in the wall, and upon the vessel being pressurized, they can result in even higher local stresses (i.e. the stresses induced by the internal pressure in addition to the residual thermal stresses). They can lead to unpredictable characteristics and possibly in failure. As such it is preferred and desireable to minimise this effect, with the heating helping to achieve that:

By heating the impregnating resin or resin-impregnated fibers prior to the fibers being applied to the liner, the situation where the whole thickness of the wall has to cure at once from a situation where none of the wall has started to cure, is mitigated or avoided. This greatly reduces internal stresses.

Should the resin be such that a full cure can not be achieved at room temperature, the entire vessel can be put in a curing oven to complete the curing process.

In combination with, or instead of, the above, the fiber layer of the high pressure vessel may be formed and cured in multiple separate stages. This process is again aimed at trying to reduce internal thermal stresses within the composite wall. The composite wall can be built up in "layers", whereby a certain thickness of wall (which is less than the total desired thickness of the wall) is produced and cured. The chosen layer thickness is one that is known to be thin enough to result in a suitably stress free section once cured. Once the first layer is fully cooled, a further layer is applied and cured, and so on, until the desired wall thickness is reached.

Preferably, the high pressure vessel is rotated while the composite layer cures. This can be during the curing phase of each individual layer (if the layer method is employed), during the single curing phase of the whole wall thickness or in fact during the entire process. This is done to avoid gravity affecting any resin that is not completely cured, which could result in asymmetry and stress concentrations once pressurized.

The vessel may further comprise a metallic internal coating provided on the inside of the liner.

The metallic internal coating may be essentially H_2S resistant, for example in accordance with IS015156.

The metallic internal coating should preferably not present sulfide stress-cracking at the 80% of its yield strength with a H_2S partial pressure of 100 kPa (15 psi), being the H_2S partial pressure calculated (in megapascals - pounds per square inch) as follows:

$$p_{H_2S} = p \times \frac{x_{H_2S}}{100}$$

where

p is the system total absolute pressure, expressed in megapascals (pounds per square inch;

x_{H_2S} is the mole fraction of H_2S in the gas, expressed as a percentage.

The vessel may further comprise a gas permeable layer interposed between the liner and the fiber layer.

The gas permeable layer may comprise glass fibers.

The vessel may further comprise a gas detector connected to the gas permeable layer for detecting a gas leakage.

The gas permeable layer may advantageously comprise an integrated gas detection device able to warn in case of leakage from the liner. The connection to such a device may by it being integrated into the wall of the vessel, e.g. in that layer. The device may be operated via a wireless transmission to a receiving unit elsewhere onboard the ship, usually nearby the high pressure vessel e.g. on the vehicle; e.g. on the hull, in a bulkhead, on a dashboard or within a wristwatch or some other portable receiving unit.

The vessel may be of a generally cylindrical shape over a majority of its length. The fiber layer extends over all of the cylindrical shape, and over substantially all of the end portions of the vessel so as substantially entirely to cover the liner/vessel.

The inner diameter of the vessel may be between 0.5 meters and 5 meters.

The inner diameter may be between 1.5 meters and 3.5 meters.

The vessel may further comprise a manhole for entering and/or inspecting the interior of the vessel.

Preferably all the following embodiments of the invention - a high pressure vessel - are for storage or transportation of a fluid-based gas or fuel such as CNG and having a weight/gas capacity ratio in the range of 13 to 65t/MMscf, or even up to 100t/MMscf. t/MMscf means metric tons per million standard cubic feet, where million standard cubic feet is a standard term for quantifying the amount of useable CNG within a high pressure vessel. The weight refers to the empty weight (mass) of the vessel in metric tonnes. The gas or fuel can be a mixture of a gaseous and liquid state, e.g. a gas with liquid fractions, or more preferably it is predominantly or entirely in a gaseous state.

A standard cubic foot (abbreviated as scf) is a measure of quantity of gas, equal to a cubic foot of volume at 60 degrees Fahrenheit (15.6 degrees Celsius) and either 14.696 psi (1 atm or 101 .325 kPa) or 14.73 psi (30 inHg or 101 .6 kPa) of pressure. A standard cubic foot is thus not a unit of volume but of quantity, and the conversion to normal cubic metres is not the same as converting cubic feet to cubic metres (multiplying by 0.0283...), since the standard temperature and pressure used are different. Assuming an ideal gas, a standard cubic foot using the convention of 14.73 psi represents 1.19804 moles (0.0026412 pound moles), equivalent to 0.026853 normal cubic meters.

Common oilfield units of gas volumes include ccf (hundred cubic feet), Mcf (thousand cubic feet), MMcf (million cubic feet), Bcf (billion cubic feet), Tcf (trillion cubic feet), Qcf (quadrillion cubic feet), etc. The M refers to the Roman numeral for thousand. Two M's would be one thousand thousand, or one million. The s for "standard" is sometimes included, but often omitted and implied. We have used it above in the statements of invention.

The structural weight of a high pressure vessel can be determined by weighing an empty high pressure vessel - one that is removed from any pipework. However, given the size of the high pressure vessels, the weight (mass) might more often be a calculated or determined value - e.g. upon considering wall thicknesses, size and shapes, and material compositions thereof, and often it will be indicated on the certification. This can be so as to allow appropriate structures to support it, e.g. on board a ship, to be designed to be in compliance with appropriately applicable factors of safety as set by available regulations and, and vehicle specifications, and by relevant regulatory bodies.

Preferably the structural weight over transported gas weight ratio is in the range of 0.7 to 3.4 [t/t], e.g. when loaded to a CNG pressure of 250 bar and a temperature of 20°C, or possibly when loaded to a pressure of 300 bar at that temperature, or when loaded to its certified (or certificated) maximum pressure or gas capacity (e.g. in scfs).

Since a gas quantity in scfs has a constant weight (mass) irrespective of its pressure and temperature, the ratio presented by fully loaded high pressure vessel (i.e. one loaded to its certificated capacity) is not dependent on temperatures and pressure.

In case of e.g. a glass-based composite Type 3 or 4 high pressure vessel the weight/certified maximum gas capacity ratio is preferably in the range of 35 to 65 or even up to 100 [t/Mscf]. This can be according to the safety factor used by the certification. Further, preferably the structural weight over certificated maximum transported gas weight ratio is in the range of 1.8 to 3.4 or even up to 5.0 [t/t], e.g. when loaded to a CNG pressure of 250 bar and a temperature of 20°C.

In case of e.g. a carbon-based composite Type 3 or 4 high pressure vessel the weight/certified maximum gas capacity ratio is preferably in the range of 13 to 22, or even up to 40 [t/Mscf]. This can be according to the safety factor used by the certification. Further, preferably the structural weight over certificated maximum transported gas weight ratio is in the range of 0.7 to 1.2 or even up to 2.0 [t/t], e.g. when loaded to a CNG pressure of 250 bar and a temperature of 20°C.

Preferably, the high pressure vessel has a waterproof over-wrap shrink-wrapped over the composite.

The present invention also provides a module or compartment comprising a plurality of the inspectable high pressure vessels as defined above, the high pressure vessels being interconnected for loading and offloading operations.

The present invention also provides a method of storing or transporting gas onshore or offshore, in particular compressed natural gas, using at least one high pressure vessel, or the module or compartment, as defined above, the gas being contained within a high pressure vessel thereof.

The present invention also provides a method of producing a high pressure vessel suitable for use at pressures in excess of at least 200 bar, preferably in excess of 250 or 700 bar, and more preferably 1000 bar or 1050 bar, the method comprising: manufacturing a cylindrical liner, impregnating fibers with a resin, winding the impregnated fibers around the liner until the fiber wall reaches the desired thickness, and curing the impregnated fiber wall.

Preferably the impregnating resin is heated, e.g. prior to winding the fibres on to the liner. This might be before or after the resin is used to impregnate the fibres.

Preferably the fiber filament winding is done in multiple stages, whereby a thickness less than the desired thickness - a "layer" - is wound on to the liner and cured, before a further layer is applied and cured. This process is then continued until the desired wall thickness is reached.

The number of iterations of this process is arbitrary and dependent on the desired thickness of the vessel wall. For a given desired wall thickness, the larger the number of separate layers applied, the thinner the layer and hence the more uniform the thermal profile of the thickness is to be, thus resulting in lower thermal stresses.

Preferably, the high pressure vessel is rotated while the fiber wall, or layer thereof, is cured. This can be during the curing phase of each individual layer (if the layer method is employed), during the single curing phase of the whole wall thickness or in constantly during the entire process. This is done to avoid gravity affecting any resin that is not completely cured, which could result in asymmetry and stress concentrations when pressurized.

The present invention also provides a vehicle for transporting gas, in particular compressed natural gas, comprising at least one vessel, or a module or compartment, as defined above.

The vehicle may be a ship.

The vehicle may have multiple high pressure vessels. They may all be interconnected, ot they may be interconnected in groups or within their modules/compartments.

The high pressure vessels can also be used for non-fuel applications, including breathing tanks as used by scuba divers, hospitals, emergency services and firemen, whereupon the contained gas may be pressurised air or oxygen, or other breathable gas mixes, or even for non breathing applications, including storing compressed gases such as helium, compressed nitrogen, compressed C02 and other gases that are in current pressurised storage, e.g. in chemical plants. The high maximum pressure of the vessels disclosed herein make the storage and manageability of these compressed gas storage devices far more user-friendly than the current, all-steel type 1 tanks that are widely in use today, which in turn can also mean greater volumes are also provideable while still allowing the pressure vessel to be manageable by a user in terms of manoeuvrability (a very large pressure vessel is more awkward to handle or manoeuvre than a smaller one of the same weight, or even, for many applications, a smaller but heavier one).

It also is known, however, that the polymeric matrix of the composite wrap adds little or no strength to the overwrap. Thus, this invention also can be used with a further novel winding arrangement that uses a dry filamentous material that is disposed over a pressure vessel liner in a dry state and that is remains in essentially a dry state (i.e. not bonded throughout with an impregnation of resin) for the life-time of the pressure vessel. This dry wrapping with filamentous materials also avoids possibility of air entrapments in the impregnating resin, which would lead to a non-homogeneous load transfer inside the composite structure.

"Essentially in a dry state" is not intended to be limited to scenarios where the pressure vessel is not exposed to water, e.g. marine or river applications (e.g. scuba diving).

After all, in those scenarios the filamentous material may become wetted or dampened by environmental moisture or the water in which the diver submerges. Therefore, the term "dry state" is instead used to refer to the condition of the filamentous material when it is disposed over the vessel's liner - it is at that time "dry", i.e. not impregnated with resin, and it remains in that dry (not impregnated with resin) state even while the vessel is put to use. Essentially dry in this context therefore does not exclude situations where the filaments/fibres are wetted by, or submerged in, water. It is dry only in the sense that it is not resin impregnated.

An external polymeric layer or coating can be applied over the dry filamentous material for environmental exposure protection or resistance on the outer surface of the dry filaments.

These additional "dry wrap" pressure vessel types - the dry wrap can be applied to any of the type 2 to 5 and type 7 pressure vessel forms - can also be used in these novel ways.

One structure for a preferred pressure vessel is a vessel having a generally cylindrical shape over a majority of its length and at least one stainless steel layer as a first layer for being in contact with the compressed fluid within the vessel, the first layer being made of low-carbon stainless steel, and the vessel further having a further external composite layer made of at least one fiber-reinforced polymer layer that will not be in contact with the fluid contained within the vessel.

The vessel will have at least an opening for gas loading and offloading. Typically it is at one end. Generally an opening is also provided at the opposite end. Such openings at each and can be referred to as axial openings. In case of Type 3 to 5 pressure vessels, the more similar are the two axial openings, the more efficient is the wrapping pattern of filaments. For example, the axial openings may both be round and they may both have the same diameter.

A plurality of the pressure vessels can be arranged in a module or compartment, and the pressure vessels can be interconnected for loading and offloading operations.

Preferably the vessels all have the same height, length or diameter. Some may have different heights, lengths or diameters to allow the vessels to be custom-fitted into the space provided for them within the relevant vehicle or module or compartment.

This or any of the other pressure vessels may further comprise an insulating layer interposed between the liner and the composite layer (e.g. a carbon fiber layer).

The insulating layer may be a gas permeable layer.

The pressure vessel may further comprise a gas permeable layer interposed between the metallic liner and the fiber layer.

The gas permeable layer may comprise glass fibers.

The pressure vessel may further comprise a gas detector connected to the gas permeable layer for detecting a gas leakage.

Another configuration for the pressure vessel may be again a generally cylindrical shape over a majority of its length and at least one opening for gas loading and offloading. However, in this configuration the pressure vessel comprises a metallic liner, a first fiber layer external and adjacent to the metallic liner, and a second fiber layer external and adjacent to the first fiber layer. The first and second fiber layers are made of different materials.

The metallic liner may be gas impermeable and/or corrosion resistant.

The metallic liner may be selected from the group comprising steel, stainless steel, nickel-based alloys, bi-phase steel, aluminum, aluminum alloys, titanium, and titanium alloys.

Either or both of the fiber layers may be made of fibers wound about the metallic liner.

The first fiber layer may comprise carbon fibers.

The second fiber layer may comprise glass fibers.

Another form of pressure vessel that can be utilised in these ways has a body defining an internal volume in which the compressed gas/fluid can be stored and an inlet for loading the compressed gas/fluid into the vessel, the body of the vessel comprising a structural shell made entirely and solely of a fibre-reinforced filament-wound composite material comprising fibres and a matrix that is substantially impermeable to the intended contents of the pressure vessel, i.e. the compressed gas or fluid.

It is preferred that in use, the compressed gas/fluid will be in direct contact with an inner side of the structural shell.

Preferably the structural shell comprises a cylinder section and two terminations, one at either end of the cylinder section, all being made of the fibre-reinforced filament-wound composite material.

Preferably the terminations are dome-like terminations.

Preferably the dome-like terminations have a geodesic shape in respect of helical wrapping of fibres around the vessel.

Preferably the fibres of the composite material comprise at least one of carbon fibres, glass fibres or Kevlar®.

Preferably the resin of the composite material comprises at least one of a polyester resin, a vinylester resin, an epoxy resin, a phenolic resin, a high-purity dicyclopentadiene resin, a bismaleimide resin and a polyimide resin.

The method of manufacturing this composite pressure vessel involves the steps of providing a disposable mandrel and winding filament fibres around the disposable mandrel to form the shape of a pressure vessel, the shape including an inlet/outlet. The inlet/outlet is typically an aperture in an end thereof. There may be two apertures, one in each end. The ends are typically opposing ends.

The method typically involves the step of removing the disposable mandrel through the inlet/outlet after the composite is cured.

Preferably the method comprises the step of aggregating the filament fibres to form a tape before winding them around the disposable mandrel.

Preferably the method comprises the step of impregnating the filament fibres with a resin before winding the fibres around the disposable mandrel.

Preferably the impregnation of the fibres takes place after the fibres have been formed into a tape and by immersing the tape into a batch of resin, such as in a bath of resin.

Preferably the method comprises the step of curing the composite while it is around the disposable mandrel, at least to a sufficient extent for it to be self-supporting.

Preferably the method comprises the further the step of curing the composite and removing the disposable mandrel once the composite has been cured at least to a sufficient extent for it to be self-supporting.

Preferably the method comprises a multi-stage curing process to avoid/reduce thermally induced mechanical defects in the composite.

Preferably the filament winder is adapted to be suitable for use with vessels with an increased wall thickness.

Preferably the mandrel comprises ice, and the removal of the mandrel may then comprise melting the ice.

Preferably the mandrel comprises compacted sand, and the removal of the mandrel then may comprise shaking the sand out of the vessel.

The mandrel may comprise a scaffold, and the removal of the mandrel may then comprise collapsing the scaffold.

The mandrel may comprise a structure formed from a disolvable chemical compound (such as one that is soluble in water) and the removal of the mandrel may then comprise the dissolution of the structure to a liquid state.

Such pressure vessels could also be installed in vehicles such as cars, lorries, buses, trains, boats or even aeroplanes.

It should also be noted that these high pressure vessels can also be applied to non vehicular uses, including those where instead of a fuel, some other gas is desired to be contained, e.g. air supplies, general gas distribution applications, medical services, industrial services, recreational services such as scuba diving and emergency service requirements such as fire extinguishers and breathing apparatus. Indeed anywhere where a pressurised steel pressure vessel is currently in use, a benefit would be found in swapping to one of the high pressure solutions provided herein.

The present invention also envisions the combination of the various optional or preferred features listed above into the other types of pressure vessel, and also the use of those so modified pressure vessels in the applications listed.

The high pressure vessel according to the present invention may reduce the cost of vessels per kg of gas, in particular CNG, transported.

A further advantage of the present invention may be the reduced weight of the high pressure vessel per unit volume of gas, and in particular CNG, transported.

The present invention may allow less plastic material to be used for the high pressure vessel, whilst maintaining its resistance to corrosion.

The current invention achieves all of this by allowing higher gas densities to be transported safely without the use of complex process facilities to refrigerate and possibly liquefy the fluid.

Fig 1A is a schematic cross section of a manhole or opening section of a pressure vessel in accordance with the present invention;

Fig 1B is a detailed schematic cross section of a manhole or opening section of a pressure vessel in accordance with the present invention;

Figure 2 is a schematic cross section of a high pressure vessel in accordance with one aspect of the present invention;

Figures 3, 4 and 5 schematically illustrate an arrangement of a plurality of vessels in modules or compartments, in perspective, from the top side, the bottom side and from above, respectively;

Figures 6A, 6B and 6C schematically illustrate possible arrangements of the vessels in modules, and in the hull of a ship;

Figure 7 schematically shows a section through a ship hull showing two modules arranged side by side; and

Figure 8 schematically shows a more detailed view of the top-side pipework.

Figure 9 is a schematic cross section of a high pressure vessel in accordance with a further aspect of the present invention;

Figure 10 is a close up of the wall section of the vessel of figure 9;

Figure 11 is a schematic cross section of a high pressure vessel in accordance with a further aspect of the present invention;

Figure 12 is a schematic cross section of a high pressure vessel in accordance with a further aspect of the present invention;

Figure 13 is a schematic close up of a potential gas leakage detection system in accordance with the present invention;

Figure 14 is a schematic cross section of a high pressure vessel in accordance with a further aspect of the present invention;

Figure 15 and 16 show a winding technique;

Figure 17 shows a section through a final embodiment of pressure vessel;

All the following embodiments described herein are designed and envisaged to be capable of containing and transporting a fuel or gas, in particular a gaseous fuel, and in particular CNG, at pressures in excess of 200 bar, more preferably in excess of 350 bar, or 700 bar, or most preferably up to 1000 bar or 1050 bar. The terms pressure vessel and high pressure vessel are often used interchangeably, and therefore do not strictly designate differences in the pressures certain vessels can withstand, unless explicitly stated.

Furthermore, although it will often be stated that a pressure vessel is for containing or transporting CNG, this does not exclude the possibility of it containing or transporting other gases and fuels, and hence all the vessels included herein are envisaged to be able to be used for a multitude of different fuels or gases.

Finally, all figures are merely representations and so are not to scale. Hence the illustrated wall thicknesses are not accurate and may not be of a sufficient size to withstand claimed pressures as shown.

Fibre-reinforced polymer, also known as fibre-reinforced plastic, is a composite material, consisting a polymer matrix reinforced with fibres, which are usually fibreglass, aramid or carbon; the polymer is generally an epoxy, vinylester, polyester or another thermosetting polymer or mixture thereof. It is desirably a component of suitable pressure vessels for the applications or embodiments described herein, and is to be found in each of types 2 to 8 pressure vessels.

The first embodiment of the present invention, in particular what is referred to in this document as a type 4 high pressure vessel, relates to a high pressure vessel, in particular for compressed natural gas containment or transport. As shown in Fig 2, the high pressure vessel 10 in accordance with one aspect of the present invention comprises at least one opening 71, 72 for gas loading and offloading and for liquid evacuation, a non-metallic liner 2, and at least one external fiber layer 3 provided on the outside of the non-metallic liner 2. With this arrangement, it is possible for the liner 2 to be wrapped or encased by an external composite layer 3.

The internal non-metallic liner 2 is capable of hydraulic containment of raw gases since a suitable thermoplastic or thermoset material is chosen for the liner such that it is non-permeable to the gas because of its micro-structural properties. Natural gas molecules cannot go through the liner because of both spacial arrangement and/or chemical affinity in these materials. Suitable materials for the liner include polymers such as high-density polyethylene (HDPE) and high-purity poly-dicyclopentadiene (DCPD). However, other materials capable of hydraulic containment of raw gases are known, and as such they might instead be used.

The internal liner 2 preferably has no structural purpose during gas, preferably CNG, transportation, loading and offloading Phases.

The non-metallic liner 2 should be corrosion-proof and capable of carrying non-treated or unprocessed gases, i.e. raw CNG. When the non-metallic liner 2 is made from thermoplastic polymers it may be preferred to use a polyethylene or similar plastic which is capable of hydrocarbon corrosion resistance.

The manufacturing of such liners is preferably achieved through rotomolding. For example, a heated hollow mold is filled with a charge or shot weight of material. It is then slowly rotated (usually around two axes perpendicular with respect to each other) thus causing the softened material to disperse and to stick to the walls of the mold. In order to maintain an even thickness throughout the liner, the mold continues to rotate at all times during the heating phase, and to avoid sagging or deformation also during the cooling phase.

When the non-metallic liner 2 is made from thermoset resins it may be preferred to use a polyester, an epoxy, a resin based on poly-dicyclopentadiene or similar plastic capable of hydrocarbon corrosion resistance. The manufacturing of such liners may again be done through rotomolding. For example, a hollow mold is filled with an unhardened thermoset material, and it is then slowly rotated causing the unhardened material to disperse and stick to the walls of the mold.

It is to be appreciated that rotating in only one axis could be enough, especially for this latter embodiment due to the lower viscosity of thermoset compounds.

In order to maintain an even thickness throughout the liner, the mold will typically continue to rotate at all times during the hardening phase (through catalysts). This can also help to avoid sagging or deformation.

This construction also allows the tank to be able to carry a variety of gases, such as raw gas straight from a bore well, including raw natural gas, e.g. when compressed - raw CNG or RCNG, or H_2, or $C0_2$ or processed natural gas (methane), or raw or part processed natural gas, e.g. with $C0_2$ allowances of up to 14% molar, H_2S allowances of up to 1,000 ppm, or H_2 and $C0_2$ gas impurities, or other impurities or corrosive species. The preferred use, however, is CNG transportation, be that raw CNG, part processed CNG or clean CNG - processed to a standard deliverable to the end user, e.g. commercial, industrial or residential.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state, and other impurities/species.

The non-metallic liner 2 can be provided such that it has only to carry the stresses due to manufacturing during the winding of fibers 3, while the structural support during pressurized transportation of gas will be carried out or provided by the external composite layer 3.

The internal surface of the non-metallic liner 2 may advantageously be coated by an internal coating 1 in order to enhance the permeability and corrosion resistance. See the optional dotted line in Figure 1B, only shown on a part of the inner surface. It would in practice be located across the entire surface, but is only shown for illustrative purposes.

The internal coating 1 of the non-metallic liner 2 may be either a special thin layer of a resin with specific low permeability properties or a thin metallic layer. The deposition of the thin protective layer 1 in the case of metals may preferably involve a catalyst able to provide chemical bonding between the organic (polymeric) substrate and the selected low permeability metal or a solution comprising a salt of the preferred metal, a complexing agent and a reducing agent.

The external composite layer 3 will typically be a fiber-reinforced polymer (composite based on glass fibers, or carbon/graphite fibers, or aramid fibers), and it is provided as a reinforcement. It is formed so as to be substantially fully wrapping the vessel 10 (including the majority of the vessel's ends) and so as to be providing the structural contribution during service.

When glass fibers are used, it may be preferred, but not limited thereto, to use an E-glass or S-glass fiber, preferably with a suggested ultimate strength of 1,500 MPa or higher and/or a suggested Young Modulus of 70 GPa or higher. When using carbon fibers, is may be preferred, but not limited thereto, to use a carbon yarn, preferably with a strength of 3,200 MPa or higher and/or a Young Modulus of 230 GPa or higher. Preferably there are 12,000, 24,000 or 48,000 filaments per yarn.

The composite matrix may preferably be a polymeric resin thermoset or thermoplastic and more precisely, if thermoset, it may be an epoxy-based resin.

The high pressure vessel 10 may further comprise a gas permeable layer interposed between the non-metallic liner 2 and the fiber layer 3. Advantageously, the gas permeable layer comprises glass fibers. The high pressure vessel 10 may further comprise a gas detector connected to the gas permeable layer for detecting a gas leakage.

The outermost portion of the external composite layer 3 may further be impregnated using a resin with a high fire resistance, such as in accordance with NGV2-2007 or other internationally recognized standards and testing procedures in order to protect the vessel 10 from fire occurrence. This resin could be a thermoset such as a phenolic polymer.

With reference to Fig 2, the opening 71 and/or 72 at least one of the tank ends 11 and/or 12 may take the form of a nozzle that is also made out of composite materials, preferably in which the reinforcing fiber is carbon or graphite and the resin matrix is epoxy-based.

The manufacturing of the composite nozzle may involve the so-called closed-mold technique.

The composite nozzle may be integrated in the composite pressure vessel structure so that the winding forces of the fibers on the pressure vessel head induce a compression state in the nozzle, being the nozzle between the wound composite and the liner,

The composite nozzle may have threaded holes in the outer surface being able to directly connect valves, pipes and other components in the process or fuel lines, without having pieces being out of the pressure vessel shape hence reducing the required room for accommodating the pressure vessel itself.

Instead of a composite nozzle, a metal nozzle may be preferred, especially for embodiments intended to experience pressures above 300bar. This is because the compressive stresses may render the use of a composite nozzle excessively complex or impractical due to the need to oversize the nozzle to allow for the expected levels of compressive stress.

The manufacturing of the external composite layer 3 over the said non-metallic liner 2 preferably involves a winding technology. This can potentially give a high efficiency in terms of production hours. Moreover it can potentially provide good precision in the fibers' orientation. Further it can provide good quality reproducibility.

The winding apparatus would need to be suitable for handling larger and/or heavier vessels than prior applications. Such a winding apparatus would require larger bearings, reinforced spindles and further adaptations to ensure the thick sidewalls required can be adequately supported.

The reinforcing fibers preferably are wound with a back-tension over a mandrel. The mandrel is constituted by the non-metallic liner 2. The non-metallic liner 2 thus constitutes the male mould for this technology. The winding is advantageously performed after the fibers have been pre-impregnated in the resin. Impregnated fibers are thus preferably deposited in layers over said non-metallic liner 2 until the desired thickness is reached for the given diameter.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layer 3 thickness will have to be thicker than current designs. The thickness of the required composite layer 3 can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the layer 3 poses a number of problems which have previously been thought of as preventing vessels 10 of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layer 3 being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art (e.g. heating the resin batch through which the fibers pass before the actual winding about the mandrel), and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel (the non-metallic liner 2) with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layer 3 is wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

Since this invention relates to a substantially fully-wrapped high pressure vessel 10, it may be preferable to use a multi-axis crosshead for fibers in the manufacturing process.

The process preferably also includes a covering of the majority of the ends (11, 12) of the high pressure vessel 10 with the structural external composite layer 3.

When using thermoset resins an impregnating basket may be used for impregnating the fibers before actually winding the fibers around the non-metallic liner 2. The impregnated fibers are then heated, as described above, as part of the method to reduce thermally induced stresses in the thick composite layer 3 of the vessel.

When using thermoplastic resins, there can be a heating of the resin before the fiber deposition, as mentioned above, in order to melt the resin just before reaching the mandrel, or the fibers may be impregnated with thermoplastic resin before they are deposited as a composite material on the metal liner. The resin is again heated before depositing the fibers in order to melt the resin just before the fiber and resin composite reaches the non-metallic liner 2. The composite may then be applied and cured in stages as explained above.

Additionally, as described in relation to the first embodiment of the present invention, a variety of methods are available to reduce thermal stresses which would otherwise build up in the thick composite layer, necessary for withstanding the substantially higher pressures.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layer thickness will have to be thicker than current designs. The thickness of the required composite layer can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the layer poses a number of problems which have previously been thought of as preventing vessels of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layer being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art, and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layer is wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

The high pressure vessel 10 may preferably be provided with at least one opening 71 and/or 72 intended for gas loading and offloading and liquid evacuation. The opening 71 and/or 72 may be placed at either end 11, 12 of vessel 10, but as shown in Fig 2 it is preferred to provide an opening 72 at the bottom end 12. It may advantageously be a 12-inch (30cm) opening for connecting to pipework.

The high pressure vessel 10 also has an opening 71 at the top end 11 and it is advantageously in the form of an at least 18-inch (45cm) wide access manhole 6, such as one with a sealed or sealable cover (or more preferably a 24-inch (60cm) manhole). It is preferably provided according to ASME (American Society of Mechanical Engineers) standards. Preferably the opening 71 is provided with closing means 73 (see Figure 1A), which allows a sealed closing of the opening during gas transportation, such as by bolting it down, but which allows internal inspection when the vessel 10 is not in use, such as by a person removing the closing means and climbing into the vessel through the opening/manhole 6.

Fig 3 illustrates an advantageous arrangement of a plurality of vessels in modules or compartments 40. The high pressure vessels 10 can be arranged in a ship's hull (see Figure 7) in modules or compartments 40 and the vessels 10 can be interconnected for loading and offloading operations, such as via pipework 61. In a preferred configuration, such modules or compartments 40 have four edges (are quadrilateral-shaped) and contain a plurality of vessels 10. The number of vessels chosen will depend upon the vessel diameter or shape and the size of the modules or compartments 40. Further, the number of modules or compartments will depend upon the structural constraints of the ship hull for accommodating the modules or compartments 40. It is not essential for all the modules or compartments to be of the same size or shape, and likewise they need not contain the same size or shape of high pressure vessel, or the same numbers thereof.

This aspect of the present invention - the arrangement of a plurality of vessels - can be applied to any of the embodiments described within, or any further high pressure vessel according to the present invention.

The vessels 10 may be in a regular array within the modules or compartments - in the illustrated embodiment a 4x7 array. Other array sizes are also to be anticipated, whether in the same module (i.e. with differently sized high pressure vessels), or in differently sized modules, and the arrangements can be chosen or designed to fit appropriately in the ship's hull.

For external inspection-ability reasons it is preferred that the distance between the vessels 10 within the modules or compartments 40 be at least 380mm, or more preferably at least 600 mm. These distances also allow space for vessel expansion when loaded with the pressurised gas - the vessels may expand by 2% or more in volume when loaded (and changes in the ambient temperature can also cause the vessel to change their volume).

Preferably the distance between the modules or compartments 40 or between the outer vessels 10A and the walls or boundaries 40A of the modules or compartments 40, or between adjacent outer vessels of neighbouring modules or compartments 40 (such as where no physical wall separates neighbouring modules or compartments 40) will be at least 600 mm, or more preferably at least 1 m, again for external inspect-ability reasons, and/or to allow for vessel expansion. Higher distance between the pressure vessels will also account for increased Joule-Thomson effects (gas expansion and temperature drop) in case of leaks in the cargo hull due to the higher operating pressure, in excess of 350 bar, or 700 bar, or most preferably up to 1000 bar or 1050 bar.

Still with reference to Fig 3, each high pressure vessel row (or column) is interconnected with a piping system 60 intended for loading and offloading operations from the bottom 12 of each vessel 10, such as through the preferably 12 inch (30cm) opening 72 to main headers, such as through motorized valves.

The main headers can comprise various different pressure levels, for example three of them (high - e.g. 1000 bar, medium - e.g. 600 or 400 bar and low - e.g. 250 or 120 bar), plus one blow down header and one nitrogen header for inert purposes.

Also as shown in Fig 3, the vessels 10 are preferred to be mounted vertically, preferably on dedicated supports or brackets, or by being strapped into place. The supports (not shown) hold the vessels 10 in order to avoid horizontal displacement of the vessels relative to one another. Clamps, brackets or other conventional high pressure vessel retention systems, may be used for this purpose, such as hoops or straps that secure the main cylinder of each vessel.

The supports can be designed to accommodate vessel expansion, such as by having some resilience.

When the vessels 10 are vertically mounted, they are less critical in following dynamic loads resulting from the ship motion. Moreover the vertical arrangement allows an easier replacement of single vessels in the module or compartment 40 when necessary - they can be lifted out without the need to first remove other vessels from above. This configuration can also potentially allow a fast installation time. Mounting the vessels 10 in vertical positions also allows condensed liquids to fall under the influence of gravity to the bottom, thereby being off-loadable from the vessels using, e.g. the 12 inch opening 72 at the bottom of each vessel 10.

Offloading of the gas will advantageously also be from the bottom of the vessel 10.

With the majority of the piping and valving 60 installed towards the bottom of the modules 40, the center of gravity of the whole arrangement will be also in a low position, which is recommended or preferred, especially for improving stability at sea, or during gas transportation.

Modules or compartments 40 are preferably kept in a controlled environment with nitrogen gas occupying the space between the vessels 10 and the modules' walls 40A, thus reducing fire hazard. Alternatively, the engine exhaust gas could be used for this inerting function thanks to its composition being rich in $C0_2$.

By maximizing the size of the individual vessels 10, such as by making them, for example, up to 6 meter in diameter and up to 30 meters in length, for the same total volume contained the total number of vessels 10 may be reduced, which in turn allows to reduce connection and inter-piping complexity, and hence reduces the number of possible leakage points, which usually occur in weaker locations such as weldings, joints and manifolds. Preferred arrangements call for diameters of at least 2m.

One dedicated module may be set aside for liquid storage (such as condensate) using the same concept of interconnection used for the gas storage. The modules 40 are thus potentially all connected together to allow a distribution of such liquid from other modules 40 to the dedicated module - a ship will typically feature multiple modules 40.

In and out gas storage piping may advantageously be linked with at least one of metering, heating, and/or blow down systems and scavenging systems through valve-connected manifolds. They may preferably be remotely activated by a Distributed Control System (DCS).

Piping diameters are preferably as follows:

18 inch. for the three main headers (low, medium and high pressure) dedicated to CNG loading/offloading.

24 inch. for the blow-down CNG line.

6 inch. for the pipe feeding the module with the inert gas.

10 inch. for the blow-down inert gas line.

10 inch. for the pipe dedicated to possible liquid loading/offloading.

All modules may preferably be equipped with adequate firefighting systems, as foreseen by international codes, standards and rules.

The transported gas, preferably CNG, will typically be at a pressure in excess of 200bar, and potentially in excess of 350bar, 600 bar, 700 bar or 800 bar, and potentially peaking at 1000 bar or 1050 bar.

In addition to high pressure versions of the type 4 pressure vessel, described as the first specific embodiment, other forms of pressure vessel can be according to the present invention. These other forms of pressure vessels include those that can be referred to as type 5, type 6, type 7 and type 8 pressure vessels. It is also possibly to apply other modified versions of these various different pressure vessel types. But in particular, in addition to the above first embodiment, the present invention can be applied to pressure vessels of type 3, 5, 6, 7 and 8.

A summary of the types of pressure vessel available are:

Type 1: All-steel pressure vessels, with the metal being used as the structure for the containment;

Type 2: Composite Hoop-Wrapped steel tanks with structural steel heads (domes) and hybrid a hybrid material body (steel + fibre-reinforced polymer, the fibre-reinforcement being in hoop sections), the hybrid material being in a load sharing condition;

Type 3: Metallic liner with non-metallic structural overwrap. The metal liner is only there for fluidic containment purposes. The non-metallic external structural overwrap is made out of, in the preferred arrangements, a fibre-reinforced polymer; other non-metallic overwraps are also possible.

Type 4: Non-metallic liner with non-metallic structural overwrap. The non-metallic liner (such as a thermoplastic or a thermosetting polymer liner) is only there for fluidic containment purposes. The non-metallic external structural overwrap can again be made out of, in the preferred arrangements, a fibre-reinforced polymer.

Type 5: A fully non-metallic structure (no separate liner), with the non-metallic structure having been built on a substrate that is removed after the manufacturing process.

Type 6: Steel body section fitted with composite heads or domes. The pressure vessels have a structural steel body section and fibre-reinforced polymer heads or domes fitted thereto with a sealed joint;

Type 7: Composite Hoop-Wrapped steel bodies, with composite heads or domes. The pressure vessels have hybrid steel + fibre-reinforced polymer hoop wrapped body section, with the materials in a load sharing condition and fibre-reinforced polymer heads or domes fitted thereto with a sealed joint.

Type 8: Near-Sphere shaped pressure vessels formed from a non-metallic liner with a non-metallic structural overwrap (like the type 4 above, but with the specific near spherical shape). These pressure vessels have a non-metallic liner (such as a thermoplastic or a thermosetting polymer) which serves only for fluidic containment purposes. The non-metallic external structural overwrap is typically made out of, in the preferred arrangements, a fibre-reinforced polymer.

As such, as well as a type 4 pressure vessel suitable for high pressure use, also according to the present invention is a type 3, 5, 6, 7 or 8 pressure vessel, the pressure vessel being for storage or transportation of a high pressure gas, preferably CNG, and having a significantly increased maximum pressure capability than both approved type 1 pressure vessels of an equivalent size and approved type 2 pressure vessels of an equivalent size. The maximum pressure being over 200 bar, preferably over 350 or 700 bar, and more preferably up to 1000 or even 1050 bar.

Type 6 pressure vessels comprise composite end domes with a steel cylindrical section. While the methods according to the present invention can be used during the manufacturing of such a vessel to increase its maximum pressure capacity, the join between the cylindrical and dome section will provide a stress concentration, thus limiting the maximum potential pressure capacity. As such, this type of pressure vessel will not be discussed further.

Weights and gas capacities are typically assigned to specific pressure vessels, or to specific designs of pressure vessels, by the relevant regulatory bodies as "certificated" characteristics thereof. This is since pressure vessels usually have to be certificated before being put into service.

As before, preferably the pressure vessel has an internal wall or surface formed of a material that is substantially inert relative to, i.e. it will tend not to corrode when in contact with, the fuel to be stored or transported. For example, the pressure vessel may have having corrosion resistance properties of at least an AISI 316 stainless steel or it may be substantially H_2S resistant, or preferably H_2S resistant, in accordance with IS015156.

As explained above, vessels capable of withstanding high pressures require thicker wall sections. Designing a metal or composite structure to withstand these loads and the associated stresses can be done using traditional methods - as would be well known by one skilled in the art - providing the effects of having a thick wall are taken into account.

Most problems associated with making vessels suitable for high pressures are encountered during the manufacturing process, rather than the design stage. As such, customised manufacturing equipment and processes may be required.

An example of standard equipment which might not be suitable for high pressure applications are the filament winders. As such, filament spindle winders may require modifying and reinforcing to allow the apparatus to withstand the additional torsion and weight resulting from the increased wall thickness. Potential issues with filament winders are equally applicable to the manufacturing of all the embodiments associated with the present invention.

Mandrels, and in particular disposable mandrels as disclosed in this application may also have to be custom made to withstand the larger forces resulting from the thicker wall section. In the case where a separate metallic or non-metallic liner are used, a separate mandrel may not be required, as the liner itself may be sufficiently strong to act as the mandrel. Each case will have to be analysed individually, as it may be more efficient to use a disposable mandrel as described herein, than to increase the liner thickness so it can act as a mandrel. Again, such issues are equally applicable to the manufacturing of all the embodiments associated with the present invention.

Preferably, the composite is cured by a multi-stage curing process. Using a single-stage curing process for a thick composite section risks impairing mechanical performance. One cause for reductions in performance is due to thermal residual stresses, often due to differences in thermal expansion characteristics between the fiber and matrix of the composite. Using a multi-stage curing process reduces the impact of this effect.

Other fuel typed transportable within any of the embodiments of the present invention, include pressurised/liquid hydrogen, LNG, GTL (gas to liquid) and LPG.

Referring now to the remaining drawings, examples of other suitable high pressure vessels will be described.

The high pressure vessel of Figures 9 and 10 is a type 3 high pressure vessel and is made of an internal metallic liner as at least a first layer (100) capable of hydraulic or fluidic containment of raw gases such as CNG (20) (Compressed Natural Gas), with an external composite layer (200). The high pressure vessel is capable of handling gases in excess of 200 bar, or preferably 350 bar or 700 bar, or even more preferably up to 1000 or 1050 bar.

Said metallic liner, as the first layer (100), is not needed to be provided in a form to provide a structural aim during CNG (20) transportation. However, it is preferred that it should be at least corrosion-proof. The preferred material is a stainless steel, or some other metallic alloy.

This construction also allows the tank to be able to carry other gases, such as natural gas (methane) with $C0_2$ allowances of up to 14% molar, H_2S allowances of up to 1.5% molar, or H_2 and $C0_2$ gases. The preferred use, however, is CNG transportation.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H2S, plus potentially toluene, diesel and octane in a liquid state.

The stainless steel is preferably an austenitic stainless steel such as AISI 304, 314, 316 or 316L (with low carbon percentages). Where some other metallic alloy is used, it is preferably a Nickel-based alloy or an Aluminum-based alloy, such as one that has corrosion resistance.

The metallic liner forming the first layer (100) preferably only needs to be strong enough to withstand stresses arising from manufacturing processes of the vessel, so as not to collapse on itself, such as those imposed thereon during fiber winding. This is because the structural support during pressurized transportation of CNG (20) will be provided instead by the external composite layer (200).

The external composite layer (200), which uses at least one fiber layer, will be a fiber-reinforced polymer. The composite layer can be based on glass, or on carbon/graphite, or on aramid fibers, or on combinations thereof, for example. The external composite layer is used as a reinforcement, fully wrapping the pressure vessels (10), including vessel ends (11, 12), and providing the structural strength for the vessel during service. In case of glass fibers, is it preferred but not limited to the use of an E-glass or S-glass fiber. Preferably, however, the glass fiber has a suggested tensile strength of 1,500 MPa or higher and/or a suggested Young Modulus of 70 GPa or higher. In case of carbon fibers, is it preferred but not limited to the use of a carbon yarn, preferably with a tensile strength of 3,200 MPa or higher and/or a Young Modulus of 230 GPa or higher. Preferably there are 12,000, 24,000 or 48,000 filaments per yarn.

The composite matrix is preferred to be a polymeric resin thermoset or thermoplastic. If a thermoset, it may be an epoxy-based resin.

The manufacturing of the external composite layer (200) over the said metallic liner (the first layer (100)) preferably involves a winding technology. This can potentially gives a high efficiency in terms of production hours. Moreover it can potentially provide good precision in the fibers' orientation. Further it can provide good quality reproducibility.

The winding apparatus would need to be suitable for handling larger and/or heavier vessels than prior applications. Such a winding apparatus would require larger bearings, reinforced spindles and further adaptations to ensure the thick sidewalls required can be adequately supported.

The reinforcing fibers preferably are wound with a back-tension over a mandrel. The mandrel is typically the liner. The liner thus constitutes the male mould for this technology. The winding is typically after the fibers have been pre-impregnated in the resin. Impregnated fibers are thus preferably deposed in layers over said metallic liner until the desired thickness is reached for the given diameter.

Since this invention preferably relates to a substantially fully-wrapped high pressure vessel (10), a multi-axis crosshead for fibers is preferably used in the manufacturing process.

The process preferably includes a covering of the majority of the ends (11, 12) of the pressure vessel (10) with the structural external composite layer (200).

In the case of the use of thermoset resins there can be a use of an impregnating basket before the fiber deposition - for impregnating the fibers before actually winding the fibers around the metal liner (100).

In the case of the use of thermoplastic resins, there can be a heating of the resin before the fiber deposition in order to melt the resin just before reaching the mandrel, or the fibers are impregnated with thermoplastic resin before they are deposited as a composite material on the metal liner. The resin is again heated before depositing the fibers in order to melt the resin just before the fiber and resin composite reaches the metal liner (100).

Additionally, as described in relation to the first embodiment of the present invention, a variety of methods are available to reduce thermal stresses which would otherwise build up in the thick composite layer, necessary for withstanding the substantially higher pressures.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layer thickness will have to be thicker than current designs. The thickness of the required composite layer can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the layer poses a number of problems which have previously been thought of as preventing vessels of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layer being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art, and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel (the metallic liner) with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layer is wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

The pressure vessel (10) is provided with an opening (120) (here provided with a cap or connector) for gas loading and offloading. It is provided for connecting to pipework - e.g. fuel lines/breathing regulators, and the like.

The vessel also has an opening 31 at the top end (11). This, however, is optional - it may be preferred to have a fully domed second end.

A plurality of the pressure vessels (10) can be arranged in modules or in compartments and they can be interconnected, for example for loading and offloading operations, such as via pipework.

The supports for holding the pressure vessels can be designed to accommodate vessel expansion, such as by having some resilience, or by mounting the vessels at their ends, whereby the cylindrical sections can expand radially without restriction.

Referring next to Figure 11, another vessel 10 in accordance with the present invention is shown. It is made of an internal metallic liner 200 capable of hydraulic or fluidic containment. The inside of metallic liner 200 is internally coated with a non-metallic layer 110, such as a polymeric layer, which is capable of containing, for example, CNG. The metal liner 200 is not needed to be provided in a form to provide a structural aim during the CNG transportation, loading and offloading.

The metal liner 200 is internally coated with the non-metallic corrosion-proof layer 110 and that liner is capable of carrying the compressed gas. Preferred material may be a carbon-steel coated metallic liner 200 with a thin polymer non-metallic layer 110 such as an epoxy resin, HDPE (High-Density Polyethylene) or PVC (Polyvinyl Chloride). Preferably it has a tensile strength of 50 MPa or higher. Preferably it has a Young Modulus of 3 GPa or higher. Preferably it is able to be substantially chemically inert.

Preferably it is corrosion-proof for a wide range of chemical compositions, including chlorides.

This construction also allows the vessel 10 to be able to carry other gases, such as natural gas (methane) with $C0_2$ allowances of up to 14% molar, H_2S allowances of up to 1.5% molar, or H_2 or $C0_2$ gases. The preferred use, however, is CNG.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state.

The metal liner 200 preferably only needs to be strong enough to withstand the mechanical stresses arising from manufacturing processes of the vessel, such as those imposed thereon when an external fiber layer 300 is being applied. This is because the structural support during pressurized transportation of gas will be provided instead by the external fiber layer 300.

Where the metal liner 200 is of carbon-steel, it could be selected from an API (American Petroleum Institute) 5L X42 or X60 or ASTM (American Society for Testing and Materials) A516 with a preferred tensile strength of 350 MPa or higher.

The external fiber layer 300 may preferably be selected from a fiber-reinforced polymer based on carbon/graphite fibers, advantageously fully wrapping the vessels 10 (including the vessel ends) and providing the structural contribution during service.

When carbon fibers are used in the external fiber layer 300, it is preferred, but not limited thereto, to use a carbon yarn with a preferred tensile strength of 3,200 MPa or higher and/or a preferred Young Modulus of 230 GPa or higher. The yarn may advantageously have 12,000, 24,000, or 48,000 filaments per yarn.

The composite matrix is preferred to be a polymeric resin thermoset or thermoplastic. More precisely, if a thermoset resin is used, it is preferred that it should be an epoxy-based resin, or alternatively a vinyl ester or polyester-based resin. This also allows achieving a cost reduction.

Since the external fiber layer 300 comprising the carbon/epoxy composite is electrically conductive like the steel used for the metallic liner 200, it is advantageous to provide an additional insulating composite layer with isolating properties in order to avoid possible galvanic coupling.

This insulating layer may advantageously be made of glass fibers embedded in epoxy resin, hence matching the resin of the external layer. Concerning glass fibers, it is preferred but not limited to the use of E glass or S glass fiber. Preferably, however, the glass fibers have a suggested tensile strength of 1,000 MPa or higher and/or a Young Modulus of 70 GPa or higher.

Alternatively, as shown in Figure 12, it may be useful to apply a polymeric coating as an insulating layer 4. In this embodiment it is between the liner 200 and the fiber layer 300. The insulating layer 4 may advantageously be selected from materials such as an epoxy resin, HDPE (High-Density Polyethylene) or PVC (Polyvinyl Chloride). Preferably the coating has a tensile strength of 50 MPa or higher and/or a Young Modulus of 3 GPa or higher.

The insulating layer 4, which typically has only to carry compressive stresses, may have porous characteristics, i.e. it may be permeable to gases in the case of leakage from the steel liner. The insulating layer 4 may advantageously then further comprise an integrated gas detection device able to warn in case of leakage from the inner liner 200. Figure 13 schematically shows a connection to such a device, which may be integrated into the wall of the vessel. Such a device might be operated via a wireless transmission to a receiving unit located nearby.

The manufacturing of the external composite layer 300 over the said metallic liner 200 (the first layer) preferably involves a winding technology. This can potentially gives a high efficiency in terms of production hours. Moreover it can potentially provide good precision in the fibers' orientation. Further it can provide good quality reproducibility.

The winding apparatus would need to be suitable for handling larger and/or heavier vessels than prior applications. Such a winding apparatus would require larger bearings, reinforced spindles and further adaptations to ensure the thick sidewalls required can be adequately supported.

The reinforcing fibers preferably are wound with a back-tension over a mandrel. The mandrel is typically the liner. The liner thus constitutes the male mould for this technology. The winding is typically after the fibers have been pre-impregnated in the resin. Impregnated fibers are thus preferably deposited in layers over said metallic liner until the desired thickness is reached for the given diameter.

Since this invention preferably relates to a substantially fully wrapped pressure vessel 10, a multi-axis crosshead for fibers is preferably used in the manufacturing process.

The process preferably includes a covering of the majority of the ends 11, 12 of the pressure vessel 10 with the structural external composite layer 300.

In the case of the use of thermoset resins there can be a use of an impregnating basket before the fiber deposition - for impregnating the fibers before actually winding the fibers around the metal liner 200.

In the case of the use of thermoplastic resins, there can be a heating of the resin before the fiber deposition in order to melt the resin just before reaching the mandrel, or the fibers are impregnated with thermoplastic resin before they are deposited as a composite material on the metal liner. The resin is again heated before depositing the fibers in order to melt the resin just before the fiber and resin composite reaches the metal liner 200.

Additionally, as described in relation to the first embodiment of the present invention, a variety of methods are available to reduce thermal stresses which would otherwise build up in the thick composite layer, necessary for withstanding the substantially higher pressures.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layer 300 thickness will have to be thicker than current designs. The thickness of the required composite layer 300 can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the layer 300 poses a number of problems which have previously been thought of as preventing vessels 10 of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layer 300 being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art, and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel (the liner 200) with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layer 300 is wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

The pressure vessel 10 may be provided with an opening 7 (here provided with a cap or connector) intended for gas loading and offloading and liquid evacuation. The opening may be placed at either end 11, 12 of the vessel 10.

The vessel 10 also is shown to have a second opening 6 at the other end 11. This is optional - the end dome may be fully rounded instead.

Referring next to Figure 14, a further embodiment of a high pressure vessel is shown for use with the present invention's intended purposes. The vessel is made of an internal metal liner 111 capable of hydraulic or fluidic containment of raw gases. The metal liner 111 is not needed to be provided in a form to provide a structural aim, during CNG transportation, loading and offloading phases.

The metallic liner 111 should be corrosion-proof and capable of containing CNG. Preferably the material used is a stainless steel, aluminium or other corrosion-proof metallic alloy.

In case of stainless steel, it is preferred but not limited to the use of an austenitic stainless steel such as AISI 304, 314, 316 or 316L (with low carbon percentages).

In case of other metallic alloys, it is recommended but not limited to the use of a Nickel-based alloy or an aluminium-based alloy capable of corrosion resistance.

This construction also allows the vessel to be able to carry other gases, such as natural gas (methane) with $C0_2$ allowances of up to 14% molar, and/or H_2S allowances of up to 1.5% molar, and also such as H_2 and/or $C0_2$ gases. The preferred use, however, is CNG.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state.

The liner 111 preferably only needs to be strong enough to withstand the stresses arising from manufacturing processes of the vessel, such as those imposed thereon during fiber winding. The structural support during pressurised transportation of gas will instead be provided by the external composite layer(s) 222, 333.

The first fiber layer 222 about the liner 111, according to the illustrated embodiment, is a fiber-reinforced polymer based on carbon/graphite. It substantially is fully wrapping the vessel (including most of the vessel ends) and it is arranged to be providing the structural contribution during service. Is it preferred but not limited to the use of a carbon yarn, preferably with a tensile strength of 3,200 MPa or higher and/or a preferred Young Modulus of 230 GPa or higher. Advantageously it can have 12,000, 24,000 or 48,000 filaments per yarn.

The second fiber layer 333, according to the illustrated embodiment, has an isolating and protective function. In use it will be in direct contact with the external environment. For these mentioned reasons, the second external fiber layer 333 can preferably be a polymer or a fiber-reinforced polymer based on glass fibers, due to its inert behavior in aggressive and marine environments, and due to its isolating properties in terms of low thermal conductivity. Is it preferred but not limited to the use of an E-glass or S-glass fiber. Preferably the fibers have a suggested tensile strength of 1,000 MPa or higher and/or a suggested Young Modulus of 70 GPa or higher.

The composite matrix, regardless of the composite layer considered, is preferred to be a polymeric resin thermoset or thermoplastic. More precisely, if a thermoset, it could be and epoxy-based resin, or alternatively a vinylester or polyester-based resin. This allows a cost reduction compared to other possible arrangements, including the traditional steel arrangement.

The manufacturing of the external composite layer 222, 333 over the said metallic liner 111 preferably involves a winding technology. This can potentially gives a high efficiency in terms of production hours. Moreover it can potentially provide good precision in the fibers' orientation. Further it can provide good quality reproducibility.

The winding apparatus would need to be suitable for handling larger and/or heavier vessels than prior applications. Such a winding apparatus would require larger bearings, reinforced spindles and further adaptations to ensure the thick sidewalls required can be adequately supported.

The reinforcing fibers preferably are wound with a back-tension over a mandrel. The mandrel is typically the liner. The liner thus constitutes the male mould for this technology. The winding is typically after the fibers have been pre-impregnated in the resin. Impregnated fibers are thus preferably deposited in layers over said metallic liner until the desired thickness is reached for the given diameter.

Since this invention preferably relates to a substantially fully-wrapped pressure vessel 10, a multi-axis crosshead for fibers is preferably used in the manufacturing process.

The process preferably includes a covering of at least most of the ends 11, 12 of the pressure vessel 10 with the structural external composite layer 222, 333.

In the case of the use of thermoset resins there can be a use of an impregnating basket before the fiber deposition - for impregnating the fibers before actually winding the fibers around the metal liner 111.

In the case of the use of thermoplastic resins, there can be a heating of the resin before the fiber deposition in order to melt the resin just before reaching the mandrel, or the fibers are impregnated with thermoplastic resin before they are deposited as a composite material on the metal liner. The resin is again heated before depositing the fibers in order to melt the resin just before the fiber and resin composite reaches the metal liner.

Additionally, as described in relation to the first embodiment of the present invention, a variety of methods are available to reduce thermal stresses which would otherwise build up in the thick composite layer, necessary for withstanding the substantially higher pressures.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layers thickness will have to be thicker than current designs. The thickness of the required composite layers 222, 333 can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the layers 222, 333 pose a number of problems which have previously been thought of as preventing vessels 10 of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layers 222, 333 being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art, and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layers 222, 333 are wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

The pressure vessel 10 has an opening 7 (here provided with a cap or connector) addressed to gas loading and offloading. It is for connecting to pipework.

The vessel 10 also has an opening 6 at the other end 11. It is optional, and the end may instead be fully domed.

As examples of the present invention, the following are presented:

1. A corrosion-proof metallic liner made out of AISI 316 stainless steel with a tensile strength of at least 500 MPa and a carbon content below or equal to 0.08%, overwrapped by a structural composite carbon fiber-based with a tensile strength of 3,200 MPa or higher and a preferred Young Modulus of 230 GPa or higher, with advantageously 12,000, 24,000 or 48,000 filaments per yarn and a second external layer made out of non-reinforced epoxy resin with a tensile strength of at least 80 MPa and a thermal conductivity of about 0.2 W»m^{-1}•K^{-1} for insulating reasons.

2. A corrosion-proof metallic liner made out of AISI 316 stainless steel with a tensile strength of at least 500 MPa and a carbon content below or equal to 0.08%, overwrapped by a structural composite carbon fiber-based with a tensile strength of 3,200 MPa or higher and a preferred Young Modulus of 230 GPa or higher, with advantageously 12,000, 24,000 or 48,000 filaments per yarn and a second external glass fiber-based composite layer with an E-glass or S-glass fiber with an suggested tensile strength of 1,000 MPa or higher and a suggested Young Modulus of 70 GPa or higher impregnated with an epoxy resin with a thermal conductivity of about 0.2 W»m^{-1}· K^{-1} for insulating reasons.

3. A corrosion-proof metallic liner, overwrapped by a structural composite carbon fiber-based with a tensile strength of 3,200 MPa or higher and a preferred Young Modulus of 230 GPa or higher, with advantageously 12,000, 24,000 or 48,000 filaments per yarn and a second external glass fiber-based composite layer with an E-glass or S-glass fiber with an suggested tensile strength of 1,000 MPa or higher and a suggested Young Modulus of 70 GPa or higher impregnated with an epoxy resin with a thermal conductivity of about 0.2 W»m^{-1}•K^{-1} for insulating reasons plus a third external layer made out of non-reinforced epoxy resin with a tensile strength of at least 80 MPa and a thermal conductivity of about 0.2 W»m^{-1}•K^{-1} for insulating reasons. This configuration also allows the vessel to have a higher thermal stability, giving the transported gas a lower temperature gradient.

Another form of pressure vessel for the present invention is a "type 3" vessel. It has an external structural layer made of a composite, fibre reinforced, material and an inner metallic liner, which can be thin. The external composite material provides the structural strength of the vessel, while the inner liner provides an impermeable layer for containment of the gas. The liner is generally made of a metal which is highly chemically resistant. The purpose of the liner, however, is not just to provide a layer suitable for contact with the gas but also that of providing a substrate over which the composite material can be formed. A way of forming said composite material is by winding its fibres around the liner. The liner, therefore, is designed so as to be able to withstand fibre winding stresses.

One method of forming such a resistant liner is that of line welding one or more sheets of metal together along edges. A plurality of similarly curved sheets of metal would usually be welded together to form the liner, although a single sheet may be rolled and then joined along a common seam. Alternatively the tube might be extruded. Further welding between the hoop section and the end domes is then performed. Those end domes can be formed through a spin forming process or by a pressing process if of a small radius (e.g. less than 1m), which processes are well known in the industry.

The welds are then usually ground down to give a smooth finish.

It should be highlighted that these methods produce the need for a significant number of welds, each of which presents numerous potential points of failure since weld lines are usually weaker than the sheet metal itself, in terms of their strength/durability properties, due to the structural changes to the material that can occur during or after the thermal shock of the welding process. In light of this, manufacturing a suitable liner requires know-how, materials, time and suitable equipment, such as welding equipment and specialist sheet-clamping equipment, and this is all adding to the costs involved.

In a further embodiment of the present invention, disclose herein with reference to Figures 15 to 17, it is possible to dispense with the liner inside the finished vessel. The following method is a general technique which can be used with any of the vessels disclosed herein, regardless of whether there is a liner present or not. In fact, there is still a benefit to using the following method when there is a liner, as the liner will not need to be structurally strong enough to take the torsion winding forces, and so a thinner liner can be used.

In order to manufacture a liner-free vessel suitable for containment of CNG or other gases or fuels, the method illustrated in Figure 15 is provided.

In that method, a plurality of reels 31, 32, 33, 34 is provided, each housing a reel of a selected fibre, for example a carbon fibre, or an aramid fibre, or Kevlar®. In one embodiment, the reels accommodate individual filaments of the selected fibre. In other embodiments, yarns of fibres can be reeled, or the fibres can be bundled into tows, ropes or cords, or braids. Alternatively, the fibres may be woven into ribbons or narrow sheets of material (a fabric of fibre), including flat-fibres or webbing.

The single fibres, yarns, tows, ropes or narrow ribbons of fibre(s) are then fed to a tape machine 35. The tape machine arranges those multiple "fibres", which are effectively one-dimensional, into a single tape 37. The tape will still be relatively narrow, but it will now be in a wider, or two-dimensional, form, i.e. it will be wider that the individual "fibres" that come off the reels 31, 32, 33, 34.

The tape can be treated as being effectively a substantially parallel arrangement of "fibres", the fibres extending largely side by side, i.e. transversally or perpendicularly to the direction of travel, along the length of the tape.

The tape 27 is then immersed into a resin, such as a batch of resin in a bath 38. Suitable resins can be, for example, polyester resins, vinylester resins, epoxy resins, dicyclopentadiene resins, phenolic resins, bismaleimide resins and polyimide resins. Such resins can generally be classified as either a thermoplastic resin or a thermosetting resin, according to their behaviour when heated and cooled. Thermoplastic resins can be re-heated and softened after they have been cured, while thermosetting resins, once cured, cannot be re-heated to soften them without causing permanent damage, i.e. they will not melt at normal manufacturing temperatures. On the other hand, thermosetting resins allow higher stiffness and higher general mechanical properties to be provided, along with their generally lower viscosity before curing of the resin (these advantages typically allow a better or faster winding/manufacturing process and a better impregnation of the composite fibers). It is observed, therefore, that thermosetting resins and thermoplastic resins can both be suitable for this method, provided that the resin of choice is formulated to be chemically CNG resistant and substantially, or virtually completely, impermeable to the component parts of CNG or whatever other gas is used at the desired operating pressures of the vessels. Those component parts will most likely comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state.

The resin impregnated tape 39 is then fed to a mechanical head 40 which is responsible for winding the impregnated tape (now shown in the drawings by reference sign 41) around the mandrel 45. Various methods can be used for winding the impregnated tape around the mandrel. A simple way, however, is that of employing a mechanical head 40 which moves back and forth one-dimensionally, i.e. along a line parallel to the mandrel, the head delivering the tape 41 as the mandrel 45 rotates. Preferably the winding process involves helical and hoop winding. Helical winding goes around the geodesic heads (ends) of the mandrel and around the openings. Hoop winding goes on the cylindrical section only in a circumferential direction. The hoop section may be arranged such that it accommodates approximately double the fiber amount of the heads, e.g. in terms of the thickness of the winding.

Additionally, as described in relation to the first embodiment of the present invention, a variety of methods are available to reduce thermal stresses which would otherwise build up in the thick composite layer, necessary for withstanding the substantially higher pressures.

As the pressures at which the vessel of the present invention will be used at are substantially higher than any design currently in use, the composite layer thickness will have to be thicker than current designs. The thickness of the required composite layer can be calculated using usual methods, known to one skilled in the art, provided that the effects of having a thick wall are taken into account.

The increased thickness of the composite layer poses a number of problems which have previously been thought of as preventing vessels of this design being commercially viable.

Thicker sections take longer to cure, and this often results in certain depths of the layer being cured while others are not. This in turn leads to thermally induced stresses, which are unacceptable.

To reduce the occurrence of thermally induced stresses a number of methods can be used in isolation or combination. In the current embodiment the impregnating resin is heated prior to filament winding. This is often done for thermoplastic resins, as explained below, however it is not normal practice for thermoset resins, and the temperature is also different to standard practice with thermoplastic resins.

The heating is done in a conventional method known to one skilled in the art, and the temperature to which they are heated is specific to the resin being used. This means that the impregnated fibers will be deposed on the mandrel with the resin already having started the curing process. This reduces the thick-wall effect of the centre of the wall curing at a different rate to the surfaces.

Additionally, the composite layer is wound and cured in a number of stages, with each stage increasing the thickness by an amount which can then be cured with an acceptably low amount of thermal stress buildup. This gradual step-wise approach eliminates the need for a large thickness of composite to be cured simultaneously.

Finally, the vessel is rotated not only during the winding process, but also the curing process. This assures that the uncured resin does not move or buildup anywhere due to gravity. This is much more of a risk with thick structures.

In the formation of the prior art type 3 vessel, the mandrel would take the form of the liner. However, in accordance with the embodiment of Figures 15 to 17, the mandrel instead takes the form of a disposable mandrel, i.e. a mandrel that can be eliminated or removed from the inside area of the vessel once the composite layer or composite laminate has been created thereon. That mandrel thus needs to be able to withstand the winding stresses during the winding of the tape, plus the lamination stresses as the layers build up - lamination refers to the process of growing the thickness of the composite wrap by gradually stacking layers of tape over one another by winding the tape continually, back and forth over the mandrel so as to pass over other previously wound layers of tape. The winding thus forms multiple helical or coiled (i.e. hooped) layers of tape so as to provide a substantially uniform or flat surface.

In the embodiment of Figure 16, the disposable mandrel 47 is made of compacted sand. Other disposable mandrels are also anticipated to be useable here, such as expandable stent-like arrangements, or braids, or balloons, or other solid arrangements such as ice or clay shells, plus other collapsible structures.

Figure 16 only shows the wound tape in loose-wind form, and prior to completing the full number of windings required, and this is for illustrating the principle of the winding only - in practice it would be wound down tight against the mandrel 47, and the tape windings would be overlayered many times so as to form the vessel's form.

Once the over-layer of fibre-reinforced composite material has been fabricated over the disposable mandrel 47, so as to have formed the desired material thickness, the sand can be removed from the centre of the vessel. This can be achieved, for example, by applying vibrations to the finished component, e.g. by means of an electromechanical shaker. The vibrations produced by the shaker will break up the compacted sand, which will then be able to be removed from the inside of the vessel, e.g. by tipping or washing it out of an aperture in an end thereof. The aperture will be formed (or left) at the end of the vessel during the winding process. Indeed, an aperture would usually be left or formed at both ends thereof. Such apertures not only allow the sand to be removed, but they also will ultimately allow CNG to be loaded into and unloaded from the vessel, during use.

The ends of the vessel are formed over dome-shaped ends of the mandrel, but only to a sufficient degree so as to leave thereat the aperture(s).

Figure 16 shows the general trajectory of the resin-impregnated tape 51 as it is wound around the disposable mandrel. The mandrel 47 has the shape of the internal volume of the CNG pressure vessel, in this case a cylinder with two dome-shaped ends or terminations.

The resin-impregnated tape 51 is supplied onto the mandrel 47 starting from an origin or first free end 50. In Figure 16, the origin 50 of the tape is located close to the left dome of the disposable mandrel 47.

While the mandrel spins around its longitudinal axis, the mechanical tape delivery head moves longitudinally (parallel to that axis) so as to create hoops or circles 53 (a coil or helix) of fibers around the mandrel 47. Those hoops or circles maintain a substantially constant angle relative to the axis along that cylindrical part of the mandrel.

When the head reaches the first (right) end of the mandrel 47, the wrapping characteristics change. For example, as it reaches the right end of the mandrel 47, it slows down, and so does the rotation of the mandrel 47. The angle of the hoops or circles therefore may be changed. Further, as the winding slows down, torsional forces are generated within the mandrel, and these are in addition to the winding forces already being generated (the winding forces tend to compress the mandrel from outside in). The torsional forces result from the momentum of the mandrel, and can be considerable if the vessel is both large and the rotational speeds vary rapidly. Such issues become particularly relevant when producing vessels suitable for withstanding high pressures as in the current invention. High pressure vessels require thicker walls than standard designs, greatly increasing the torsional force exerted on the mandrel. Such additional torsional forces, however, would also have occurred in arrangements where the mandrel takes the form of a liner, and as such have been an existing problem with the known over-liner winding techniques, whereby it has been something that has contributed to the need to make those liners stronger, and thus heavier, than ultimately desirable, so as to prevent them from deforming out of shape as a result of the wrapping. However, when using the disposable mandrel of the present invention, such heavier mandrels do not cause a problem for the final product since the disposable mandrel will not remain within the finished vessel.

The winding apparatus itself would also need to be considered when handling larger and/or heavier vessels than prior applications. It is likely the apparatus would require larger bearings, reinforced spindles and further adaptations to ensure the thick sidewalls and mandrel required can be adequately supported.

Another advantage of having a filled structure/mandrel or a structure with radial components is potentially a better behavioural response to torsional winding forces than a traditional liner, which is usually a thin-walled approximation and having a smaller material section.

This aspect of the present invention therefore offers a considerable advantage over the prior art.

With the compacted sand solution for the mandrel, there should be little at issue in relation to handling the additional torsional forces either. That is because the compacted sand can be made to have significant robustness to such loadings. Other solutions for the mandrel can also offer such advantages. For example, a solid mandrel formed from a destructible, dissolvable or meltable material (including compacted sand, wax, ice, clay, gypsum and many other granular or dusty, yet compactable, materials) can be designed such that it cannot easily twist out of shape. Likewise, a fracturable clay liner, or collapsible structures like balloons, or braid or stent-like arrangements, or other collapsible scaffolds, can be made such that they are strong enough to survive such forces, but yet still being removable through the aperture(s). Such scaffolds can even support arrangements such as compacted sand pads or ice pads, thereby making the mandrel significantly lighter than a solid mandrel.

Returning to the process of winding the composite, once the fibre has reached the first end of the mandrel, it is wound around the dome of the mandrel at that end, albeit leaving the aperture part of the vessel, at that end, uncovered, and then it is returned towards the other end of the mandrel through a further coiled path 54 generally diagonally across the body of the mandrel 47. This path will typically have a different angle to the preceding coil, although that is optional, and it may even be sufficiently angulated so as not to form a full loop around the cylindrical section of the vessel. Preferably it loops around less than half of the vessel's circumference, and even more preferably it loops around even less than one third or perhaps one quarter of the vessel's circumference before inverting back towards line of passage back towards the first end again, usually at the same angle as the first-described passage towards that first end.

The speed of rotation of the mandrel, and the speed of movement of the head 40, will be controlled - reduced - at the second end of the mandrel too. Further, the tape is wound around the dome of the mandrel at that second end much like that at the first end, again leaving an aperture for the vessel at that second end.

When the winding operation is concluded, the tape is cut and a second free end of the tape 52 is formed. This is accommodated on the layer of fibres already wound around the mandrel.

The vessel is now ready for curing (or "cooking"), where needed.

At the end of the curing, the disposable mandrel can be removed in an appropriate manner, such as by the vibration technique for compacted sand, or by dismantling the scaffold, etc.

The above process has been illustrated herein only schematically.

It should be noted that several layers of tape will need to be wound around the mandrel until a desired thickness, such as one of several mm or cm, is eventually obtained. The actual thickness that is desirable for a given vessel will depend upon the target pressure containment capacity, and also the diameter of the finished vessel. Conventional hoop-stress analysis can be used for determining these desired dimensions since the strength of the fibres, and the angles of winding, are all known. It is important that the effects of having a thick wall are considered and shear stresses are taken into account, in particular with high pressure scenarios as with the present invention.

Multiple axis filament winding machines can also be used to implement a method of the present invention. For example, 2-axes or 3-axes filament winding machines can be used. These are machines whose fibre delivery head can move respectively in a plane or in a 2- or 3-dimensional space. It is even known that winding machine heads can be shifting and turning with up to 5-axes.

Further, the number of axes around which the mandrel can spin could be two, three or more, instead of just the one (longitudinal) axis as described above.

The machine used will depend on the design of the desired vessel, i.e. its size and shape.

An example of a finished product obtained with the manufacturing process illustrated above can be seen in Figure 17. In this Figure, the vessel 64 is made entirely and solely of a structural portion of fiber-reinforced composite material 62. It was wound around a disposable mandrel, presenting an inner surface 63 directly into contact with the CNG. The structural composite itself therefore is capable of containing the CNG within the vessel - no liner or internal coating is needed (although a coating may beneficially be applied if desired, from inside of the vessel).

Various different forms of pressure vessel have therefore been described.

The pressure vessels described herein can carry a variety of gases, such as raw gas straight from a bore well, including raw natural gas, e.g. when compressed - raw CNG or RCNG, or H_2, or $C0_2$ or processed natural gas (methane), or raw or part processed natural gas, e.g. with $C0_2$ allowances of up to 14% molar, H_2S allowances of up to 1,000 ppm, or H_2 and $C0_2$ gas impurities, or other impurities or corrosive species. The preferred use, however, is high pressure CNG transportation, be that raw CNG, part processed CNG or clean CNG - processed to a standard deliverable to the end user, e.g. commercial, industrial or residential.

The CNG will typically be at a pressure in excess of 200bar, and preferably in excess of 350 bar or 700 bar, and preferably up to 1000 bar.

CNG can include various potential component parts in a variable mixture of ratios, some in their gas phase and others in a liquid phase, or a mix of both. Those component parts will typically comprise one or more of the following compounds: C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}, C_6H_{14}, C_7H_{16}, C_8H_{18}, C_9+ hydrocarbons, $C0_2$ and H_2S, plus potentially toluene, diesel and octane in a liquid state, and other impurities/species.

The present invention has been described above purely by way of example. Modifications in detail may be made to the invention within the scope of the claims appended hereto.

Examples:

1. A composite pressure vessel made of carbon or graphite fibres having a strength of 3200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12000, 24000 or 48000 filaments per yarn, and a thermosetting resin (epoxy-based or high-purity poly-dicyclopentadiene-based resin), the vessel being obtained by over-wrapping a disposable mandrel made of clay of generally cylindrical shape.

2. A composite pressure vessel made of carbon or graphite fibres having a strength of 3200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12000, 24000 or 48000 filaments per yarn, and a thermosetting resin (epoxy-based or high-purity poly-dicyclopentadiene-based resin), the vessel being obtained by over-wrapping a disposable mandrel made of ice.

3. A composite pressure vessel made of carbon or graphite fibres having a strength of 3200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12000, 24000 or 48000 filaments per yarn, and a thermosetting resin (epoxy-based or high-purity poly-dicyclopentadiene-based resin), the vessel being obtained by over-wrapping a mandrel made of a chemically etchable material.

4. A composite pressure vessel made of E-glass or S-glass fibres having a strength of 1500 Mpa or higher and a Young Modulus of 65 GPa or higher and a thermosetting resin (epoxy-based or high-purity poly-dicyclopentadiene-based resin), the vessel being obtained by over-wrapping a spherical mandrel which is made of modules which can be mechanically disassembled, and the single components or modules can be pulled out of the vessel, once disassembled, through the vessel's inlet/outlet aperture.

5. A composite pressure vessel made of E-glass or S-glass fibres having a strength of 1500 MPa or higher and a Young Modulus of 65 GPa or higher and a thermosetting resin (epoxy-based or high-purity poly-dicyclopentadiene-based resin), the vessel being obtained by over-wrapping filaments of the fibres on a disposable mandrel made of gypsum.

6 A thermoplastic liner 2 such as high-density polyethylene - HDPE with a density between 0.9 and 1.1 g/cm^3, a tensile strength of at least 30 MPa over-wrapped with a composite structure 3 based on carbon or graphite fiber reinforcement preferably using a carbon yarn with a strength of 3,200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12,000, 24,000 or 48,000 filaments per yarn and a thermoset resin (epoxy-based or high-purity poly-dicyclopentadiene-based resins). The thermoplastic liner 2 is produced by multi-axis rotomolding as explained in the description of the invention.

7. A thermoset liner 2 such as high-purity poly-cyclopentadiene - pDCPD with a density between 0.9 and 1.1 g/cm^3, a tensile strength of at least 65 MPa over-wrapped with a composite structure 3 based on carbon or graphite fiber reinforcement using a carbon yarn with a strength of 3,200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12,000, 24,000 or 48,000 filaments per yarn and a thermoset resin (epoxy-based or high-purity poly-dicyclopentadiene-based resins). The thermoset liner 2 is produced by a single-axis rotomolding machine as explained in the description of the invention.

8. A thermoset liner 2 such as high-purity poly-cyclopentadiene - pDCPD with a density between 0.9 and 1.1 g/cm^3, a tensile strength of at least 65 MPa over-wrapped with a composite structure 3 based on carbon or graphite fiber reinforcement using a carbon yarn with a strength of 3,200 MPa or higher and a Young Modulus of 230 GPa or higher, with 12,000, 24,000 or 48,000 filaments per yarn and a thermoset resin (epoxy-based or high-purity poly-dicyclopentadiene-based resins) and a metallic internal coating 1 of the liner capable of H_2S resistance in accordance with the International Standard (ISO) 15156. The thermoset liner is produced by a single-axis rotomolding machine to be produced as explained in the description of the invention.

9. A thermoplastic liner 2 such as high-density polyethylene (HDPE) with a density between 0.9 and 1.1 g/cm^3 and a tensile strength of at least 30 MPa is over-wrapped with a composite structure 3 based on an E-glass or S-glass fiber with an suggested ultimate strength of 1,500 MPa or higher and a suggested Young Modulus of 70 GPa or higher and thermoset resin (epoxy-based or high-purity high-purity poly-dicyclopentadiene-based resins). The thermoplastic liner 2 is produced by multi-axis rotomolding as explained in the description of the invention.

10. A thermoset liner 2 such as high-purity poly-cyclopentadiene - pDCPD with a density between 0.9 and 1.1 g/cm^3, a tensile strength of at least 65 MPa over-wrapped with a composite structure 3 based on an E-glass or S-glass fiber with an suggested ultimate strength of 1,500 MPa or higher and a suggested Young Modulus of 70 GPa or higher and thermoset resin (epoxy-based or high-purity poly-dicyclopentadiene-based resins). The thermoset liner 2 is produced by a single-axis rotomolding machine as explained in the description of the invention.

11. A thermoset liner 2 such as high-purity poly-cyclopentadiene - pDCPD with a density between 0.9 and 1.1 g/cm^3, a tensile strength of at least 65 MPa over-wrapped with a composite structure 3 based on an E-glass or S-glass fiber with an suggested ultimate strength of 1,500 MPa or higher and a suggested Young Modulus of 70 GPa or higher and thermoset resin (epoxy-based or high-purity poly-dicyclopentadiene-based resins) and a metallic internal coating 1 of the liner 2 capable of H_2S resistance in accordance with the International Standard (ISO) 15156. The thermoset liner 2 is produced by a single-axis rotomolding machine as explained in the description of the invention.

No doubt many other effective alternatives will occur to the skilled person. It will be understood that the invention is not limited to the described embodiments and encompasses modifications apparent to those skilled in the art lying within the spirit and scope of the claims appended hereto. Additionally, any methods or techniques used in relation to one specific embodiment are thought to be applicable to mutatis mutandis to any of the other embodiments, all combinations of which are felt to be within the scope of the present invention.

CLAIMS

1. A high pressure vessel (10) for fuel containment or transport at a pressure in excess of 200 bar, the high pressure vessel (10) comprising:

   at least one opening (7) for gas loading and offloading and for liquid evacuation;
   a liner (2); and
   at least one external fiber layer (3) provided on the outside of the liner (2).

2. The high pressure vessel according to claim 1, wherein the liner is non-metallic.

3. The high pressure vessel according to any of the preceding claims, wherein the fuel can be stored or transported at a pressure in excess of 350 bar.

4. The high pressure vessel according to any of the preceding claims, wherein the fuel can be stored or transported at a pressure in excess of 700 bar.

5. The high pressure vessel according to any of the preceding claims, wherein the fuel can be stored or transported at a pressure of up to 1000 bar.

6. The high pressure vessel according to any preceding claim, wherein the liner (2) is substantially chemically inert.

7. The high pressure vessel according to claim 5, wherein the liner (2) has a corrosion resistance of at least that of stainless steel.

8. The high pressure vessel according to claim 1 or 2, wherein the liner (2) is selected from the group comprising: high-density polyethylene, high-purity poly-cyclopentadiene, epoxy resins, polyvinyl chloride.

9. The high pressure vessel according to any one of the preceding claims, wherein the fiber layer (3) is made of fiber wound about the liner (2).

10. The high pressure vessel according to any one of the preceding claims, wherein the fibers in the fiber layer (3) are selected from the group of carbon fibers, graphite fibers, E-glass fibers, or S-glass fibers.

11. The high pressure vessel according to any of the preceding claims, wherein the fibers are coated with a thermoplastic or thermoset resin, forming a composite layer.

12. The high pressure vessel according to claim 11, wherein the fibers are impregnated with resin before being applied to the outside of the liner

13. The high pressure vessel according to claim 11 or 12, wherein the fibers are coated with a thermoset resin.

14. The high pressure vessel according to any of the preceding claims, wherein the fibers are carbon fibers.

15. The high pressure vessel according to claim 13 or claim 14 when dependent on claim 13, wherein the thermoset resin is selected from the group comprising epoxy-based or high-purity poly-dicyclopentadiene-based resins.

16. The high pressure vessel according to any of claims 13 to 15 when dependent upon claim 12, wherein the resin-impregnated fibers are heated, prior to being applied to the outside of the liner.

17. The high pressure vessel according to any of claims 11 to 16, wherein the composite layer is formed and cured in multiple separate stages.

18. The high pressure vessel according to any of claims 11 to 17, wherein the high pressure vessel is rotated while the composite layer cures.

19. The high pressure vessel according to any one of the preceding claims, further comprising a metallic internal coating (1) provided on the inside of the liner (2).

20. The high pressure vessel according to claim 19, wherein the metallic internal coating (1) is essentially H_2S resistant.

21. The high pressure vessel according to any of the preceding claims, further comprising a gas permeable layer (4) interposed between the liner (2) and the fiber layer (3).

22. The high pressure vessel according to claim 21, wherein the gas permeable layer (4) comprises glass fibers.

23. The high pressure vessel according to claim 21 or 22, further comprising a gas detector (5) connected to the gas permeable layer (4) for detecting a gas leakage.

24. The high pressure vessel according to any of the preceding claims, wherein the high pressure vessel (10) is of a generally cylindrical shape over a majority of its length.

25. The high pressure vessel according to any of the preceding claims, wherein the inner diameter of the vessel (10) is between 0.5 meters and 5 meters.

26. The high pressure vessel according to any of the preceding claims, wherein the inner diameter of the vessel (10) is between 1.5 meters and 3.5 meters.

27. The high pressure vessel according to any of the preceding claims further comprising a manhole (6) for entering and/or inspecting the interior of the vessel (10).

28. The high pressure vessel according to any of the preceding claims, wherein the high pressure vessel and has a weight/gas capacity ratio in the range of 35 to 100 t/Mscf.

29. The high pressure vessel according to any of the preceding claims, wherein the high pressure vessel has a weight/gas capacity ratio in the range of 13 to 40 t/Mscf.

30. The high pressure vessel according to any of the preceding claims, wherein the structural weight of the high pressure vessel over transported gas weight ratio is in the range of 0.7 to 5.0.

31. The high pressure vessel according any of the preceding claims, wherein the structural weight of the high pressure vessel over transported gas weight ratio is in the range of 1.8 to 5.0.

32. The high pressure vessel according any of the preceding claims, wherein the structural weight of the high pressure vessel over transported gas weight ratio is in the range of 0.7 to 2.0.

33. The high pressure vessel of any one of the preceding claims, wherein the high pressure vessel has a waterproof over-wrap shrink-wrapped over the composite layer.

34. A module or compartment (40) comprising a plurality of the inspectable high pressure vessels (10) as defined in any one of the preceding claims, the high pressure vessels being interconnected for loading and offloading operations.

35. A method of storing or transporting gas onshore or offshore, in particular compressed natural gas, using at least one high pressure vessel according to any one of claims 1 to 33, or the module or compartment of claim 34, the gas being contained within a high pressure vessel thereof.

36. A method of producing a high pressure vessel suitable for use at pressures in excess of 200 bar, the method comprising:

manufacturing a cylindrical liner;

impregnating fibers with a resin;

winding the impregnated fibers around the liner until the fiber wall reaches the desired thickness; and

curing the impregnated fiber wall.

37. A method of producing a high pressure vessel according to claim 36, wherein the impregnated fibers are heated prior to being wound on to the liner.

38. A method of producing a high pressure vessel according to claim 36 or 37, wherein the fiber filament winding is done in multiple stages, whereby a thickness less than the desired thickness (a layer) is wound on to the liner and cured, before a further

layer is applied and cured, the process continuing until the desired wall thickness is reached.

39. A method of producing a high pressure vessel according to any of claims 36 to 38, wherein the high pressure vessel is rotated while the fiber wall or layer is cured.

40. A vehicle for transporting gas, in particular compressed natural gas, comprising at least one vessel (10) according to any one of claims 1 to 33 or a module or compartment (40) of claim 34.

41. The vehicle according to claim 40, wherein the vehicle is a ship.

42. The vehicle according to claim 40 or 41, wherein there are multiple high pressure vessels (10) and they are interconnected.

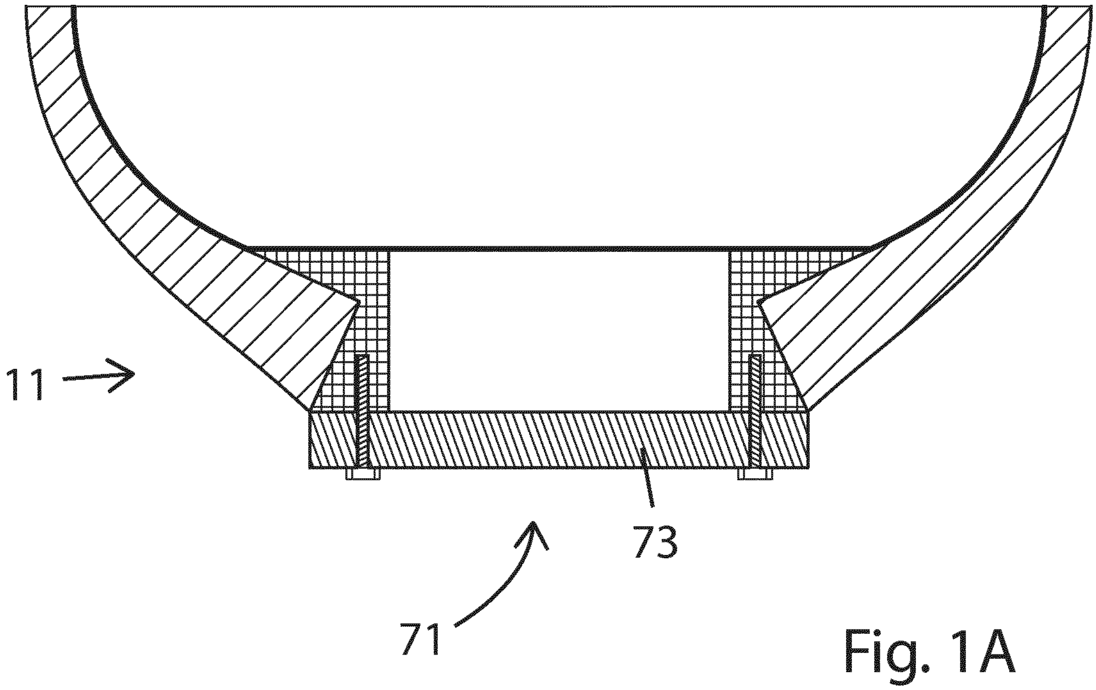

Fig. 1A

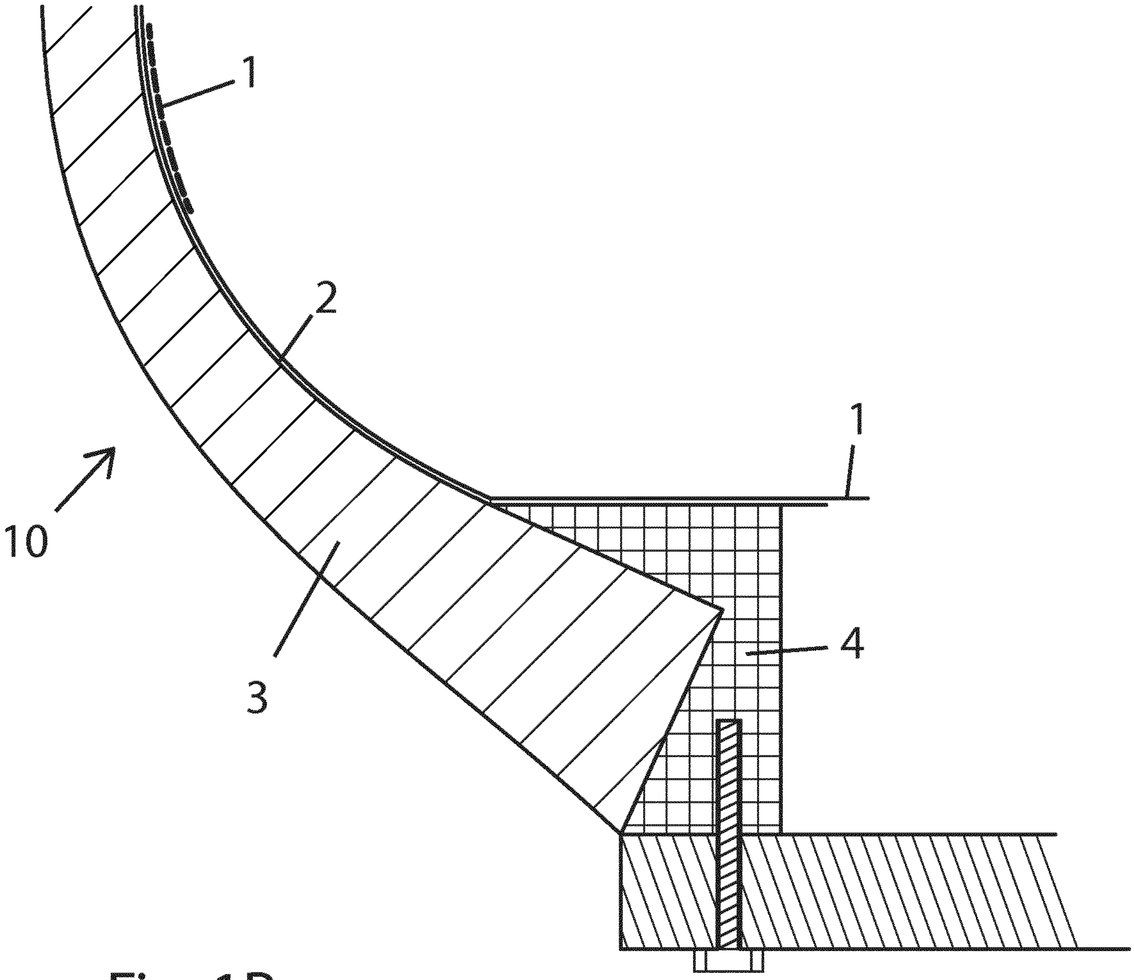

Fig. 1B

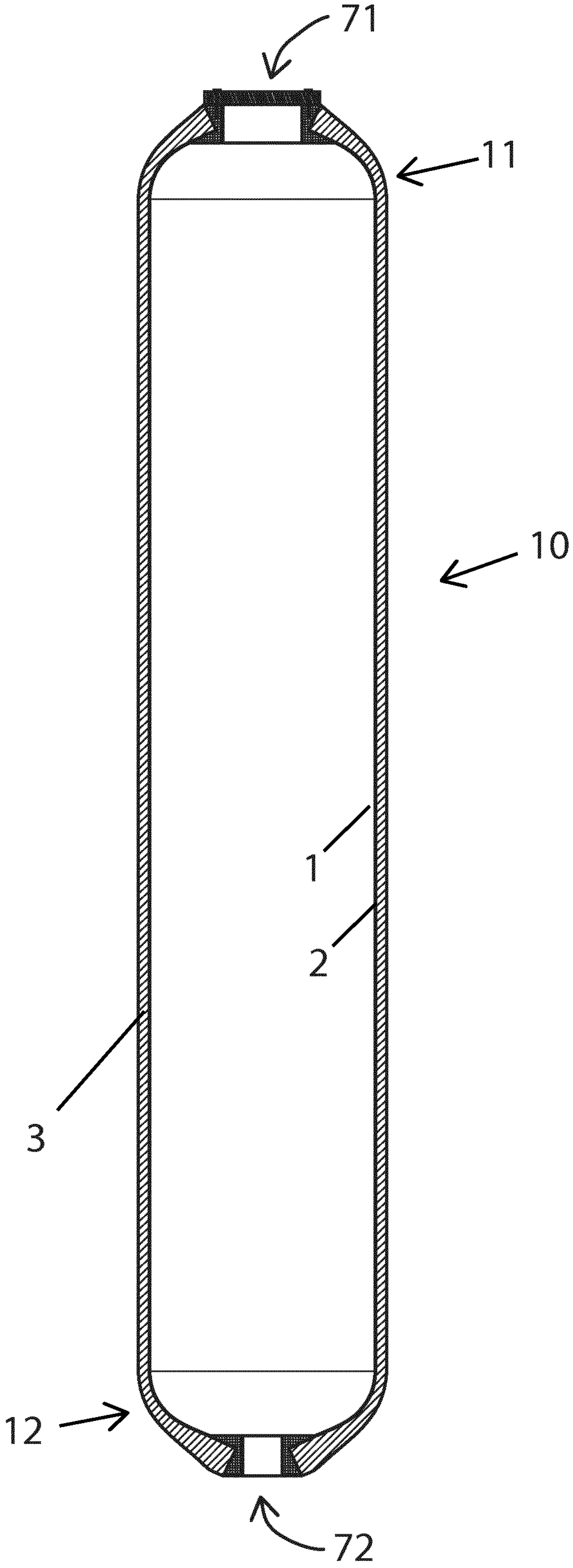

Fig. 2

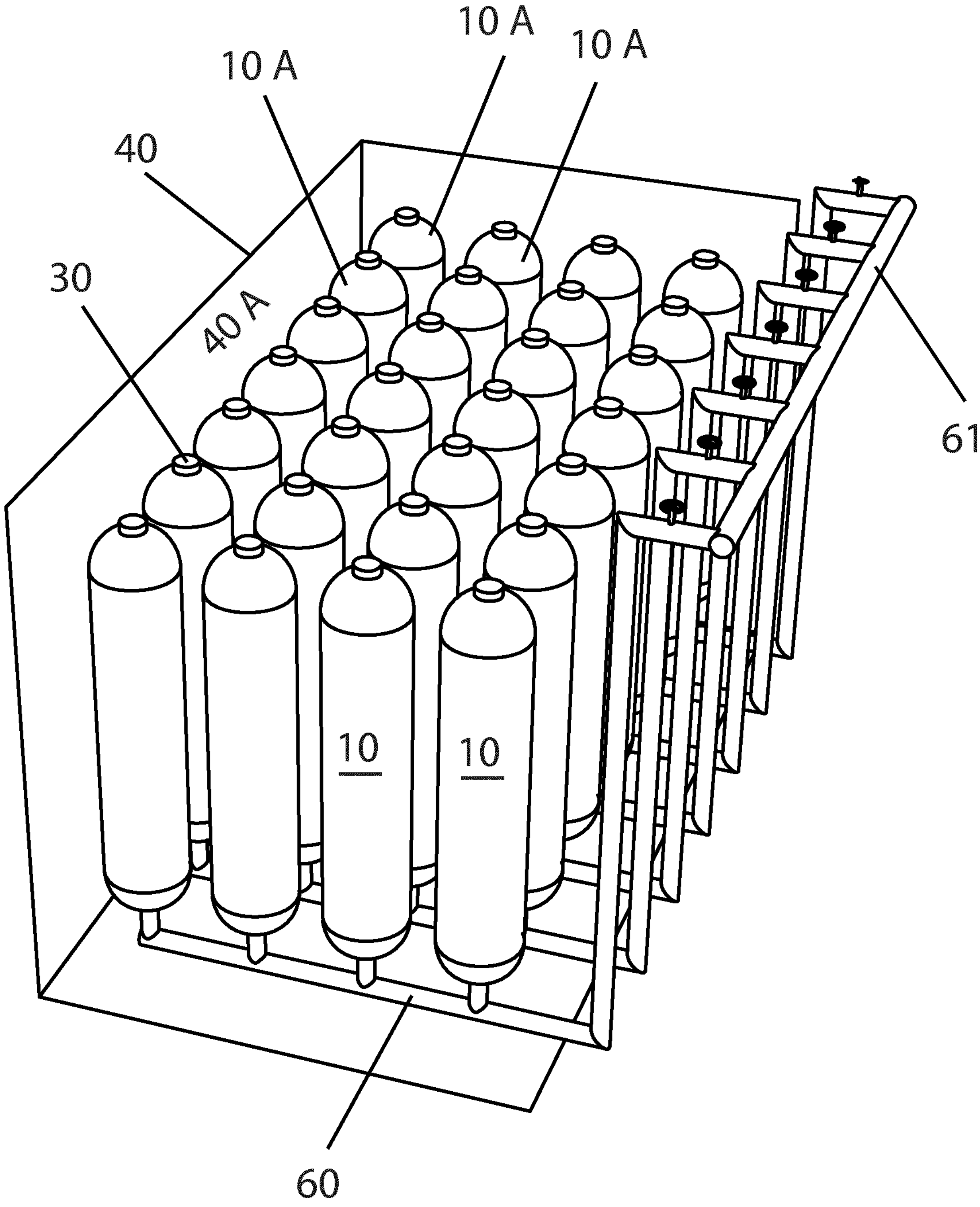

Fig. 3

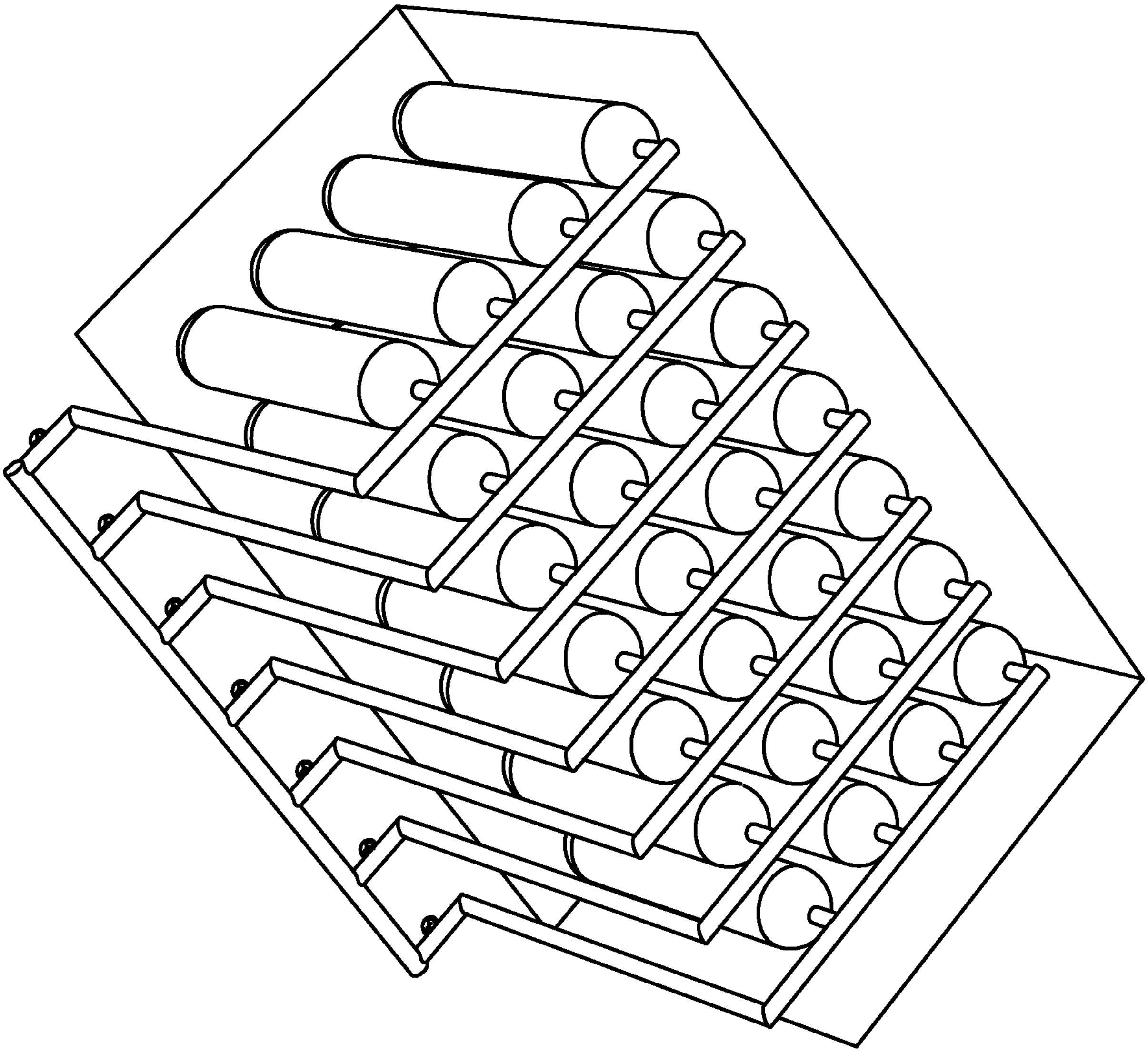

Fig. 4

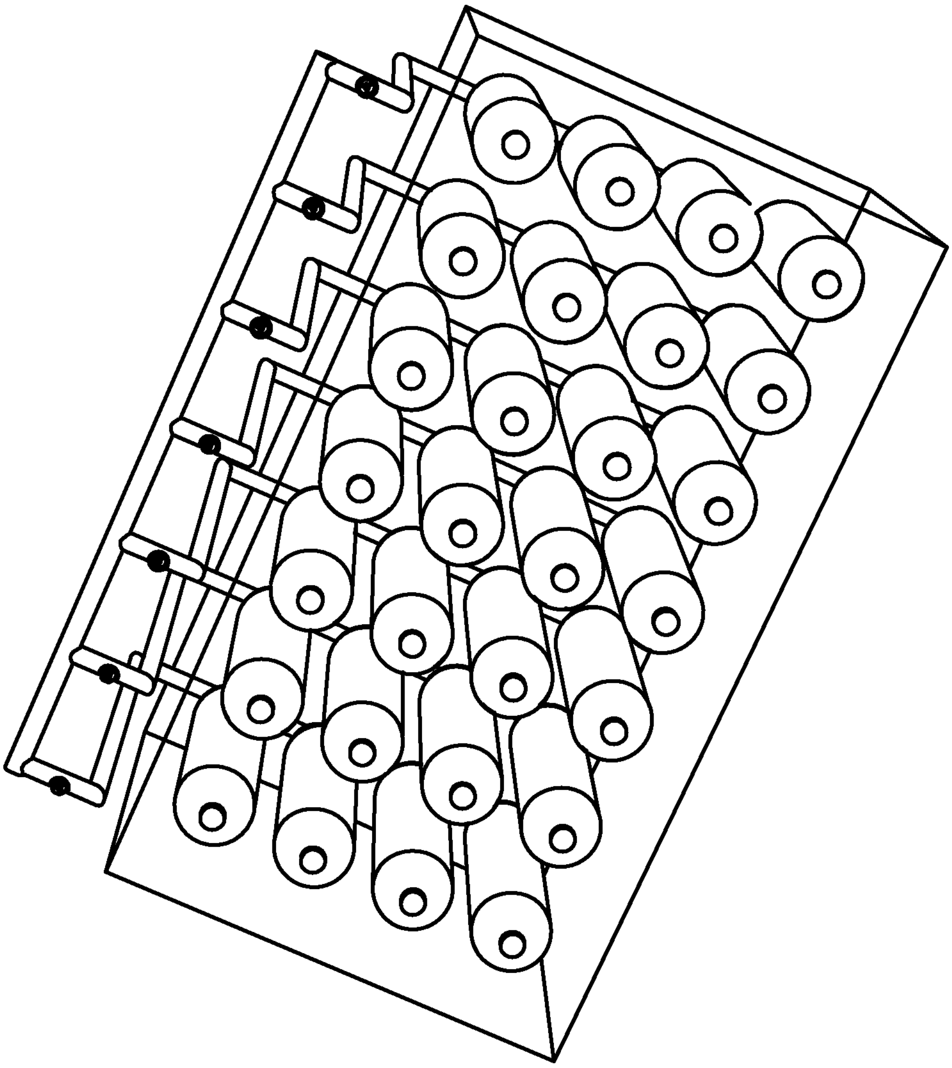

Fig. 5

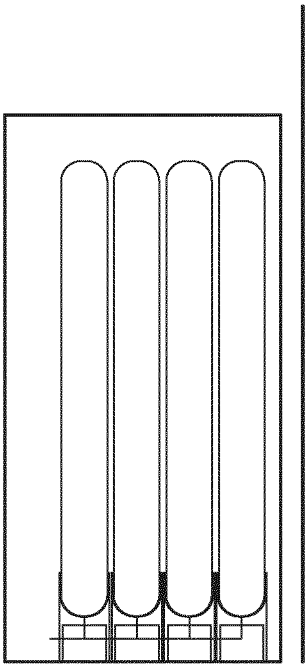

Fig. 6B

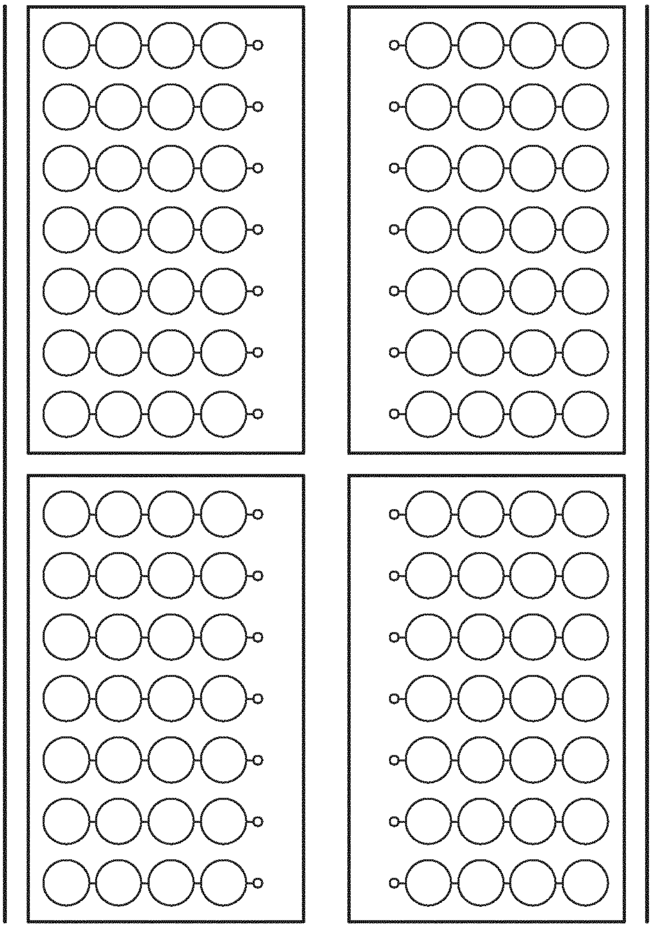

Fig. 6C

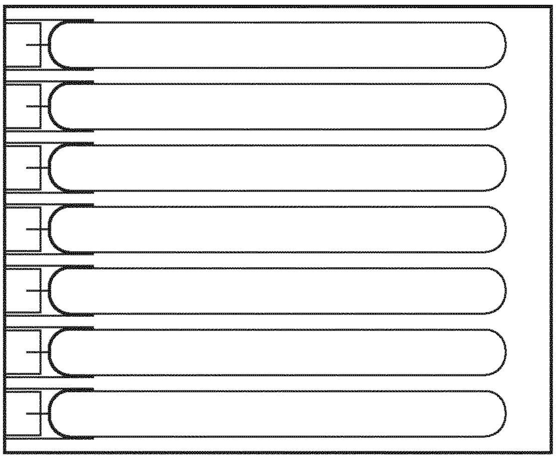

Fig. 6A

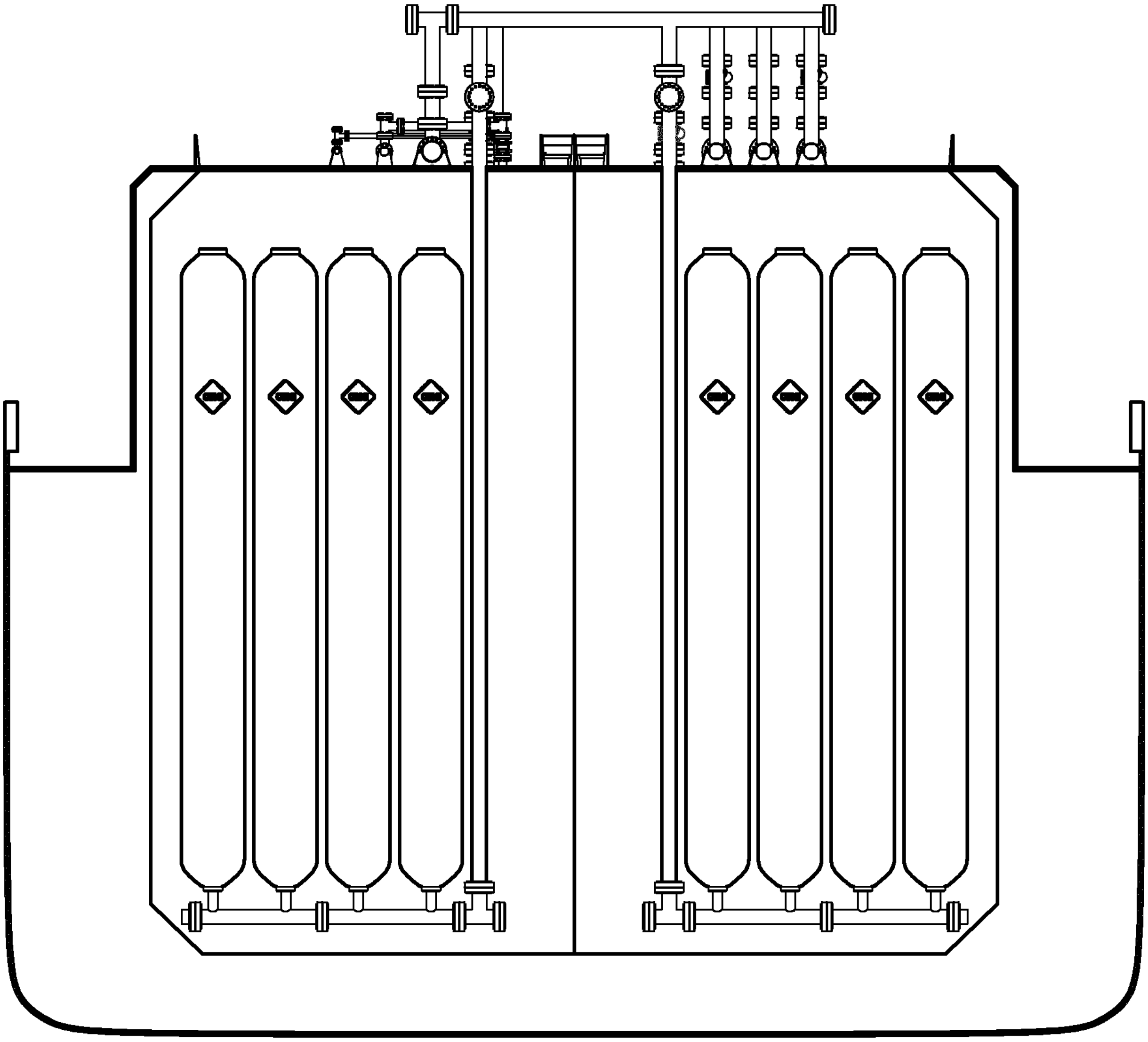

Fig. 7

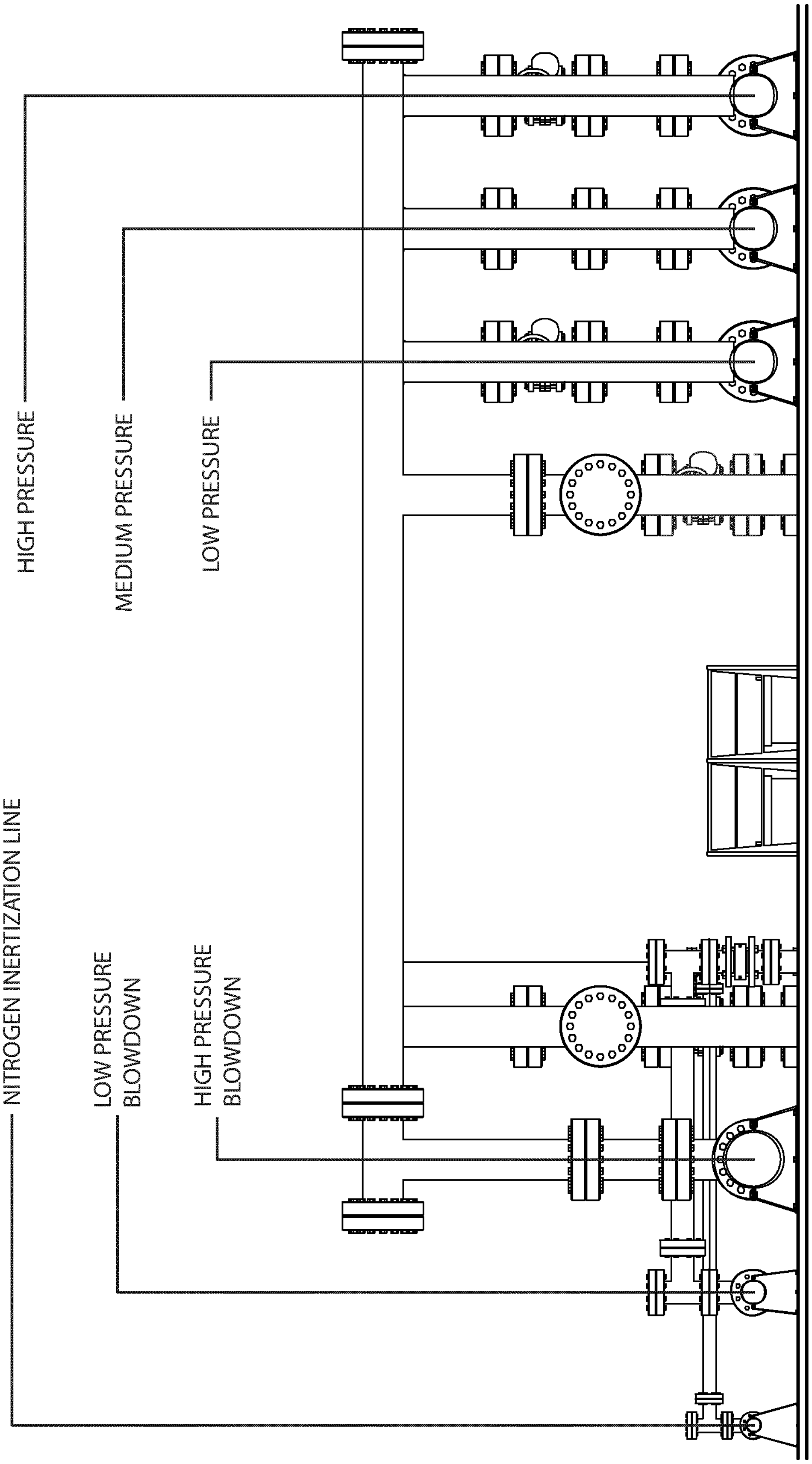
HIGH PRESSURE
MEDIUM PRESSURE
LOW PRESSURE
NITROGEN INERTIZATION LINE
LOW PRESSURE BLOWDOWN
HIGH PRESSURE BLOWDOWN

Fig. 8

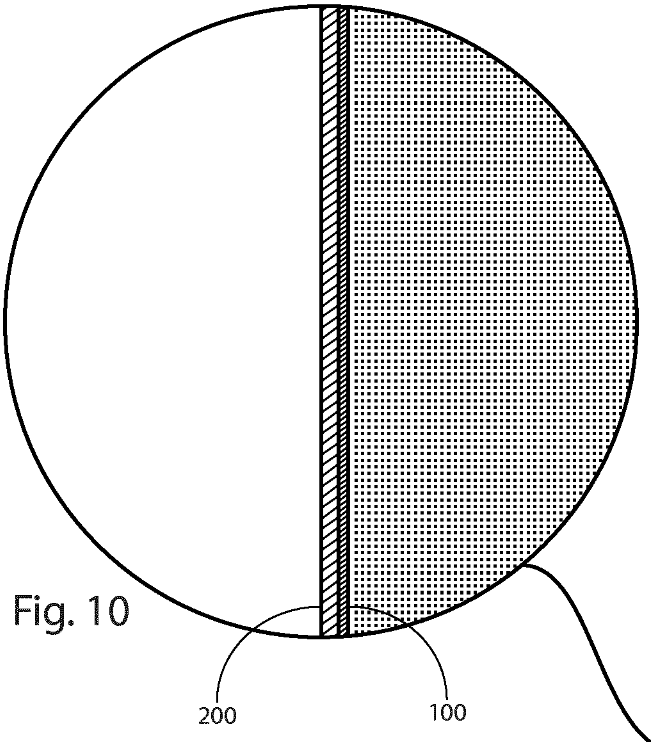

Fig. 10

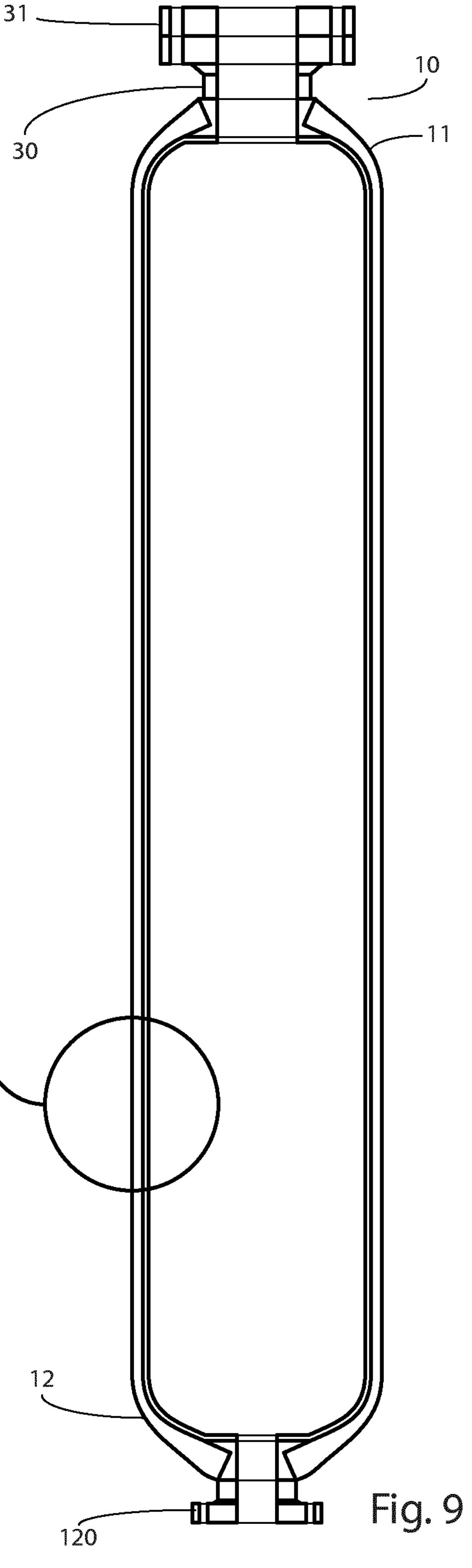

Fig. 9

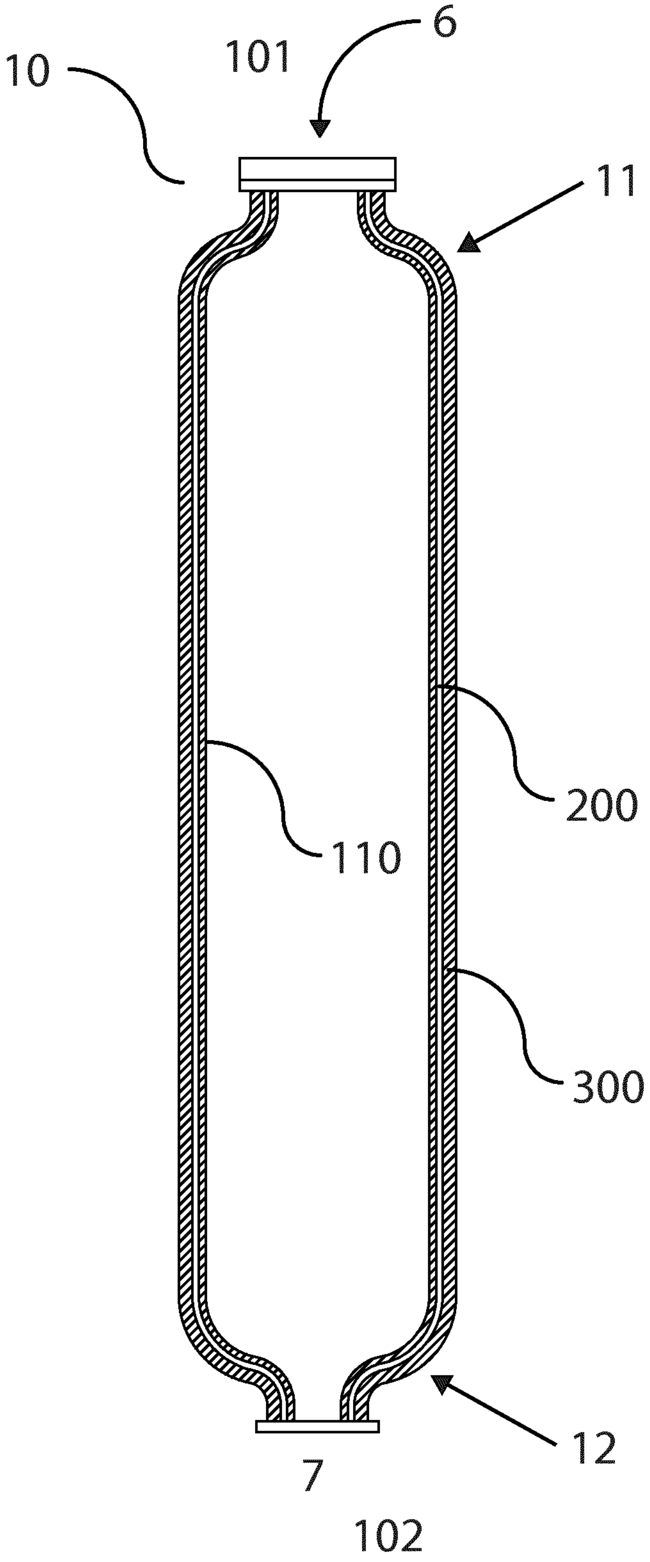

Fig. 11

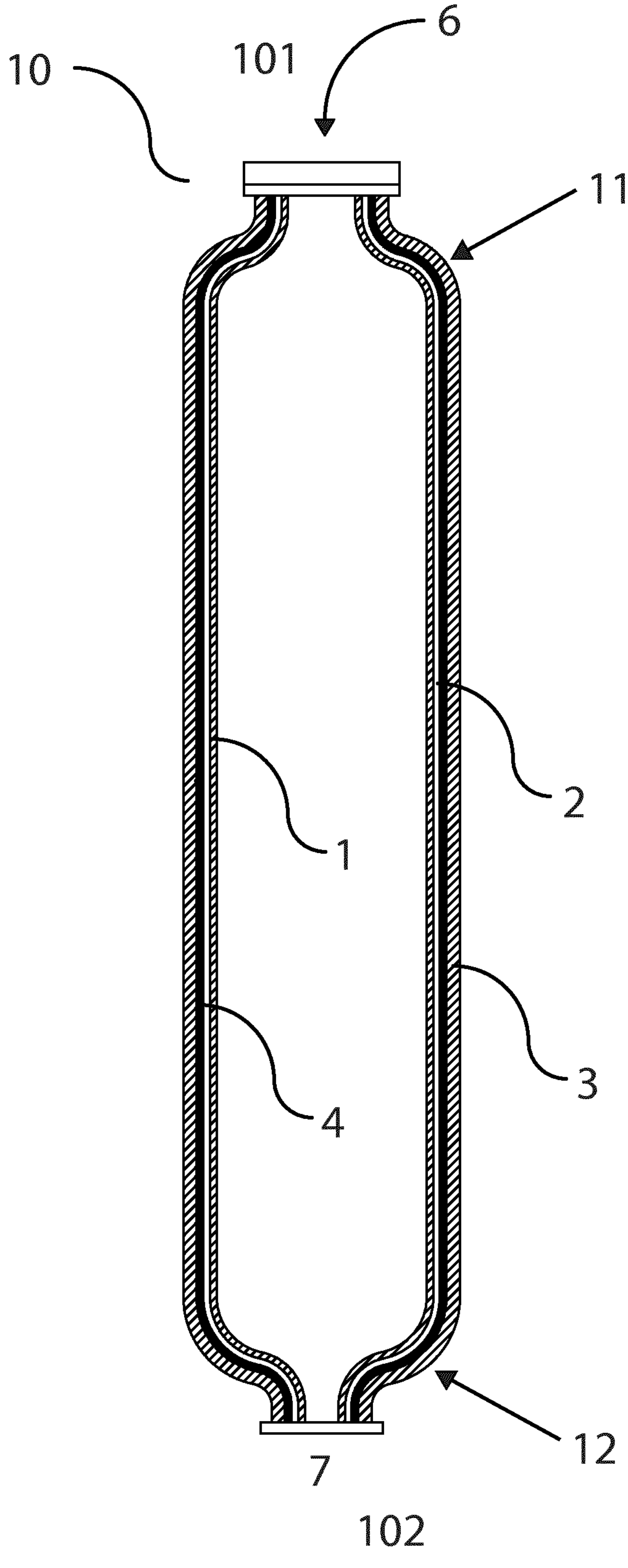

Fig. 12

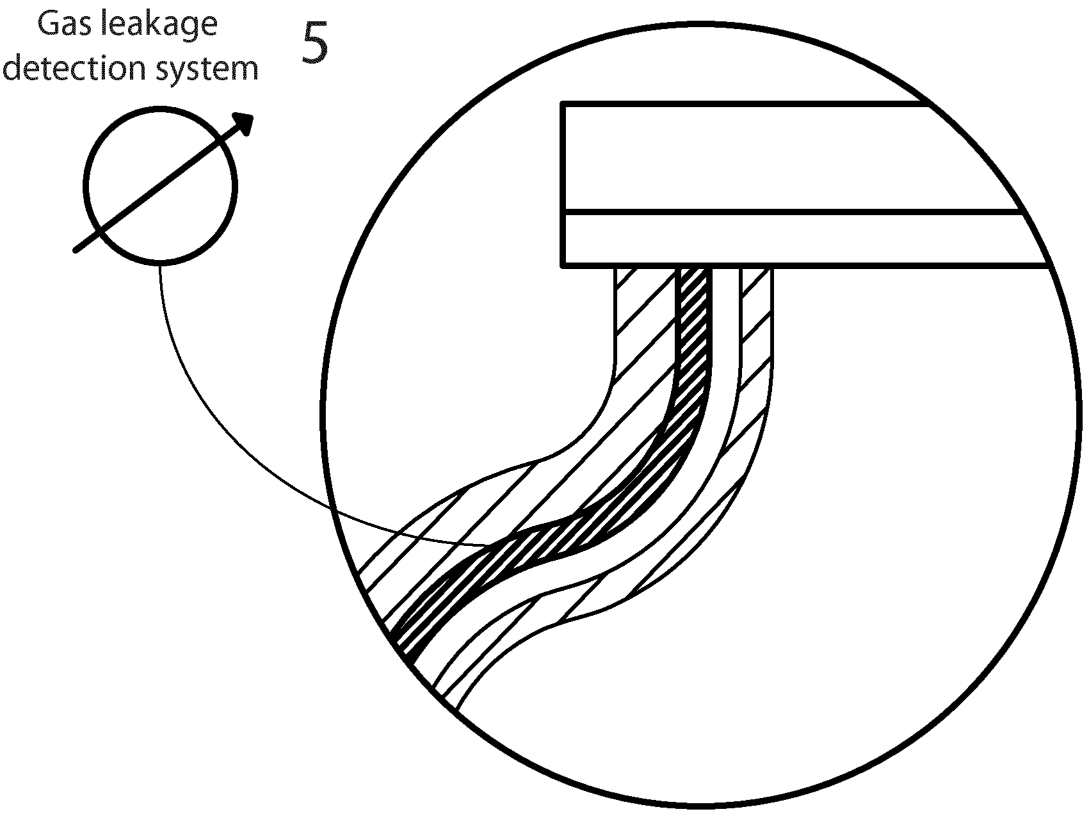

Fig. 13

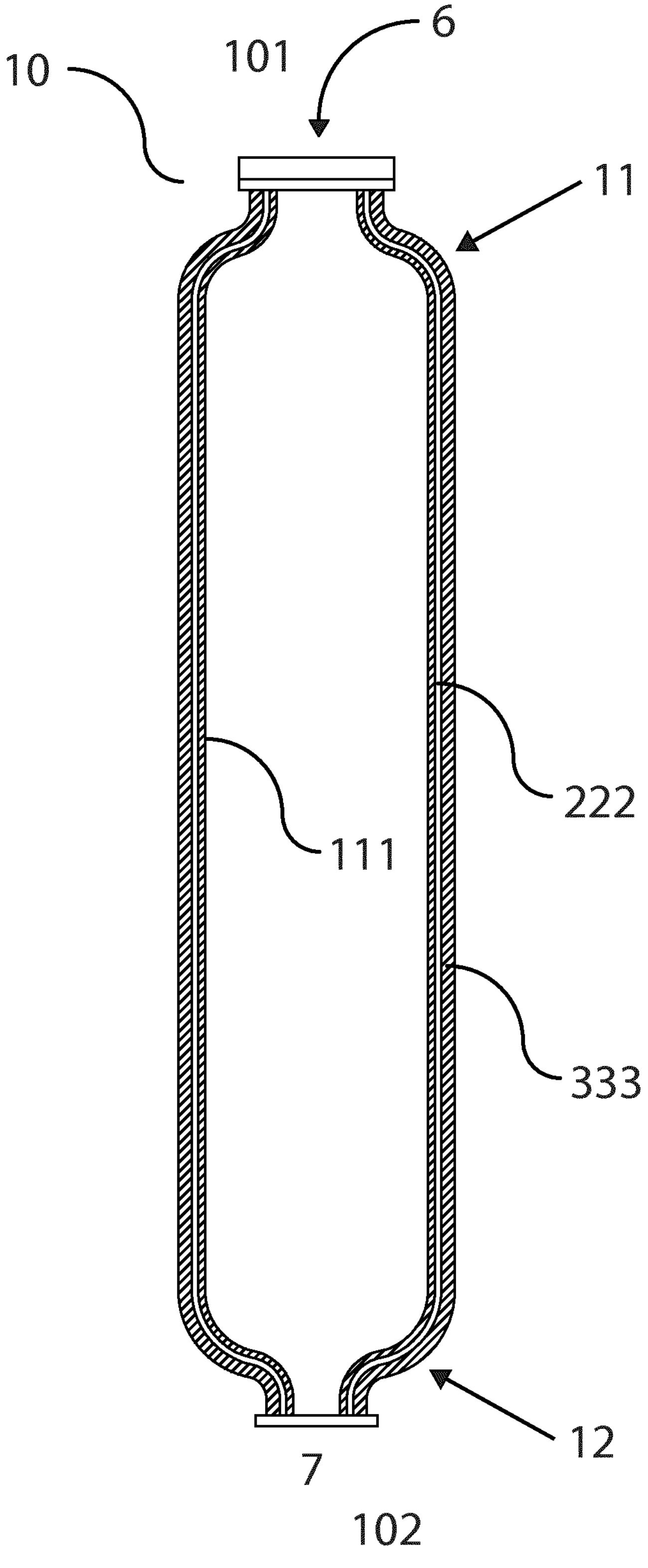

Fig. 14

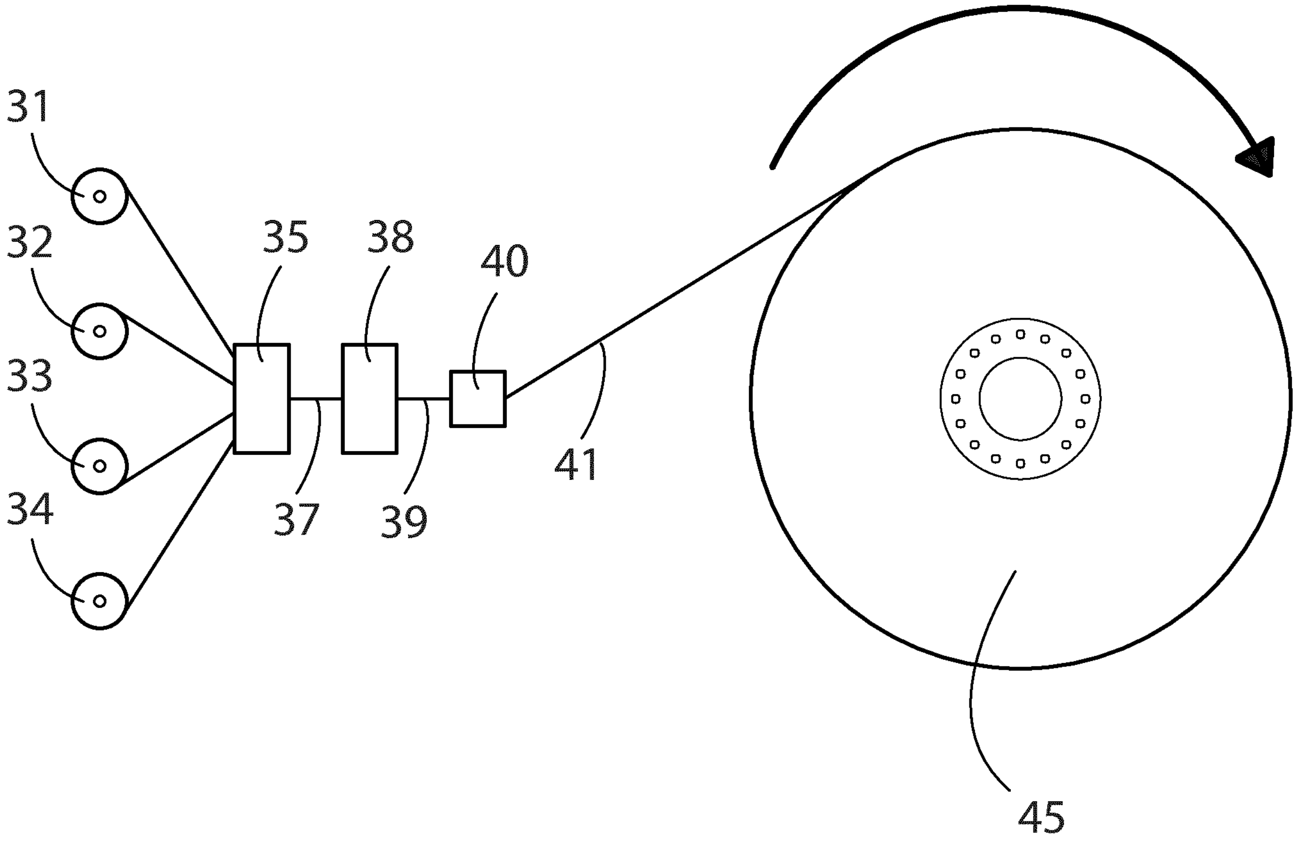

Fig. 15

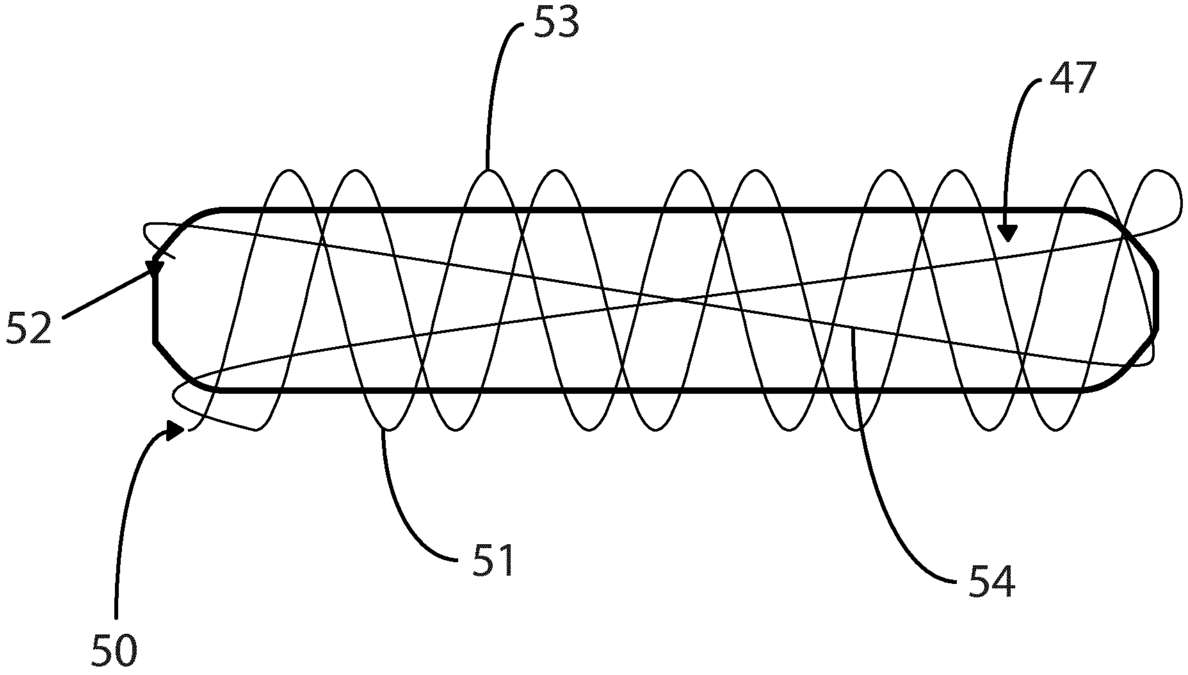

Fig. 16

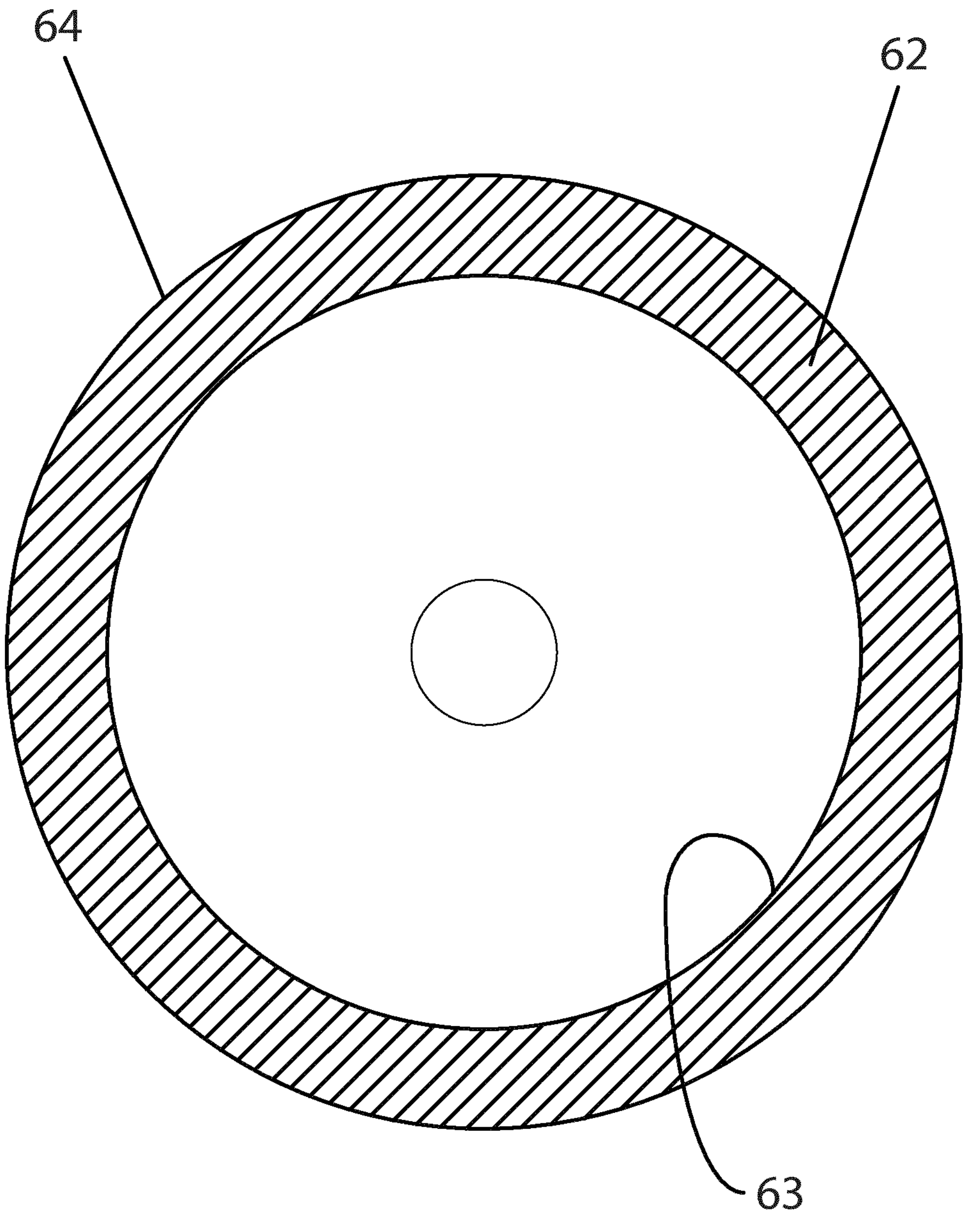

Fig. 17