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Caldwell

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[54] **PORTABLE LIFE SUPPORT SYSTEM**

[75] Inventor: **Bruce D. Caldwell**, Hitchcock, Tex.

[73] Assignee: **Oceaneering International, Inc.**, Houston, Tex.

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Appl. No.: **07/869,249**
Filed: **Apr. 15, 1992**

[51] **Int. Cl.**^{7} **F17C 9/04**
[52] **U.S. Cl.** **62/50.4**; 62/259.3; 62/50.2; 165/46
[58] **Field of Search** 62/259.3, 50.2, 62/50.4; 165/46

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Primary Examiner—Ronald Capossela
Attorney, Agent, or Firm—Kurt S. Myers

[57] **ABSTRACT**

The invention in its preferred embodiment is a portable life support system providing the wearer of a garment with temperature regulation and a breathable atmosphere using cryogenic technology. Wherein a liquid cryogen is vaporized by heat exchange with the wearers body and the vaporized cryogen is delivered to the wearer as a breathable atmosphere.

34 Claims, 6 Drawing Sheets

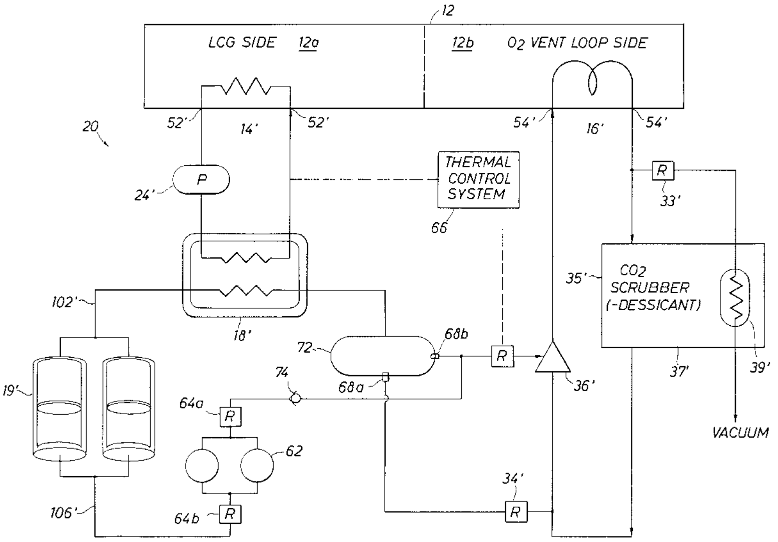

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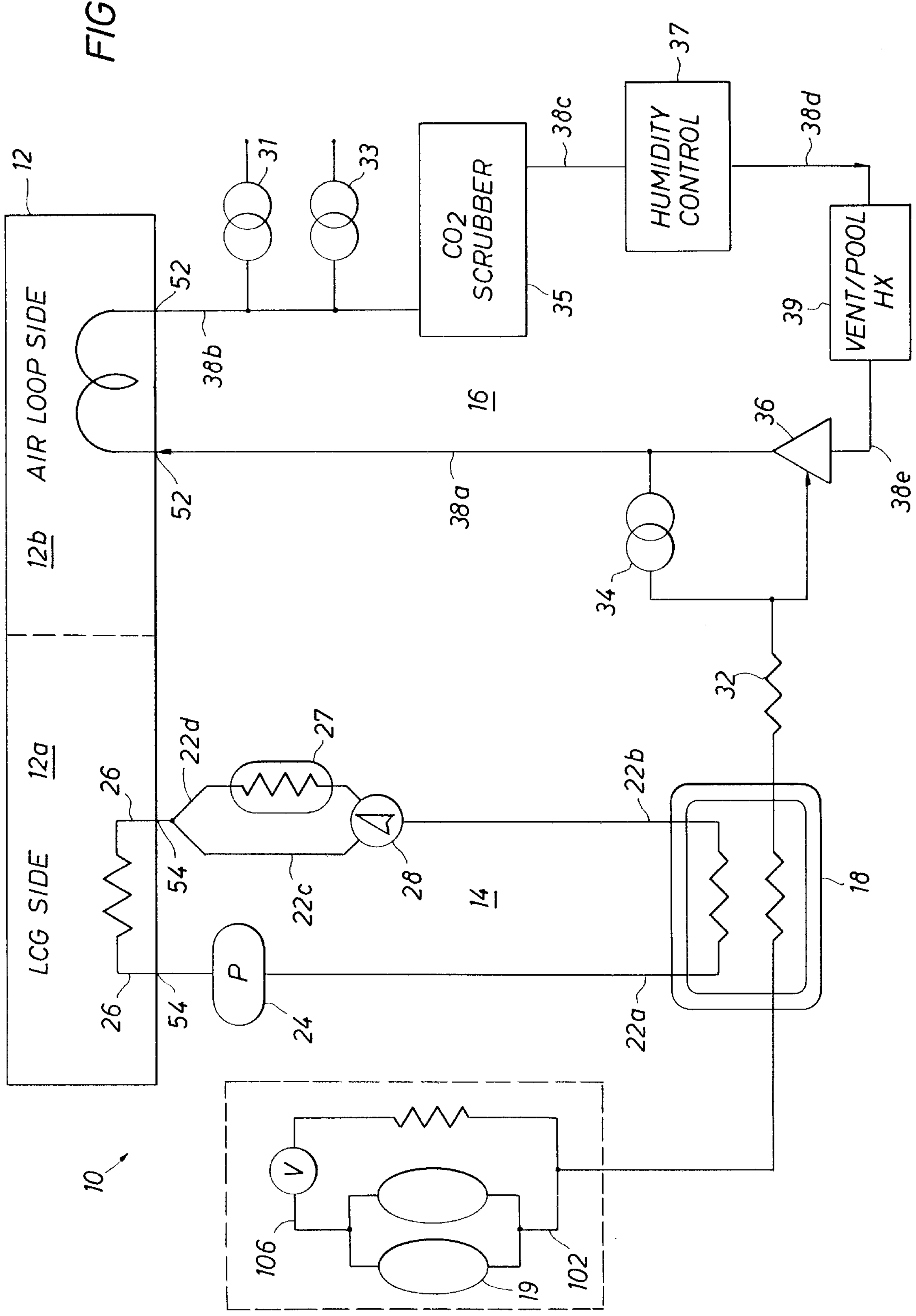
FIG. 1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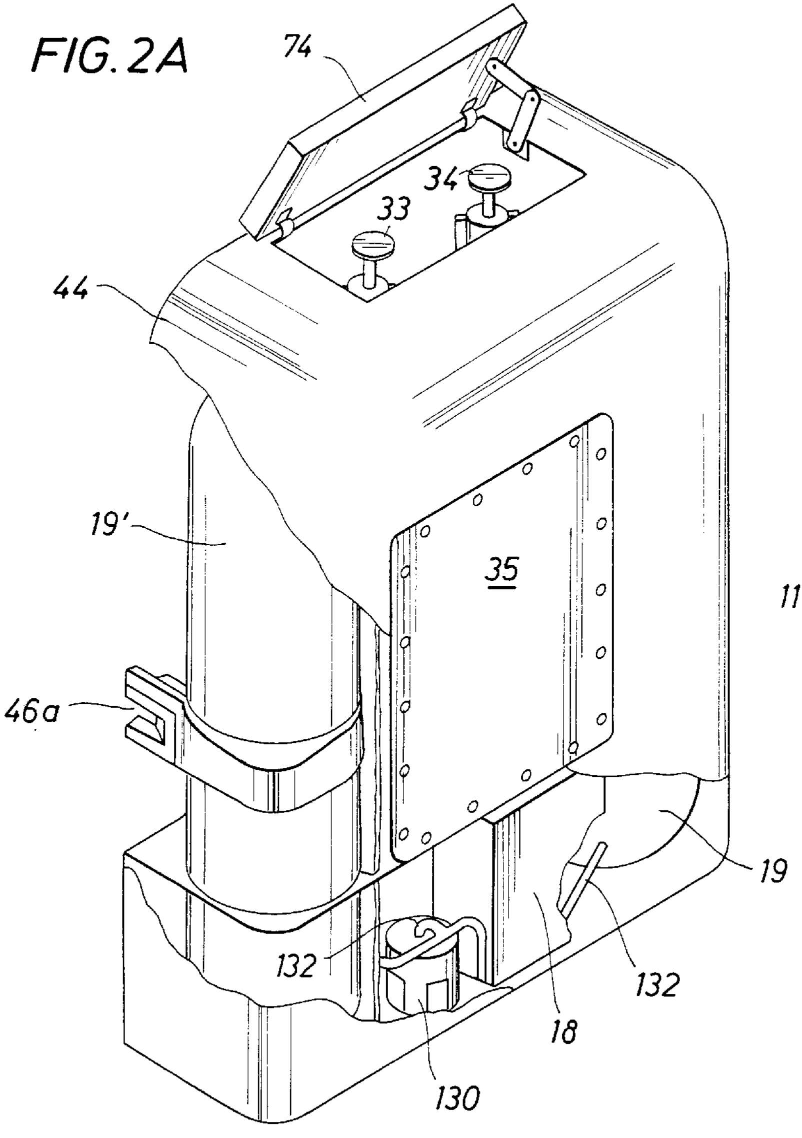
12
12a
12b
LCG SIDE
AIR LOOP SIDE
14
16
18
19
22a
22b
22c
22d
24
P
26
26
27
28
31
32
33
34
35
CO2 SCRUBBER
36
37
HUMIDITY CONTROL
38a
38b
38c
38d
38e
39
VENT/POOL HX
52
52
54
54
102
106
V

FIG. 2A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34
33
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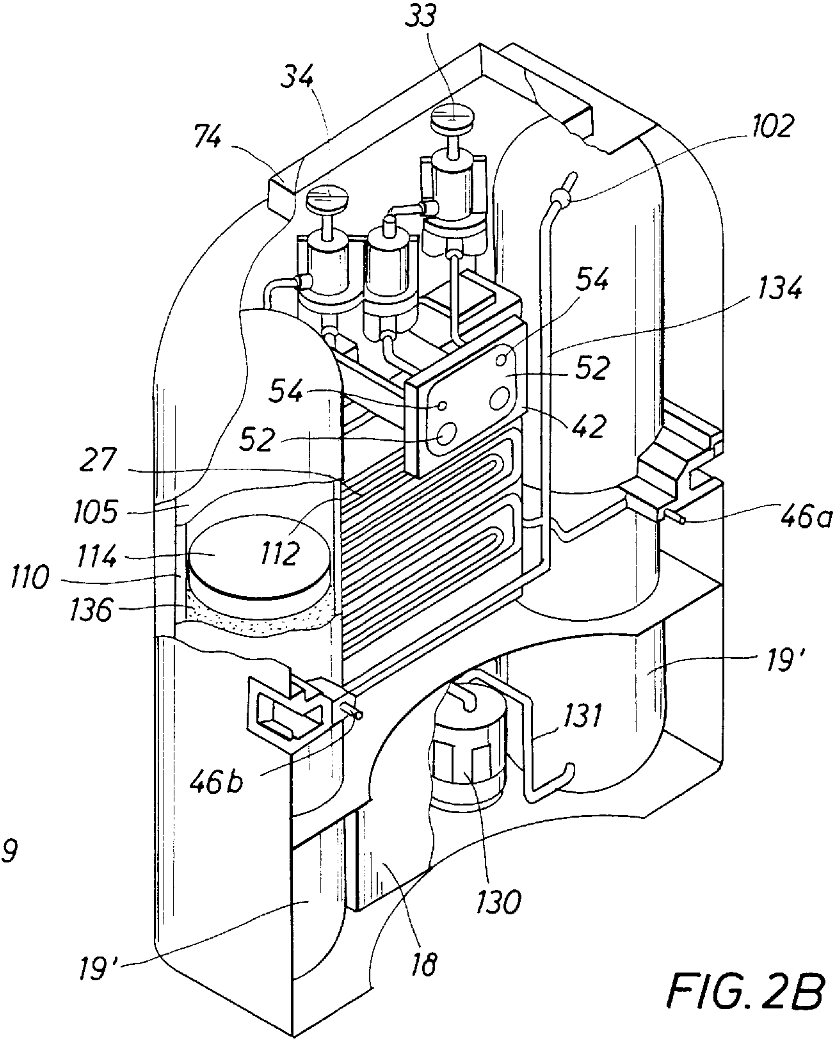
19'
35
46a
19
132
132
130
18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34
74
102
54
134
52
54
42
52
27
105
112
46a
114
110
136
19'
131
46b
130
19'
18

FIG. 2B

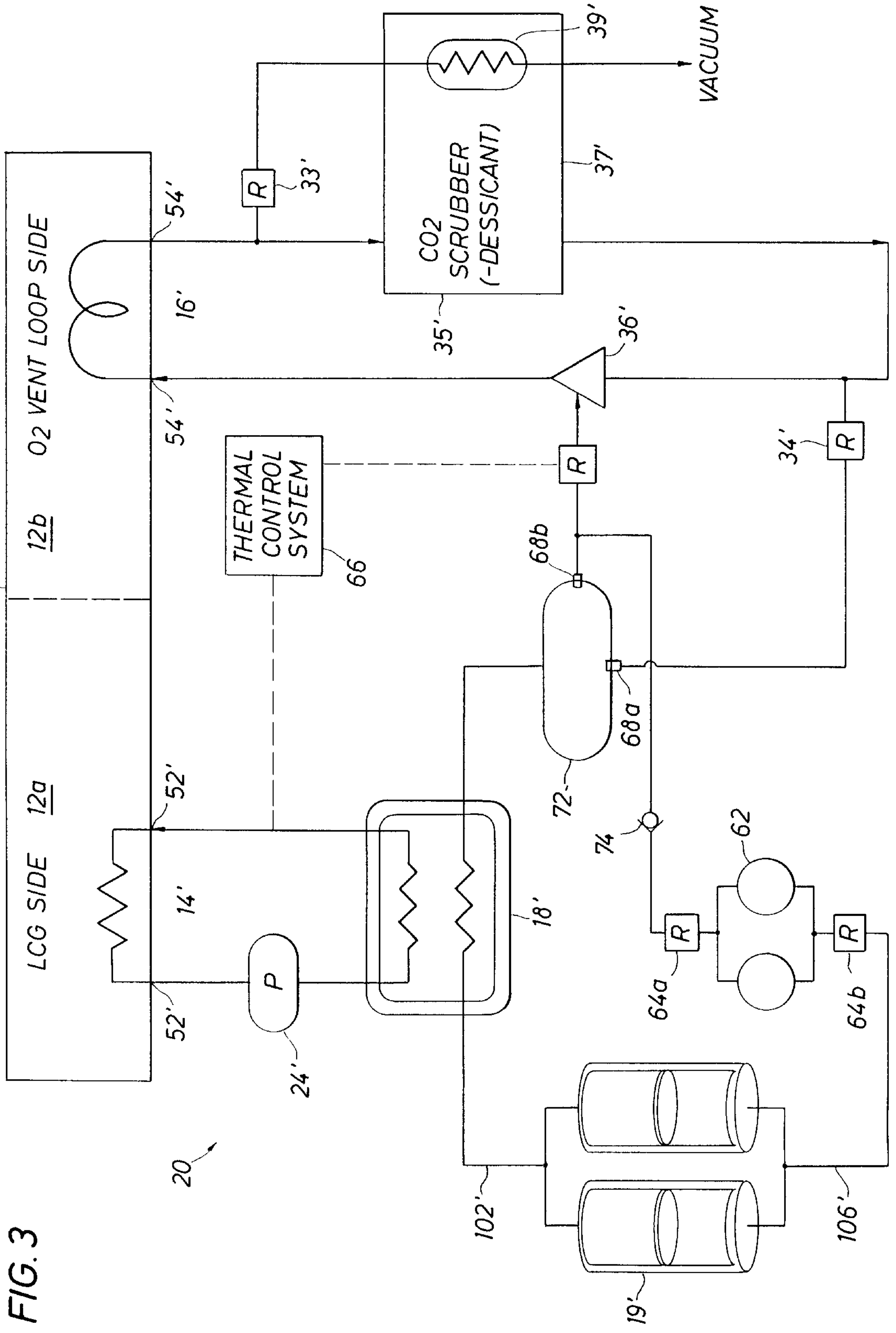
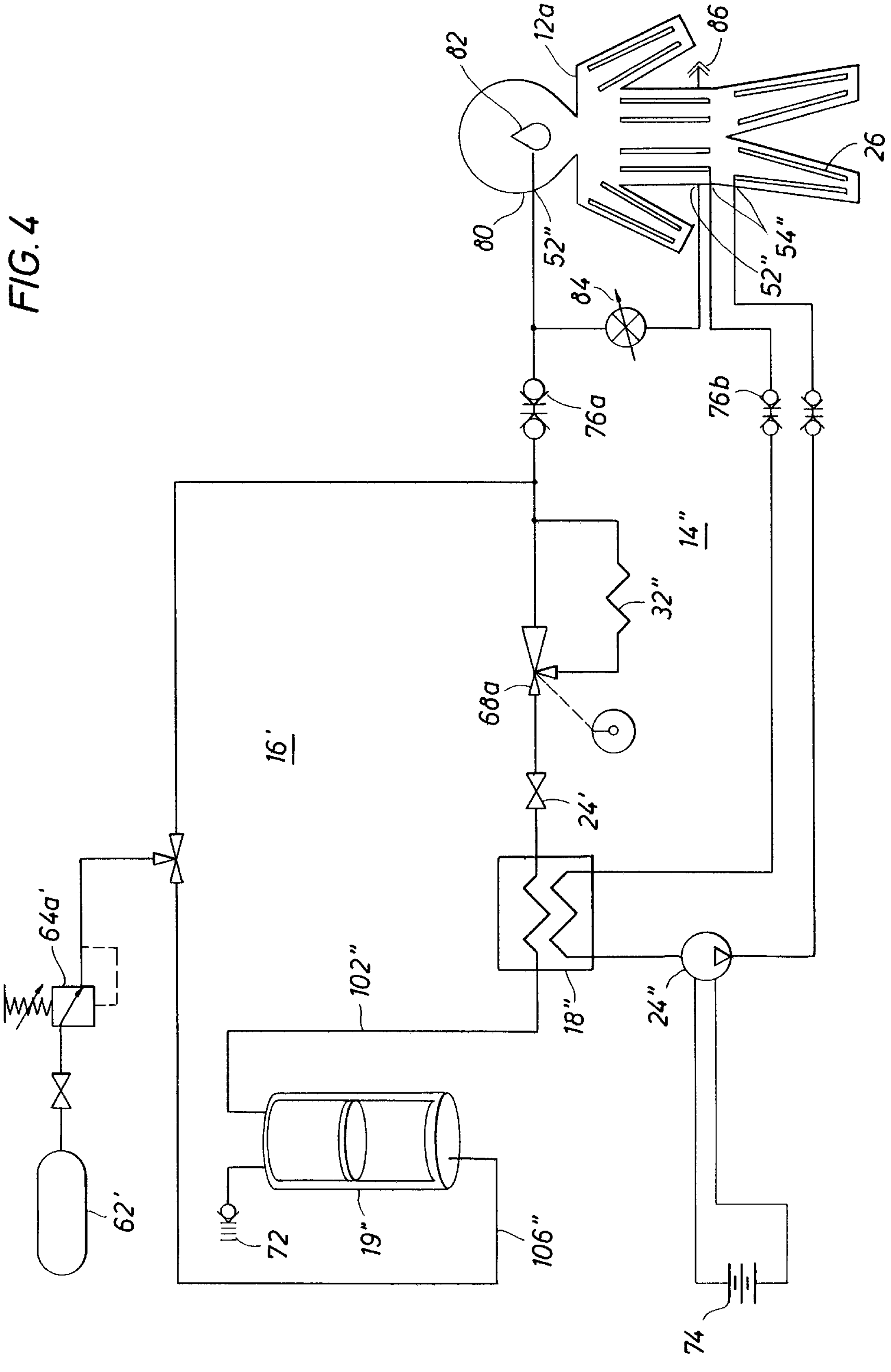

VACUUM
39'
R
33'
CO2
SCRUBBER
(-DESSICANT)
37'
35'
36'
54'
54'
16'
O2 VENT LOOP SIDE
12b
12
THERMAL
CONTROL
SYSTEM
66
R
34'
R
68b
68a
72
74
62
R
64a
R
64b
LCG SIDE
12a
52'
52'
14'
P
24'
18'
102'
106'
19'
20

FIG. 3

FIG. 4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12a
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52"
52"
54"
84
76a
76b
14"
32"
68a
16'
24'
64a'
102"
18"
24"
62'
72
19"
106"
74

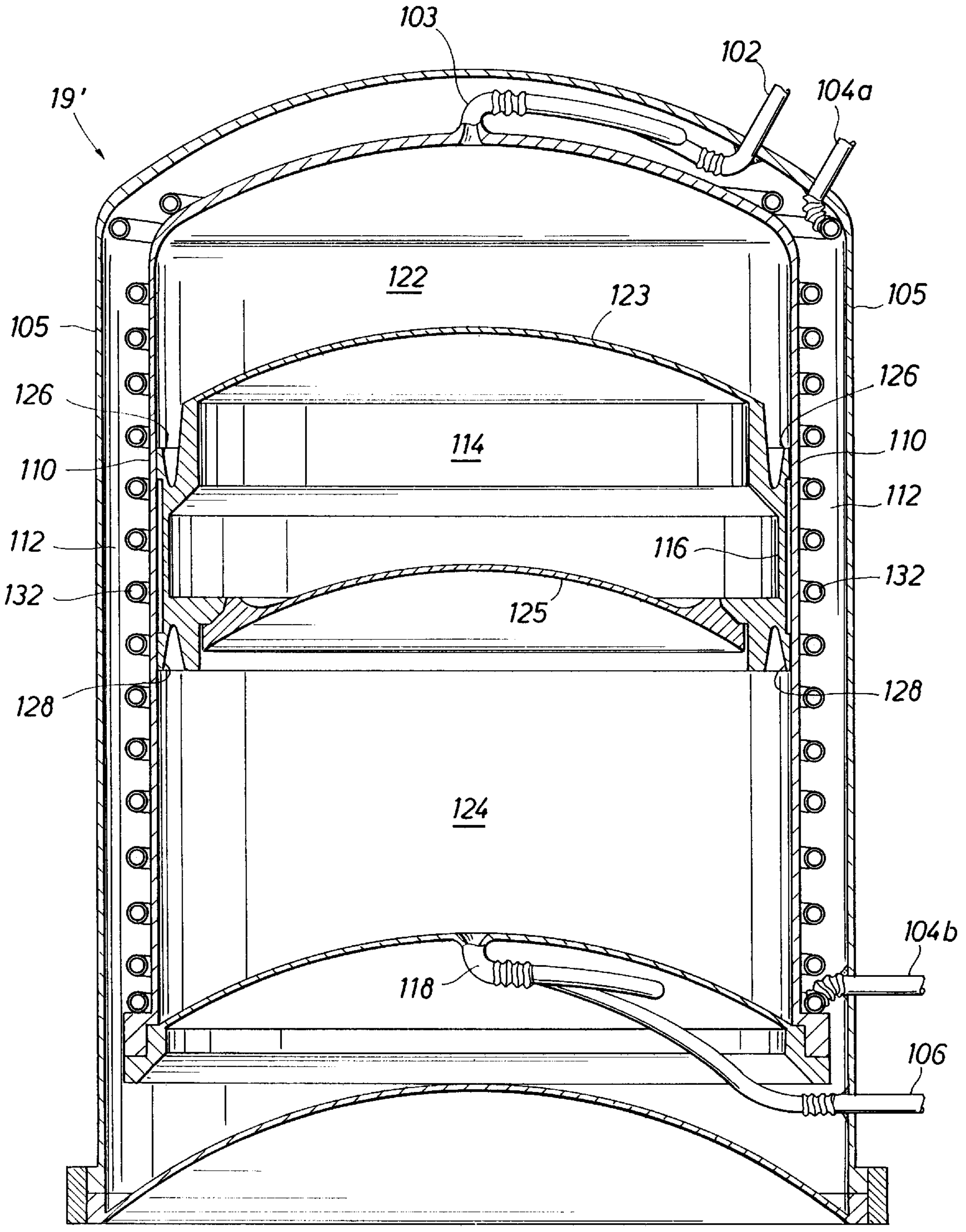
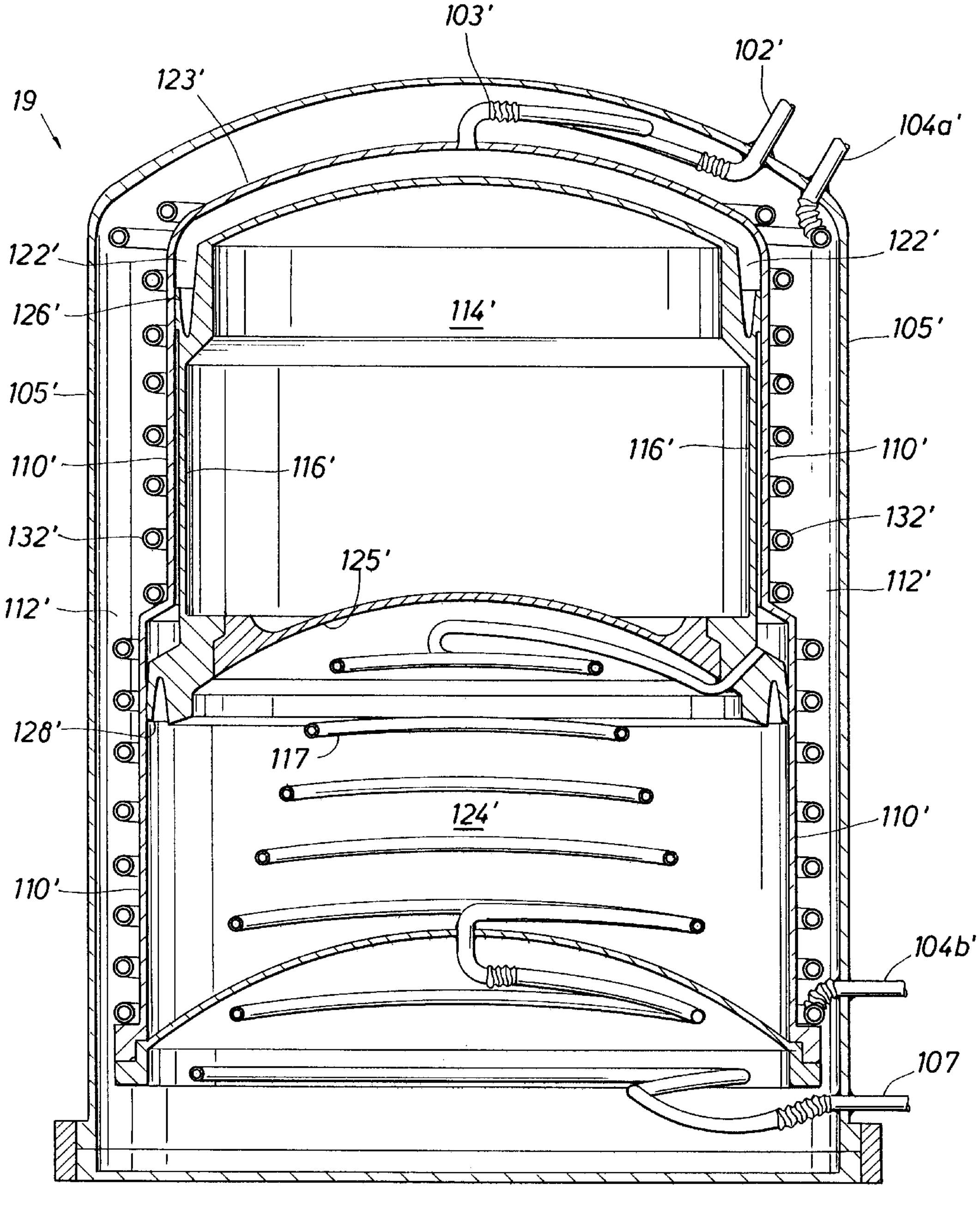

103
102
104a
19'
105
122
123
105
126
126
114
110
110
112
105
112
116
132
132
125
128
128
124
104b
118
106

FIG. 5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19
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105'
110'
116'
116'
110'
132'
132'
125'
112'
112'
128'
117
124'
110'
110'
104b'
107

FIG. 6

PORTABLE LIFE SUPPORT SYSTEM

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention pertains to a portable life support system and, more particularly, an improved portable life support system employing a liquid cryogen to provide temperature regulation and breathable atmosphere for the wearer of a garment or suit.

2. Description of the Prior Art

Portable life support systems are typically used in environments that are uninhabitable or otherwise hostile to humans. Examples of such environments include space, underwater, fire fighting, and hazardous materials handling. The two most critical requirements of a portable life support system, from an environmental control perspective, are providing body temperature regulation and a breathable atmosphere for the users.

Technical requirements for such systems vary widely and are constrained by activity type and performance level. However, generally desirable characteristics of personal portable life support systems include a weight that can be carried by a single person, a size that can be carried by a single person without undue loss of mobility, operation without the necessity for an umbilical, and a design that will not impair the dexterity of the user. Although these characteristics may vary depending on the environment, they are generally desirable and generally consistent.

Subsystems providing breathable atmosphere for portable life support systems are generally classed as either open circuit, semi-closed circuit, or closed circuit, depending on the proportion of atmosphere recirculated. In an open circuit subsystem, atmosphere is immediately vented from the system upon exhalation by the user whereas all atmosphere exhaled is recycled in a closed system. A semi-closed system falls somewhere in between, venting significant amounts of exhaled atmosphere but also recirculating large amounts.

Breathable atmosphere subsystems may also be grouped according to the type of breathing mechanism employed. The simplest type is the "free flow" system, wherein atmosphere is provided to the user at a continuous, relatively constant rate regardless of the level of activity. A "demand" system employs a demand regulator like those used with SCUBA equipment to provide breathable atmosphere only when the user inhales atmosphere, i.e., on demand. Demand systems can be employed orally or with a combined oral and nasal delivery.

The need for a hazardous material suit for liquid fuel handlers prompted efforts by the United States Army in this area by the early 1960's. These efforts were primarily directed at systems having separate subsystems dedicated to either body temperature regulation or breathing, but were eventually directed to the use of "liquid air" as a cryogenic fluid to provide both body temperature regulation and breathable atmosphere. The design incorporated a straight semi-closed circuit breathing system in which a breathable atmosphere was generated by vaporizing liquid air. The vaporization process provided minimal cooling and body temperature regulation was achieved through circulation and recirculation of vaporized cryogen through the user's suit.

A cryogenic fluid may be defined as a fluid which boils (i.e., changes state from liquid to gas) at temperatures less than approximately 110K at atmospheric pressure. Examples of the cryogen include both nitrogen and oxygen (the primary components of "liquid air") as well as hydrogen, helium and methane. As used herein, "cryogen" shall refer to a cryogenic fluid and "cryogenic technology" shall refer to knowledge, techniques, and equipment for harnessing the physical properties of cryogenic fluids to practical applications.

However, cryogenic technology in portable life support systems quickly encountered many technical constraints. Portable life support system technology furthermore diverged from the approach in the early Army studies to create two schools of thought as the technology matured. One school of thought continued to use cryogen for cooling and to generate breathable atmosphere. This approach is disclosed in U.S. Pat. No. 3,064,448 issued to P. E. Whittington, U.S. Pat. No. 3,117,426 issued to R. A. Fischer et al., U.S. Pat. No. 3,227,208 issued to V. L. Potter, Jr. et al., and U.S. Pat. No. 2,990,695 issued to D. A. Leffingwell, Jr.

The divergent school of thought was prompted by efforts to achieve breakthroughs in efficiency and began by separating the body temperature regulation and breathing subsystems. Examples of this school of thought are found in U.S. Pat. No. 4,172,454 issued to Warnecke et al., and U.S. Pat. Nos. 4,286,439 and 4,459,822 issued to Pasternack. The separation of temperature regulation and breathing subsystems removed technical constraints to permit use of more effective and more dangerous coolants that were not cryogenic fluids. As noted in the '454 Warnecke et al. patent, some in the art switched to solid coolants such as dry ice instead of cryogenic fluids.

One of the primary difficulties that led to the divergence of thought was that the early applications of cryogenic technology could not produce high efficiencies in terms of adequate and controllable body cooling and duration per unit weight. We have discovered that the source of this problem was ineffective heat exchange. Cooling was primarily provided by heat exchange between circulating air and the user's body i.e., in a gas phase loop. Our invention takes advantage of the fact that heat exchange in a liquid phase loop is far superior to heat exchange in a gas phase loop. This superiority arises from a number of factors, foremost of which is greater control over the heat exchange process.

A second difficulty that still plagues cryogenic life support systems arises from the reliance of such systems on user orientation relative to the field of gravity. Breathable atmosphere subsystems employing air under pressure, such as SCUBA, are "orientationally independent" because the gas under pressure will expand through its natural properties to provide constant supply to the user. However, liquids perform fundamentally differently and require a motive force for delivery to the point of heat exchange where they vaporize. Virtually all cryogenic systems known heretofore employ gravity by storing the liquid cryogen relative to the point of heat exchange and current "orientationally independent" delivery systems are inefficient and costly.

The current systems deliver the dewar contents by separating the vaporized cryogen in the dewar, which is then pressurized, and the liquid cryogen, which is expelled by the force exerted by pressurized vaporized cryogen in the dewar. The separation results from the differing effects of gravity on the liquid cryogen and the vaporized cryogen and operates to separate them. An intake port in the dewar is submerged by the separated liquid cryogen which is then delivered by the further effects of gravity. Relying on gravity therefore causes a marked decrease in performance because whenever the system user affects the orientation of the delivery with respect to the gravitational field, the dewar contents lose pressurization and delivery becomes less effective as the vaporized cryogen is rapidly vented through the intake port which is no longer submerged in the liquid cryogen.

The problem is compounded in space where there is only negligible gravity regardless of orientation. Most systems in space therefore use "liquid acquisition devices" which employ an extremely fine mesh to separate the gas and liquid phases. However, the mesh is extremely fine and consequently very sensitive to manufacturing tolerances and very expensive. Also, liquid acquisition devices must be "tuned" to the particular cryogen in use and so are not readily adaptable to a wide variety of cryogens. There consequently also is some debate as to whether liquid acquisition devices are efficiently operable with cryogenic mixtures comprising two or more cryogens having separately identifiable physical properties.

Thus, the inability to achieve effective heat transfer and to develop a satisfactory orientationally independent delivery caused some in the art to abandon cryogenic technology or to adopt undesirable but necessary alternatives. These shortcomings affected both primary functions of the system and resulted in the functional division of the system as first proposed in the 1960's into separate, functionally dedicated, subsystems. This, in turn, led to the return of compressed gas for breathable atmospheres and dangerous liquid coolants, and even solid coolants, for temperature regulation.

It is therefore an object of this invention to overcome these problems with portable life support system employing cryogenic technology that effectively combines body temperature regulation and delivery of a breathable atmosphere.

It is furthermore an object of this invention that, in various embodiments, the system employs breathable atmosphere subsystems in open circuit, semi-closed circuit, and closed circuit configurations with either straight or demand supply via either oral or combination oral/nasal regulators.

It is a still further object of this invention to provide a system which employs orientationally independent delivery of liquid cryogen from storage to the point of heat exchange.

SUMMARY OF THE INVENTION

The invention in its preferred embodiment is a portable life support system providing temperature regulation and a breathable atmosphere using cryogenic technology. The invention comprises a liquid cooled garment, a source of liquid cryogen, a means for circulating the liquid cryogen from the source in heat exchange relation with the liquid of the garment to vaporize the liquid cryogen and cool the wearer of the garment, and a means for delivering the vaporized cryogen to the wearer for breathing.

BRIEF DESCRIPTION OF THE DRAWINGS

A more particular description of the invention briefly summarized above can be had by reference of the exemplary preferred embodiments illustrated in the drawings of this specification so that the manner in which the above cited features, as well as others that will become apparent, are obtained and can be understood in detail. The drawings nevertheless illustrate only typical, preferred embodiments of the invention and are not to be considered limiting of its scope as the invention will admit to other equally effective embodiments.

In the drawings:

FIG. **1** is a schematic illustration of an embodiment of a portable life support system constructed in accordance with the present invention which employs a semi-closed circuit breathing loop;

FIGS. **2**A and **2**B are cutaway, perspective illustrations of a part of a portable life support system that is worn on the back of the user in accordance with the present invention such as the system of FIG. **1** and how it interfaces with the rest of the embodiment comprising the garment and those elements not worn on the back;

FIG. **3** is a functional schematic illustration of a second, alternative embodiment of a system which also employs a semi-closed circuit breathing loop;

FIG. **4** is a schematic illustration of a third embodiment of the invention which employs an open circuit, demand breathing loop;

FIG. **5** is an illustration of one embodiment of a positive expulsion dewar having a gas charged piston mechanism as may be employed in the systems of FIGS. **1**–**4**; and

FIG. **6** is an illustration of another embodiment of a positive expulsion dewar having a piston mechanism as may be employed in the systems of FIGS. **1**–**4**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The system of FIG. **1**, generally denoted **10**, is a portable life support system for use in underwater environments wherein cooling is required, including, but not limited to, warm water diving such as in heated pools, power plant cooling water, nuclear reactor contaminant vessels, or shallow tropical waters. Operations in underwater environments must account for increased pressures (relative to atmospheric pressure) and so system **10** compensates for pressure fluctuations as described below.

Portable life support system **10** is generally comprised of garment **12**, cooling loop **14**, breathing loop **16**, heat exchanger **18**, and dewars **19**. As best illustrated in FIG. **4**, garment **12** in the preferred embodiment is worn by the user inside suit **80** which isolates the user from the surrounding environment. However, the functions of garment **12** and suit **80** may be combined in some embodiments. Heat exchanger **18** and dewars **19** technically can be considered as a part of both cooling loop **14** and breathing loop **16** since their functions are required by both, but are treated separately to facilitate discussion of the operation of system **10** as a whole. Suit pressurization regulator **34**, overpressure relief regulator **31**, and back-pressure regulator **33** provide pressure regulation to maintain suit pressure of suit **80** equal to or at a constant pressure differential over ambient pressure within system **10** in response to pressure fluctuations in the environment in a manner well known to the art.

In operation, dewars **19** store liquid cryogen and deliver the liquid cryogen to heat exchanger **18**. In the preferred embodiment the liquid cryogen is "liquid air", essentially liquid oxygen diluted with liquid nitrogen, but other cryogens may be acceptable depending on the application. Cooling loop **14** is a closed, cooled liquid loop, the cooled liquid of which absorbs the heat from the wearer's body and transfers the absorbed heat to the liquid cryogen delivered by dewars **19** to heat exchanger **18**. The liquid cryogen vaporizes and the vaporized cryogen is warmed (as explained below) as the heat is transferred from the cooled liquid. The warmed vaporized cryogen is then delivered to the user as breathable atmosphere via breathing loop **16**.

Body temperature regulation for the wearer of garment **12** is provided via temperature control of the cooled liquid circulated through cooling loop **14**. As best shown in FIG. **4**, garment **12** is comprised of liquid cooled garment **12** and an outer protective garment, referred to as a "suit" **80** which provides environmental isolation for the wearer of garment **12**, both as are commonly, known in the art. As such, garment **12** has a number of "tubes" sewn into it that comprise a series of arteries to conduct a cooled liquid, such as water, in a predetermined pattern over the body of the person wearing the garment.

These "tubes" are functionally represented as garment line **26** in FIG. **1** and are best shown in FIG. **4**. The cooled liquid absorbs the heat of the wearer's body as it courses through the tubes, thereby warming the liquid and cooling the wearer through heat exchange. The tube suit which comprises garment **12** is merely one means by which a conduction convection heat exchange relationship with the body of the wearer of the garment and other means may be equally acceptable.

Cooling loop **14** comprises insulated lines **22***a–c,* water pump **24**, garment line **26**, auxiliary heat exchanger **27**, and proportional diverter valve **28**. Water pump **24** provides the motive force that pumps the cooled liquid throughout cooling loop **14**. Temperature control for the water in cooling loop **14** is provided by the operation of auxiliary heat exchanger **27** and proportional diverter valve **28** in response to fluctuations in cooled liquid temperature caused by the heat exchange process in garment line **26** and heat exchanger **18**.

If the cooled liquid temperature is too low for user comfort, the proportional diverter valve **28** senses this condition and automatically diverts some of the cooled liquid through auxiliary heat exchanger **27**. In the embodiment of FIG. **1**, auxiliary heat exchanger **27** exposes the cooled liquid to the heat of the water in which the user is diving to warm the cooled water. The diverted liquid is then returned to the undiverted liquid to raise the average temperature of the cooled liquid as a whole. However, this feature may not be necessary in all embodiments as is illustrated by system **20** in FIG. **3** and system **40** in FIG. **4**.

Proportional diverter valve **28** likewise reduces the amount of cooled liquid diverted through auxiliary heat exchanger **27** when the average temperature of the cooled liquid as a whole is too high in order to reduce the temperature. The desired average temperature of the cooled liquid may vary depending upon factors such as the anticipated level of activity and the temperature of the water in which the user is diving, but should generally be at least less than the standard 91° F. skin temperature of the human body and preferably 55°–80° F.

Breathing loop **16** comprises excess cryogen vaporizer **32**, suit pressurization regulator **34**, ejector **36**, lines **38***a–e,* overpressure relief regulator **31**, backpressure regulator **33**, carbon dioxide scrubber **35**, humidity control **37**, and auxiliary heat exchanger **39**. Excess cryogen vaporizer **32** performs two vial safety functions. First not all of the liquid cryogen delivered by dewars **19** to heat exchanger **11** is necessarily vaporized, especially if cooling loop **14** malfunctions, and so vaporizer **32** ensures that no liquid cryogen enters the breathing loop to harm the user. Second, vaporized cryogen can be as cool as −300° F. so vaporizer **32** warms the vaporized cryogen to a breathable temperature. Once all liquid cryogen is vaporized and warmed, it is introduced to breathing loop **16** via alternative paths through suit pressurization regulator **34** and ejector **36**.

Breathing loop **16** of system **10** is a semi-closed circuit and so significant amounts of exhaled atmosphere are vented and significant amounts are recycled. Ejector **36** provides the motive force for recycling the vaporized cryogen in a manner well known to those of ordinary skill in the art through momentum transfer of a high velocity gas jet without moving parts. Carbon dioxide scrubber **35** removes carbon dioxide and humidity control **37** removes moisture introduced to the exhaled atmosphere by the metabolic processes of the user.

Suit pressurization regulator **34**, overpressure regulator **31** and backpressure regulator **33** operate in conjunction to control the relative pressure in the suit in response to fluctuations in the operating environment's absolute pressure in a manner well known to those in the art. Pressure regulation is generally necessary if the suit pressure is to be maintained at a pressure differential above ambient and/or the external pressure is variable. This configuration is relevant for external pressures above atmospheric pressure, as in underwater, at atmospheric pressures where a small positive pressure prevents contamination, as in hazardous materials handling, or below atmospheric pressures as in space.

Auxiliary heat exchanger **39** provides some temperature regulation by selectively exposing the circulating atmosphere, in thus embodiment, to the temperature of the water in which the user is diving for removing heat from exothermic carbon dioxide and water absorption. Thus, the primary purpose of auxiliary heat exchanger **39** is to dump heat from the vaporized cryogen introduced into breathing loop **14** by scrubber **35** and humidity control **37**. Auxiliary heat exchanger **39** may therefore be omitted in some embodiments where there is no need to dump such heat.

Ejector **36**, carbon dioxide scrubber **35**, suit pressurization regulator **34**, overpressure regulator **31**, and backpressure regulator **33** may each be any one of several known and commonly available to those in the art. None of the common alternatives for these components is particularly preferred over the others. Humidity control **37**, however, is generally preferred to be a desiccant bed for underwater applications as is commonly known and available to those in the art, although other forms of humidity control may be acceptable or even desirable in other embodiments. Furthermore, ejector **36**, carbon dioxide scrubber **35**, humidity control **37**, and auxiliary heat exchanger **39** are not required for embodiments employing open circuit breathing loops as illustrated in FIG. **4** instead of semi-closed circuit breathing loops.

FIGS. **2**A and **2**B are graphical illustrations of components of a portable life support system such as system **10** in FIG. **1**, system **20** in FIG. **3**, or system **40** in FIG. **4** the (a) may be worn on the back of the user. The components are mounted in housing **44** and communicate with garment **12** through suit **80** via interface plate **42**. Interface plate **42** has ports **52** through which breathing loop **16** enters and leaves the suit for ventilation and ports **54** through which cooling loop **14** enters and leaves the suit to cool the wearer.

A cutaway of one of dewars **19**' in FIG. **2**B shows a water charged piston mechanism whereas dewars **19** in system **10** of FIG. **1** are self-pressurizing dewars. It is therefore shown that system **10**, as well as alternative embodiments system **20** in FIG. **3** and system **40** in FIG. **4** disclosed herein, can employ self-pressurizing dewars or externally charged dewars. The structure and operation of both self-pressurizing dewars and externally pressurized dewars, including differences and similarities between the two, are discussed more fully below.

The "backpack" configuration of FIGS. **2**A–B is especially designed to be mounted to a suit (typically called the "SSA" or "space suit assembly") currently used by the National Aeronautics and Space Administration of the United States of America for the Space Transportation System and in its underwater training programs, which is the preferred embodiment of suit **80**. Housing **44** is mounted to the hard upper torso of the SSA (not shown) worn by the user of system **10** via mounting means **46***a–b* and several screw connections (not shown) in interface plate **52** in a manner well known to those in the art. The SSA with housing **44** mounted thereto then constitutes what is known as the extra-vehicular mobility unit ("EMU").

Alternative system **20** shown in FIG. **3** also employs a semi-closed circuit breathing loop and consequently has many components in common with system **10** of FIG. **1**. Common components having like functions are given like numbers in FIG. **3**. For instance, heat exchanger **18**' and water pump **24**' in FIG. **3** have like functions to heat exchanger **18** and water pump **24** in FIG. **1** previously discussed. The particular embodiment of FIG. **3** is intended for future applications in space whose primary difference from the embodiment of FIG. **1** is the lack of heat exchange with the environment. Cooling control is achieved by varying the flow rate of the cryogen to vaporizer **18**'. This embodiment can be used in any environment and employs gas-charged dewars **19**'.

Notable difference from the embodiment of FIG. **1** is the addition of secondary oxygen pack **62** and its associated dewar pressurization regulators **64***a–b,* which are included in anticipation of requirements of the National Aeronautics and Space Administration of the United States federal government. As such, secondary oxygen pack **62** and dewar pressurization regulators **64***a–b* are not necessary to the practice of the invention although their inclusion may be desirable for some applications. Their inclusion in the particular embodiment of FIG. **3**, however, is necessary as they provide pressurization for dewar **19**' as discussed more fully below. Also, dewars **19** in FIG. **1** are modified to provide neutral buoyancy and trim in underwater environments, as discussed further below, which is not a consideration in system **20**.

Temperature regulation provided by proportional diverter valve **28** and auxiliary heat exchanger **27** in system **10** of FIG. **1** is provided in system **20** by varying the amount of cryogen delivered to and processed by vaporizer **18** under the control of thermal control system **66** in FIG. **3**. Thermal control subsystem **66** could be implemented as a diverter valve and heat exchanger for heating such as is found in FIG. **1**. However, this design would have limited utility in some environments whose temperatures are not sufficiently warm to provide the necessary heat to cooling loop **14**'.

Excess cryogen vaporizer **32** of FIG. **1** has no analog in FIG. **3**. However, low temperature shutoffs **68***a–b* monitor the temperature of cryogen released from accumulator **72** to prevent dangerously cold cryogen from reaching the wearer of the apparatus and the garment **12**. The flow of breathable atmosphere in the preferred embodiment of FIG. **3** will not be interrupted by the operation of shutoffs **68***a–b* because of feed from secondary oxygen pack **62** through pressurization regulator **64***a* which bypasses accumulator **72** and shut-offs **68***a–b*.

FIG. **4** is a functional schematic of a third system, generally denoted **40**, which employs an open circuit, demand breathing loop. As was true of system **20** in FIG. **3**, system **40** has many components in common with system **10** of FIG. **1**, and like components bear like numbers. FIG. **4** also has components that are analogous to components found in system **20** in FIG. **3** but not found in system **10** of FIG. **1** that bear like numbers. FIG. **4** also illustrates several features of system **40** common to both system **10** of FIG. **1** and system **20** of FIG. **3** but not shown in those Figures. These features include port **72** through which dewar **19**" is filled with liquid cryogen, battery **74** to power water pump **24**", and quick-disconnects **76***a–b* that are used to connect components housed separately from liquid cooled garment **12** as shown in FIGS. **2**A and **2**B, and protective enclosure suit **80**.

However, system **40** employs an open-circuit, demand breathing loop and so atmosphere exhaled by the user is not recycled and to this extent system **40** is considerably different from systems **10** and **20**. Breathable atmosphere is delivered via positive pressure demand regulator **82** which may be either an oral mask or an oral/nasal mask. Open-circuit demand breathing loop **16**" may be equally suitable for application with cooling loop **14** of system **10** in FIG. **1** and cooling loop **14**' of system **20** in FIG. **3** just as semi-closed circuit breathing loop **16** and **16**' and systems **10** and **20**, respectively, may be applicable to system **40** in FIG. **4** when properly modified.

In System **40**, body temperature regulation is provided by cooling in two different ways. First, the flow of vaporized cryogen into and out of the user's lungs via the demand regulator **82** is directly related to the user's work rate and, hence, the metabolic heat buildup. The warmed, vaporized cryogen is still cool enough to absorb heat from the user's body during breathing and thereby performs a cooling function. As the user works harder, the rate of liquid cryogen flowing to vaporizer **18**" increases. The temperature of cooling loop **14**" therefore decreases which provides removal of heat from the user.

When used in environments having near atmospheric pressures, the user's breathing rate will provide approximately two-thirds of the metabolic heat load throughout the range of work rates. In general, additional cooling will be required. This is achieved by the second means of cooling control which is provided by cooling control valve **84**. This can be a simple metering valve which the user opens when additional cooling is needed. Opening this valve allows vaporized cryogen to flow directly to the interior of the suit and provides some ventilation to the suit which will remove perspiration. Evaporation of perspiration provides substantial cooling and ventilating the suit improves evaporation and user comfort. The vaporized cryogen used to ventilate the suit is exhausted from the suit through suit pressure relief valve **86** in the suit.

FIGS. **5**–**6** illustrate alternative embodiments for dewars **19** and **19**' in FIGS. **1**, **3**, and **4**. Technically, a "dewar" is understood in the art to mean a vessel for containing liquid cryogen. However, the alternative embodiments in FIGS. **5**–**6** each provides a mechanism for positively expelling the liquid cryogen stored therein from the dewar to its associated delivery lines. These embodiments are therefore more properly called "positive expulsion dewars". In this manner, the positive expulsion dewar both stores and delivers liquid cryogen for either the breathing loop. The cooling loop, or both as in the preferred and illustrated embodiments of this invention. The term "dewar" as used herein with reference to the claimed invention shall be understood to mean "positive expulsion dewar."

FIG. **5** is a cross-sectional view of positive expulsion dewar **19**' that is externally pressurized and which employs a gas charged piston mechanism. Piston **114** is movably disposed within inner pressure vessel **110** which, in turn, is mounted within outer pressure vessel **105** using a cantilevered spoke design (not shown). The cantilevered spokes run from the exterior surface of inner pressure vessel **110** to the interior surface of outer pressure vessel **105** in chamber **112**. Inner pressure vessel **110** can be mounted within outer pressure vessel **105** using equally satisfactory alternatives to cantilevered spokes, such as straps or webbing, as are well known in the art for retaining the heat conduction paths from outer pressure vessel **105** to inner pressure vessel **110**. Inner pressure vessel **110** in the preferred embodiment is a 304 L, stainless steel pressure vessel whose contents are insulated by a vacuum induced in chamber **112** between inner pressure vessel **110** and outer pressure vessel **105**.

Piston **114** is preferably constructed as a single unit from one or more materials exhibiting low conductivity and expansion characteristics in both structural and sealing applications, such as KEL-F81 or ultra high molecular weight polyethylene (UHMWPE). The internal volume of piston **114** is evacuated and filled with alternating layers of multi-layer insulation for additional insulation of the liquid cryogen as is well known to those in the art. Piston **114** is portrayed in FIG. **5** in a position indicating that the liquid cryogen contents are three-quarters expelled.

Piston **114** defines upper chamber **122**, annular chamber **116**, and lower chamber **124**, by virtue of sealing engagement between annular flange **126** and annular flange **128** and the interior surface of inner pressure vessel **110**. The pressure of the contents of chamber **122** exert a force against forward side **123** of piston **114** and the contents of chamber **124** exert a force against reverse side **125** of piston **114**. No provisions are made for venting annular chamber **116** between the seals of annular flanges **126** and **128** because piston **114** is of constant diameter and its movement will not be hindered by the buildup of pressure in annular chamber **116**.

Liquid cryogen is introduced into and delivered from upper chamber **122** via port **102** and line **103**. Prior to filling, piston **114** is retracted by increasing the pressure in chamber **122** relative to chamber **124**, whereupon chamber **122** is filled with liquid cryogen. Liquid cryogen is then delivered via line **103** and port **102** to the system heat exchanger such as heat exchanger **18**, **18'**, or **18"** in FIGS. **1**, **3**, and **4**, respectively, by supplying pressurized gas to chamber **124** which applies force to piston **114**, thereby pressurizing the liquid cryogen in chamber **122**.

A gas pressure sufficiently high to positively expel liquid cryogen from upper chamber **122** must be maintained in lower chamber **124**. Typically, "sufficiently high" simply means a greater pressure in lower chamber **124** than in upper chamber **122**. The preferred method employs an external pressure vessel (not shown) containing was under pressure and a pressure reducing valve (not shown) to ensure that a constant gas pressure is supplied to lower chamber **124**.

As piston **114** moves upward and reduces the pressure of the gas in the increased volume of lower chamber **124**, the pressure reducing valve allows more gas from the external pressure vessel to enter lower chamber **124** to maintain sufficient gas pressure. The amount of force for positively expelling liquid cryogen can be simply controlled by adjusting the pressure reducing valve to obtain a desired pressure differential between the pressure in lower chamber **124** and upper chamber **122**. System **20** in FIG. **3** and system **40** in FIG. **4** are examples of systems employing externally pressurized dewars with a gas charged piston mechanism.

FIG. **2** illustrates an alternative to gas charging dewar **19'** which is primarily applicable only for underwater diving. The system includes dewar pressurization pump **130** (shown only in FIGS. **2A–2B**) which pumps water **136** obtained from the environment into the lower chamber of dewar **19'** defined by piston **114** via line **131** to maintain the differential pressure in dewar **19'** during operations. Although this alternative has limited application in most environments other than underwater, the principle of an external means for pressurizing the dewar is analogous to gas charging discussed above. For underwater applications, this pressurization technique has the added advantage over gas-charging of maintaining neutral-buoyancy and trim of the user because the density of the liquid oxygen liquid nitrogen mixture is similar to that of water.

Before filling operations begin, the temperature of inner pressure vessel **110** is generally higher than cryogenic temperatures and so either some liquid cryogen introduced into upper chamber **122** will boil off to cool inner pressure vessel **110** and piston **114** or inner pressure vessel **110** and piston **114** must be pre-cooled. Chamber **112** therefore contains cooling coil **132** used for pre-cooling inner pressure vessel **110** before liquid cryogen is introduced.

Liquid cryogen for pre-cooling enters cooling coil **132** through port **104***a* and exits via port **104***b* and cools inner pressure vessel **110** prior to its fill or recharge. This reduces and minimizes vaporization (or "boil off") of liquid cryogen introduced into upper chamber **122** of inner pressure vessel **110** during filling operations. Cooling coil **132** may be used with a closed-cycle refrigerator for pre-cooling operations. However, in applications where there is no need to minimize consumable waste and boil off of liquid cryogen is acceptable, pre-cool may be omitted altogether.

FIG. **6** illustrates positive expulsion dewar **19** that is self-pressurizing which by virtue of a differential area piston mechanism, with parts having analogs in the embodiment in FIG. **5** having numbers like those analogs. Differential area piston **114'** has less pressure responsive surface area on forward side **123'** than on reverse side **125'** and is profiled to minimize the ullage volume of liquid cryogen at the full stroke position of its movement. Piston **114'** engages the interior wall of inner pressure vessel **110'** with upper flange **126'** and lower flange **128'** thereby defining upper chamber **122'**, annular chamber **116'**, and lower chamber **124'**. Annular chamber **116'** deflated in inner pressure vessel **110'** by the seals of annular flanges **126'** and **128'** is vented via line **117** and relief port **107** to prevent the buildup of pressure in annular chamber **116'** that would inhibit movement of piston **114'** if the either of the seals created by annular flanges **126'** and **128'** leak. Helical coil **132'** provides pre-cool for the dewar for filling operations.

The differential area of piston **114'** in FIG. **6** allows for self-pressurization of the dewar. Vaporized cryogen from the heat transfer process described above can be partially diverted into chamber **124'** through an analog of line **118** and port **106** of FIG. **5** that is not shown in FIG. **6** for the sale of clarity. Alternatively, as shown in FIG. **1**, an auxiliary heat exchanger can be provided to partially vaporize delivered liquid cryogen which can then be diverted to lower chamber **124'**. The vaporized cryogen will be at the same pressure as the liquid cryogen in chamber **122'** (or a slightly lower pressure) but the surface of forward side **123'** of piston **114'** in chamber **122'** is smaller than is the surface area of reverse side **125'** of piston **114'** in chamber **124'**, thus providing the necessary force required to move piston **114'**. Thus, there are two ways to overcome frictional forces and to provide pressure for expelling liquid cryogen from the dewar: either by using differential pressure generated from an external source as in the embodiment of FIG. **5** or by using differential area in the piston as in the embodiment of FIG. **6**.

It is therefore evident the invention claimed herein may have many alternative and equally satisfactory embodiments without the departing from the spirit or essential characteristics thereof. The invention is adaptable in many facets, ranging from dewar to breathing loop design, depending on the particular application. For instance, all embodiments disclosed herein employ positive expulsion dewars, but dewars employing liquid acquisition devices can be substituted albeit with some loss of performance. The preferred embodiments disclosed above must consequently be considered illustrative and not limiting of the scope of the invention as it may admit to other equally effective embodiments.

What is claimed is:

1. A portable life support system, comprising:

a liquid cooled garment;

a backpack supporting the life support system comprising:

an orientationally independent dewar for containing liquid cryogen;

means for circulating liquid cryogen from said dewar in heat exchange relation with [the] *a* cooling liquid so as to cool the wearer of the garment and vaporize the liquid cryogen; and

means for delivering vaporized cryogen to the wearer of said garment for breathing purposes.

2. The portable life support system of claim **1**, wherein the [heat exchanging] *circulating* means comprises:

an insulated housing;

a loop for circulating the cooling liquid through the interior of the garment and the housing; and

means for circulating liquid cryogen through the housing intermediate the [source] *dewar* and the delivering means.

3. The portable life support system of claim **2**, wherein the delivering means includes a loop for recirculating vaporized cryogen to the wearer of said garment.

4. The portable life support system of claim **1**, wherein said orientationally independent dewar is a positive expulsion dewar.

5. The portable life support system of claim **4**, wherein said positive expulsion dewar is externally charged.

6. The portable life support system of claim **4**, wherein said positive expulsion dewar is self-pressurizing.

7. The portable life support system of claim **1**, wherein said means for delivering vaporized cryogen is an open circuit system.

8. The portable life support system of claim **1**, wherein said means for delivering vaporized cryogen is a semi-closed system.

9. A portable life support system, comprising:

a liquid cooled garment;

a backpack supporting the life support system comprising:

an orientationally independent dewar for containing and delivering liquid cryogen; and

a heat exchanger for exchanging heat between the cooling liquid and the liquid cryogen delivered from the dewar.

10. The portable life support system of claim **9**, wherein said orientationally independent dewar is a positive expulsion dewar.

11. The portable life support system of claim **10**, wherein said positive expulsion dewar is externally charged.

12. The portable life support system of claim **10**, wherein said positive expulsion dewar is self-pressurizing.

13. A portable life support system, comprising:

a liquid cooled garment through which cooling liquid may be circulated;

a backpack supporting the life support system comprising:

a source of liquid cryogen; *and*

means for delivering liquid cryogen from said source at a varying rate in heat exchange relation with the cooling liquid to cool the cooling liquid, thereby varyingly regulating the temperature of the cooling liquid.

14. A portable life support system as in claim **13**, wherein the circulation rate of the liquid cryogen is correlated to the respiration rate of the system user to regulate the temperature of the cooling liquid as the system user's respiration rate varies.

15. A portable life support system as in claim **14**, wherein the liquid cryogen is vaporized and the delivering means includes an open-demand breathing loop.

16. A portable life support system as in claim **13**, wherein the liquid cryogen is vaporized and the delivering means includes a semi-closed breathing loop.

17. A portable life support system as in claim **13**, wherein the cooling liquid, when circulated, is circulated at a constant rate.

18. A portable life support system as in claim **13**, wherein said source is an orientationally independent dewar.

19. A portable life support system, comprising:

a liquid cooled garment through which cooling liquid may be circulated;

a backpack supporting the life support system comprising:

a source of liquid cryogen;

means for circulating liquid cryogen from said source in heat exchange relation with the cooling liquid to cool the cooling liquid and vaporize the liquid cryogen; and

means for delivering vaporized cryogen to the wearer of said garment for breathing purposes, said delivering means delivering vaporized cryogen at a varying rate, thereby varyingly regulating the temperature of the cooling liquid.

20. A portable life support system as in claim **19**, wherein the delivery rate of the liquid cryogen is correlated to the respiration rate of the system user to regulate the temperature of the cooling liquid as the system user's respiration rate varies.

21. A portable life support system as in claim **20**, wherein the delivering means includes an open-demand breathing loop.

22. A portable life support system as in claim **19**, wherein the delivering means includes a semi-closed breathing loop.

23. A portable life support system as in claim **19**, wherein the cooling liquid, when circulated, is circulated at a constant rate.

24. A portable life support system as in claim **19**, wherein said source is an orientationally independent dewar.

25. A portable life support system, comprising:

a backpack housing means supporting a life support system including:

an orientationally independent dewar for containing liquid cryogen;

a heat exchanger for exchanging heat between liquid cryogen and a heat source; and *means for delivering liquid cryogen from said dewar to said heat exchanger in heat exchange relation with the heat source so as to provide vaporized cryogen for breathing purposes.*

26. The portable life support system of claim 25, wherein said dewar includes said delivering means.

27. The portable life support system of claim 25, further comprising

a liquid cooled garment exposed to the body heat of its wearer and thermally connected to said heat exchanger, whereby the cooling liquid in said garment exchanges heat with the liquid cryogen in said heat exchanger to cool the wearer and provide vaporized cryogen to the wearer for breathing purposes.

28. The portable life support system of claim 25, wherein

the heat source is ambient air.

29. The portable life support system of claim 25, wherein

said delivering means comprises an open-demand breathing loop through which the vaporized cryogen is delivered.

30. The portable life support system of claim 25, wherein

said delivering means comprises a semi-closed breathing loop through which the vaporized cryogen is delivered.

31. As in claim 9, including

means for controlling the temperature of the cooling liquid.

32. As in claim 27, including

means for controlling the temperature of the cooling liquid.

33. A portable life support system, comprising:

a housing means supporting a life support system of a size and shape to be carried as a backpack including:

an orientationally independent dewar for containing liquid cryogen;

heat exchange means for circulating liquid cryogen from said dewar in heat exchange relation with a heat source so as to provide vaporized cryogen for breathing purposes; and

means for delivering said vaporized cryogen to the wearer of said backpack for breathing purposes.

34. A portable life support system according to claim 33 which further includes:

a heat exchanger between said heat exchange means and said means for delivering said vaporized cryogen to vaporize any excess liquid cryogen and warm said vaporized cryogen to a breathable temperature.

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