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(54) REUSABLE HYBRID COOLING SYSTEM OF A COLD SPLIT AND JOINT

(57) The invention relates to a cooling system of a semiconductor radiation detector or any other electronic or optical component that needs to be cooled to operate or to achieve optimal signal-to-noise ratio; such components as field-effect transistors, superconducting magnets, optical lenses, or infrared sensors. The hybrid cooling system is based on a melting cryogen 14 cooled to the solid state by a detachable electromechanical cryocooler 23. The melting cryogen works as a thermal buffer keeping the temperature of an object of cooling 1 low enough and stable using an energy barrier accumulated at the phase transition. The hybrid cooling system is the most effective when a cryocooler cold tip 15 is detached from a vessel filled with a cryogen and optimal weight and size characteristics of an operating device are provided when the cryocooler itself is removed from the device after the cryogen cooling to the solid state. The invention allows multiple attachments and detachments to be made between the cooled cryogen and the cryocooler cold tip without the necessity to wait for the cryogen warm-up above its melting point and without the necessity in generation or restoration of vacuum (reduced air pressure) in the connection chamber afterwards; therefore, the invention represents a reusable hybrid cooling system of a cold split and joint.

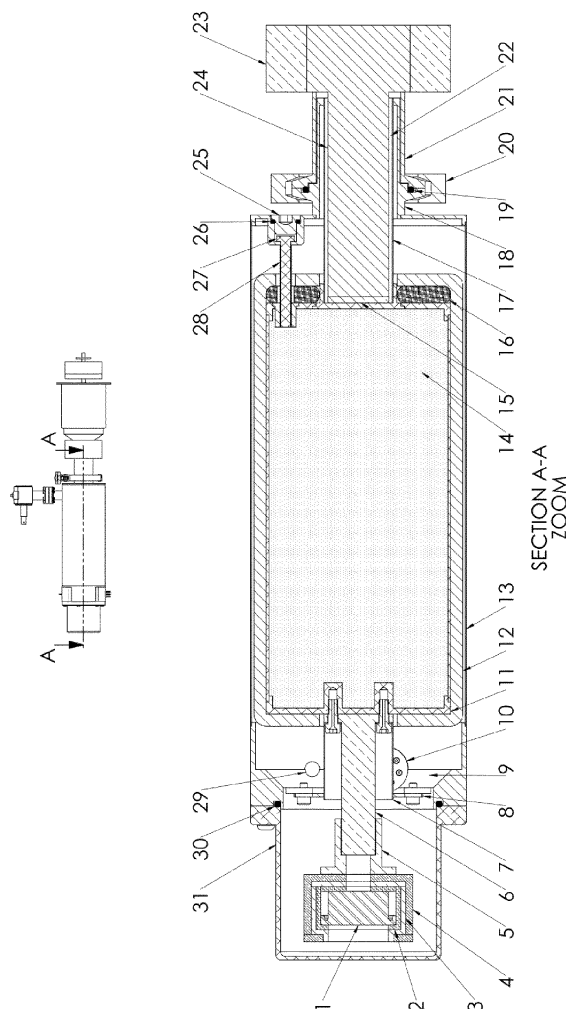


Fig. 9

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Description**Field of the invention**

[0001] The invention relates to a cooling system of a semiconductor radiation detector or any other electronic or optical component that needs to be cooled to operate or to achieve optimal signal-to-noise ratio; such components as field-effect transistors, superconducting magnets, optical lenses, or infrared sensors. The invention provides a highly portable cryogenic apparatus for the detection of radiation, receipt, processing, or transmission of electrical signals, or generation of electromagnetic fields.

Background of the invention

[0002] Semiconductor radiation detectors such as high-purity germanium (HPGe) detectors are widely used for the measurement of gamma-radiation due to the advantage in the energy resolution they provide compared to the scintillation detectors, however, to operate they need to be cooled to low, cryogenic temperatures. Traditionally, semiconductor detectors have been cooled by liquid nitrogen. In this cooling method, the energy barrier (characterized by the enthalpy of vaporization) at the phase transition from liquid to gaseous state is used to keep the detector cold.

[0003] In 1970th, as an alternative to liquid nitrogen cooling, melting cryogen cooling was suggested (Tanner et al. MELTING CRYOGEN COOLING FOR RADIATION LOGGING PROBE. Patent. US 3,709,932A. 1972), and the first borehole logging device with a semiconductor Ge(Li) detector cooled by melting propane was constructed (Tanner et al. A PROBE FOR NEUTRON ACTIVATION ANALYSIS IN A DRILL HOLE USING ²⁵²Cf, AND A Ge(Li) DETECTOR COOLED BY A MELTING CRYOGEN. Article. NIM 100, 1972).

[0004] Propane was transferred to the solid aggregate state by liquid nitrogen. During the melting of propane, the detector temperature remained low enough and constant. In this cooling method, the energy barrier (characterized by the enthalpy of fusion) at the phase transition from solid to liquid state was used to keep the detector cold.

[0005] In another device [Boynton. CANISTER CRYOGENIC SYSTEM FOR COOLING GERMANIUM SEMICONDUCTOR DETECTORS IN BOREHOLE AND MARINE PROBES. Article. NIM 123, 1975], an application of exchangeable canisters filled with propane and pre-cooled by liquid nitrogen was suggested.

[0006] In 1985, a design of a cryogenic cell filled with melting cryogen was invented [Burchell et al. CRYOGENIC CELL. Patent. US 4, 658, 601. 1985].

[0007] Later, a melting cryogen working at the phase transition from solid to liquid state to keep an HPGe detector cold was called a cryoaccumulator (Sokolov et al. Autonomous Deep-water Gamma Spectrometer based on HPGe Detector. Article. ESARDA Symposium Proceedings, 1999).

[0008] In 2005, optimal properties of a melting chemical compound were described in the context of a melting cryogen cooling system for portable instrumentation [Stein et al. CRYOGENIC COOLING DEVICE. Patent. WO 2006/010772A1].

[0009] With regard to cryostats and portable cryocoolers for semiconductor radiation detectors cooling the following inventions form the state-of-the-art:

- Tench, Jr. CONVERTIBLE CRYOSTAT. Patent. US 4,510,758. 1985.
- Martin et al. MODULAR PHOTON DETECTOR CRYOSTAT ASSEMBLY AND SYSTEM. Patent. US 4,851,684. 1989.
- Katagiri. ELECTRIC-COOLED TYPE SEMICONDUCTOR RADIOACTIVE RAY DETECTOR. Patent. US 5,552,609. 1994.

Summary of the invention

[0010] The present invention represents a hybrid cooling system of a cold split and joint. The hybrid cooling system is based on a melting cryogen (the passive object of storage of cooling power) and an electromechanical cryocooler (the active object of cooling power production). The cooling system is applied to an object that needs to be cooled, such object as a semiconductor radiation detector.

[0011] The invention provides optimal energy resolution for a semiconductor radiation detector by switching the cryocooler off during spectrometric measurements and goes beyond the state-of-the-art by providing methods and corresponding means for making the hybrid cooling system reusable and of a cold split and joint. Thus, the invention provides the possibility of a repeatable cryocooler detachment from a cooled to the solid state cryogen, and a repeatable cryocooler attachment to the cryogen after its melting, and without the necessity of waiting for the cryogen warm-up above 0 °C (melting point of ice).

[0012] The possibility of the cryocooler detachment after the cryogen cooling to its melting point for subsequent operation of a main operational device, containing an object of cooling, makes the hybrid cooling system of a cold split and provides the following advantages:

- a) Decreased heat load to the cryogen, when a cryocooler cold tip is detached;
- b) Reduced mass of the device, containing an object of cooling, when the cryocooler itself is removed.

[0013] In its turn, the possibility of the cryocooler attachment to the cryogen having a temperature near its melting point and below 0°C, makes the hybrid cooling system reusable and of a cold joint.

Detailed summary of the invention

[0014] The hybrid cooling system represents a combination of the following two objects: a cryogen (the passive object of storage of cooling power) and an electromechanical cryocooler (the active object of the cooling power production). The hybrid cooling system is applied to an object that needs to be cooled, such object as a semiconductor radiation detector.

[0015] The cryogen is filled into a thermally insulated vessel (such as Dewar), and, represents a chemical compound having melting temperature permitting the operation of an object of cooling. The cryogen is cooled to a solid crystalline state using an electromechanical cryocooler. To achieve this, the cryocooler cold tip is brought into mechanical contact (direct or through a thermal interface material) with a wall of a vessel filled with the cryogen, or, is brought into direct contact with the cryogen itself.

[0016] When the cryogen is cooled to the melting point, the cryocooler is switched off, and the operating temperature of the object of cooling is maintained solely by the melting cryogen, using accumulated at the phase transition energy barrier characterized by the enthalpy of fusion.

[0017] The hybrid cooling system is more effective when the cryocooler cold tip is detached from the cryogen vessel after the cryogen cooling, and optimal weight and size characteristics of a main operational device containing an object of cooling are provided when the cryocooler itself is removed from the device after the cryogen cooling. To achieve this, several variants of a hybrid cooling system are provided. These variants can be classified by a type of a cryogen-cryocooler connection chamber and are described below.

[0018] According to the invention, the cryogen-cryocooler connection can be made:

- a) In a vacuum chamber having compressible/expandable metal bellows, wherein the reusability is achieved by the attachment/detachment of a cryocooler cold tip to/from a wall of an encapsulated vessel filled with the cryogen; in this case, re-evacuation of the connection chamber is not required, however, the cryocooler is not removable.
- b) In a hermetically sealed air chamber with minimized air volume, wherein the reusability is achieved by a prompt cryocooler joint/split to/from an encapsulated cryogen vessel using a corresponding connection interface which facilitates this, i.e. quick-release flanges, an elastomer O-ring and a quick-release clamp.
- c) In a hermetically sealed air chamber, partially filled with a liquid chemical compound having a melting temperature preferably lower than the melting temperature of a cryogen.
- d) By immersion of the cryocooler cold tip directly into a cryogen when the cryogen is in the liquid state.

[0019] The hybrid cooling system is free from periodic re-filling of externally supplied refrigerants such as liquid nitrogen. In the case of its application to the cooling of a semiconductor radiation detector, it provides an advantage over direct electromechanical cooling in terms of spectrometric characteristics of the detector, because no deterioration of energy resolution associated with mechanical vibrations occurs, as the cryocooler is normally switched off during measurements. In the context of portable instrumentation, the main measuring device with the hybrid cooling system has the weight advantage, as after cryogen cooling to the solid state, the device doesn't require batteries for powering the cryocooler, and when the cryocooler itself is removed the weight of the main measuring device is further decreased.

[0020] With regard to the application of a hermetically sealed air chamber for the connection between a cryocooler cold tip and an encapsulated cryogen, the present invention is characterized by the set of the following distinctive features:

- a) It is intended to avoid evacuation (creation of reduced air pressure) of the connection chamber, but in the meantime, it provides reusability of the hybrid cooling system of a cold split and joint;
- b) Mechanical connection between a cryocooler cold tip and a wall of a vessel filled with a cryogen is made under pressure, applying a quick-release clamp;
- c) The time of the cryocooler attachment or detachment from a wall of a vessel filled with a cryogen (the connection chamber is unsealed) is minimized for the reduction of the amount of ice forming on the cold surfaces in the connection chamber, to provide the reusability of the hybrid cooling system.
- d) The amount of air in the connection chamber can be additionally reduced by the application of a liquid chemical compound or a solid-state air displacer such as a PTFE tube filling air gaps.

[0021] With regard to the application of a liquid chemical compound in the cryocooler-cryogen connection chamber, the present invention has the following distinctive features:

- a) The melting point of a chemical compound is preferably lower than the melting point of the cryogen, in this case, when the cryogen is cooled to its solid state, the cryocooler can be detached immediately from the cooled cryogen vessel because the cryocooler cold finger/tip is immersed in the chemical compound which remains to be liquid;
- b) The time of the cryocooler attachment or detachment from the cryogen vessel (the connection chamber is unsealed) can be increased;
- c) In the case, when a mechanical connection under pressure between a cryocooler cold tip and a wall of a vessel filled with the cryogen is established (applying a quick-release clamp), the compound keeps the cryocooler detachable, by preventing air access to the place of contact, and therefore preventing the formation of ice and adhesion of a cryocooler cold tip to the wall of the vessel filled with the cryogen;
- d) In the case, when no mechanical connection under pressure between a cryocooler cold tip and a wall of a vessel filled with the cryogen is established, the compound works as a thermal interface material, and, is intended to decrease the mechanical load to the cryocooler cold tip.

Detailed description of the invention

[0022] The reusable hybrid cooling system of a cold split and joint which contains a passive cooling element - a melting cryogen and an active cooling element - an electromechanical cryocooler is described. The invention provides optimal energy resolution for a semiconductor radiation detector by switching the cryocooler off during measurements and it ensures that multiple cooling cycles with connections and disconnections between the cryocooler cold tip and the cryogen can be made without the necessity of waiting for the cryogen warm-up.

[0023] The following sequence of operations illustrated in **Fig. 1** describes a typical operational cycle of the reusable hybrid cooling system of a cold split and joint:

- a) The cryogen is initially warm, at the temperature above 0°C (**point 1**).
- b) A cryocooler cold tip is attached (either directly or through a thermal interface material, which could also be in a liquid state) to a wall of a vessel filled with the cryogen. The attachment is made either in a hermetically sealed air connection chamber (in which the air volume is minimized) using a quick-release clamp (in this case the cryocooler can be disconnected and removed from the cryogen vessel), or, in a vacuum-insulated connection chamber using bellows (in this case the cryocooler can't be disconnected and removed from the cryogen vessel without breaking the vacuum, only the cold tip can be detached). The cryocooler cold tip can also be immersed directly into a cryogen.
- c) The cryocooler is switched on.
- d) The cryogen temperature is decreasing (between **points 1** and **4**).
- e) The melting temperature of the cryogen is reached (**point 2**).
- f) The cryogen is transferred to the solid aggregate state and a maximum energy barrier at the phase transition is accumulated (**point 3**). From this moment, the cryocooler can be switched off and disconnected and the main operational device can be used by the operator; or the cooling power of the cryocooler can be decreased to maintain the temperature just below the melting point of the cryogen. In the Figure, the cryocooler power was not adjusted, so between **points 3** and **4** the cryogen is being gradually overcooled.
- g) The cryocooler is switched off (**point 4**) and the cryocooler cold tip is preferably disconnected from the wall of the vessel filled with the cryogen. In the case of the sealed air connection chamber, the cryocooler itself is preferably removed from the main operational device, and the connection chamber is hermetically closed by a cork with a PTFE plug, using an elastomer O-ring and a quick-release clamp. The plug removes air from the connection chamber. This operation is performed promptly to prevent the formation of ice in the connection chamber.
- h) The temperature of the overcooled cryogen is rising (between **points 4** and **5**).
- i) The melting point of the cryogen is reached, however, the cryogen remains solid (**point 5**).
- j) While the cryogen is melting (between **points 5** and **6**), the temperature of an object of cooling is stable while the main operational device is in use by an operator. An autonomous operation time of the device at a given melting temperature is defined by the physical volume of the cryogen, heat load to the cryogen, and its enthalpy of fusion.
- k) When the whole cryogen is melted, its temperature and the temperature of the object of cooling start to rise. At this point, the cryocooler can be connected again to the vessel with the cryogen at a temperature below 0°C, for example at **point 7**, without the necessity to wait for the cryogen warm-up to the temperature above 0°C.

In the case of the application of the air connection chamber, the clamp is released and the cork is removed. The cryocooler cold tip is attached to the wall of the cryogen vessel using the quick-release clamp. The chamber is sealed by the elastomer O-ring. These operations are performed promptly to prevent the formation of ice in the connection chamber (avoid adhesion of the cryocooler cold tip to the wall of the vessel filled with the cryogen).

In the case of the application of the vacuum connection chamber, the bellows are compressed to put the cryocooler cold tip into mechanical contact with the wall of the vessel filled with the cryogen.

If the cryocooler is switched on again at **point 7**, the cooling time (solidification of the cryogen) will be shorter compared to the time of the initial cooling from room temperature because the cryogen was already pre-cooled.

[0024] Several variants of the reusable cooling system of a cold split and joint are provided. These variants, described in detail below, are also classified by the type of a cryocooler-cryogen connection chamber in **Table 1**.

[0025] In the first variant of the hybrid cooling system of a cold split and joint (**Figs. 2 and 5**), a cryogen is filled into a thermally (vacuum) insulated vessel **2**, having a closed end to which a cryocooler **4** is attached. A cryocooler cold tip is attached (brought into mechanical contact) to a wall of a vessel filled with the cryogen in a vacuum-insulated connection chamber **3**. The walls of the connection chamber represent metal bellows that can be compressed or expanded. The cooling system can be applied to any object of cooling positioned in a thermally (vacuum) insulated cryostat **1**.

[0026] For the cryogen cooling (transfer from gaseous/liquid to solid state), the cryocooler cold tip **17** is mechanically attached to the wall **13** of the vessel filled with the cryogen **6** by compressing the bellows (**Figs. 3 and 6**), and after the cryogen cooling, it is mechanically detached by expanding the bellows (**Figs. 4 and 7**).

[0027] Because the connection is made in a vacuum, the cryocooler cold tip can be detached from the wall of the vessel filled with the cryogen while the cryogen is cold, however, the cryocooler itself can't be removed from the main operational device, which contains an object of cooling and the cryogen, without breaking the vacuum-tight connection.

[0028] In the second variant of the reusable hybrid cooling system of a cold split and joint (**Fig. 8**), a cryogen is filled into a thermally (vacuum) insulated vessel **2** having a closed-end, to which, by means of a quick-release clamp **3**, a cryocooler **4** is attached. The attachment is made in a hermetically sealed air connection chamber. The cooling system can be applied to any object of cooling positioned in a thermally (vacuum) insulated cryostat **1**.

[0029] According to **Fig. 9**, for the cryogen **14** cooling, the cryocooler **23** is attached to an outer cryogen vessel **13** through compatible flanges **18, 21**. The cryocooler cold tip **15** is put in direct mechanical contact under pressure with a wall of the inner vessel **11** filled with the cryogen in a hermetically sealed by an elastomer O-ring **19** connection chamber, applying a quick-release clamp **20**.

[0030] Space **22** available for ambient air in the sealed connection chamber (and therefore the number of water molecules) is minimized to prevent adhesion of the cryocooler cold tip to the wall of the inner vessel due to the formation of ice during cooling.

[0031] Application of the sealed cryogen-cryocooler connection chamber with a minimized free volume available for ambient air allows detachment of the cryocooler after the cryogen cooling, and, multiple cooling cycles with attachments and detachments between the cold wall (having a temperature below 0 °C) of the vessel filled with the cryogen and the cryocooler cold tip can be made when time duration of each connection is minimized. The values of the maximum air volume and the maximum time duration of each connection or disconnection (the connection chamber is unsealed) depend on the relative humidity of the ambient air.

[0032] Solely as a non-restrictive indication, for the air at atmospheric pressure and with a relative humidity of 80 percent, 10 cycles with connection and disconnection between a cryocooler cold tip and a cold wall of the vessel filled with the cryogen can be made when the amount of the air in the connection chamber is reduced to a volume of about 1 cm³ per 1 cm² of a contact area (a cryocooler cold tip area), and each connection or disconnection time (the chamber is unsealed) is limited to a period of about 5 seconds.

[0033] The closed inner vessel filled with the cryogen provides the possibility to use a cryogen which can be in the liquid or gaseous state at normal temperature and pressure, and it allows keeping any spatial orientation of the device (i.e. horizontal, vertical, etc.) during attachment of the cryocooler to the cryogen, the cryogen cooling and detachment of the cryocooler, i.e. during the complete cooling and operating cycle.

[0034] The process of the cryocooler detachment is shown in **Fig. 10**.

[0035] After the cryocooler detachment, to minimize air volume in the connection chamber and therefore to prevent the formation of ice, the chamber is closed with a Styrofoam plug **12** and is hermetically sealed using an elastomer O-ring **9**, applying a quick-release clamp **7** to quick-release flanges **6, 8** as shown in **Fig. 11**.

[0036] To generate centers of crystallization and to distribute thermal gradients more uniformly across the cryogen volume, the inner vessel filled with the cryogen may contain a heat exchanger in the form of a metal foam **1** brazed to the inner vessel walls **2** (**Fig. 12**). Also, it is an object of the invention, a dual-wall neck of the vacuum insulated vessel representing a part of the cryogen-cryocooler connection chamber. The wall **6** facing the vacuum is ultra-thin (thickness of about 0.1 mm) and is made from a metal alloy having low thermal conductivity, such as stainless steel, and the wall **8** facing the air from both sides is rather thick (thickness of about 1 mm) and is made from plastic or fiberglass. The plastic/fiberglass neck can be mounted using epoxy **9, 10**, preferably after vacuum bake-out of the cryogen-cryostat assembly, allowing heat treatment at higher temperatures.

[0037] Also, the invention provides a removable plastic/fiberglass neck mounted using threads **6, 12**, as shown in **Fig. 13**; to facilitate the fiberglass neck removal and, therefore, allow for a vacuum bake-out servicing at higher temperatures.

[0038] In the third variant of the hybrid cooling system of a cold split and joint (**Fig. 14**), a cryogen is filled into a vacuum-insulated vessel **4** having an open end. The cryogen is liquid at room temperature and normal pressure and a cryocooler

cold finger **15** is immersed into it.

[0039] A cryocooler **16** is attached to an outer cryogen vessel **6** using quick-release flanges **10, 12**, and applying a quick-release clamp **11**; forming a connection chamber, sealed by an elastomer O-ring **13**.

[0040] After the cryogen **1** cooling (transferring from liquid to solid aggregate state), the cryocooler is switched off. At this point instead of providing the cooling power the cryocooler conducts heat with a maximum temperature gradient at its tip **3**. The cryogen rapidly melts around the cryocooler cold finger **2**. Soon the cryocooler cold finger can be detached from the cryogen and the cryocooler itself can be removed from the device without the necessity of warming the whole cryogen up. Multiple cooling cycles with repetitive solidifications of the cryogen can be performed.

[0041] Also, it is an object of the invention, a functional element representing a dual-wall neck of the vacuum-insulated vessel having an open end (**Figs. 15 and 16**). The wall **8** facing vacuum **5** is ultra-thin (thickness of about 0.1 mm) and is made from a metal alloy such as stainless steel, and the wall **9** facing the air is rather thick (thickness of about 1 mm) and is made from plastic or fiberglass. The plastic neck is removable and is mounted using epoxy or for easier removal using threads at both ends **10, 11**, preferably after a vacuum bake-out of the cryogen-cryostat assembly.

[0042] Another object of the invention is a liquid chemical compound **5** filled into a cryocooler-cryogen connection chamber (**Fig. 17**) of the second variant of the hybrid cooling system of a cold split and joint. The compound, having a melting point preferably lower than the melting point of a cryogen, prevents the formation of ice at the cold surfaces and allows immediate detachment of a cryocooler cold tip **3** from a wall **2** of a vessel filled with the cryogen **1** after the cryogen cooling. Also, in this case, as shown in **Fig. 18** the cryocooler cold tip **3** may not be in direct mechanical contact with the wall of the vessel filled with the cryogen **2**, so the liquid compound **5** can serve as a thermal interface material, reducing mechanical load on a cryocooler cold finger **4**.

[0043] Also, it is an object of the invention, a standalone cryogen vessel with a neck which accepts either a cryocooler or a cold finger of a standalone cryostat. Initially, a cryocooler **3** is attached through this neck (**Fig. 19**) and after a cryogen cooling it is detached and replaced by the cryostat **1**, containing an object of cooling (**Fig. 20**). The vessel filled with the cryogen can be either with an open or a closed end. The corresponding designs of a closed standalone cryogen vessel and a compatible cryostat are shown in **Figs. 21 and 22**.

[0044] The cryostat of **Fig. 22** contains an HPGe detector **1** having ion-implanted n+ and p+ electrodes, a cartridge with Zeolite **9**, which effectively absorbs water molecules, hydrogen getters **13**, and an electrical feedthrough **10** for activation of the getters. The cryostat is closed with an endcap **18** made from aluminium, is sealed by a metal, preferably gold-plated O-ring **17**, and is evacuated to ultra-high vacuum through a valve **15**. The cryostat along with the detector is designed so, to be exposed to high-temperature treatment (vacuum bake-out over 350 °C) to achieve low outgassing rates and keep, therefore, ultra-high vacuum insulation for a long time.

[0045] The standalone cryogen vessel can be replaced with an identical one, in which the cryogen is pre-cooled while the previous vessel is in operation. In its turn, the detector can be pre-cooled by the cryocooler using a functional element which represents a metal tube with identical flanges at both ends (**Fig. 23**). The tube is sealed by two elastomer O-rings **8, 10**, forming a sealed connection chamber in which a detector cold finger **1** is brought into mechanical contact with a cryocooler cold tip **7**. To provide the possibility of splitting of the cold components the amount of air in the connection chamber is minimized, it can also be achieved using a solid tube **6**, made from material having low thermal conductivity, such as a PTFE, which fills a space **4** replacing the air.

[0046] The reusable hybrid cooling system of a cold split and joint can be used for a variety of applications, as an example, in **Figs. 24 and 25** two HPGe spectrometers designed around the concepts of the first and the second variants of the hybrid cooling system are sequentially shown.

[0047] The first spectrometer provides the following advantages:

- a) No deterioration of the detector energy resolution associated with mechanical vibrations produced by an electromechanical cryocooler occurs, because after the cryogen cooling to solid state the cryocooler is switched off for the spectrometric measurements;
- b) After the cryogen cooling to solid state, the cryocooler cold tip is detached from the cold cryogen; the heat load to the cryogen is decreased, and the autonomous operation time of the spectrometer is therefore extended.

[0048] The second spectrometer, in addition, allows the complete removal of the cryocooler from the cryogen vessel, and therefore, a significant reduction of the weight of a main operational device (the spectrometer) used by an operator for the measurements is provided by the invention.

Table 1 - Classification of the hybrid cooling system depending on the type of connection chamber.

	Type of the connection chamber	Principle of connection	Type of connection	Operational characteristics of the cooling system
1.	A vacuum-tight chamber with an encapsulated cryogen and metal bellows.	Compression and decompression of the bellows.	Contact connection under pressure between a cryocooler cold tip and a wall of a vessel filled with the cryogen. Can be done through a metal thermal interface material such as indium.	The cryocooler cold tip can be connected to or disconnected from the cold wall (cooled below 0 °C) of the vessel filled with the cryogen. The cryocooler itself can't be removed from the main operational device which contains a cryostat and the cryogen.
2.	A hermetically sealed air chamber with an encapsulated cryogen and minimized fixed air volume when sealed.	A cryocooler (or a detachable cryostat) cold finger is manually plugged into the connection chamber using quick-release flanges, an elastomer O-ring and a	a) Contact connection under pressure between a cryocooler cold tip and a wall of the vessel filled with the cryogen. Can be done through a metal thermal interface material such as indium.	The cryocooler cold tip can be connected to or disconnected from the cold wall (cooled below 0 °C) of the vessel filled with the cryogen. The cryocooler itself can be removed from the main operational device which
		quick-release clamp.	b) Same as above plus the chamber is filled with a liquid chemical compound having a melting point, preferably lower than the melting point of the cryogen; the liquid prevents the formation of ice at the place of contact by blocking access of the water molecules to the cryocooler cold tip. Vertical orientation of the cryogen vessel is required during cooling. c) Connection via liquid thermal interface material, preferably having a melting point lower than the melting point of the cryogen. Provides reduced mechanical pressure on a cryocooler cold tip. The vertical orientation of the cryogen vessel is preferable during cooling.	contains a cryostat with an object of cooling and the cryogen.
3.	A hermetically sealed air chamber with an open cryogen vessel and a fixed air volume when sealed.	A cryocooler or a cryostat cold finger is manually plugged into the connection chamber using quick-release flanges, an elastomer	Direct immersion of a cryocooler cold finger in the cryogen. The vertical orientation of the cryogen vessel is preferable during cooling and	The cryocooler cold tip can be connected to the liquid cryogen and disconnected from the cooled cryogen only when some time required for the melting of a part

(continued)

	Type of the connection chamber	Principle of connection	Type of connection	Operational characteristics of the cooling system
		O-ring and a quick-release clamp.	sealing. To keep its properties e.g. temperature of crystallization, the cryogen mustn't be hygroscopic.	of the cryogen around the cryo-cooler coldfinger is passed. The cryo-cooler can be completely removed after that from a main operational device containing an object of cooling and a cryogen.

Brief description of the drawings

[0049]

In **Fig. 1** a complete cooling and operational cycle of the hybrid cooling system is shown. The repeatable possibility to disconnect a cryocooler at point **4** and connect it again at point **7** is provided by the invention, making the hybrid cooling system reusable and of a cold split and joint.

The first variant of the hybrid cooling system of a cold split and joint applied to an object of cooling positioned in a cryostat **1** is shown in **Figs. 2** and **5**. The system contains an encapsulated cryogen vessel **2** which is integrated (shares common vacuum insulation) with a cryostat and with a detachable but not removable cryocooler **4**. The walls of a chamber for the connection between a cryocooler and a cryogen vessel represent metal bellows **3** which are compressible, so the length of the chamber can be decreased or increased without breaking the vacuum insulation.

In **Figs. 3** and **6** details of the first variant of the hybrid cooling system of a cold split and joint are shown. A cryocooler cold finger **17** is attached to a wall of an inner vessel **13** filled with a cryogen in vacuum **5**. The attachment is achieved by compressing the bellows.

In **Fig. 3** an inner vessel filled with the cryogen is relatively short and is fixed by a holder **8** able to prevent longitudinal and transverse displacements of the inner vessel with reference to an outer vessel **15**.

In **Fig. 6** the inner vessel filled with the cryogen is relatively long and is supported by a holder **8**, which prevents the inner vessel displacement along an X-axis **32**, and a neck **19** with a bearing **21**, which prevents the inner vessel displacement across the X-axis.

In **Figs. 4** and **7** a cryogen **1** is cooled to the solid state, and a cryocooler cold tip **6** is detached from a wall of vessel **2** filled with the cryogen by decompressing or expanding the bellows so that vacuum insulation **5** is kept.

The second variant of the reusable hybrid cooling system of a cold split and joint is shown in **Fig. 8**. The system contains an object of cooling, positioned in a vacuum-insulated cryostat **1** and integrated with a vacuum-insulated encapsulated vessel filled with a cryogen **2**, to which an electromechanical cryocooler **4** is attached using a quick-release clamp **3**.

In **Fig. 9** the hybrid cooling system of a cold split and joint is applied to the cooling of an HPGe detector **1**. The cooling system contains an encapsulated cryogen **14** cooled by a detachable cryocooler **23**. The contact connection between a cryocooler cold tip **15** and a wall of an inner vessel **11** filled with the cryogen is made in a hermetically sealed connection chamber. The cryocooler cold tip can be detached from or attached to the wall of the inner vessel using a quick-release clamp **20**. The cryocooler itself can be split from an outer cryogen vessel **13** and removed from a main

operational device which contains an object of cooling and a cryogen immediately after the cryogen cooling.

In **Fig. 10** a cryogen **1** is cooled to the solid state; a cryogen-cryocooler connection chamber is unsealed, and a cryocooler cold tip **6** is detached from a wall of a vessel filled with a cryogen **2**. A cryocooler is in the process of removal from a main operational device which contains an object of cooling and the cryogen.

After the cryocooler removal, the connection chamber is promptly plugged with a PTFE or a Styrofoam plug **12** and is sealed by an elastomer O-ring **9**, using a cork **8** and applying a quick-release clamp **7**, as shown in **Fig. 11**.

The connection chamber is designed so, to minimize the volume of ambient air **11** inside the chamber during and after cryogen cooling, and therefore, to prevent the formation of ice at the contact between the cryocooler cold tip and the wall of the vessel filled with the cryogen. While the cryocooler is connected, most of the air is removed by the cryocooler cold finger itself; when the cryocooler is disconnected, the chamber is plugged with the PTFE or Styrofoam plug to remove air from the chamber and therefore prevent the formation of ice on the cold surfaces.

In **Fig. 12** a vessel to be filled with a cryogen **2** has a closed-end and a dual-wall neck. The wall of the neck **6** facing vacuum **5** is made from a metal alloy such as stainless steel, and the wall **8** facing air from both sides is made from plastic or fiberglass. The plastic/fiberglass neck is mounted using epoxy **9, 10**.

The vessel to be filled with the cryogen also contains a metal foam **1**, intended to distribute thermal gradients more uniformly across the cryogen volume and to generate centers of crystallization in the cryogen.

In **Fig. 13** the fiberglass neck **10** is mounted using threads **6, 12**, and air **8** is trapped in-between the stainless steel **9** and fiberglass walls of the neck by two elastomer O-rings **7, 11**.

In **Fig. 14** an inner vessel **4** filled with a cryogen has an open end, and a cryocooler cold tip **3** is immersed into it. A cryocooler **16** is attached to an outer cryogen vessel **6** through quick-release flanges **10, 12** and applying a quick-release clamp **11**, forming a connection chamber which is hermetically sealed by an elastomer O-ring **13**. The cryogen is shown in two aggregate states: solid **1** and liquid **2**.

In **Fig. 15** a cryogen vessel has an open end and a dual neck. The neck **8** facing vacuum **5** is made from a metal alloy such as stainless steel, and the neck **9** facing air from both sides is made from plastic or fiberglass. The plastic/fiberglass neck is mounted using epoxy **10, 11**, preferably after vacuum bake-out of a cryostat-cryogen vessel assembly.

In **Fig. 16** a cryogen vessel has an open end and a dual neck. The neck **8** facing vacuum **5** is made from a metal alloy such as stainless steel, and the neck **9** facing air from both sides is made from plastic or fiberglass. The plastic/fiberglass neck can be easily mounted and re-mounted, if necessary, after vacuum bake-out of a cryostat-cryogen vessel assembly using threads **10, 11**.

In **Fig. 17** a connection chamber is filled with a chemical compound **5** having a melting temperature, preferably, below the melting point of a cryogen. The chemical compound prevents access of ambient air containing water molecules to the place of contact in-between a wall of a vessel filled with the cryogen **2** and a cryocooler cold tip **3**; it, therefore prevents the formation of ice and adhesion of the cryocooler cold tip to the wall of the vessel filled with the cryogen.

In the Figure, the cryogen **1** is in the solid state and the compound is in the liquid state due to the lower melting temperature of the compound; so the detachment of the cryocooler cold tip can be done immediately after the cryogen cooling.

In **Fig. 18** a chemical compound **5** having a melting temperature, preferably, below the melting point of a cryogen **1** is filled into a connection chamber. The liquid compound serves as a thermal interface material between a cryocooler cold tip **3** and a wall of a vessel filled with a cryogen **2**. Contact pressure is not applied to the cryocooler cold tip.

In **Fig. 19** a standalone cryogen vessel **1**, which can have either an open- or a closed-end, is connected through a sealed connection chamber to a detachable cryocooler **3** using a quick-release clamp **2**.

In **Fig. 20** a standalone cryogen vessel **3**, which can have either an open- or a closed-end, is connected through a sealed connection chamber to a standalone cryostat containing an object of cooling **1**, using a quick-release camp **2**.

Fig. 21 shows a standalone cryogen vessel **1** which can be coupled through a sealed connection chamber either with a cryocooler or with a standalone cryostat, having a compatible connection interface.

Fig. 22 shows a standalone cryostat **16** having a connection interface to be coupled instead of a cryocooler, through a sealed connection chamber, with a standalone cryogen vessel having either an open or a closed end.

In **Fig. 23** a tubular connection chamber for the connection between a cryostat cold finger **1** and a cryocooler cold tip **7** is shown.

In **Fig. 24** a spectrometer having the reusable hybrid cooling system of a cold split and joint with a detachable but not removable cryocooler is shown.

In **Fig. 25** a spectrometer having the reusable hybrid cooling system of a cold split and joint with a removable cryocooler is shown. The cryocooler is removed.

Detailed description of the drawings

[0050] In **Fig. 1** a cooling cycle provided by the reusable hybrid cooling system of a cold split and joint is described by the temperature curve.

[0051] At **point 1** a cryocooler is connected to a cryogen vessel; so the cryocooler cold tip is put into mechanical contact (direct or through a thermal interface material) with a wall of the vessel filled with the cryogen, or, with the cryogen itself; and the cryocooler is switched on.

[0052] Between **points 1** and **4** the temperature of the cryogen is decreasing.

[0053] At **point 2** the melting temperature of the cryogen is reached.

[0054] Between **points 2** and **3** molecules of a chemical compound of the cryogen are losing their kinetic energy.

[0055] At **point 3** the cryogen is cooled to its solid state, and the maximum energy barrier at the phase transition characterized by the enthalpy of fusion is accumulated.

[0056] Between **points 3** and **4** overcooling of the cryogen occurs.

[0057] At **point 4** the cryocooler is switched off and preferably disconnected.

[0058] Between **points 4** and **5** the temperature of the cryogen is rising. At **point 5** the melting point of the cryogen is reached.

[0059] Between **points 5** and **6** the cryogen is melting (molecules of the chemical compound of the cryogen are getting kinetic energy).

[0060] At **point 6** a phase transition occurred and the whole cryogen became liquid.

[0061] Onwards **point 6** the temperature of the cryogen is rising.

[0062] The invention provides the possibility to connect the cryocooler again, for the cryogen cooling, for example at **point 7**, without the necessity of waiting for the cryogen warm up above 0 °C.

[0063] In **Fig. 2** the cooling system is applied to an object of cooling which is placed in a cryostat **1**. The cryostat is integrated with a cryogen vessel **2**. An inner vessel filled with a cryogen is cooled by a detachable but not removable cryocooler **4**. A contact connection between a cryocooler cold tip and a wall of the vessel filled with the cryogen is made in a vacuum-insulated connection chamber. The walls of the chamber are made compressible/expandable from metal bellows **3**, so the length of the chamber can be decreased or increased, and the cryocooler cold tip can be attached to or detached from the wall of the vessel filled with the cryogen without breaking the vacuum.

[0064] In **Fig. 3** an object of cooling, such as an HPGe detector **1**, is surrounded by an electrical insulator **2**, is placed in a holder **3**, and is collimated **4** by a vacuum-compatible material, having high density and a high atomic number, such as tungsten. The whole assembly is coupled through a copper adapter **6** with a copper cold finger **7**. The cold finger is attached to an inner vessel **13** filled with a cryogen **16** by means of vented screws **12**. The inner vessel is made from aluminium, copper or stainless steel alloy and is wrapped with multilayer insulation **14**. A cryostat-cryogen assembly is evacuated through a seal-off valve **24** to the pressure of about 10^{-6} Torr. An outer vessel **15** is made from stainless steel and is integrated with (welded to) the detector cryostat **25**. The inner vessel is supported by a holder **8**. The holder prevents movement of the inner vessel with reference to the outer vessel along an X-axis **28**. The holder is also strong enough to prevent movement of the inner vessel (which is relatively short) across the X-axis. The holder allows a cryocooler cold tip **17** to be put into mechanical contact under pressure with the wall of the inner vessel.

[0065] A cryocooler cold head **19** is integrated with (welded to) the outer cryogen vessel using stainless steel bellows **18**. For the inner vessel filling with the cryogen, a liquid/gas feedthrough **22** is foreseen. The feedthrough is sealed by a gasket **21** and is closed by PTFE **23** and pressure **20** plugs. A molecular sieve **11** is placed between the wall of the inner vessel and the multilayer insulation.

[0066] For the cooling of the cryogen, the cryocooler cold tip is attached to the inner vessel in a vacuum-insulated

environment **5**, which is shared between the cryostat, the cryogen vessel and a cryogen-cryocooler connection chamber. The attachment is made by compressing the bellows and applying contact pressure between the cryocooler cold tip and the wall of the vessel filled with the cryogen.

[0067] Fig. 4 shows the connection chamber shown in Fig. 3, but the cryogen **1** is cooled to the solid state, the cryocooler is switched off, and the cryocooler cold tip **6** is mechanically detached from the wall of the inner vessel filled with the cryogen **2**. The vessel is wrapped with the multilayer insulation **3**. Stainless steel bellows **7** are welded to the outer vessel **4**. For the cryocooler detachment, the bellows, shown in the Figure, are decompressed. Space **5** is evacuated to the pressure of about 10^{-6} Torr. For the filling of the inner vessel with the cryogen, a feedthrough **10** made from a stainless steel tube with bellows is foreseen. The feedthrough is sealed by a gasket **9** and is closed with PTFE **11** and pressure **8** plugs.

[0068] In Fig. 5 the cooling system is applied to an object of cooling, such as an HPGe detector, which is placed in a cryostat **1**. The cryostat is integrated with a cryogen vessel **2**. An inner vessel filled with a cryogen is cooled by a detachable but not removable cryocooler **4**. The contact connection between a cryocooler cold tip and a wall of the vessel filled with the cryogen is made in a vacuum-insulated connection chamber. The walls of the chamber are made compressible/expandable from metal bellows **3**, so the length of the chamber can be decreased or increased, and the cryocooler cold tip can be attached to or detached from the wall of the vessel filled with the cryogen without breaking the vacuum.

[0069] In Fig. 6 an object of cooling, such as an HPGe detector **1**, is surrounded by an electrical insulator **2**, is placed in a holder **3**, and is collimated **4** by a vacuum-compatible material, having high density and a high atomic number, such as tungsten. The whole assembly is coupled through a copper adapter **6** with a copper cold finger **7**. The cold finger is attached to an inner vessel **13** filled with a cryogen **16** by means of vented screws **12**. The inner vessel is made from aluminium, copper or stainless steel alloy and is wrapped with multilayer insulation **14**. A cryostat-cryogen assembly is evacuated through a seal-off valve **28** to the pressure of 10^{-6} Torr. An outer vessel **15** is made from stainless steel and is integrated with (welded to) the detector cryostat **30**. The inner vessel is supported by a coaxial holder **8** attached to the body of the cryostat by means of screws **9**. The holder is designed to prevent movement of the inner vessel with reference to the outer vessel along an X-axis **32**; so a cryocooler cold tip **17** can be put, manually or electromechanically, into mechanical contact under pressure with the wall of the inner vessel.

[0070] A cryocooler **23** is attached to the outer cryogen vessel using stainless steel bellows **20**. For the filling of the inner vessel with the cryogen, a liquid feedthrough **27** is foreseen. The liquid feedthrough is sealed by a gasket **25** and is closed by PTFE **26** and pressure **24** plugs. A molecular sieve **11** is placed between the wall of the inner vessel and the multilayer insulation.

[0071] For the cooling of the cryogen, the cryocooler cold tip is attached to the inner vessel in a vacuum-insulated environment **5**. The attachment is made by compressing the bellows and applying contact pressure between the cryocooler cold tip and the wall of the vessel filled with the cryogen.

[0072] At the end of a neck **19** of the inner vessel, a linear-motion bearing **21** is located (welded to the neck). The bearing is coupled with the cryocooler cold finger **18**. Balls of bearing **22** are made from a material having low thermal conductivity such as Zirconia ceramics. By this design, a low heat flow from the cryocooler body to the cryogen is achieved, and a coaxial orientation of the inner vessel filled with the cryogen with reference to the outer vessel is supported.

[0073] Fig. 7 shows the connection chamber shown in Fig. 6, but the cryogen **1** is cooled to the solid state, the cryocooler **12** is switched off, and the cryocooler cold tip **6** is mechanically detached from the wall of the inner vessel filled with the cryogen **2**.

[0074] The outer vessel **4** is integrated with the detector cryostat and with the stainless steel bellows **11**, which are decompressed. At the end of the neck **8** of the vessel filled with the cryogen, the linear-motion bearing **9** is located. The bearing is coupled with the cryocooler cold finger **7**. The balls of bearing **10** are in mechanical contact with the cryocooler cold finger. A space **5** between the vessels and the cryocooler cold finger and the inner vessel neck is evacuated to the pressure of about 10^{-6} Torr.

[0075] For the filling of the inner vessel with the cryogen, the liquid feedthrough **16** made from stainless steel bellows is foreseen. The liquid feedthrough is sealed by the gasket **14** and is closed by the PTFE **15** and pressure **13** plugs.

[0076] In Fig. 8 the reusable hybrid cooling system of a cold split and joint is shown. The system contains a cryostat **1** (with an object of cooling) integrated with (welded to) a cryogen vessel **2**. The cryogen is cooled by a detachable and removable cryocooler **4**. A contact connection under pressure between the cryocooler cold tip and a wall of a vessel filled with the cryogen is made in a connection chamber in which the air volume is minimized. The chamber is sealed by an elastomer O-ring and the contact connection under pressure is achieved by applying a quick-release clamp **3**. Due to the application of a quick-release connection interface (i.e. quick-release flanges and the quick-release clamp), the cryocooler-cryogen split/joint time (the chamber is unsealed) can be short (less than 10 seconds), what makes the cooling system reusable.

[0077] In Fig. 9 an object of cooling, such as a planar HPGe detector **1**, is surrounded by an electrical insulator **2**, is placed in a detector holder **3** and is collimated **4**. The whole assembly is coupled through a copper adapter **5** with a copper cold finger **6**. The cold finger is attached to an inner vessel **11** filled with a cryogen **14** using vented screws. The cryogen could be in the liquid or gaseous state at normal temperature and pressure. The inner vessel is made from stainless steel,

aluminium or oxygen-free copper and is wrapped with a multilayer insulation **12**. Space **9** is evacuated through a seal-off valve **29** to the pressure of about 10^{-6} Torr. An outer vessel **13** is made from stainless steel and is integrated with the detector cryostat. The inner vessel is supported coaxially with reference to the outer vessel by a holder **8** via a thermal bridge **7**, what prevents the neck **17** from deformation. The neck is made from stainless steel or fiberglass. The cryostat has electrical feedthroughs **10**, is closed by an aluminium endcap **31**, and is sealed by an elastomer or metal O-ring **30**.

[0078] For the filling of the inner vessel with the cryogen, a liquid feedthrough **28** made from stainless steel is foreseen. The feedthrough is sealed by a gasket **26** and is closed with PTFE **27** and pressure **25** plugs. A molecular sieve **16** is placed between the wall of the inner vessel and the multilayer insulation.

[0079] For cryogen cooling, a cryocooler cold tip **15** is attached to the wall of inner vessel **11** in a sealed by an elastomer O-ring **19** connection chamber. The attachment is made through quick-release flanges **18**, **21** using a quick-release clamp **20**, applying contact pressure to the cryocooler cold tip (to achieve good thermal transfer), and compressing the O-ring. The space **22** between a cryocooler cold finger **24** and the neck, filled with ambient air, is minimized.

[0080] **Fig. 10** shows the connection chamber of the cooling system shown in **Fig. 9**, but the cryogen **1** is frozen, and the cryocooler **13** is in the process of splitting from the cryogen vessel **4**.

[0081] The connection chamber is unsealed by removing the quick-release clamp, liberating the flanges **9**, **11**, and decompressing the O-ring **10**. The cryocooler cold tip **6** is detached from the wall of the inner vessel **2**. Ambient air **12** fills the space between the cryocooler cold finger **7** and the inner vessel neck **8**.

[0082] For the filling of the inner vessel with the cryogen, the liquid feedthrough **15** made from stainless steel is foreseen. It is closed by the PTFE plug **16** and is sealed by the gasket **15** using the pressure plug **14**. Space between the inner and the outer vessels of the Dewar is evacuated to the pressure of about 10^{-6} Torr. To support a high vacuum, the molecular sieve **5** is placed between the wall of the inner vessel and the multilayer insulation **3**.

[0083] **Fig. 11** shows the connection chamber of the cooling system shown in **Fig. 9**, but the cryogen **1** is frozen and the cryocooler is detached.

[0084] The cryogen-cryocooler connection chamber is closed by a PTFE or Styrofoam plug **12**, which effectively removes air **11** from the connection chamber. The connection chamber is hermetically sealed by an elastomer O-ring **9**, using a quick-release clamp **7** and a cork with a flange **8** compatible with the cryogen vessel flange **6**. Both measures, along with a prompt cryocooler attachment and detachment, reduce the amount of ice formed at the cold surfaces in the connection chamber and prevent adhesion of the cryocooler cold tip to the wall of the vessel filled with the cryogen; what is essential for a reusable operation of the cooling system.

[0085] For the filling of the inner vessel with the cryogen, the liquid feedthrough **15** made from stainless steel is foreseen. It is closed by the PTFE plug **16** and is sealed with the gasket **14** using the pressure plug **13**. The space **5** between the inner **2** and the outer **4** vessels of the Dewar is evacuated to the pressure of about 10^{-6} Torr. To support a high vacuum, the molecular sieve **17** is placed between the wall of the inner vessel and the multilayer insulation **3**.

[0086] In **Fig. 12** a cryogen Dewar has a dual neck. The wall of a neck **6** facing vacuum **5** is ultrathin (about 0.1 mm) and is made from a metal alloy such as stainless steel, and the wall of a neck **8** facing the air from both sides is relatively thick (about 1 mm), to provide good mechanical strength, and is made from fiberglass (or plastic). The dual-neck provides improved vacuum outgassing characteristics compared to a single fiberglass neck, or improved thermal conductivity values compared to a single thicker stainless steel neck. The fiberglass neck is mounted using epoxy **9**, **10**. The air **7** between the necks is trapped and doesn't penetrate in a cryocooler-cryogen connection chamber. A metal foam **1** is placed inside an inner vessel **2**. The foam serves for the creation of centers of crystallization, and, distributes thermal gradients more uniformly across the cryogen volume. The cryogen is filled in the inner vessel through a feedthrough **15**, which is hermetically closed by a pressure plug **13**, and is sealed with an elastomer or copper gasket **14**.

[0087] In **Fig. 13** a cryogen Dewar has a dual neck. The wall of a neck **9** facing vacuum **5** is ultrathin and is made from a metal alloy having low thermal conductivity such as stainless steel, and the wall of a neck **10** facing the air from both sides is relatively thick and is made from fiberglass or plastic.

[0088] The fiberglass neck is mounted using threads **6**, **12**, preferably after a vacuum bake-out of a cryostat-cryogen vessel assembly. Two elastomer O-ring seals **7**, **11** are foreseen; the seals block air **8** in between the two necks, so the air can't penetrate to the sealed connection chamber.

[0089] A metal foam **1** is brazed to the walls of an inner vessel **2**. After the cryogen filling a liquid/gas feedthrough **17** is hermetically closed by a plug **15** and is sealed with a gasket **16**. Such configuration of the feedthrough allows cryogen filling after a vacuum bake-out of the cryostat-cryogen assembly.

[0090] In **Fig. 14** an inner vessel **4**, filled with a cryogen being in a liquid state at room temperature and normal pressure, has an open end; and a cryocooler cold finger **15** is brought in direct contact with the cryogen. Most of the volume of the cryogen is in a solid crystalline state **1**, however, a part of the cryogen volume **2** is melted around the cryocooler cold finger and its tip **3**. The Figure illustrates the last phase of the following cycle:

- a) The cryogen was in the liquid aggregate state (for example, at room temperature);
- b) For the cryogen cooling the cryocooler was plugged into the connection chamber and was fixed using a quick-

release clamp **11**, so the cryocooler cold finger is immersed into the cryogen;

c) The cryocooler was switched on;

d) The cryogen was cooled to the solid state **1**;

e) The cryocooler was switched off;

f) After some time, defined by a heat flow from the cryocooler body to its tip, a part of the cryogen **2** is melted around the cryocooler cold finger and cold tip; so at this point, the cryocooler cold finger/tip can be detached from the cryogen and the cryocooler itself can be unplugged and removed from the cryogen vessel.

[0091] In **Fig. 15** a vessel **1** to be filled with a cryogen has an open end, and a cryogen Dewar has a dual neck. The wall of a neck **8** facing vacuum **5** is ultrathin and is made from a metal alloy such as stainless steel, and the wall of a neck **9** facing air **4** from both sides is made from fiberglass or plastic and is relatively thick. The fiberglass neck can be mounted using epoxy **10**, **11** as shown in the Figure, or using threads at both ends as shown in **Fig. 16**.

[0092] The dual-neck concept allows mounting of the fiberglass neck after a vacuum bake-out of a cryostat-cryogen vessel assembly, what provides the possibility to increase heat treatment temperature.

[0093] In **Fig. 17** a cryocooler cold tip **3** is brought into mechanical contact with a wall **2** of the vessel filled with a cryogen **1**. A chemical compound **5** having a melting point preferably lower than the melting point of the cryogen is filled in a cryocooler-cryogen connection chamber, so a cryocooler cold finger **4** and its cold tip are immersed into it. The liquid chemical compound removes a part of the air from a cryocooler-cryogen connection chamber and prevents access of water molecules of the remaining air to the place of contact between the wall of the cryogen vessel and the cryocooler cold tip; thus, preventing the formation of ice and adhesion of the cryocooler cold tip to the wall of the vessel containing cooled cryogen. When the melting point of the liquid in the connection chamber is lower than the melting point of the cryogen, the detachment of the cryocooler can be done immediately after the cryogen cooling.

[0094] In **Fig. 18** a cryocooler cold finger **4** and a cold tip **3** are brought into mechanical contact with a liquid chemical compound **5** having a melting point preferably lower than the melting point of a cryogen **1**. The liquid compound serves as a heat (cold) transfer medium between the cryocooler cold tip and a wall of vessel **2** filled with the cryogen, eliminating the requirement for the cryocooler cold tip and the wall of a vessel filled with the cryogen to be in mechanical contact under pressure.

[0095] The usage of a liquid chemical compound as a thermal interface material decreases axial mechanical load on the cryocooler cold finger. When the melting point of the chemical compound is lower than the melting point of the cryogen, the detachment of the cryocooler can be done immediately after the cryogen cooling.

[0096] In **Fig. 19** a standalone cryogen vessel **1** is joint with a detachable cryocooler **3**. The joint is made in a hermetically sealed connection chamber, applying a quick-release clamp **2**. An inner vessel filled with a cryogen may have either a closed or an open end. The cryogen vessel is equipped with an ion pump **4** to support vacuum thermal insulation.

[0097] After the cryogen cooling, the cryocooler can be split from the cryogen vessel and the cryogen vessel can be joined with a compatible cryostat afterwards.

[0098] In **Fig. 20** a standalone cryogen vessel **3** is joined with a detachable cryostat **1**. The joint is made in a hermetically sealed connection chamber, applying a quick-release clamp **2**. An inner vessel filled with a cryogen may have either a closed or an open end. The cryogen vessel is equipped with an ion pump **4** to support vacuum thermal insulation.

[0099] After the cryogen melting, the cryogen vessel can be split from the detachable cryostat and can be replaced with a similar vessel containing a pre-cooled cryogen.

[0100] In **Fig. 21** a design of a detachable standalone cryogen vessel with a single neck is shown. An outer vessel **1** has a flange **10** for the connection to a cryocooler or a cryostat. The flange can be hermetically sealed by an elastomer O-ring **11** by applying a quick-release clamp. The outer vessel is made from stainless steel or other metal alloy and contains a vacuum valve **8**, hermetically sealed by a pair of elastomer O-rings **9**. An inner vessel **5** is made from stainless steel, aluminium or copper alloy, and is attached to the outer vessel through a thermal bridge **12**, representing a stainless steel or a fiberglass neck. The inner vessel is filled with a cryogen **6** through a liquid/gas feedthrough **16**. The feedthrough is closed with PTFE **15** and pressure **13** plugs and is sealed by an elastomer O-ring **14**. Two cartridges with a molecular sieve **4**, **7** are attached to the wall of the inner vessel. The space **2** between the inner and the outer vessel is evacuated to a high vacuum. The inner vessel is wrapped with a multilayer insulation **3**.

[0101] The standalone cryogen vessel may also have two similar necks located at opposite ends, so a cryostat and a cryocooler can be connected to the cryogen vessel simultaneously.

[0102] In **Fig. 22** a design of a detachable standalone cryostat **16** is shown. The cryostat has a similar connection interface to a cryocooler, including an outer diameter of the end of a cold finger housing **8** and dimensions of a flange **14**, as to be coupled with a standalone cryogen vessel.

[0103] The cryostat contains an object of cooling, such as a planar HPGe detector **1**, placed in an electrical insulator **4**, and surrounded by a copper holder **2** and a tungsten collimator **3**. The detector holder is attached through a copper adapter **6** to a copper cold finger **7**. The cold finger is attached to the cryostat through a long and thin thermal bridge **8** made from a metal alloy of low thermal conductivity, such as stainless steel. A cartridge with a molecular sieve (such as Zeolite, which

effectively absorbs water molecules) **9** is attached to the cold finger. The cryostat also contains hydrogen getters **13**, placed behind an infrared screen **12**, and an electrical feedthrough **10** for the activation of the getters. The cryostat is closed with an endcap made from aluminium **18**, is sealed with a metal O-ring **17**, and is evacuated through a valve **15**. The cryostat is designed to achieve an ultra-high vacuum **5** supported for a long time.

[0104] In **Fig. 23** the cold finger **1** of the vacuum-insulated cryostat **2** shown in **Fig. 22**, is coupled with a cryocooler cold tip **7** by means of a tubular metal adapter **5** and two quick-release clamps **9**, **11**, forming a sealed by two elastomer O-rings **8**, **10** connection chamber. Most of the air **4** from the chamber is removed by the application of a PTFE tube **6**.

[0105] In **Fig. 24** a design of a spectrometer having the first variant of the hybrid cooling system of a cold split and joint is shown. The spectrometer contains a cryostat **1** with an HPGe detector. The cryostat is integrated with a cryogen vessel and with a cryocooler as per **Figs. 2, 3** and **4**. A cryocooler cold tip is connected to the cryogen in a vacuum environment using bellows. An electronics section of the spectrometer **2** contains a preamplifier, an amplifier, a multichannel analyzer, a high-voltage power supply, a temperature logger, and batteries; along with Ethernet **3** and USB **5** data transfer interfaces to the PC, and a socket for the charging the batteries **4**.

[0106] The cryocooler, attached to an inner frame **8** of the spectrometer body, can be moved back and forth with reference to an outer frame **7** by means of a screw **6**, rotated mechanically or electromechanically. For heat removal from the cryocooler compressor and its head, an air fan **9** is foreseen.

[0107] The spectrometer has a plastic housing **10** and a metal handle **11** and is equipped with a microprocessor with a display **12**.

[0108] In **Fig. 25** a design of a spectrometer having the second variant of the hybrid cooling system of a cold split and joint is shown. The spectrometer contains a cryostat **1** with an HPGe detector. The cryostat is integrated with a cryogen vessel. An electronics section of the spectrometer **2** contains a preamplifier, an amplifier, a multichannel analyzer, a high-voltage power supply, a temperature logger, and batteries; along with Ethernet **3** and USB **5** data transfer interfaces to the PC, and a socket for the charging the batteries **4**.

[0109] The cryogen vessel has an interface for the connection to a removable cryocooler as shown in **Fig. 9**. The chamber is closed with a Styrofoam plug and is sealed by an elastomer O-ring using a cork **6** and applying a quick-release clamp **7**. The spectrometer has a plastic housing **8** and a metal handle **9**. The handle is removable; it provides access to a connector for the powering of an ion pump. The spectrometer is equipped with a microprocessor with a display **10**.

Claims

1. A reusable hybrid cooling system of a cold split and joint which provides the possibility to perform repeated cooling cycles including connections and disconnections between a cryocooler cold tip and a melting cryogen without the necessity to wait for the cryogen warm-up above the temperature of 0 °C (melting point of ice).

2. The reusable hybrid cooling system of a cold split and joint of claim 1, containing a vacuum-insulated connection chamber for the connection between a melting cryogen vessel and a cryocooler, wherein

a) walls of the connection chamber are made from metal bellows, so a cryocooler cold tip can be attached or detached from the wall of the vessel filled with the cryogen by compressing or decompressing the bellows and without breaking the vacuum;

b) thermal transfer for the cryogen cooling is achieved by applying contact pressure between the cryocooler cold tip and the wall of the encapsulated vessel filled with the cryogen.

3. The reusable hybrid cooling system of a cold split and joint of claim 2, wherein a vessel filled with a cryogen has a neck with a linear-motion bearing at one end, coupled to a cryocooler cold finger, so the cold finger can be moved through the bearing, and a cryocooler cold tip can be detached or attached to the wall of the vessel filled with the cryogen using metal bellows (**Figs. 5, 6** and **7**).

4. The reusable hybrid cooling system of a cold split and joint of claim 1, wherein

a) for the cooling of a cryogen to a solid state, a cryocooler cold tip is attached to a wall of an encapsulated vessel filled with the cryogen in a hermetically sealed air connection chamber, by applying contact pressure using a quick-release clamp;

b) the cryocooler attachment can be made promptly, using quick-release flanges and a quick-release clamp;

c) the volume of air and therefore number of water molecules in the connection chamber is minimized to prevent the formation of ice and adhesion of the cryocooler cold tip to the wall of the vessel filled with the cryogen;

d) when the cryogen is cooled to the solid state, the cryocooler cold tip can be promptly detached from the wall of

the vessel filled with the cryogen without the necessity of warming the cryogen up and the cryocooler itself can be promptly removed from the cryogen vessel;

e) after the cryocooler removal, a Styrofoam/PTFE plug can be promptly inserted in the chamber to replace the air, and the chamber is hermetically sealed using said quick-release clamp and a cork with a compatible flange;

f) after the cryogen melting, the cryocooler can be connected again for cryogen cooling, so the cooling cycle, described above, can be repeated.

5. The hybrid cooling system of a cold split and joint of claim 1, containing in a vessel filled with a cryogen a heat exchanger in the form of a metal foam, which serves for the formation of centers of crystallization in the cryogen, and provides more uniform distribution of thermal gradients across the cryogen volume (**Fig. 12**).

6. The hybrid cooling system of a cold split and joint of claim 1, comprising a cryogen vessel having an open end and a detachable cryocooler connected to this open end through compatible flanges using a quick-release clamp, so the cryocooler cold tip can be immersed directly into the cryogen, which is liquid at room temperature and normal pressure, and after the cryogen cooling to the solid state, the cryocooler cold tip can be detached from the cryogen, without necessity in warming the whole cryogen up, however, some time, defined by the heat load to the cryocooler cold tip from the turned off cryocooler, and required for a part of the cryogen to melt around the cryocooler cold tip, should pass (**Fig. 14**).

7. A dual-wall neck of the connection chambers of claims 4 and 6, wherein the wall of the neck facing the vacuum from one side is ultra-thin (thickness of about 0.1 mm) and is made from a metal alloy such as stainless steel, and the wall of the neck facing the air from both sides is rather thick (thickness of about 1 mm) and is made from plastic or fiberglass.

8. The dual-wall neck of claim 7 applied to the connection chamber of claim 4, wherein the fiberglass neck is mounted using threads at both ends, preferably after vacuum bake-out of a cryostat-cryogen vessel assembly, and the air in-between the metal and fiberglass walls is locked by two elastomer O-rings, to block the penetration of said air in a cryocooler-cryogen connection chamber (**Fig. 13**).

9. A sealed connection chamber of claim 4, wherein for the cooling of an encapsulated cryogen, a cryocooler cold tip is brought into direct mechanical contact under pressure with a wall of a vessel filled with a cryogen, and the chamber is at least partially filled with a liquid having a melting point preferably below a melting point of a cryogen (**Fig. 17**).

10. A sealed connection chamber of claim 4, wherein for the cooling of a cryogen, a cryocooler cold tip is brought into thermal contact with a wall of a vessel filled with a cryogen through a liquid chemical compound having a melting point preferably below a melting point of a cryogen (**Fig. 18**).

11. A standalone cryogen vessel having a sealed connection chamber as per claims 4 or 6, so, at first, a cryocooler is connected to a cryogen vessel and, after a cryogen cooling, the cryocooler is replaced by a standalone cryostat, containing an object of cooling (**Figs. 19, 20 and 21**).

12. A standalone cryostat having a compatible connection interface (compatible dimensions of a coldfinger housing and a flange) for the connection to a standalone cryogen vessel of claim 11 instead of a cryocooler.

13. A standalone vacuum insulated cryostat of claim 12, designed to be exposed to a high-temperature treatment (vacuum bake-out over 350 °C) to achieve low outgassing rates and keep high-vacuum insulation for a long time, and therefore containing an HPGe detector with ion-implanted electrodes, a cartridge with Zeolite (to absorb water molecules), getters (for hydrogen absorption), electrical feedthrough for activation of the getters, an endcap sealed by a metal, preferably gold-plated O-ring (**Fig. 22**).

14. A tubular hermetically sealed connection chamber having compatible flanges for the connection between a cold tip of a standalone cryostat of claims 12 and 13 and a cold tip of a cryocooler, using two elastomer O-rings and two quick-release clamps, wherein most of the air from the chamber is removed by the application of a PTFE tube inserted in the chamber (**Fig. 23**).

15. The reusable hybrid cooling system of a cold split and joint of claim 1, applied to the cooling of a semiconductor radiation detector, providing at least one of the following advantages:

a) no deterioration of detector energy resolution associated with mechanical vibrations produced by an electro-

mechanical cryocooler occurs as the cryocooler is switched off for spectrometric measurements after cryogen cooling;

b) after cryogen cooling a cryocooler cold tip is detached from the vessel filled with the cryogen, and the heat load to the cryogen is, therefore decreased, so the autonomous operation time of a detector (proper operating temperature) is, therefore extended;

c) after cryogen cooling the cryocooler itself is removed from the main measuring device containing an object of cooling and a cryogen and the weight of the main measuring device used by an operator is, therefore reduced.

Amended claims in accordance with Rule 137(2) EPC.

1. The first type of a reusable hybrid cooling system of a cold split and joint, wherein

a) for the cooling of a cryogen to a solid crystalline state, a cryocooler cold tip is attached to a wall of an encapsulated vessel filled with the cryogen in a hermetically sealed air connection chamber, by applying contact pressure using a quick-release clamp;

b) the cryocooler attachment is made using quick-release flanges and a quick-release clamp;

c) the volume of air and therefore, the number of water molecules in the connection chamber is minimized to prevent the formation of ice and adhesion of the cryocooler cold tip to the wall of the vessel filled with the cryogen;

d) when the cryogen is cooled to the solid aggregate state with a melting point below 0 °C, the cryocooler cold tip is promptly detached from the wall of the vessel filled with the cryogen without warming the cryogen up and the cryocooler itself is promptly removed from the cryogen vessel;

e) after the cryocooler removal, a Styrofoam or a PTFE plug is promptly inserted in the chamber to replace the air, and the chamber is hermetically sealed using said quick-release clamp and a cork with a compatible flange;

f) after the cryogen melts, the cryocooler is promptly connected again for cryogen cooling, so that the cooling cycle with mechanical joint and split between the cryocooler cold tip and the wall of the vessel filled with the melting cryogen, performed at a temperature below 0 °C, exposing the chamber to the ambient air, and avoiding the generation of reduced air pressure in the connection chamber by any additional means apart from the temperatures of the cryocooler cold tip and the cryogen, is repeated.

2. The second type of a reusable hybrid cooling system of a cold split and joint, containing a vacuum-insulated connection chamber for the connection between a melting cryogen vessel and a cryocooler, wherein

a) walls of the connection chamber are made from metal bellows, so a cryocooler cold tip can be attached or detached from the wall of the vessel filled with the cryogen by compressing or decompressing the bellows and without breaking the vacuum;

b) thermal transfer for the cryogen cooling is achieved by applying contact pressure between the cryocooler cold tip and the wall of the encapsulated vessel filled with the cryogen.

3. The third type of a reusable hybrid cooling system of a cold split and joint, comprising a cryogen vessel having an open end and a detachable cryocooler connected to this open end through compatible flanges using a quick-release clamp, so the cryocooler cold tip is immersed directly into the cryogen, which is liquid at room temperature and normal pressure, and after the cryogen cooling to the solid state, the cryocooler cold tip is detached from the cryogen, without warming the whole cryogen up, however, certain time, defined by the heat load to the cryocooler cold tip from the turned off cryocooler, and required for a part of the cryogen to melt around the cryocooler cold tip, should pass.

4. The reusable hybrid cooling system of a cold split and joint of claims 1, 2 or 3, containing in a vessel filled with a cryogen a heat exchanger in the form of a metal foam, which serves for the formation of centers of crystallization in the cryogen, and provides more uniform distribution of thermal gradients across the cryogen volume.

5. A dual-wall neck of the connection chamber of the reusable hybrid cooling system of claims 1 or 3, wherein the wall of the neck facing the vacuum from one side is rather thin with a thickness of about 0.1 mm, contains bellows and is made from a metal alloy such as stainless steel, and the wall of the neck facing the air from both sides is rather thick with a thickness of about 1 mm and is made from plastic or fiberglass.

6. The dual-wall neck of claim 5, wherein the fiberglass neck is mounted using threads at both ends, preferably after vacuum bake-out of a cryostat-cryogen vessel assembly, and the air in-between the metal and fiberglass walls is preferably locked by two elastomer O-rings to block the penetration of said air in a cryocooler-cryogen connection chamber.

7. A sealed air connection chamber for the reusable hybrid cooling system, wherein for the cooling of an encapsulated cryogen, a cryocooler cold tip is brought into direct mechanical contact under pressure with a wall of a vessel filled with a cryogen, and the chamber itself is at least partially filled with a cryogen.
- 5 8. A sealed air connection chamber for the reusable hybrid cooling system, wherein for the cooling of an encapsulated cryogen, a cryocooler cold tip is brought into direct mechanical contact with a wall of a vessel filled with a cryogen, and the chamber is at least partially filled with a liquid chemical compound having a melting point below a melting point of a cryogen.
- 10 9. A sealed air connection chamber for the reusable hybrid cooling system, wherein for the cooling of an encapsulated cryogen, a cryocooler cold tip is brought into thermal contact with a wall of a vessel filled with a cryogen, through the cryogen itself separately filled in the connection chamber.
- 15 10. A sealed air connection chamber for the reusable hybrid cooling system, wherein for the cooling of an encapsulated cryogen, a cryocooler cold tip is brought into thermal contact with a wall of a vessel filled with a cryogen through a liquid chemical compound filled in the connection chamber and having a melting point below a melting point of a cryogen.
- 20 11. A standalone cryogen vessel having a sealed connection chamber as per claims 1, 3, 7, 8, 9 or 10, so, at first, a cryocooler is connected to a cryogen vessel and, after a cryogen cooling, the cryocooler is replaced with a standalone cryostat, containing an object of cooling.
12. A standalone cryostat having a compatible connection interface i.e. compatible dimensions of a coldfinger housing and a flange for the connection to a standalone cryogen vessel of claim 11 instead of a cryocooler.
- 25 13. A standalone vacuum insulated cryostat of claim 12, designed to be exposed to a high-temperature treatment i.e. vacuum bake-out over 350 °C to achieve low outgassing rates and keep high-vacuum insulation for a long time, and therefore containing an HPGe detector with ion-implanted electrodes, a cartridge with Zeolite to absorb water molecules, getters for hydrogen absorption, electrical feedthrough for activation of the getters, an endcap sealed by a metal, preferably gold-plated O-ring.
- 30 14. A tubular hermetically sealed connection chamber having compatible flanges for the connection between a cold tip of a standalone cryostat of claims 12 and 13 and a cold tip of a cryocooler, using two elastomer O-rings and two quick-release clamps, wherein most of the air from the chamber is removed by the application of a PTFE or Styrofoam tube inserted in the chamber.
- 35 15. The reusable hybrid cooling system of a cold split and joint of claims 1, 2 or 3 applied to the cooling of a semiconductor radiation detector, which provides the following advantage: no deterioration of detector energy resolution associated with mechanical vibrations produced by an electromechanical cryocooler occurs as the cryocooler is switched off for spectrometric measurements after cryogen cooling.
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Figures

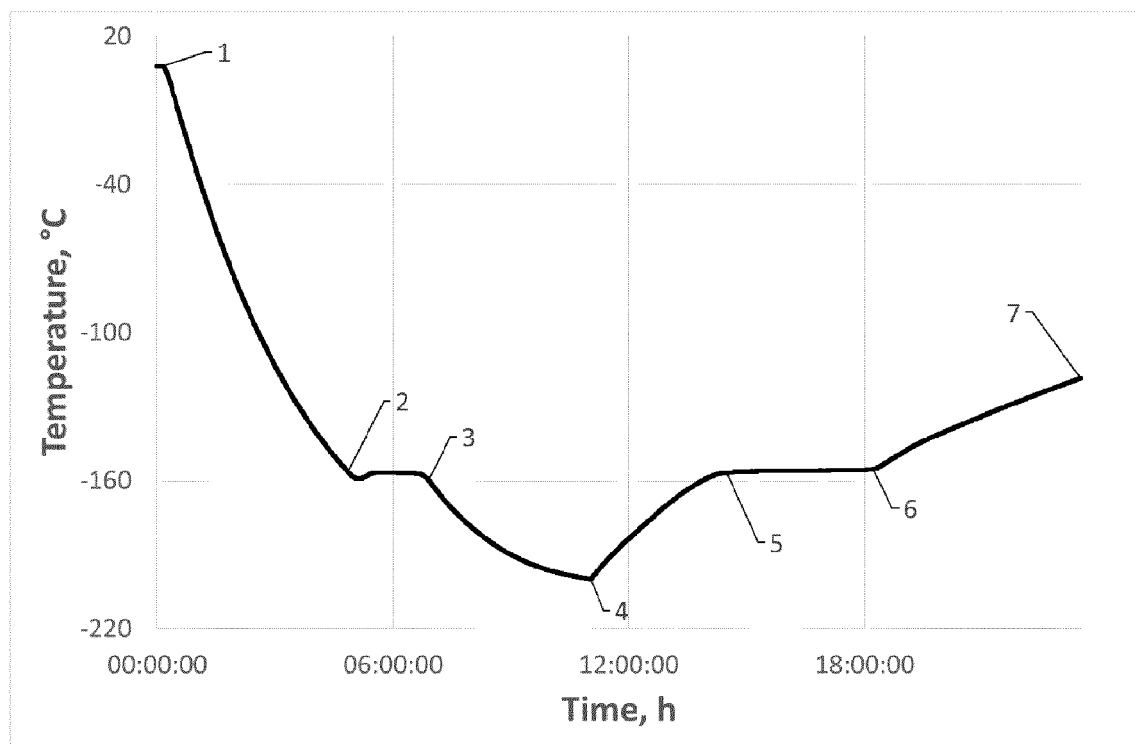


Fig. 1

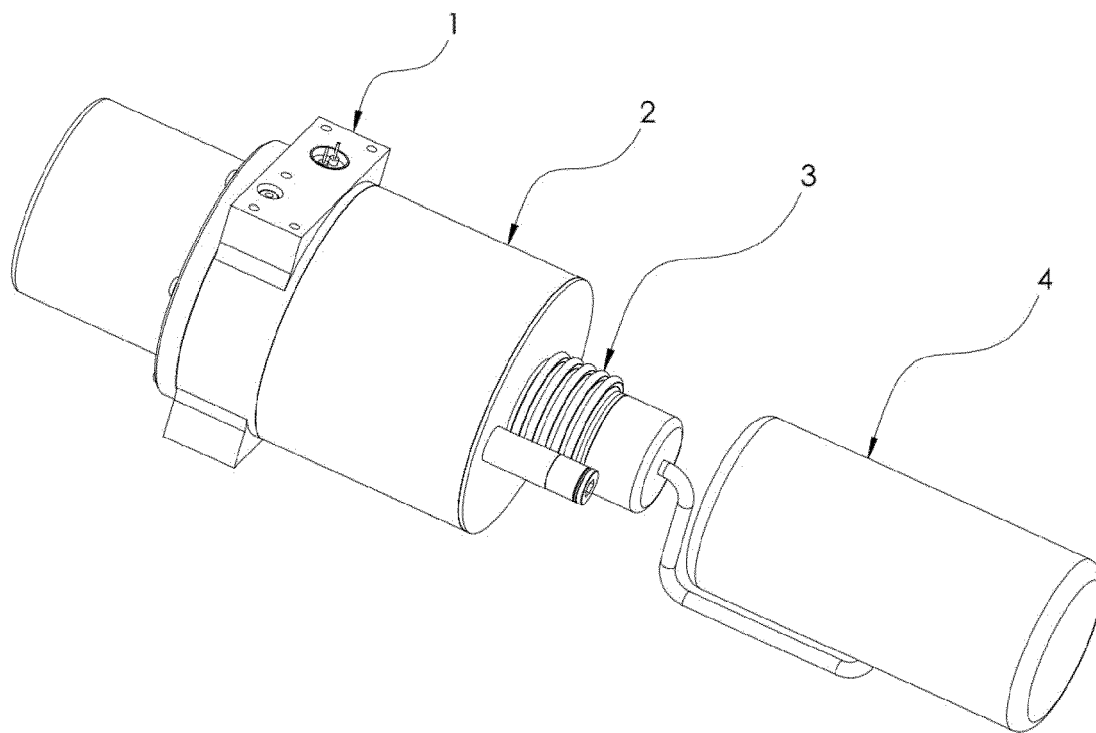


Fig. 2

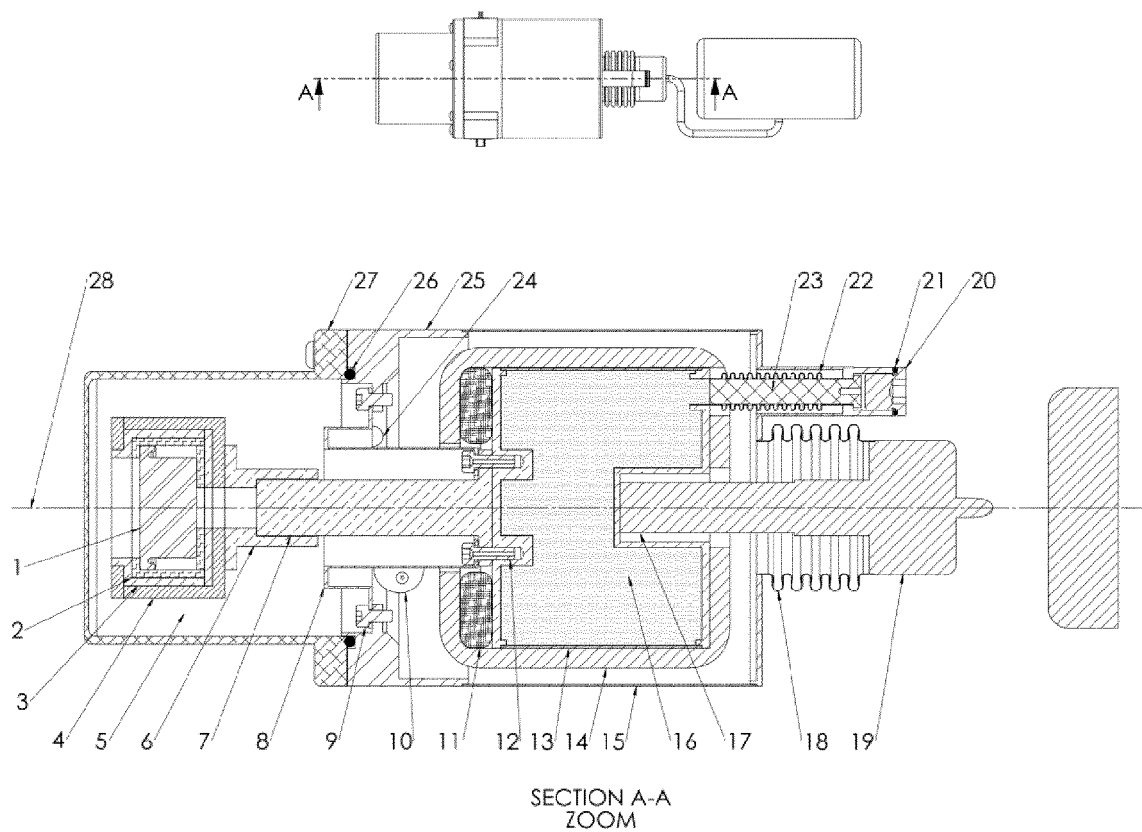


Fig. 3

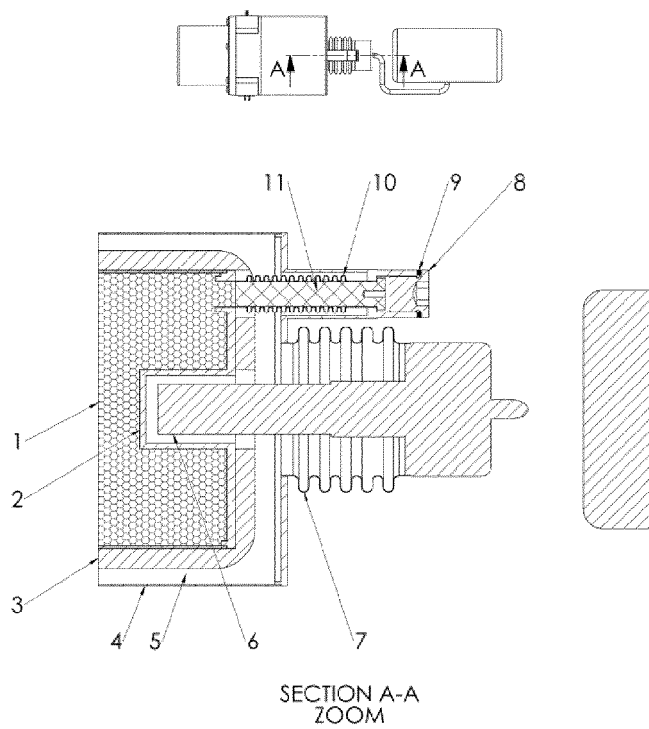


Fig. 4

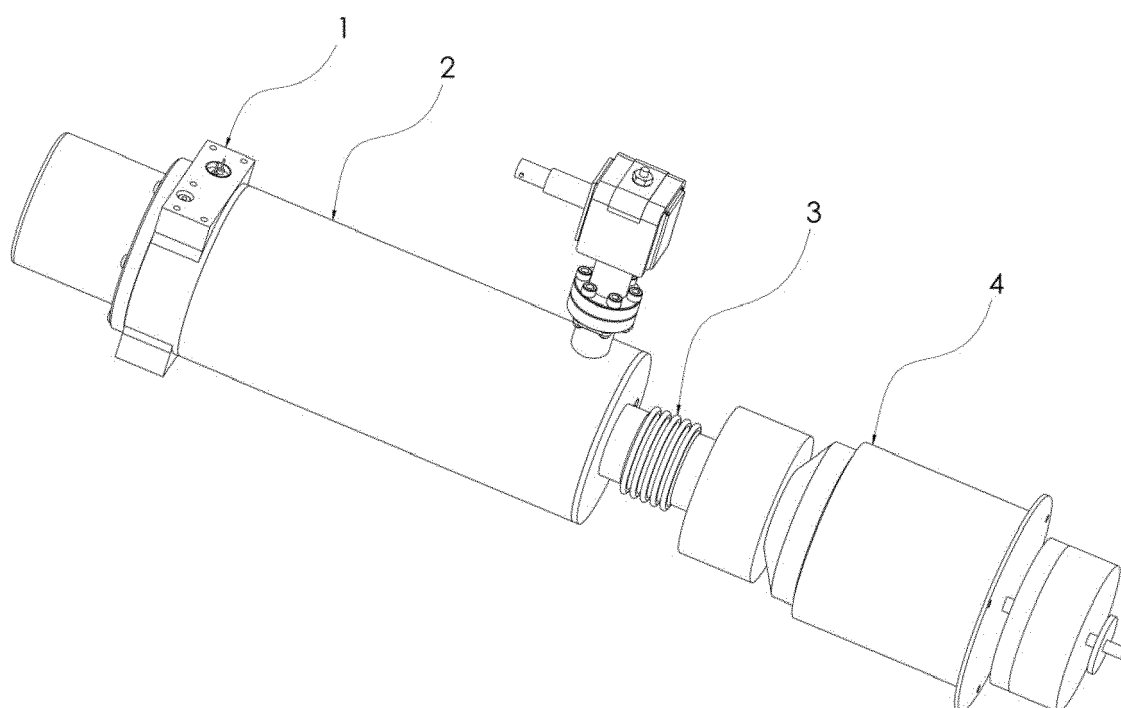


Fig. 5

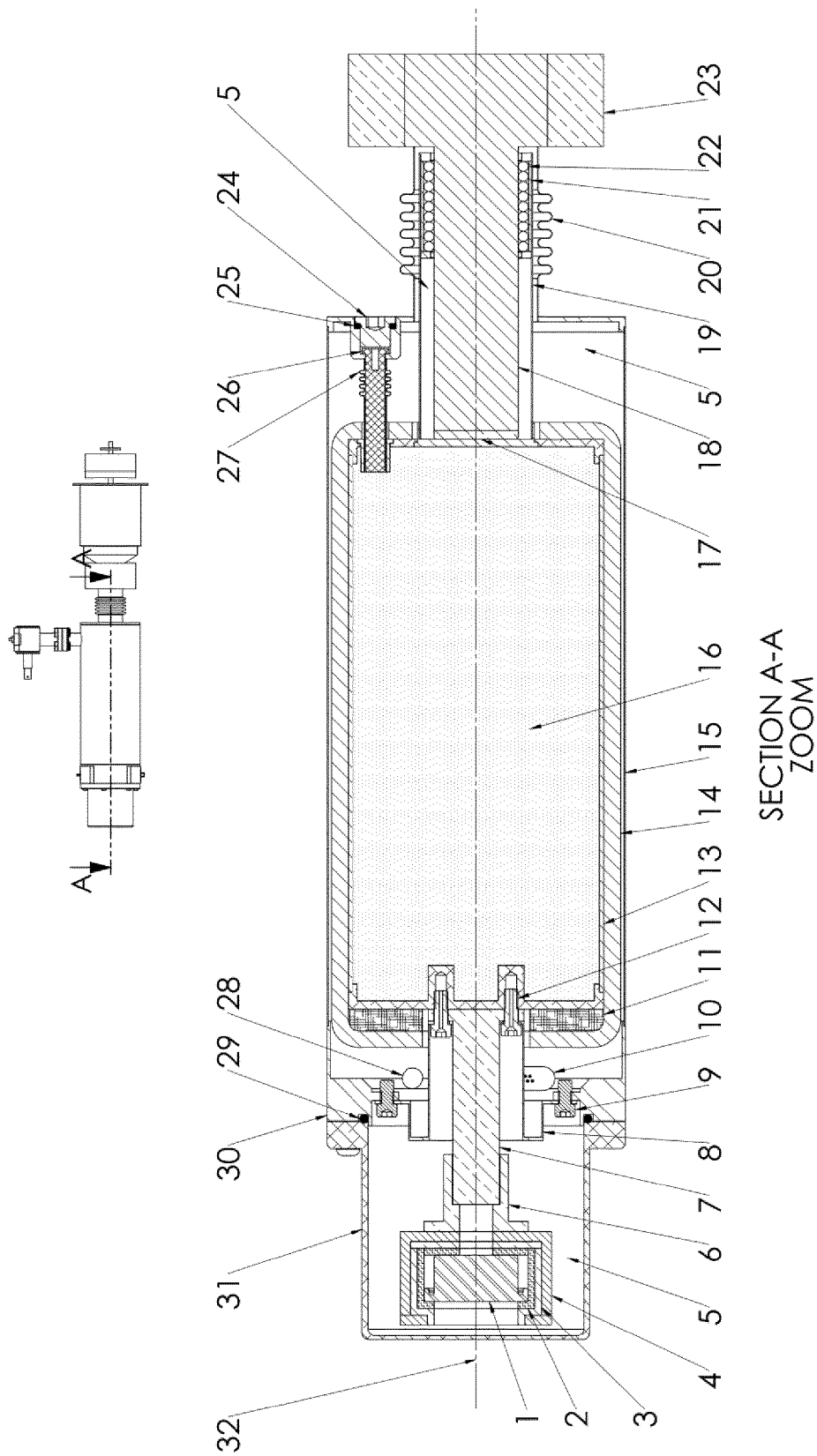


Fig. 6

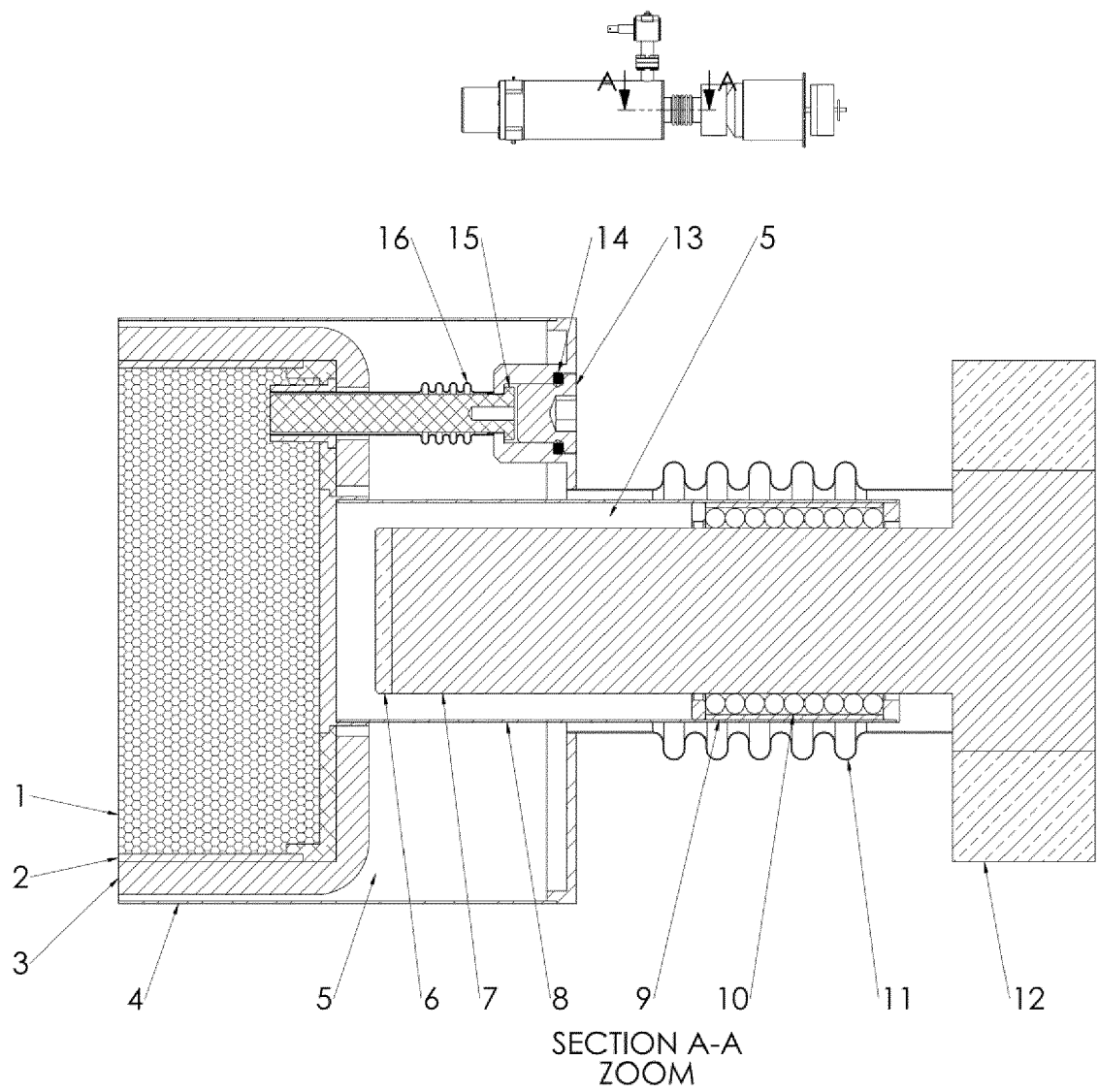


Fig. 7

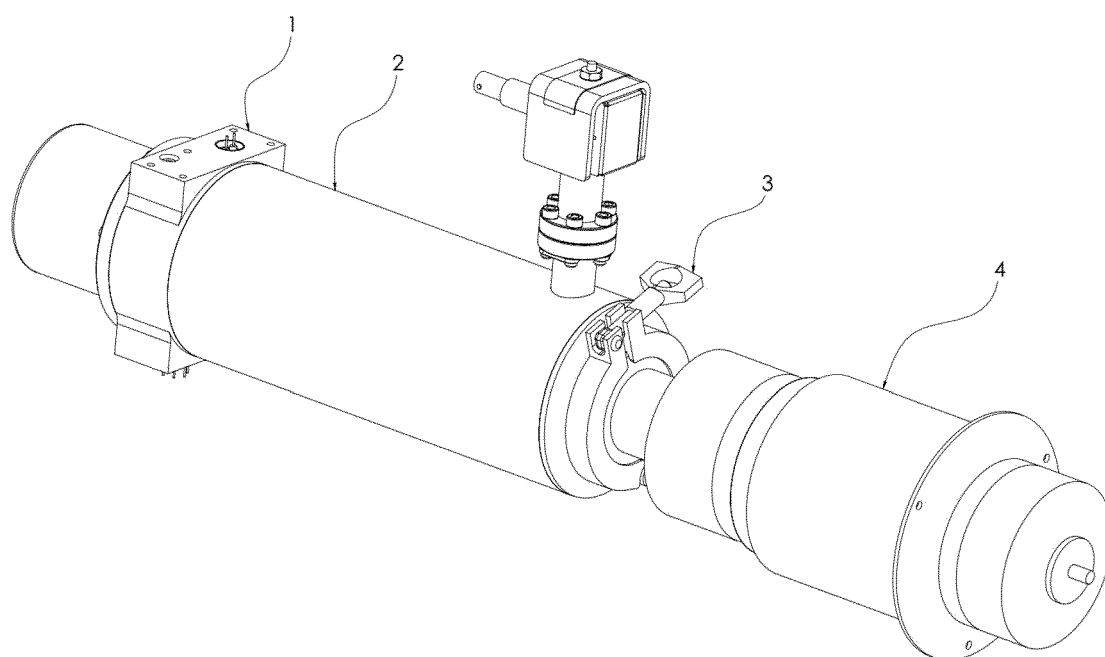


Fig. 8

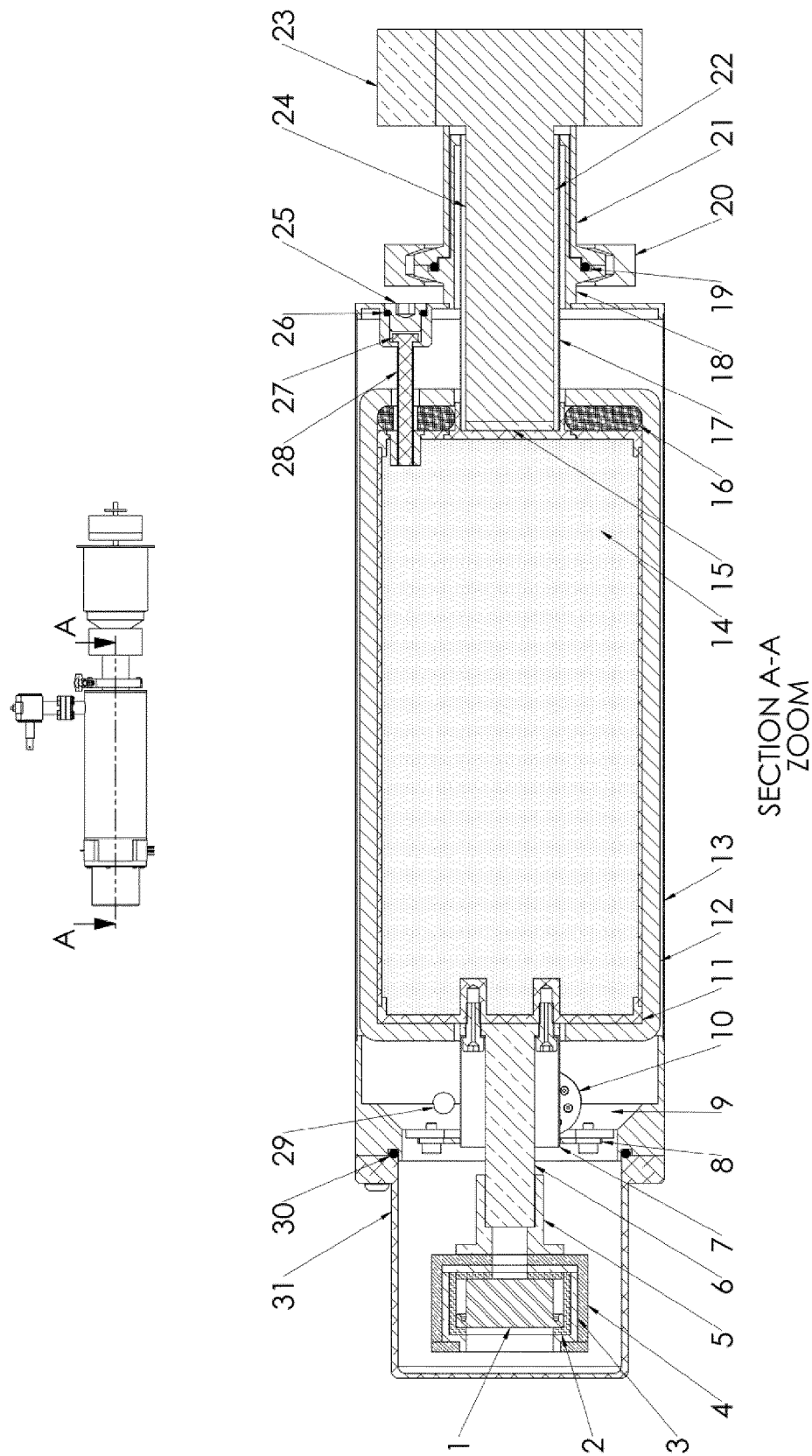


Fig. 9

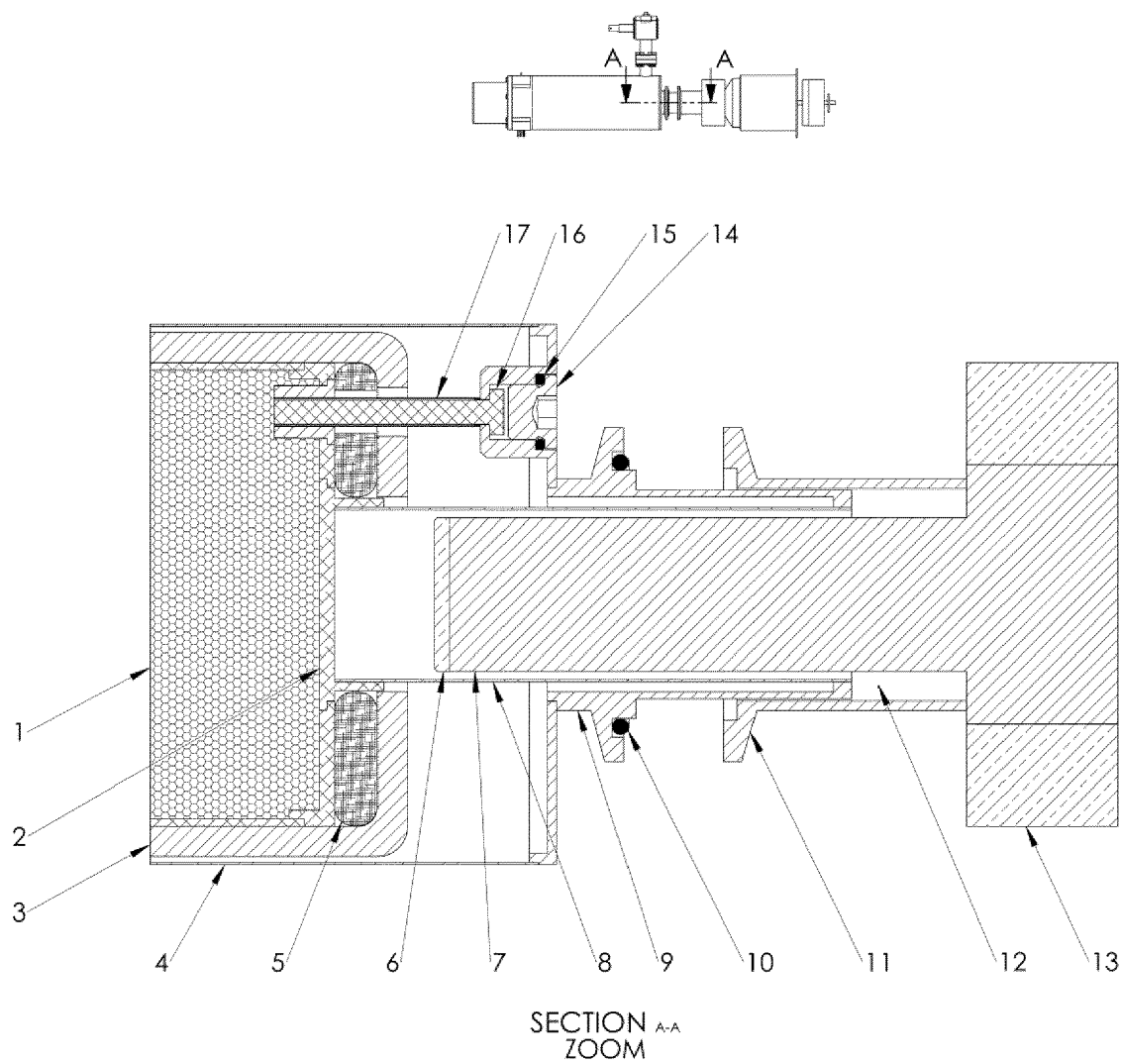


Fig. 10

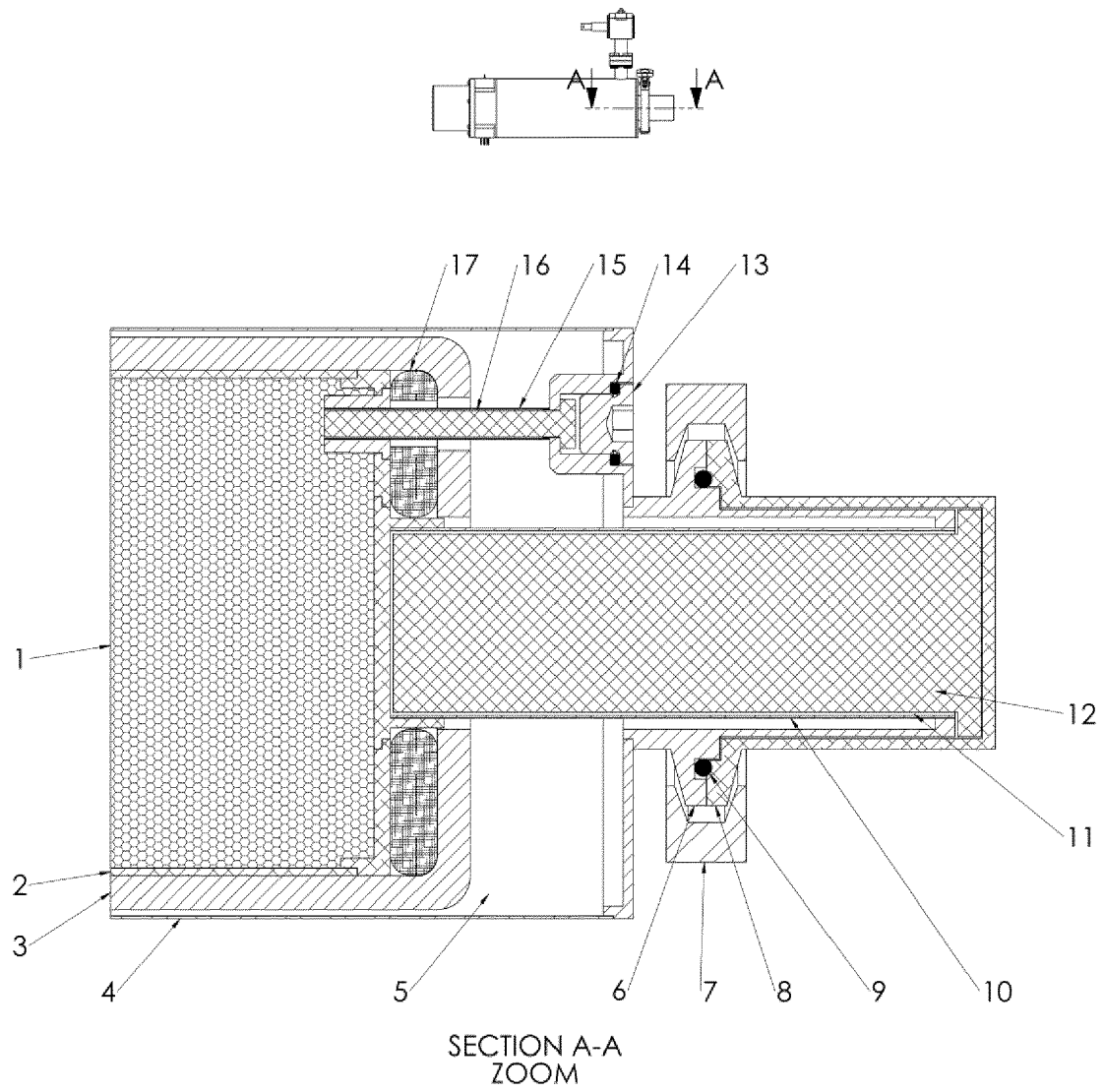


Fig. 11

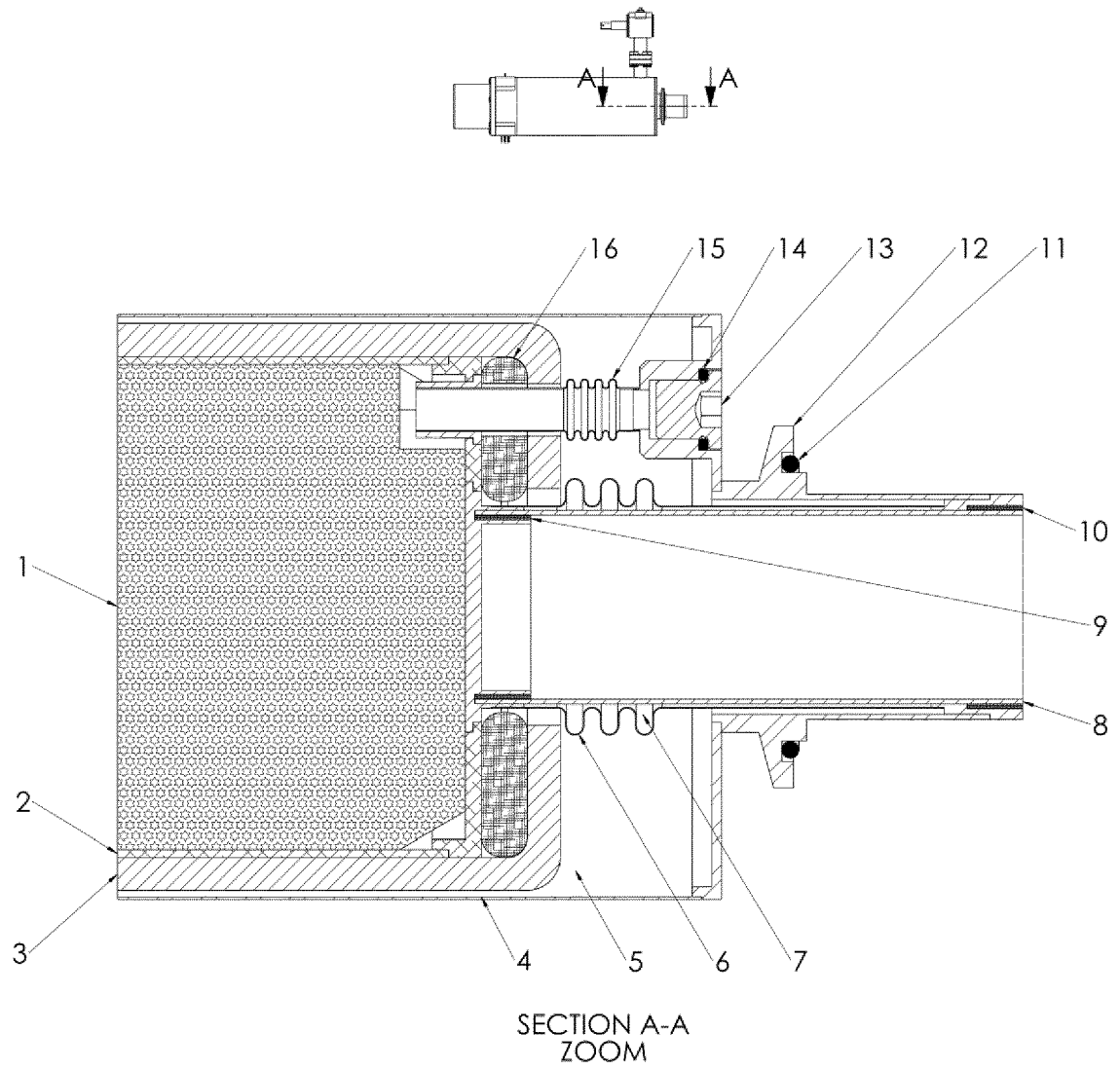


Fig. 12

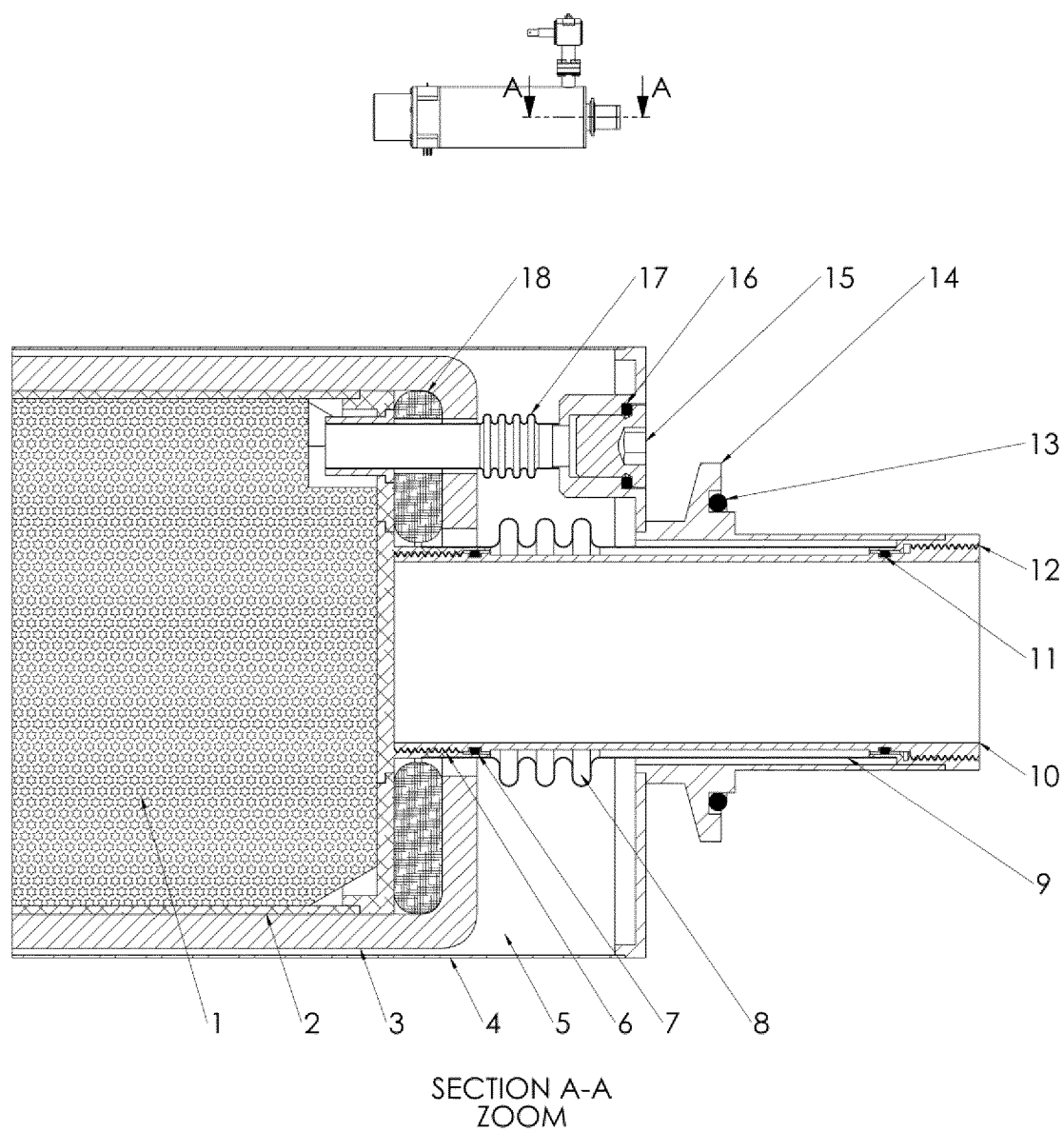


Fig. 13

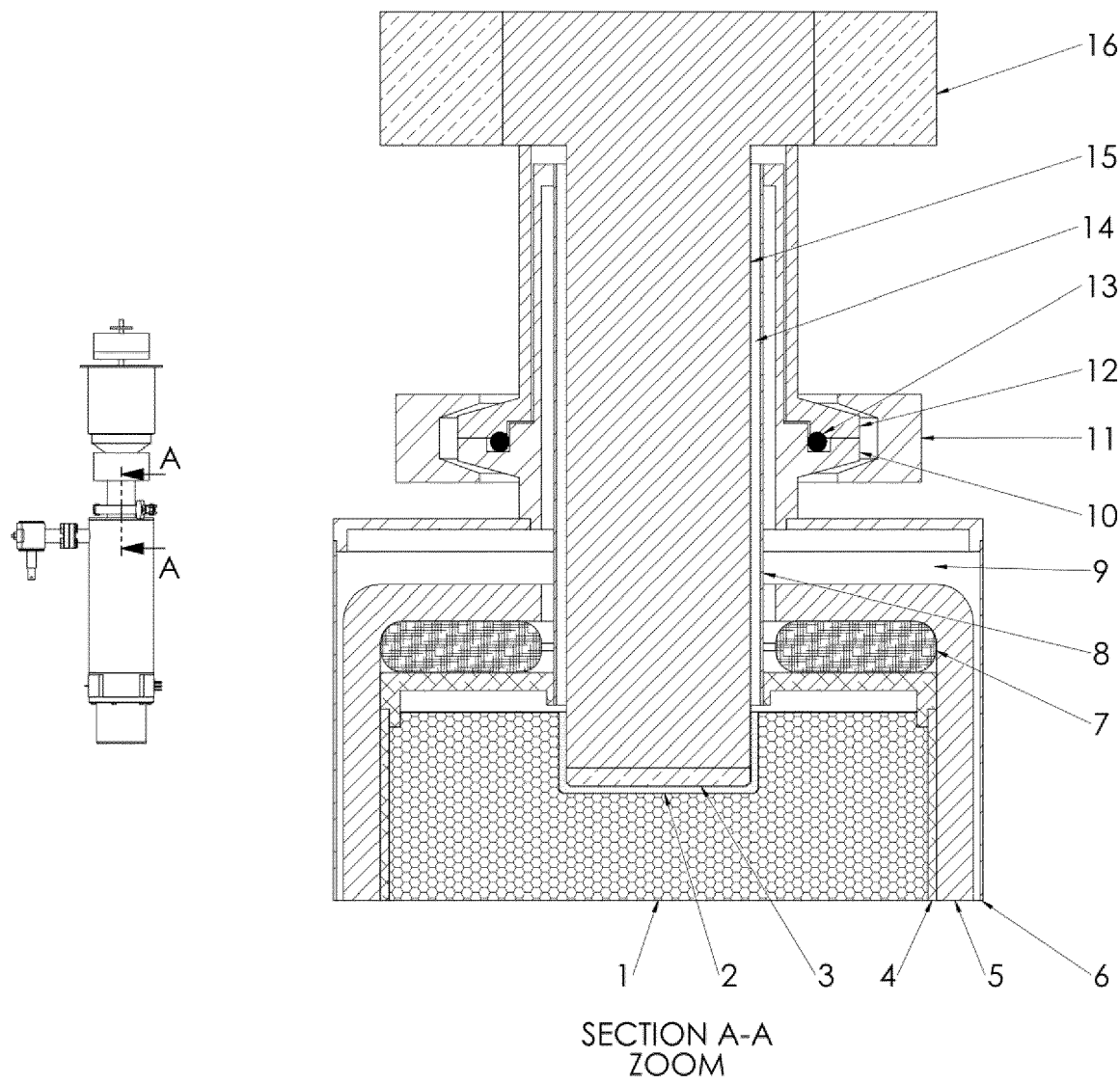


Fig. 14

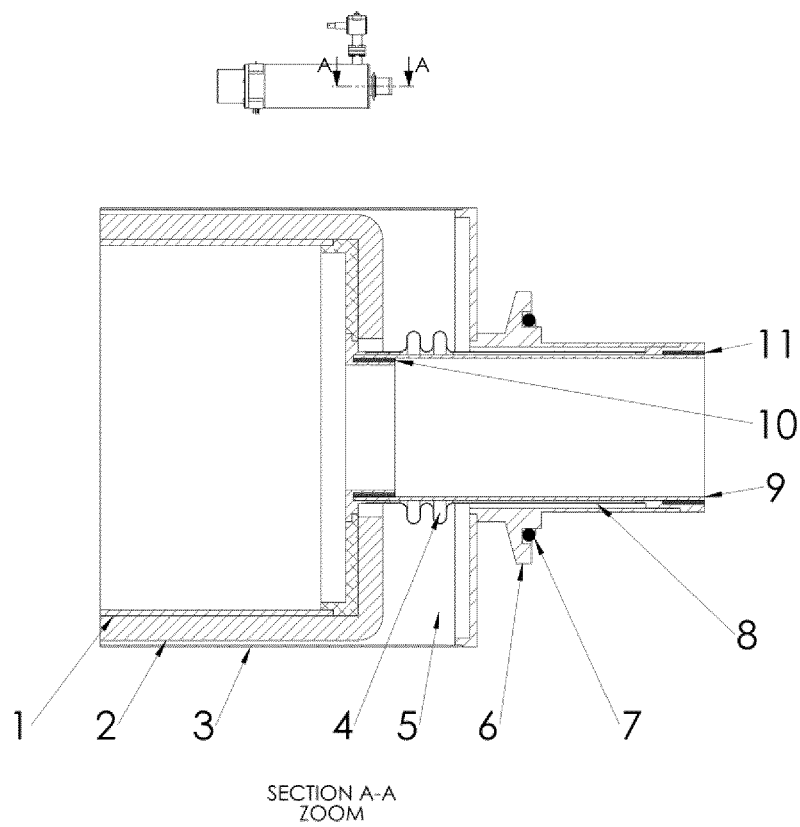


Fig. 15

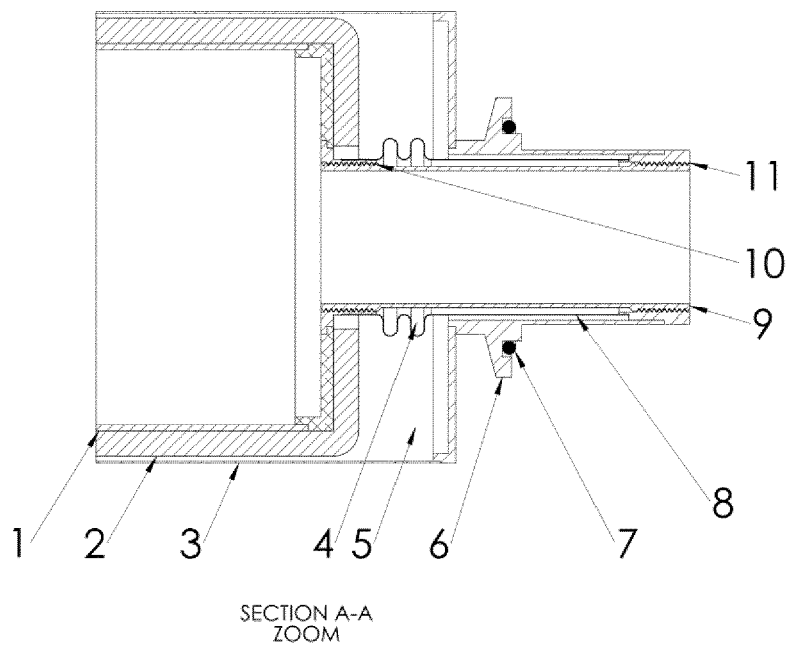


Fig. 16

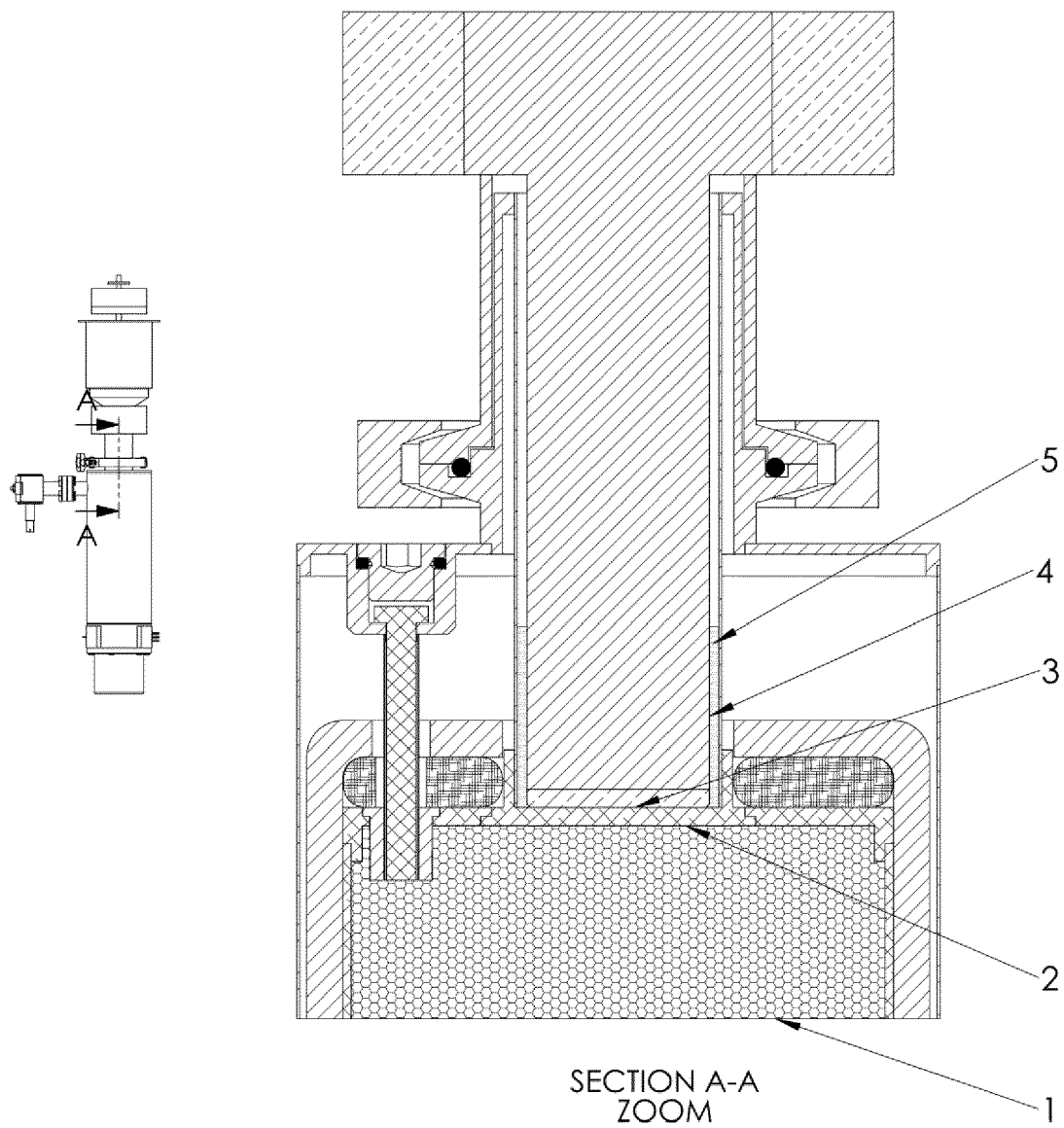


Fig. 17

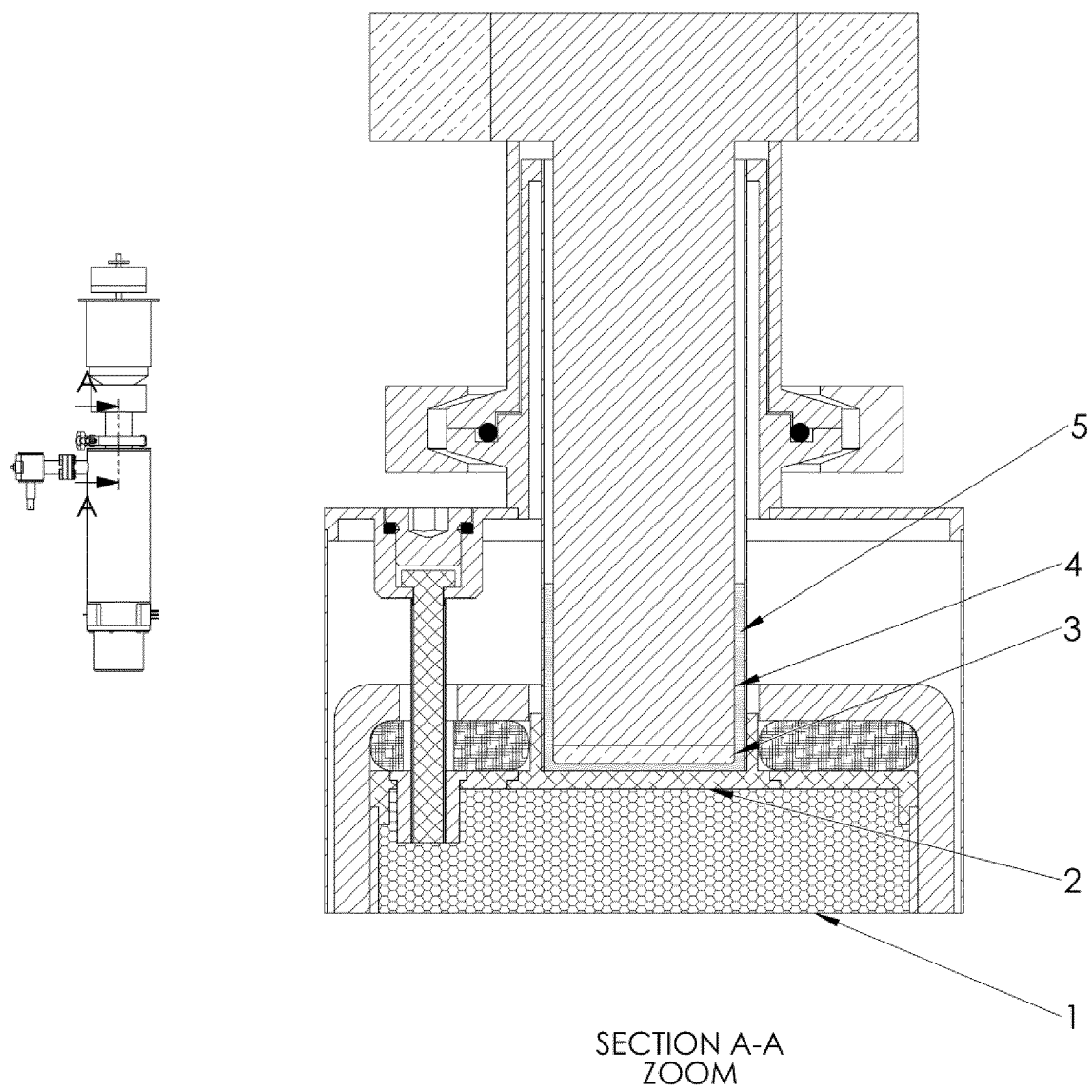


Fig. 18

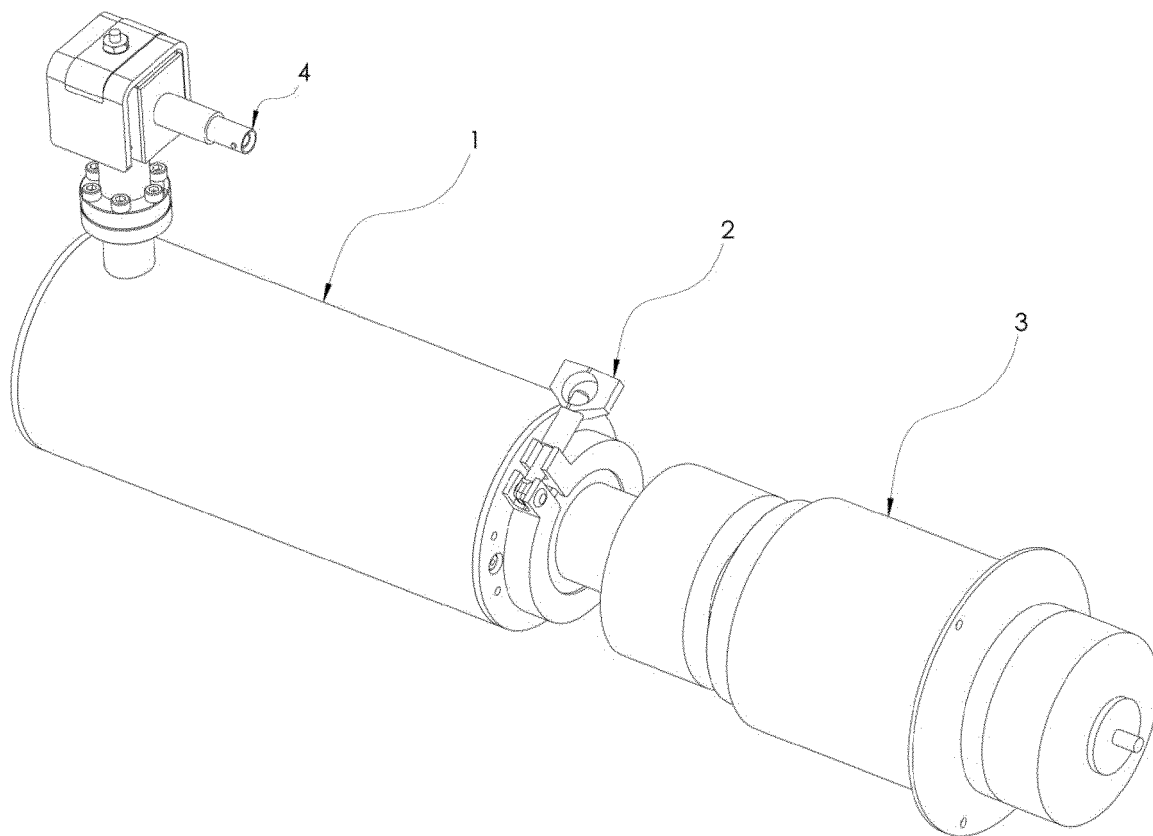


Fig. 19

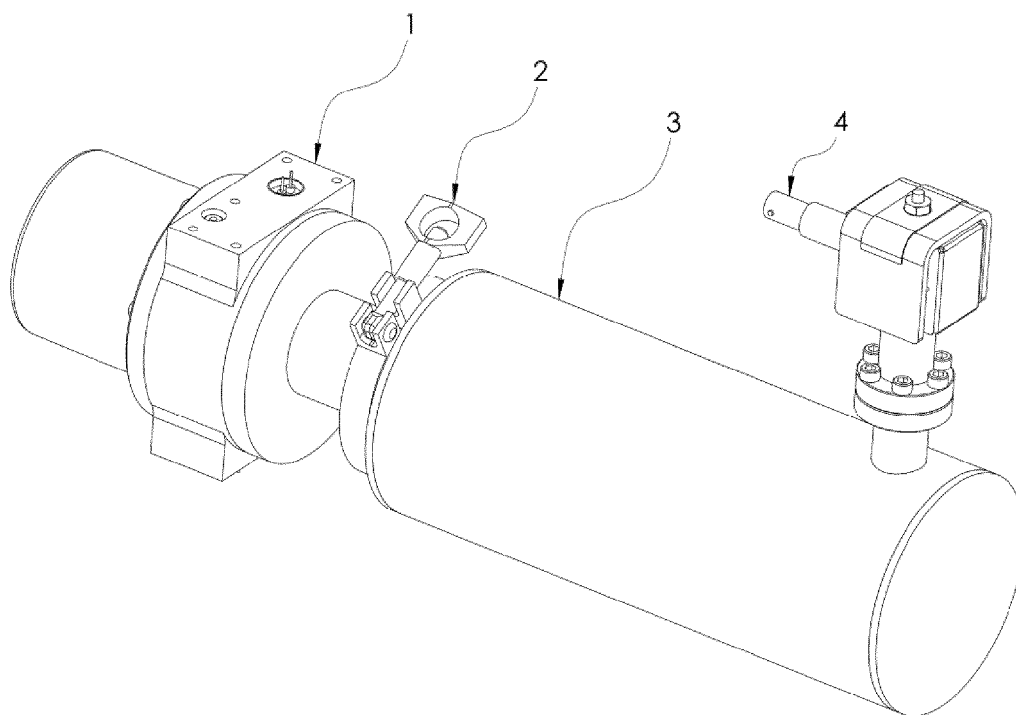


Fig. 20

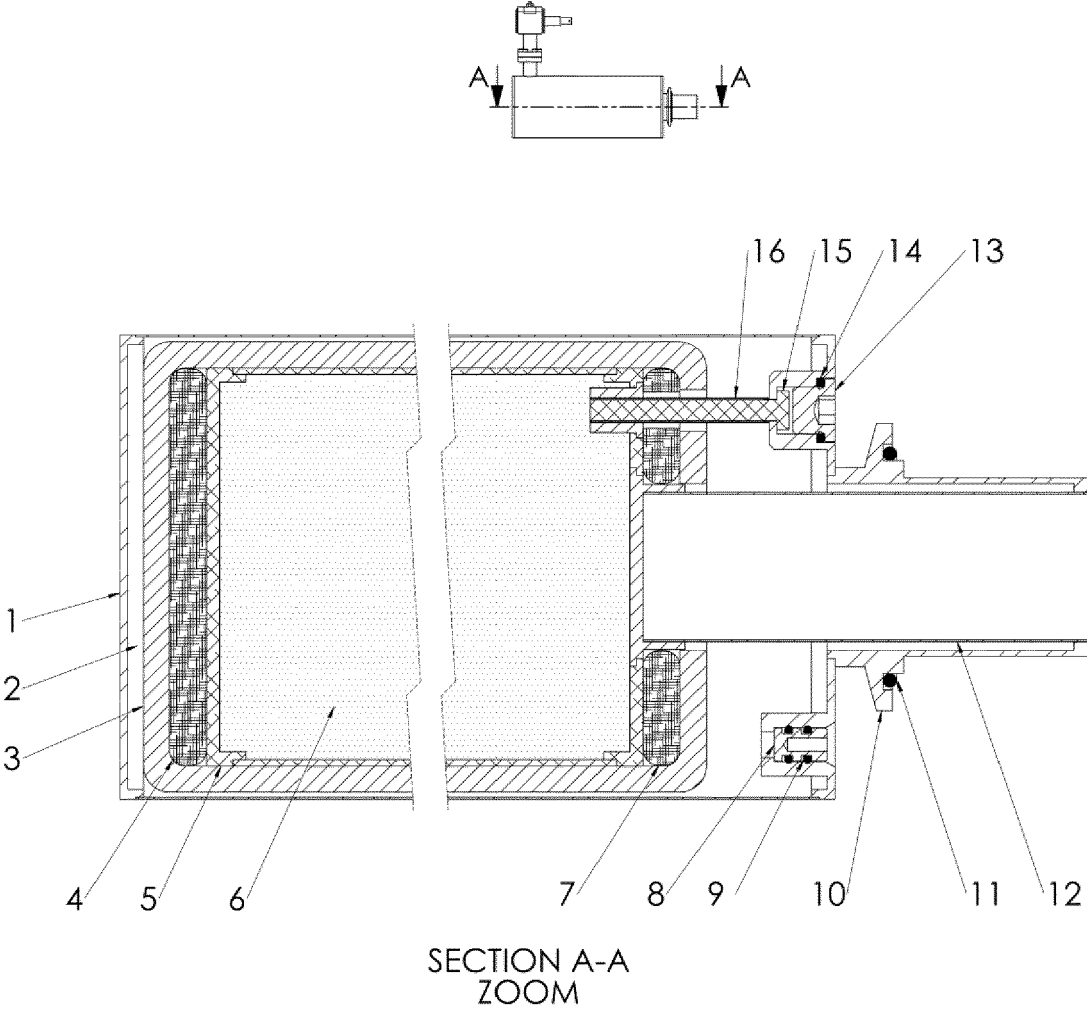


Fig. 21

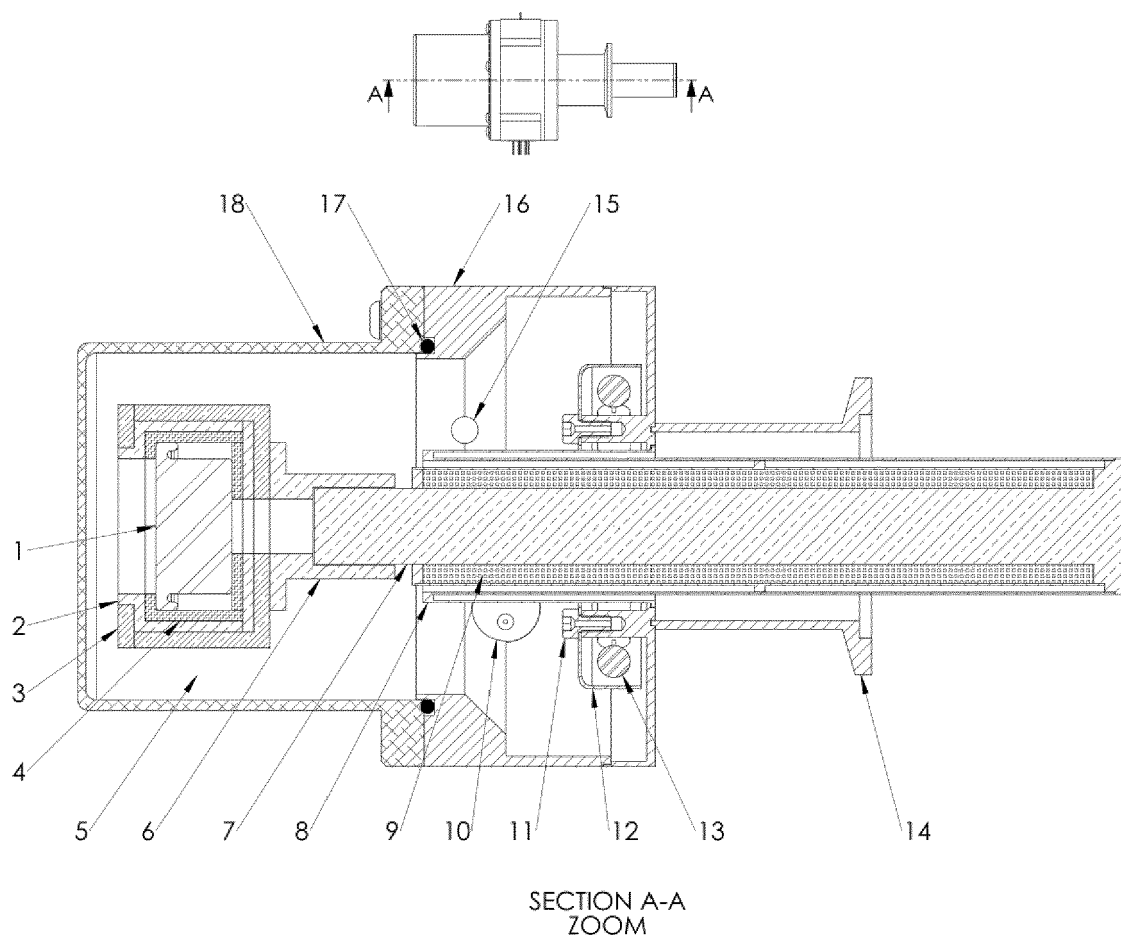


Fig. 22

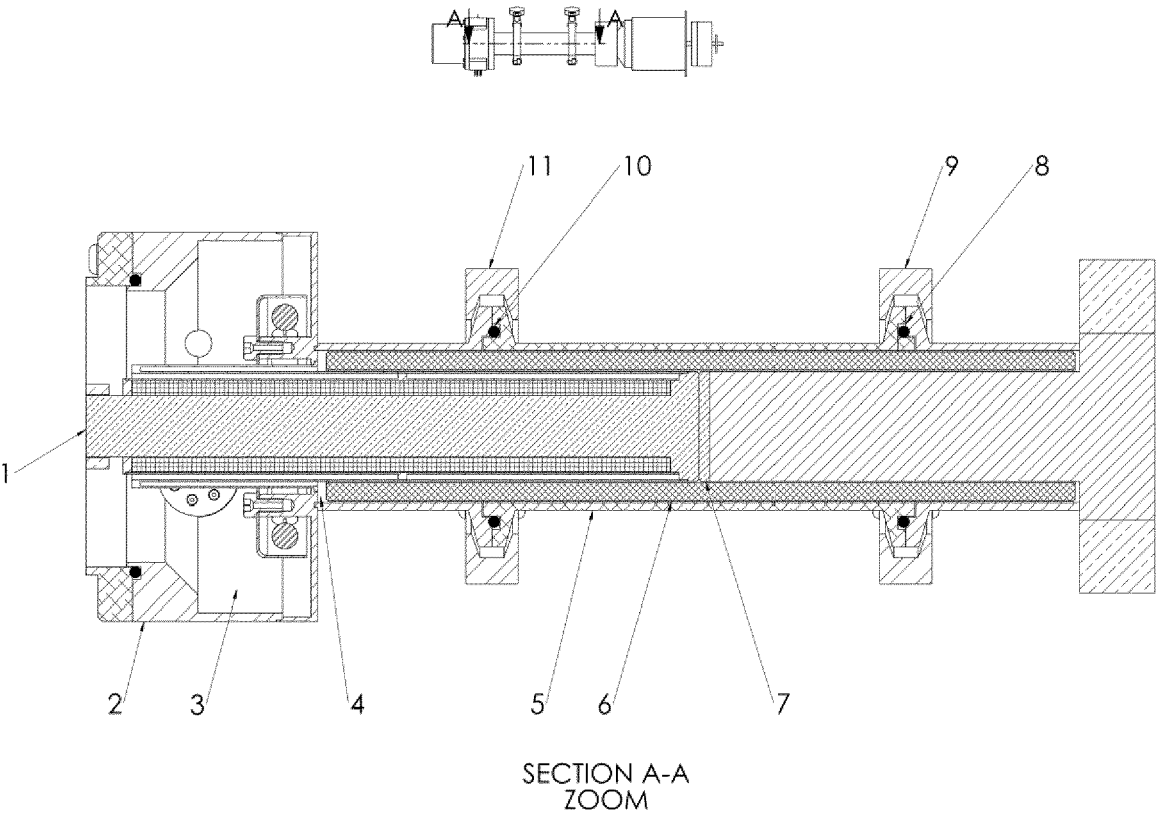


Fig. 23

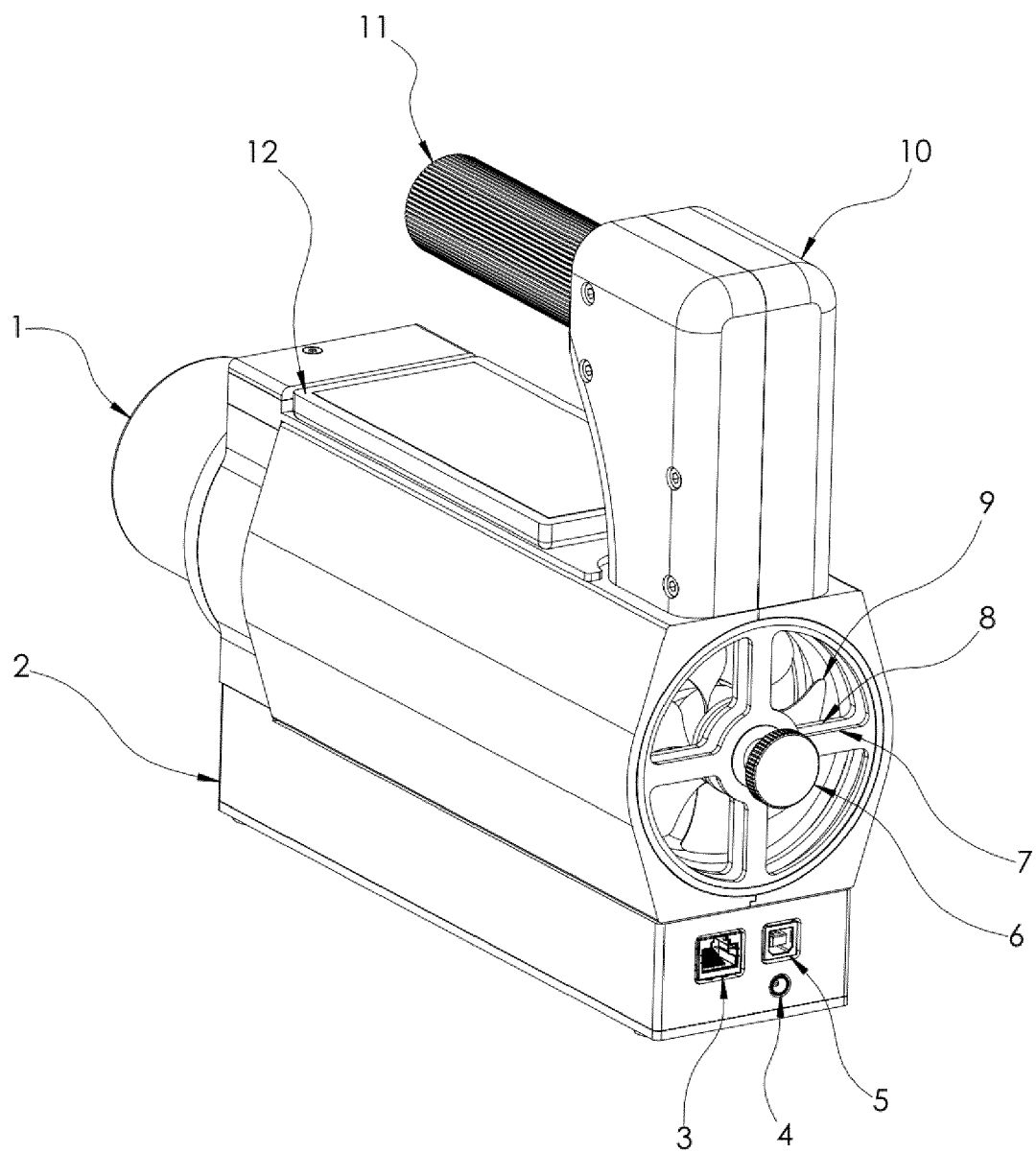


Fig. 24

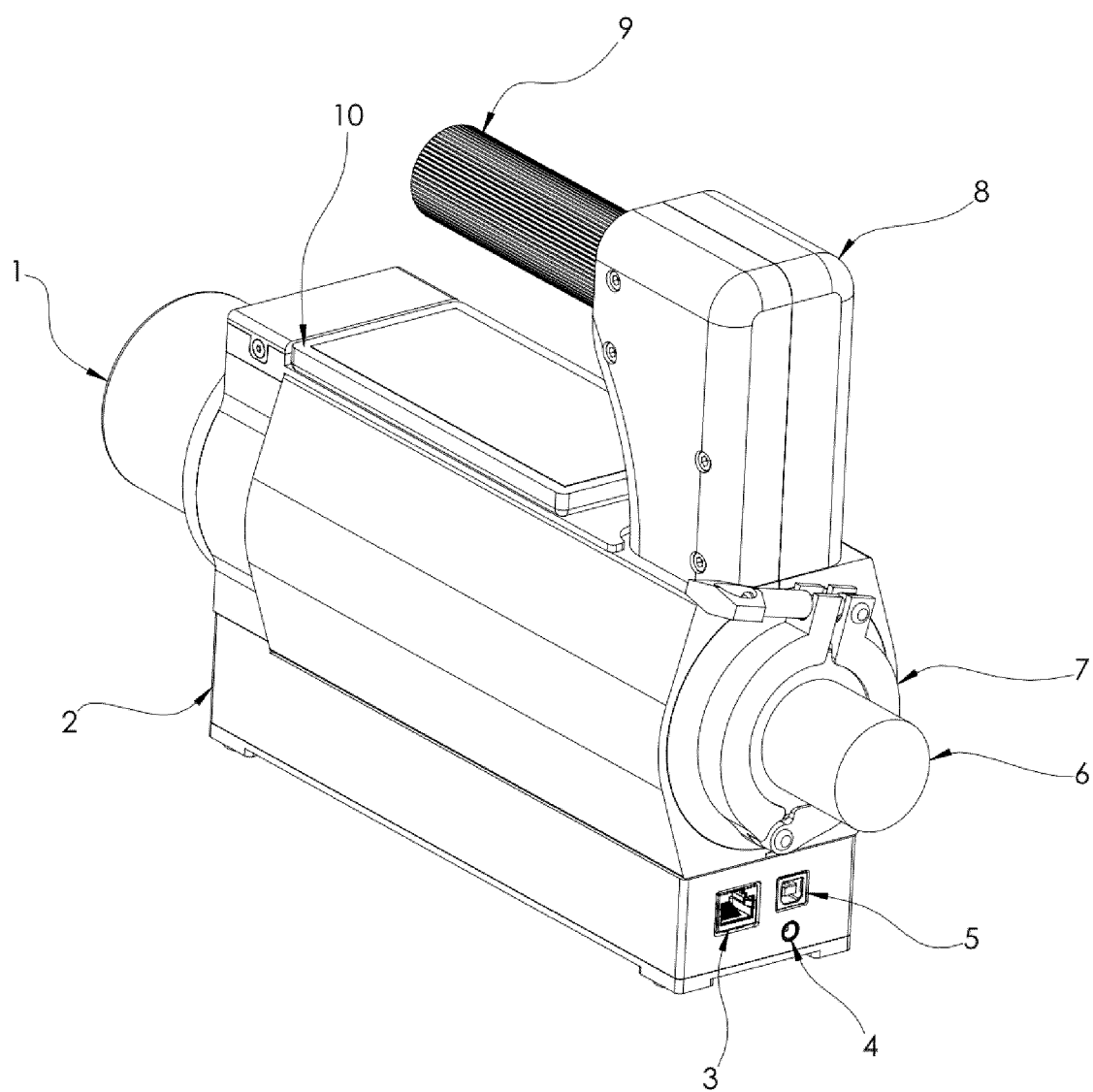


Fig. 25



EUROPEAN SEARCH REPORT

Application Number

EP 23 21 0784

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Y	* column 2, line 5 - line 48; figures 1, 2 *	2, 3	F25B9/00
Y	US 4 510 758 A (TENCH JR ORREN K [US]) 16 April 1985 (1985-04-16) * figure 4 *	2, 3	
X	BONFAIT G ET AL: "20K Energy storage unit", CRYOGENICS, ELSEVIER, KIDLINGTON, GB, vol. 49, no. 7, 1 July 2009 (2009-07-01), pages 326-333, XP026156393, ISSN: 0011-2275, DOI: 10.1016/J.CRYOGENICS.2009.03.003 [retrieved on 2009-03-20]	1	
A	* the whole document *	2-14	
A	WO 2006/010772 A1 (TARGET SYSTEMELECTRONIC GMBH [DE]; STEIN JUERGEN [DE] ET AL.) 2 February 2006 (2006-02-02) * the whole document *	1	TECHNICAL FIELDS SEARCHED (IPC) F25D F25B
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The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 18 March 2024	Examiner de Graaf, Jan Douwe
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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18-03-2024

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