

[54] LIFE SUPPORT SYSTEM AND METHOD

[75] Inventor: Halbert Fischel, Los Angeles, Calif.

[73] Assignee: E & M Laboratories, Van Nuys, Calif.

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[51] Int. Cl.: A62b 7/06

[58] Field of Search: 128/140, 142-142.7, 128/145, 203; 62/45, 50, 223; 55/267, 268, 269

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Primary Examiner—Kyle L. Howell

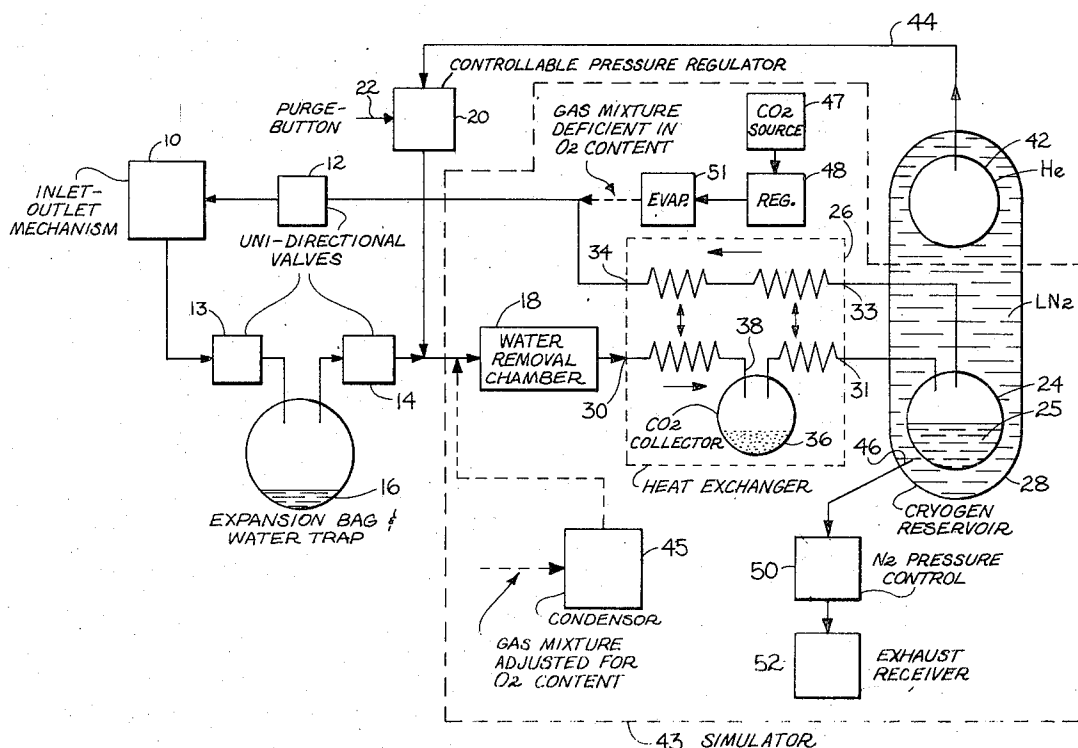
Attorney, Agent, or Firm—Fraser and Bogucki

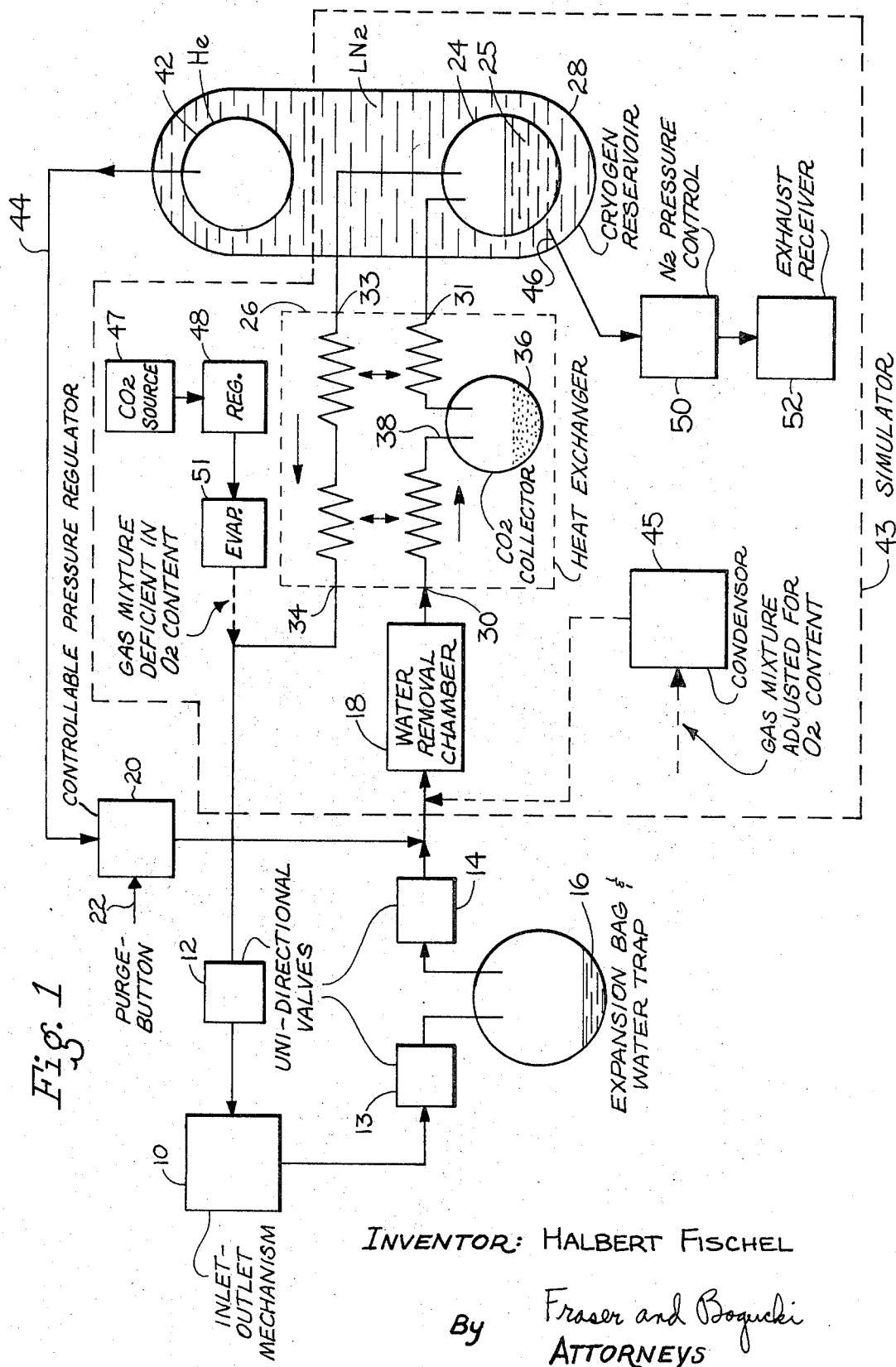
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ABSTRACT

Life support is provided by a cryogenic closed circuit system for either hyperbaric, isobaric or hypobaric respiratory environments. Oxygen content in a gas mixture is maintained in a selected partial pressure range by establishing thermodynamic equilibrium between a liquid oxygen supply, which is maintained at an appropriate temperature, and a gas mixture within an enclosed volume communicating with the liquid oxygen. Incoming gases are passed into the gas-containing volume and adjusted to an appropriate partial pressure of oxygen solely by virtue of saturation equilibrium, and independently of ambient pressure and gas mixture variations. The useful life of a given oxygen supply volume is greatly extended because of the high compaction ratio of liquid oxygen with respect to oxygen gas at standard temperature and pressure, and because of full physiological use of the oxygen. The temperature of the liquid oxygen may be controlled through the use of a cryogenic reservoir, a cryogenic refrigerator or other means. A heat exchanger may be deployed in the closed circuit system to cool incoming contaminated gases to cryogenic levels and to heat outgoing breathable gases to acceptable levels, and to provide more efficient use of the cryogen. The closed circuit system may further include means for compensating for ambient pressure variations by the injection of an inert gas or gases and for cleansing of incoming gases by removal of water vapor and carbon dioxide.

44 Claims, 8 Drawing Figures





VAPOR PRESSURE EQUILIBRIUM CURVES

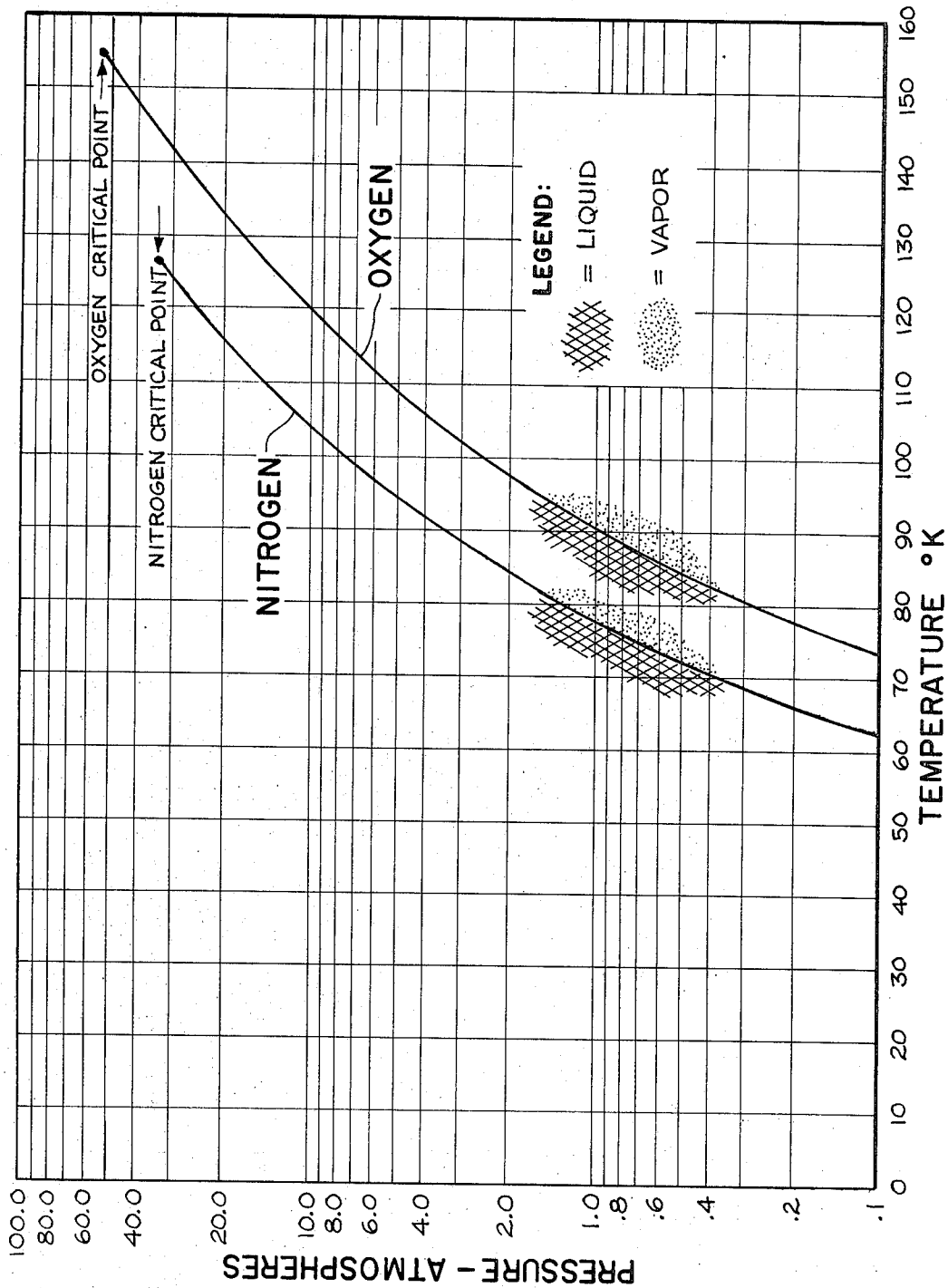
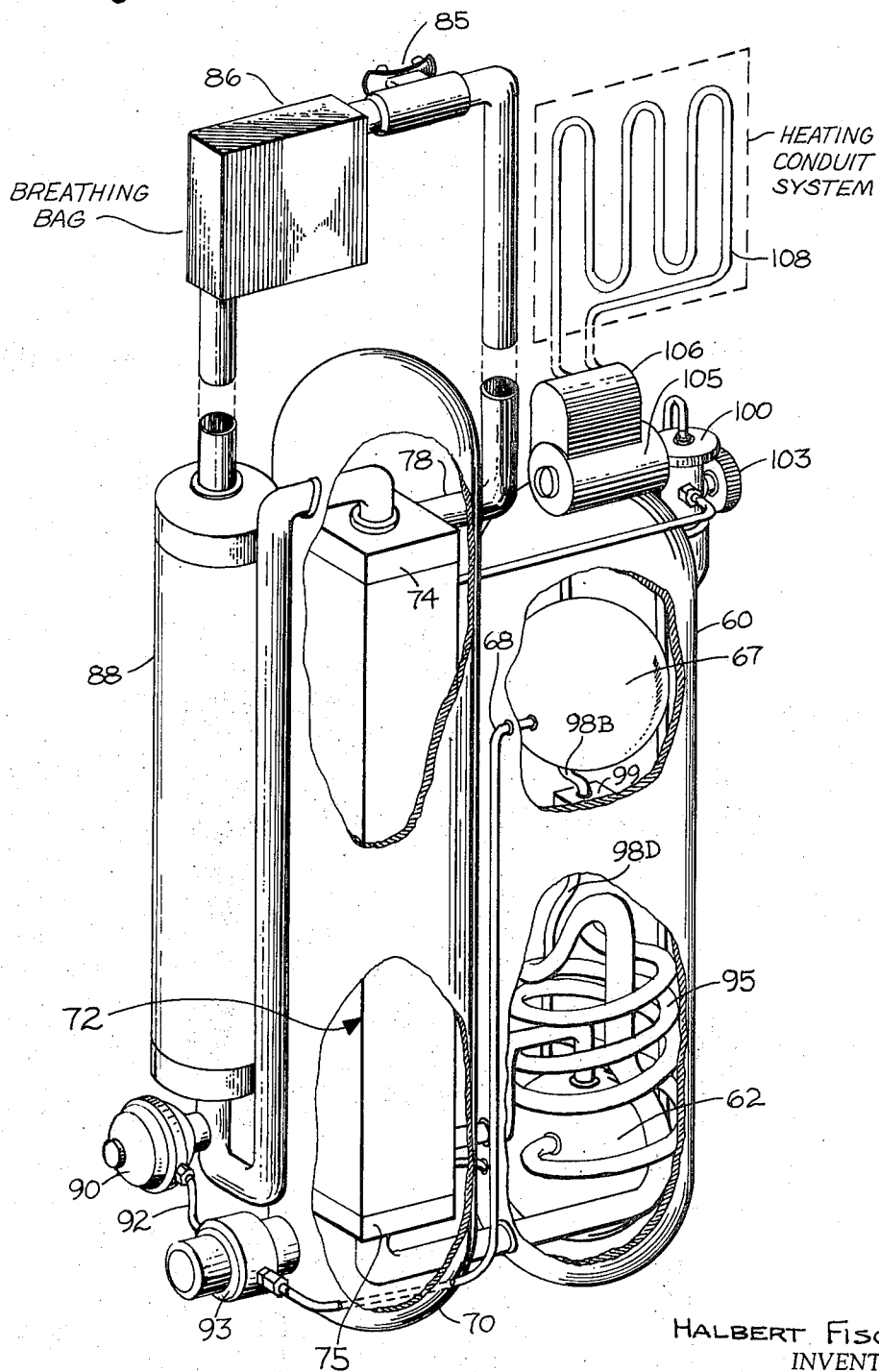


Fig. 2

INVENTOR: HALBERT FISCHER

By Fraser and Bogucki
ATTORNEYS

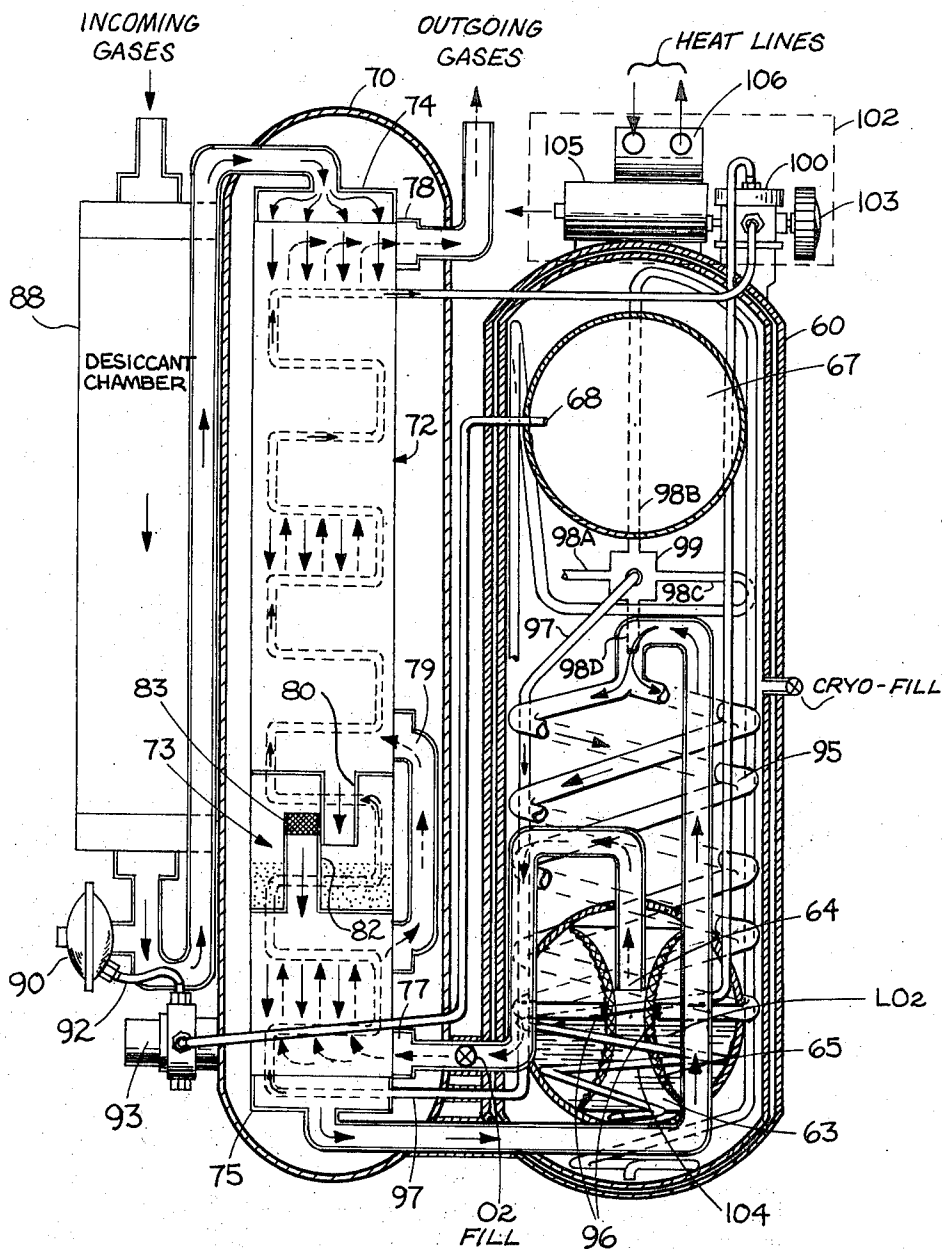
Fig. 3



HALBERT FISCHEL
INVENTOR.

BY *Fraser and Bogucki*
ATTORNEYS

Fig. 4



INVENTOR: HALBERT FISCHER

By *Fraser and Bozack*
ATTORNEYS

Fig. 5

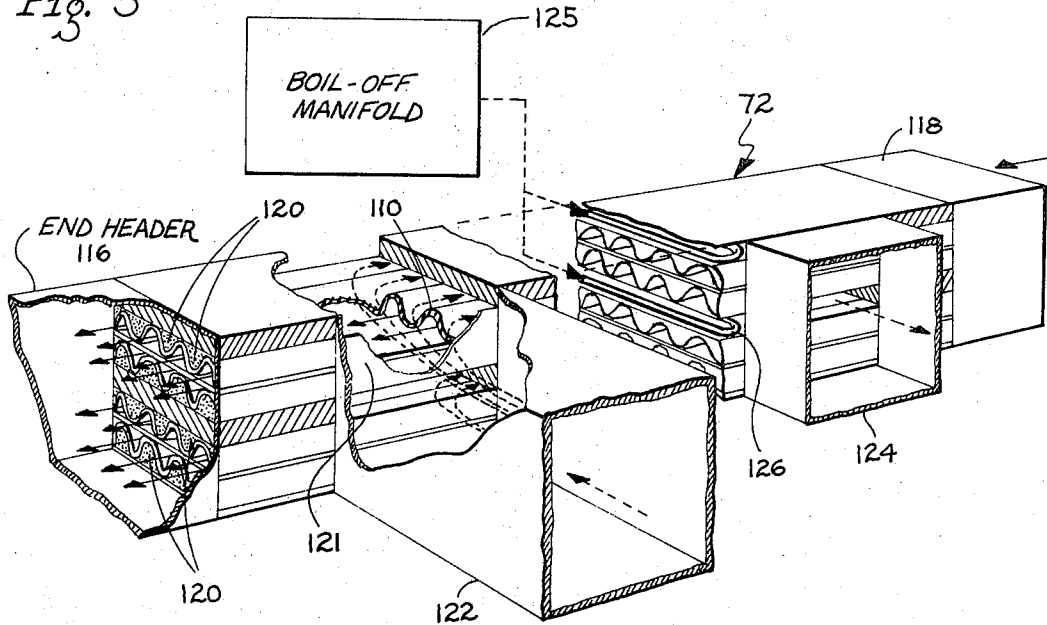
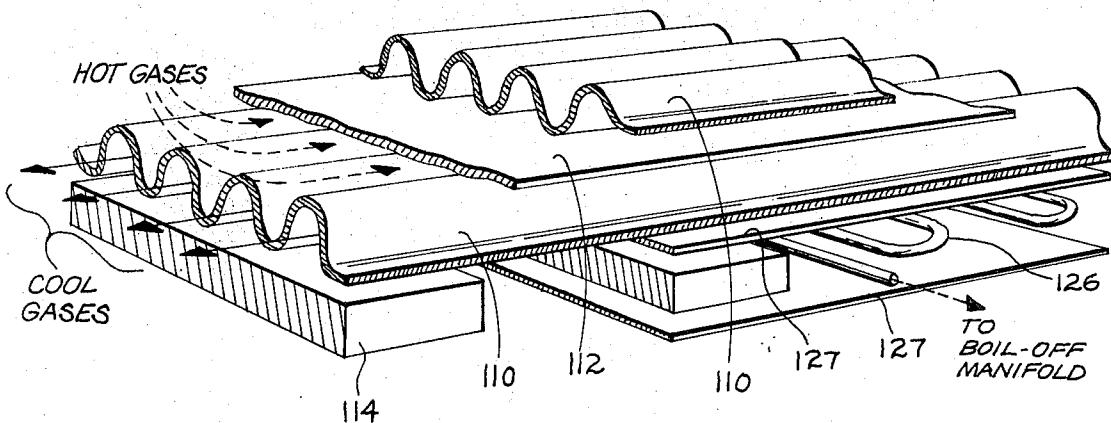


Fig. 6

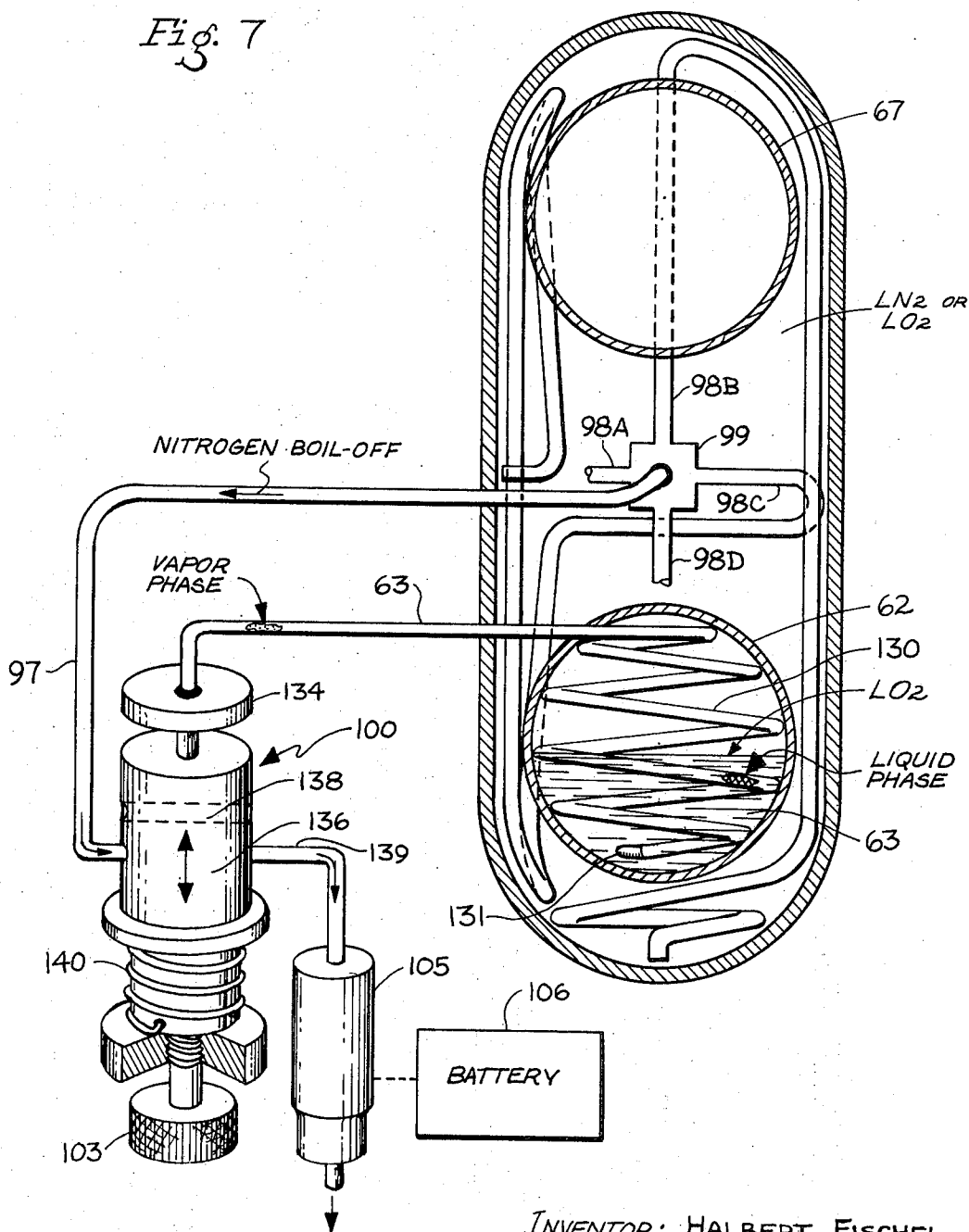
HEAT EXCHANGE MEMBRANE SEGMENT
(GREATLY ENLARGED)



INVENTOR: HALBERT FISCHEL

By Fraser and Boquehi
ATTORNEYS

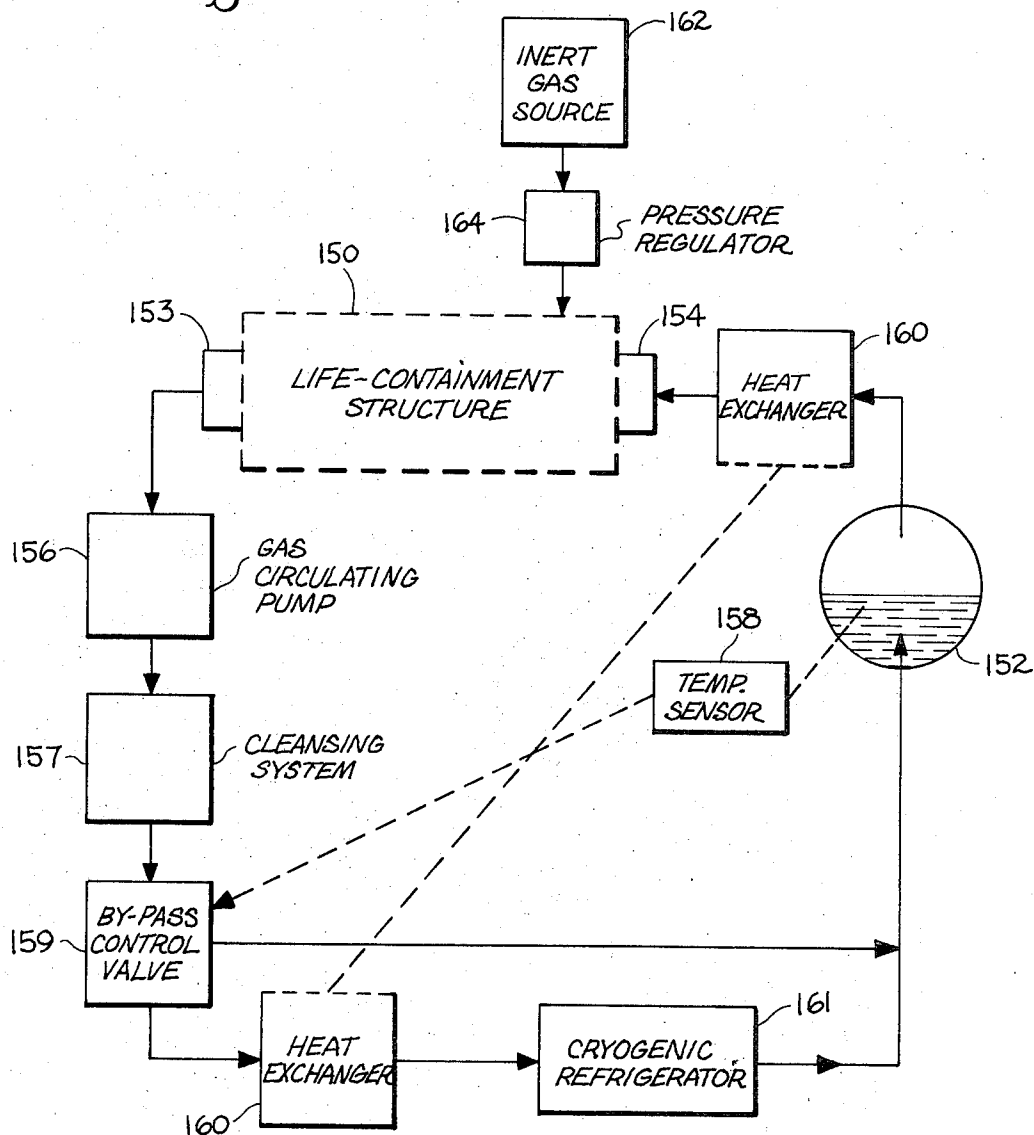
Fig. 7



INVENTOR: HALBERT FISCHER

By Fraser and Boquet
ATTORNEYS

Fig. 8



INVENTOR: HALBERT FISCHER

By Fraser and Bozuechi
ATTORNEYS

LIFE SUPPORT SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to systems for adjusting the gas constituents in a gaseous environment and particularly to closed circuit systems providing breathable gas mixtures in hostile environments and in self-contained life support systems.

2. Description of the Prior Art

As underwater explorations and other operations in hostile environments for scientific and industrial purposes have increased, concentrated attention has been directed to the development of life support systems. To the present, such systems have taken a limited number of basic forms. One widely employed underwater life support system is based upon the use of an externally serviced diving helmet or suit, sealed partially or entirely about a diver and providing a constant pressurized supply of fresh gases while withdrawing contaminated gases. Self-contained underwater breathing apparatus, or SCUBA gear, is most widely used in its open circuit version. That is, gas tanks carried by a diver provide fresh gases in appropriate mixture, and contaminated gases are expelled from the system.

The amount of gas taken in by users in a single breath increases with pressure. Because the duration of use of a given breathable gas supply is limited by volume and weight to that which can be manipulated by a diver or supported by an underwater system, work has also been directed toward semi-closed circuit systems by virtue of their more efficient utilization of the gas supply. In such systems, at least in theory, the contaminating gases (principally CO₂, hydrocarbons, and water vapor) are eliminated from the system, and a portion of the oxygen supply is recirculated so that its use rate is limited, in part, to that at which it is physiologically converted by users and that which is lost from the system where the latter is ventilated with fresh oxygen.

More recently, a number of underwater life support systems have been devised in which diving bells or tanks maintain preselected gas mixtures, either by self-contained systems or by couplings to surface sources. These systems have the advantage of providing easy ingress and egress to the substantial depths in which they are contained, but generally rely upon umbilical connections or open circuit arrangements. Some systems use low temperature (cryogenic) reservoirs for supplying the needed gases to a semi-closed circuit arrangement in which mixtures are continuously sensed and proper valving adjustments are made for the injection of effluent oxygen gas from the reservoir. Such systems are both large and complicated in their present form.

NATURE OF THE PROBLEM

A number of considerations greatly complicate the problems involved in providing life support in hostile environments such as are encountered under positive pressure conditions. Regardless of the pressure at which a diver is working, he must have available the proper amount of oxygen, and this amount, in terms of oxygen partial pressure, is in the range of 0.2 to approximately 1 atmosphere. Thus in working at substantial depths (200-400 feet), divers are required to breathe a mixture in which the oxygen is a very low percentage,

e.g. 5 to 2 percent respectively, of the complete mixture. Unless one is to be confined to a given depth or required to make constant adjustments oxygen percentage variations must be made automatically because either an excess or deficiency will be fatal within a short time, the former from oxygen poisoning and the latter from anoxia. Maintenance of precise ratios is also of great importance in reducing the possibilities of non-fatal injury and in reducing the time needed for decompression.

The term "positive pressure" is here intended to refer to an hyperbaric environment, or one in which the environmental pressure exceeds that of a normal human environment. If the pressure is high enough it is intrinsically hostile to human life, just as is an hypobaric environment if its pressure is sufficiently low. Taking the normal atmospheric range as a reference, the hypobaric environment may also be referred to as a negative pressure environment. Even an isobaric environment may be hostile to human existence and may require a life support system, as if temperature extremes or excessive pollutants are encountered.

The proper breathing mixture for positive pressure environments is not comparable to that of normal atmospheres. There is of course the requirement that the exhaled carbon dioxide be removed from the system if the gas is to be recirculated. If the system is fully or semi-closed circuit, it is further desirable that there should be no substantial variation in the breathing pressure required as CO₂ accumulates, as is the case when a back pressure exists. The narcotic effects of inert gases under pressure must be suppressed or eliminated. For example, if nitrogen is present in the breathing mixture it should be limited to a partial pressure of no greater than approximately 50 psi. For these and other reasons, breathable mixtures for underwater work primarily use helium or some other stabilizing inert gas or mixture of inert gases and oxygen in combination.

Other critical requirements imposed on life support systems stem from the necessity of deriving the longest possible useful life from given supplies of oxygen and supportive gases, and from the safety factors inherently required for all such apparatus. The volume and mass which can be manipulated by a diver, for example, represents one controlling limitation on an underwater system. Within such limitations, the longer a given supply of oxygen and supportive inert gas can be used and the greater will be the work capacity of the user or users. The work capacity increases disproportionately with oxygen supply duration because of the time consumed in preliminary preparations, travel to and from a work site, and subsequent decompression. Even if the starting and returning point is an underwater station, and if depths are so great that the energy capacity of the diver is the most significant limitation, the safety factors inherent in a greater supply of breathable gas are self evident. Safety factors generally are of great concern at present, because modern systems rely on mechanical and pressure responsive valves whose failure, catastrophic or intermittent, is intolerable.

OTHER ENVIRONMENTS AND FUNCTIONAL REQUIREMENTS

As systems have been more widely used, other factors than safety have also become more significant. For example, when breathing a mixture having high helium content, body heat losses are extreme. Thus, means

must be provided for heating underwater devices or stations in order to maintain reasonable working or living conditions. The expenditure of heat is generally unrelated to the performance of other functions within a life support system, but if it could be effectively combined with the life support function, the entire installation would not only be more compact and less costly but available energy sources would be more efficiently utilized.

Systems of this nature are required to perform a variety of different functions, including the cleansing from contaminated gases of water vapor, toxic hydrocarbons, and carbon dioxide, the use of efficient heat transfer arrangements, and the exercise of necessary control functions for regulating temperatures, and, where necessary, pressures. The present invention is concerned with all such aspects, because although they are corollary to the principal problem of controlling the partial pressure of a selected gas within the gas mixture, they are fundamental to the principal objectives of life support systems, and additionally have a substantial number of independent uses. Many of these functional requirements are satisfied by systems in accordance with the invention in particularly advantageous and unique fashion, as is separately pointed out hereafter.

Other life support systems may confront wholly different environments but nonetheless must provide a breathable mixture in the proper pressure range. In superatmospheric and space systems hypobaric environments are encountered and it is often preferred to use pure oxygen at a selected subatmospheric pressure. While pressure regulation is relatively simple, failures can still occur. Perhaps greater dangers are introduced by the flammability of a pure oxygen breathing medium, and these dangers may be greatly reduced by admixing even a minor proportion of inert gas. With existing systems, the extraction of contaminants from pure oxygen maintained at a given pressure involves relatively simple regulatory problems. When, however, the oxygen is to be diluted in a given proportion with a suitable inert gas, substantial additional equipment must be utilized with present techniques. The constituents of the gas mixture must be determined with relation to the total pressure in the system, and the needed corrections must be made by appropriate combinations of injections of pure gas constituents and withdrawal of the gas mixture.

SUMMARY OF THE INVENTION

The purposes and objectives of the present invention are achieved for life support systems by automatic adjustment of oxygen partial pressure by passing a gas mixture containing oxygen through a temperature controlled gas-liquid-oxygen interface. The liquid oxygen is in communication with an enclosed gas-containment volume and is maintained at a preselected temperature or within a selected temperature range, establishing a partial pressure of oxygen vapor in the enclosed volume that is independent of the partial pressures of other gases and ambient pressure variations. This form of control may be employed for other gases, and whether the selected gas must be added to or extracted from the system. By bringing the vapor content to saturation quickly, the partial pressure of the selected constituent in a mixture may be continually corrected.

Closed circuit systems have particular advantages for life support applications, but an aspect of the invention is that regulation in this manner may be effected with other systems and with a variety of further modifications. In the hypobaric (negative pressure) environments, such form of regulation may provide the basis for maintaining selected proportionalities between oxygen and an inert gas constituent in the mixture. The pressure of the selected gas may be maintained within a selected broad or narrow range. A substantial variation may be introduced in the temperature of the liquid reservoir in communication with the vapor without changing the partial pressure range of the corresponding vapor by controlled dilution of the liquid in the reservoir. Thus, the invention encompasses a number of methods, as well as a number of apparatus concepts dealing with both system and subsystem aspects.

In accordance with several of the principal aspects of the invention, a fully closed circuit system may employ a gas-liquid interface volume in a highly interrelated fashion with other functional subsystems to provide a complete life support system for environments hostile to man. A chamber containing the gas-liquid interface volume is, in one specific example, disposed within a cryogenic reservoir and incoming and outgoing gases are passed through the enclosed volume for adjustment of oxygen contact. The gases are preliminarily and subsequently passed through a high efficiency heat exchanger, to cool the incoming contaminated gases substantially, and to reheat the outgoing properly compensated gas mixture to a breathable temperature level. During cooling, CO_2 is precipitated from the gases. In conjunction with the same system, gaseous helium may also be more efficiently stored in a separate container within the cryogenic reservoir, and injected into the incoming gases to compensate for ambient pressure variations.

A benefit of this usage of liquid oxygen in a closed circuit arrangement is that dramatic increases in operative cycle time for the system are achieved because of the high compaction ration of liquid oxygen, and because efficient use is made of heat exchange relationships, and because oxygen is not dissipated. The system operates automatically over a wide dynamic range and with the needed precision. The primary requirements as to absolute and relative pressure variations are fully met.

Closed circuit systems in accordance with the invention for use in superatmospheric and space environments may use a cryogenic refrigerator for adjusting the gas-liquid-oxygen interface temperature. The cryogenic refrigerator may be a power operated unit or comprise a passive unit giving up heat to the environment. Dependent upon the oxygen temperature adjustment needed, controlled cooling of the circulating gas may be effected as needed by varying rates or proportions of flow, or the efficiency of the cryogenic refrigerator.

A significant aspect of the invention relates to control of the partial pressure of the oxygen in the enclosed volume. The temperature of the oxygen is sensed and used to control boil off from the cryogenic reservoir in order to regulate the back pressure therein. A feature of this system is an arrangement for automatic and reliable temperature control. The vapor pressure of the single constituent within the cryogenic reservoir represents the total pressure in this essentially closed con-

tainer, and the vapor pressure is therefore stable for a given temperature of the cryogen and varies isomorphically with the cryogen temperature. The back pressure of the cryogen is regulated to adjust its temperature, thus to adjust the temperature of the liquid oxygen which is maintained in thermal equilibrium with the cryogen in which it is immersed. The oxygen partial pressure is therefore maintained within selected limits, irrespective of the oxygen supply, variations in system demand, and variations in the breathable mixture.

Another feature of the invention is a temperature control arrangement that is analog in nature, completely self contained, and highly accurate and reliable. A hollow sensing tube has a sealed end containing a liquid disposed within the liquid oxygen supply, so that the liquid sealed in the tube assumes the temperature of the liquid oxygen. The tube itself contains an entrapped gas-liquid interface within an invariant volume, so that the pressure within the tube is essentially the vapor pressure of the liquid, and thus varies with the liquid oxygen temperature. At the temperature range of the liquid oxygen, a substantial pressure is generated within the tube and this pressure varies within a wide dynamic range. The pressure regulates the back pressure of the cryogen by operating a diaphragm mechanically coupled to control the venting of the boil-off gases from the cryogenic reservoir. This portion of the system comprises a closed loop servo that maintains the liquid oxygen temperature within any predetermined range as long as there are adequate cryogenic sources available.

Systems in accordance with the invention for control of the partial pressure of a gas are reciprocal in nature, in that they may also extract a gas to reduce an excess in a gas mixture. Accordingly, systems and methods are also provided by which a selected gas, such as oxygen, may be condensed from a given mixture. Test systems are provided, in one specific example, which the operation of a life support system is tested under conditions corresponding to actual operation. The test system continually simulates the breathing of users by extracting oxygen from a breathable mixture, and returns an oxygen deficient mixture to which contaminants may be added.

Another feature of systems in accordance with the invention is a heat exchanger providing extremely efficient heat transfer between the incoming and outgoing gases. The heat exchanger passes the incoming and outgoing gases in counter-current fashion along adjacent passageways on opposite sides of thin heat exchanger membranes. Substantially direct heat transfer over large surface areas is effected, with thin sheets of gases moving linearly to provide wide temperature differentials over short length with relatively little pressure drop. The oxygen and cryogen are more efficiently utilized, and the proper temperatures are maintained for both the breathable and cryogenic mixtures. The heat exchanger entities may be built up in successive laminations to achieve desired cross-sectional passageway areas. Furthermore, standardized heat exchanger elements may be added together in series or parallel fashion to increase heat exchange surface area. The heat exchanger entities may be disposed in opposed and facing relation, and arranged to receive other conduit systems in selected heat exchange relation to provide either a heat source or heat sink effect. In a particular system in accordance with the invention, boil-off gases

from a cryogenic reservoir may be passed through the heat exchanger to extract heat from the gases and to further increase the efficiency of the system by providing a tertiary heat transfer effect.

The precipitation point of CO₂ is reached within a very short length as the incoming contaminated gases are cooled, and these factors are used to advantage in novel systems and methods for cleansing CO₂ from the gases. At the appropriate point along the length of the heat exchanger, at which CO₂ precipitates, the gases are directed into an enclosed volume, but without substantial change of pressure. CO₂ precipitate is accumulated in a receiving chamber, while the cleansed gases are diverted into the succeeding section of the heat exchanger. Because the CO₂ particles are uncompacted and travel in unrestricted fashion along linear paths without encountering substantial pressure drops, the CO₂ mass remains loose and permeable and does not clog the passageways or otherwise impede normal gas flow.

Further in accordance with the invention, means are provided for insuring rapid and stable attainment of equilibrium conditions in control of the breathable mixture. Incoming expiratory gases are not only passed through the heat exchanger, but are additionally passed in isothermal relationship with the cryogen by flowing along a length of conduit within the cryogenic reservoir immediately prior to entering the vessel containing liquid oxygen. Thus, in accordance with this feature, the system reduces the thermal exchange occurring within the vessel containing the liquid oxygen. Furthermore, the internal arrangement within the liquid oxygen vessel facilitates establishment of the desired equilibrium relationships between gas and liquid. A wicking member extending from the liquid oxygen into the gas-containing volume is substantially fully wetted by the liquid oxygen and greatly increases the surface area of liquid oxygen in communication with the gas mixture. The oxygen level in the mixture is quickly brought to saturation for the given liquid oxygen temperature while the gas mixture is concurrently brought into thermodynamic equilibrium.

A number of additional features of use in cryogenic systems have separate utility and importance. The liquid oxygen does not pass through the conduits containing the incoming expiratory gases because these conduits are disposed such that the liquid tends ultimately to return irrespective of temporary attitude changes. A bifurcated conduit system having oppositely facing ports normally above the liquid oxygen insures that the line is always open to pass expiratory gases. A tortuous conduit system is also used to assure free passage of boil-off gases from the cryogen. A set of four conduits are used, in one specific example, each extending from a common manifold within the cryogen reservoir, and each following at least two orthogonally disposed reentrant paths whose individual limits are more than half the corresponding internal dimension of the reservoir.

In accordance with other aspects of the invention, gas cleansing and needed pressure adjustments may also be effected within the system. A variable volume chamber may be coupled into the inlet portion of the system, to expand and contract to compensate for lung volume changes. Incoming gas may be passed through a water removal device. Inert gas injected prior to the

heat exchanger may be used to flush the entire system when required.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of a system in accordance with the invention for life support for positive pressure environments, and including an alternative simulator system;

FIG. 2 is a graphical representation of phase equilibrium relationships for oxygen and nitrogen plotted against temperature and pressure;

FIG. 3 is a perspective view, partially broken away, of an example of a detailed system in accordance with the invention for use in positive pressure environments;

FIG. 4 is a side sectional view of the system of FIG. 2;

FIG. 5 is an idealized and simplified view of a heat exchanger system for use in the system of FIGS. 3 and 4.

FIG. 6 is a perspective, partially broken away and greatly enlarged, detailed view of a portion of the heat exchanger of FIG. 5;

FIG. 7 is a combined block diagram and partially broken away perspective of a temperature control system for use in the system of FIGS. 3 and 4; and,

FIG. 8 is a block diagram representation of a different form of life support system in accordance with the invention useful in negative pressure environments.

DETAILED DESCRIPTION OF THE INVENTION

1. Life Support System for Positive Pressure Environments

The diagram of FIG. 1 illustrates a complete system in idealized form, and also a basic modification that accomplishes a complementary purpose. It should be expressly understood, however, that the various aspects of the present invention can be applied to many different needs in different ways. The system of FIG. 1 is highly integrated and performs the various functions needed for a life support system for hostile environments, particularly hyperbaric environments. Depending upon system requirements and particular environments, however, only certain of the aspects need be employed. Also, as shown in greater detail hereafter, individual features, and variations and modifications of the features can be utilized in various combinations. For a given life support system, the most suitable combination will be dependent on such factors as whether the system is intended for individual or multiple use, whether it is to be a fixed or mobile system, whether it is to be used in a positive pressure or negative pressure environment, and whether the user is to be isolated from or exposed directly to the environment.

The closed circuit system of FIG. 1 incorporates an inlet outlet device 10, such as a diver's mouthpiece for an individual mobile unit or appropriate couplings to a volume containing breathable gas in a self-contained diving system. The volume to which the purified and properly adjusted gas mixture is fed and from which contaminated gases are drawn forms a part of the closed circuit system. In most positive pressure systems the gases in the volume are at pressures of several atmospheres or more. The flow path for gases in the system is established by a set of unidirectional valves 12, 13, 14 which insure circulation of gases in the proper direction in the system. As is conventional with many

positive pressure systems for individual use, an expansion bag 16 is coupled in the flow path for the incoming contaminated gases and outgoing purified gases. Thus an individual breathes into the expansion bag 16 and then withdraws gases through the system via the expansion bag 16, so that the bag 16 eases the work of breathing by compensating for changes in lung volume. The bag 16 further acts as a condensation collector for some of the water vapor in the gas.

Further water vapor present in the incoming gases is removed in a conventional water removal chamber 18, such as a desiccant unit. Compensation for changes in ambient pressure is achieved by injecting pressurized gaseous helium through a controllable pressure regulator 20 of any suitable commercially available type. The pressure regulator 20 may include a control valve actuator 22, referred to as a purge button, which may be manually actuated to fully open the helium line for momentarily pressurizing the system. The incoming gases are passed from the water removal chamber 18 into an enclosed liquid oxygen vessel 24 having a gas-containing volume separate from but communicating with liquid oxygen 25. Gases are extracted from the gas-containing volume and returned through the unidirectional valve 14 to the inlet-outlet mechanism 10. The incoming gases, cleansed of water vapor, may have carbon dioxide removed by any conventional means, and may be lowered to an appropriate temperature level by any conventional cooling means, such as a cryogenic reservoir or refrigerator. Although a heat exchanger 26 is shown and has particular advantages, its use is not required in delivering appropriately conditioned gases to the gas-containing region of the liquid oxygen reservoir 24. Similarly, the gases withdrawn from the liquid oxygen reservoir 24 may be heated to a breathable temperature by suitable mechanisms added to or separately utilized in the installation.

It should be appreciated that important aspects and advantages of the present invention derive from the combination thus far described. Proper adjustment of the proportion of oxygen in the cleansed gas mixture is necessary to provide a breathable inspiratory mixture. This result is effected by the closed circuit system components described above. As pointed out previously, the partial pressure of the oxygen is required to be between approximately 0.2 and 1 atmospheres, in order to avoid the injurious deficiency and excess conditions. In accordance with the present invention no gas mixing or control valve arrangement need be employed for injection or proportionment of oxygen nor need sensing or detecting equipment for direct measurement of oxygen pressure or percentage be used. The temperature of the liquid oxygen in the vessel 24 is maintained in a selected range, e.g., approximately 77° K-90° K establishing a predetermined oxygen gas partial pressure in the gas-containing volume communicating with the liquid oxygen. The oxygen partial pressure is solely dependent upon equilibrium conditions in the gas-liquid-oxygen interface. The equilibrium conditions are achieved when the oxygen vapor is at saturation level while the gas mixture is in thermodynamic equilibrium with the liquid.

Equilibrium for oxygen at saturation is depicted in the pressure versus temperature phase equilibria curves for oxygen and nitrogen in FIG. 2. These equilibrium relationships between multiple phase partial pressures and temperatures are not significantly affected by the

partial pressure of other constituent gases, or by the absolute pressure level of the mixed gases. Consequently, when the liquid oxygen temperature is kept between selected limits, the oxygen partial pressure is also controlled, so that the oxygen content in the breathable mixture is related directly to the needs of the user, and not to the characteristics of the respirator gas mixture itself. In effect, physiological needs are supplied by nascent gas from the liquid oxygen 25. Again, it should be explicitly noted that although superior temperature control can be achieved by utilizing a cryogenic reservoir 28 encompassing, wholly or partially, the liquid oxygen vessel 24, the controlling criterion is the maintenance of a selected gas-liquid interface temperature range, and not the means by which the range is obtained. For example, an adequately large liquid oxygen reservoir maintained in an insulated environment may have adequate life for many uses, even though no adjustable control is used to maintain the liquid oxygen temperature within the selected range.

Particular advantages derive, however, from the system of FIG. 1, especially when used with individual and mobile equipment. A heat exchanger 26, of the counter-current type, passes the incoming contaminated gases from an inlet side 30 to an outlet side 31 of the heat exchanger in a flow direction opposed to the breathable gas mixture passing from its inlet 33 to its outlet 34. Thus, the incoming expiratory gases moving between the points 30 and 31 are brought from near the breathing temperature level down to the near cryogenic level, while the outgoing inspiratory mixture is raised in temperature approximately through the same range. The drop in temperature of the incoming gases precipitates the contaminated carbon dioxide, which may therefore be removed in a solid CO₂ collector 36 coupled into a bypass conduit 38 in the conduit for the incoming gases.

The cryogenic reservoir 28 is preferably insulated, and contains liquid nitrogen or another suitable cryogen or cryogenic mixture having a boiling point comparable to that of liquid oxygen, provided that the critical temperature, the upper bound of the vapor-pressure equilibrium curve, of the cryogen is not below the operating temperature of the liquid oxygen. The cryogenic reservoir 28 may also encompass a gaseous helium containment vessel 42 coupled by a conduit 44 to the controllable pressure regulator 20. Storage of the gaseous helium vessel 42 at low temperature in this fashion provides an extremely large gas volume for use in the breathable mixture. Other gases, such as neon or argon, may, however, be used for pressure adjustment of the breathable mixture.

The cryogenic reservoir 28 is maintained in the selected temperature range desired for the liquid oxygen. To this end, a boil-off intake 46 is coupled to a conduit passing through a pressure control 50 to an exhaust receiver 52. While the boil-off gases may be employed for heat exchange purposes as well, the primary use of this arrangement is to regulate the temperature of the cryogen through control of the back pressure of its vapor, as is described in greater detail below. The pressure control 50 may comprise simply a mechanically biased valve, or may utilize other expedients set forth hereafter. The exhaust receiver 52 may take any of a variety of forms, and is employed to isolate the environment from the nitrogen pressure control 50 by supplying the energy needed (if any) to exhaust the boil-off gases into

the environment. Typically, a pump will be suitable for this purpose. Where feasible, however, a vacuum reservoir or a separate utilization device may be used as the receiver.

To summarize, therefore, the vital functions of a life support system are accomplished within this system. Not only is the oxygen partial pressure regulated, but appropriate compensation is made for pressure changes in the hyperbaric environment, as reflected within the closed circuit system. Contaminants are removed and the appropriate breathable mixture is continuously supplied. This system provides a high degree of protection against catastrophic failure, inasmuch as no sensitive operative components are employed that are critical to the functioning of the system. The oxygen partial pressure control has, in effect, a long time constant inasmuch as the temperature of the cryogenic reservoir and the liquid oxygen cannot shift suddenly. Therefore in the event that temperature control becomes inoperative, adequate time is available for the user to observe and adjust system conditions.

This closed circuit system also provides a highly interrelated usage of temperature relationships through the disposition of the various component parts of the system. These relationships may, however, be considerably revised. If a suitably large cryogenic reservoir 28 may be employed, the heat exchanger 26 may be of relatively small size or low efficiency, or may in fact be completely eliminated. Where the heat exchanger 26 is of a highly efficient type, the useful duration of a given supply of cryogen is greatly increased and therefore the volume of cryogen may be reduced. For example, in one practical system in accordance with the invention, a heat exchanger having approximately 98 percent efficiency at a uniform counter-current heat transfer rate of 500 BTU/min. but relatively small size is used in conjunction with a compact cryogenic reservoir 28 within which a liquid oxygen vessel 24 and a gaseous helium vessel 42 are maintained. This system provides an operative life in excess of 5 hours at ambient pressures in excess of 500 psi with about one-half cu. ft. of fluid storage. The unit is not only highly efficient but may be compact and light in weight.

The feasibility of use of liquid oxygen in this closed circuit system will be further evident from the following considerations. The heat capacity of 1 mole of helium gas, taking helium as the inert gas, at constant pressure is about 5 calories per degree Kelvin. The average breathing rate for one man is approximately one-half to 1.0 moles per minute at atmospheric pressure going from relaxed activity to moderate work. As a comparative reference, at 50 atmospheres of ambient pressure, corresponding to 1,620 feet of ocean water depth, the moderate work respiratory rate goes to 50 moles per minute. If expiratory gas, entering the system, is at a nominal temperature of 285° Kelvin (°K) and the cryogenic control temperature is at 85° K. then a heat exchanger efficiency of 97.5 percent causes a temperature differential of approximately 5° Centigrade (°C) over the 200° K. range, substantially throughout the length of the counter-current heat exchanger. Thus, 5° C. of equivalent heat will be transferred in the thermal exchange from the expiratory gas to the cryogen before entering the liquid oxygen container. The corresponding heat dump at 50 atmospheres of pressure is 250 gram-calories per minute per degree Kelvin of temperature differential for a respiratory minute volume com-

parable to 1.0 mole of gas at standard conditions of 1.0 atmosphere at 4° C. For 5° C. of temperature drop to the cryogenic fluid temperature, the heat transferred is 1,250 calories per minute. This is approximately the heat of vaporization of 1.0 mole of liquid nitrogen or oxygen at the temperatures employed. Thus, the boil-off rate of these fluids, used as jacketing cryogenics is about 1 mole per minute at an ocean depth of 1,620 feet. This is a fluid consumption rate of about 2.0 liters per hour of duration. The boil-off rate is about 0.8 standard cubic feet per minute.

2 Life Support Test System

Automatic adjustment of oxygen content in an incoming gas can be, it is to be noted, reciprocal in direction or opposite in purpose from a life support system, or both. In the generalized system of FIG. 1 flow in the direction reverse to that shown is not contemplated. As to that part of the system concerned with control of oxygen partial pressure reverse and different operation are fully feasible. FIG. 1 does additionally illustrate an arrangement serving to provide the converse function to a life support system. Specifically that portion of FIG. 1 within the dotted line box 43 labeled simulator and including the additional functional units coupled into the heat exchanger 26 and cryogenic reservoir system by dotted line connections serves as a simulator or test system having characteristics corresponding to a human user. In this system, the interface to any conventional life support system (not shown) is represented at the left margin of the dotted line box 43. The life support system under test provides a gas mixture adjusted for oxygen content into the test system, and receives a gas mixture deficient in oxygen content. Therefore the test system may be called a humanoid as well as a simulator or other test system for evaluation of life support systems under arbitrary pressure conditions.

In this variation of the system of FIG. 1, water in the incoming gas mixture may conveniently be removed by a condenser 45 preceding the final water removal or desiccant device 18. The CO₂ collector 36 is bypassed, as shown by the dotted coupling within the heat exchanger 26 inasmuch as the system under test is to provide the necessary removal of CO₂ and toxic hydrocarbons. Water removal is however employed to prevent clogging of the heat exchanger lines.

The source of inert gas 42 is not employed, this constituent again being supplied by the system being tested. A substantially constant or intermittent flow of gaseous carbon dioxide into the system may be injected into the outgoing gas mixture from a source 47 through a regulator 48. Finally, water vapor corresponding to the approximate amount present in an expiratory mixture is added by passing the outgoing gas through an evaporator 51.

Heretofore, appropriate testing of a life support system has demanded either human participation or the use of a complex test system. In either event adequate simulation of human usage under hyperbaric or other pressure conditions has not been satisfactorily achieved. The test system of FIG. 1 may be placed in a test environment at any pressure desired for operation of a life support system and still provide the desired humanoid simulation. The back pressure control 50 for the cryogen is set to maintain the liquid oxygen temperature such that the outgoing gas contains less than a breathable oxygen mixture. The system under test is thus required to make up the deficiency in re-

turning the gas mixture to the simulator unit 43. Further, the water vapor introduced by the evaporator 51 and the CO₂ from the source 47 are eliminated during operation as a part of the test. As the life support system purifies the outgoing gases from the simulator and adds oxygen the simulator 43 depresses the oxygen content to impose a continued demand for oxygen. The liquid oxygen temperature is held, for pure oxygen, below a temperature level at which the oxygen partial pressure is less than 0.2 atmospheres, for example. Both systems may be cycled through various pressure and temperature ranges and the effective simulation of human demand is thus accomplished.

3. Detailed System for Positive Pressure Environments

A detailed example of a system in accordance with the invention is illustrated in FIGS. 3 and 4, to which reference may now be made. This detailed example comprises a self-contained system which not only provides a closed circuit life support arrangement for an individual, but additionally makes available heat by-products for use in the system.

In the arrangement of FIGS. 3 and 4, a cryogenic system is used comprising a cylindrical storage vessel 60 for a suitable cryogen, here liquid nitrogen. The storage vessel 60 is provided with cryogenic insulation, not shown in detail, such as a double wall structure with an intermediate spacing maintained at vacuum. Alternatively, the wall of the storage vessel may be a composite including cryogenic insulation of the type having multiple layers of heat reflective material, e.g., thin aluminum sheet between which layers are interspersed glass or other fibrous mats. A liquid oxygen tank 62 is disposed within the principal storage vessel 60, the tank being of spherical form and only partially filled with liquid oxygen 63, so that an enclosed volume is maintained above the liquid oxygen 63 for containment of gases. The liquid oxygen less than half fills the spherical container so that gas outlet port 64 which reaches to the center of the sphere does not extend into the liquid in any orientation. The liquid oxygen may be fed in by an inlet valve coupled to the conduit leading to the port 64. A wicking member 65 here having the general form of a hollow surface of revolution is disposed within the liquid oxygen tank 62, and extending into the liquid oxygen 63. The wicking member 65 may comprise any woven screen or fibrous material, such as asbestos, that is capable of being wetted by the liquid oxygen and thus greatly increasing the area of the exposed surface. The gas-liquid interface region is increased to assure total saturation of incoming gases with oxygen vapor and rapid attainment of thermodynamic equilibrium at a given temperature between the oxygen in the liquid and gas states.

A helium tank 67 is also disposed within the storage vessel 60, and an outlet conduit 68 is extended into the interior of the helium tank 67 for injection of inert gas into the system as is described in greater detail below.

An advantageous arrangement of a heat exchanger system 72 for incoming and outgoing gases disposes the conduits for the gases in heat exchange relationship within a second storage vessel 70 here mounted adjacent and in parallel relation to the storage vessel 60 for the cryogen. Through advantageous use of a heat exchanger 72 comprising formed membranes defining multiple parallel passages and arrayed to form a gener-

ally rectangular cross-section, as described in greater detail in FIGS. 5 and 6 below, a heat exchange system of minimal volume and high effective heat transfer surface area is provided. For each of manipulation of the life support system by an individual diver the second storage vessel 70 may be side-by-side relation to the cryogen storage vessel 60. The heat exchanger 72 may, as illustrated, comprise a principal elongated section at one end, separated by a CO₂ trap and filter section 73 from a relatively shorter section at the other end. The principal heat exchange section may, for purposes of fabrication and assembly, be divided into a group of standardized, series coupled shorter sections. Reference should be made to the detailed views of FIGS. 5 and 6 and the accompanying description for better understanding of the internal arrangement of the heat exchanger elements.

In general terms, however, incoming expiratory contaminated gases (indicated by solid line arrows) enter a terminal header 74, providing an inlet to selected heat exchanger passageways. After passage through the heat exchanger and cooling to a suitable temperature, these gases are collected in an outlet terminal header 75. The heat exchanger 72 is arranged such that the cleansed and properly compensated gases follow flow paths (illustrated by the dotted lines arrows as directed upwardly in these Figures) opposite to the adjacent but distinctly separated passageways containing contaminated gases, in counter-current relation. An inlet side header 77 feeds the compensated gases from the tank 62 to particular passageways from which they are extracted from the heat exchanger 72 at an outlet side header 78. Interposed between the ends of the heat exchanger 72, and shunting the CO₂ filter 73, the compensated gases are passed through a bypass conduit 79.

The CO₂ filter 73 may take any of a number of forms, any of which comprise a means for removing the flocculent solid CO₂ precipitate from the gas flow within the heat exchanger 72. In the arrangement shown, the incoming gases are cooled to a level at which the gaseous carbon dioxide begins to precipitate out of solution in the form of a solid residue, this being at approximately three-quarters of the length of the heat exchanger 72 in one practical system. In the CO₂ filter 73, an outlet 80 from the principal length of the heat exchanger 72 is disposed spaced apart from and slightly overlapping an inlet 82 for the remaining part of the heat exchanger 72. The inlet 82 is covered with a fine screen 83 acting to insure separation of the solidified CO₂ from the gas stream taken into the remainder of the system.

Significant advantages are derived from this combination of the CO₂ filter 73 and heat exchanger 72. As is described in greater detail below, the heat exchanger 72 provides substantially linear passageways having no substantial transitions. This together with the fact that there is a substantial cross-sectional area available for gas flow in a given direction during heat transfer results in a low pressure gradient and little velocity change along the length of flow. The high efficiency of the heat exchanger precipitates the CO₂ within a relatively short length, this length being less than 4 inches in the practical system referred to. The substantially enclosed chamber defined by the CO₂ filter is fully open to the solid CO₂ particles. Along this relatively short length of passage, the CO₂ particles are not acted on by any sub-

stantial mechanical or physical forces, and a mass of unpacked particles is collected in the bottom (as seen in FIG. 3) receiving chamber portion of the CO₂ filter 73. The gas stream is diverted in an arcuate path through the screen 83 and into the inlet 82. The overlapping relation of the outlet 80 and the inlet 82 facilitates segregation of the flocculent solid CO₂, but inasmuch as this material does not tend to adhere to other elements such as the screen 83, no substantial back pressure is introduced into the system.

For better insulation, the second storage vessel 70 may be sealed and its interior maintained at vacuum, or alternatively it may be filled with foam or a conventional cryogenic insulative material.

The flow path of incoming gases into the system originates at the mouthpiece 85 of the breathing apparatus and passes through the conduit system including the expansion bag 86 (shown only generally) into an inlet portion of the water removal device, here comprising a desiccant chamber 88. Coupled into the conduit at the outlet portion of the desiccant chamber 88 is a regulator valve 90 responsive to the pressure of the hyperbaric environment. The regulator valve 90 opens into a conduit 92 connected to the outlet conduit 68 having access to the helium tank 67. A regulator 93 in the helium line may be used to introduce a desired pressure drop into the gas from the high pressure helium tank 67. If desired, the helium line may be passed in heat exchange relation to a warmer body so as to be brought closer to a breathable level. The regulator valve 90 includes a purge button for pressurizing the system with helium to cleanse lines and insure free flow. A unique safety capability is thus added to the system by virtue of the closed circuit arrangement in combination with inert gas injection at high pressure. If clogging does occur in the heat exchanger passageways, or if liquid should be introduced into conduits forming part of the system, these may be virtually instantaneously reopened for use by the injection of high pressure helium. This flushing of the system does not affect the oxygen balance in the system when the purging is completed, because the proper oxygen proportion is substantially immediately restored.

For simplicity of illustration, a harness for the diver operating the unit has not been shown inasmuch as any conventional backpack or harness structure may be utilized. Similarly, the unidirectional control valves have not been illustrated in FIGS. 3 and 4.

The incoming gases flow from the outlet terminal header 75 of the heat exchanger 72 into the storage vessel 60. Within the storage vessel 60, the gas stream is further cooled by being passed in heat exchange relation to the cryogen in coils 95 wound within the storage vessel 60. The coils 95 provide an isothermal heat exchange between the cryogen and the incoming gas stream, and the resultant cooling of the gas stream is sufficient to insure that the heat balance within the liquid oxygen tank 62 is not substantially disrupted by the incoming gases. In other words, expiratory gases do not tend to heat the liquid oxygen excessively.

To insure continued flow, the gas line containing the incoming gases is divided into two separate lines forming the coils 95, each curving in an opposite sense and terminating within the liquid oxygen tank 62 in facing and opposed inlet ports 96 that are above the level of the liquid oxygen. In the normal position of operation of this system, the attitude of the tanks is generally as

shown in FIG. 3, i.e., at least somewhat vertical. When the tanks are in this attitude, the inlet ports 96 lie above the liquid oxygen level. A constant attitude cannot of course be assumed under all conditions of operation. Therefore, the use of two ports 96 insures that irrespective of tilting in one direction or another at least one of the ports 96 will be open to the incoming gas stream. Furthermore, even though the remaining port 96 may temporarily be filled, liquid oxygen within it returns to the main portion of the tank 62 as soon as the attitude of the system is again approximately normal.

The gas outlet port 64, centrally disposed within the wicking member 65, provides a means for withdrawal of the compensated gases from the gas containment volume within the liquid oxygen tank 62 irrespective of the orientation of the latter. These gases are passed out of the storage vessel 60 into the inlet side header 77 of the heat exchanger and returned through the conduit system via the outlet side header 78 to the mouthpiece 85.

It has previously been stated that a number of means, including a large cryogen mass, may be utilized for maintaining the partial pressure of the oxygen within a selected range. The arrangement shown in FIGS. 3 and 4 employs the removal of boil-off gases from the cryogen at an appropriate rate determined directly by the temperature within the liquid oxygen tank 62. The arrangement is only generally described here, inasmuch as further details as to the heat exchange relationships and control of venting are described in detail in conjunction with FIGS. 5 to 7 below.

Boil-off gas line 97 extends directly into the cryogen storage vessel and feeds the boil-off gases through a supply manifold to interdigitated and convoluted paths within the heat exchanger 72. During filling of the vessel 60 the cryogen may be fed in via the gas line 97. The boil-off gases extract heat from the heat exchanger 72 in passage through a manifold system to a venting control valve 100. No liquid valving arrangement is needed because the pressure of the boil-off gases in the line 97 is arranged block flow of the liquid within the boil-off line 97. Confluent cryogen boil-off uptake lines 98A, 98B, 98C and 98, with ends open and extending into the cryogen storage volume, are disposed within the cryogenic storage vessel in a manner which precludes the escape of liquid by gravity feed. The confluent lines 98 A-D are joined in a common header 99 to boil-off line 97 within the cryogenic storage vessel. The arcuate paths of the several gas uptake lines 98 A-D are designed to provide a liquid trap for virtually any orientation of the system although there is always at least one clear path for gas flow. The common uptake manifold header 99 is disposed within the cryogen containing vessel to provide an opportunity for fluids momentarily trapped in the uptake lines due to rapid movements, to evaporate within the confines of the vessel for the purpose of exerting the full influence of their related cooling capacity. Each of the gas uptake lines 98 A-D terminates in a distinct separate region within the cryogenic reservoir 60. Each follows a pair of mutually orthogonal reentrant paths within the reservoir 60, the limits of each reentrant path being spaced more than half the corresponding dimension of the reservoir 60.

The venting control valve 100 is a regulator operating in response to a controlling mechanical force to pass the gases into a boil-off receiver system 102. A

control knob 103 may be adjusted, as described in more detail below, to select an appropriate operating level. The desired controlling mechanical force for regulating the boil-off rate passing into receiver system 102 is exerted from a thermal sensor tube arrangement 104 described in detail in conjunction with the description of FIG. 7. At this point it suffices to state that the thermal sensor tube 104 extends into the interior of the liquid oxygen tank 62 and in response to the temperature therein generates a mechanical force action on the venting control valve 100. Consequently, when the temperature of the gas-liquid interface in the liquid oxygen tank 62 rises above a predetermined point, the pressure in the sensor tube 104 opens the venting control valve 100, to pass the boil-off cryogen gases into the receiver system 102. The cryogen pressure, and therefore temperature, are correspondingly adjusted, and the liquid oxygen temperature is maintained within the desired range.

A positive action receiver system 102 is required to extract the boil-off gases only when a low pressure receiver is not available. In hypobaric environments, the environments themselves can comprise an infinite receiver. In fixed and other self-contained systems, there may be a receiver available of a different type, such as a gas or liquid container whose principal contents are gradually utilized for other purposes and which thus effectively provides a low pressure enclosure of increasing volume as the system operates, or those principal contents (solid, liquid or gas) absorb or chemically combine with the boil-off gases to form a residue (solid or liquid) resulting in a pressure that is lower than the pressure of the boil-off gases at the entrance to the receiver system 102.

The receiver system 102 of the mechanism, as shown in FIGS. 3 and 4, however, is of particular utility for hyperbaric, individual diver, systems. The vented gases are withdrawn by a compressor 105 driven by a battery 106. An outlet vent on the compressor 105 simply injects the gases into the environment, although a separate collector tank could be used to limit bubbling of gases into the environment. The heat generated within the battery 106 and the compressor 105 is also usefully employed in the system, however, inasmuch as a cooling fluid is circulated in a closed conduit path (not illustrated in detail to simplify the representation) through heat transfer conduits 108 in the diver's suit. Most receiver systems are exothermic in character, giving off heat as they operate, and this heat, as shown, is employable for the benefit of a system user, whether an individual wearing a suit or a group of individuals within a self-contained system.

The presence of these different subsystems, however, is illustrative of the many significant aspects of the invention which are corollary to the fundamental aspect of adjustment of the breathable gas mixture. Apart from straightforward and reliable flow direction controls and a compensating regulator for ambient pressure, it will be observed that a breathable oxygen mixture is provided without any mechanisms for performing sensing, computing or regulating functions. The inlet gases are brought to a suitable temperature range within the heat exchanger 72, being purified through the action of the expansion bag 86, desiccant or condensing and freezing chamber 88 and carbon dioxide filter 73. Upon entering the gas-containing volume within the liquid oxygen tank 62, the gases are in an en-

environment whose characteristics, in terms of partial pressure of oxygen, are determined solely by the saturation and thermodynamic equilibrium relations between the liquid oxygen, and the gas mixture including gaseous oxygen in communication with it, as previously described. When the temperature in the liquid oxygen tank 62 is maintained in a selected range, the partial pressure of oxygen is automatically kept within the approximately 0.2 to 1 atmosphere range that is required for the breathable mixture.

Inasmuch as the basic source of replenishment oxygen is in liquid form, a large breathable oxygen supply is available, greatly in excess of amounts which can be manipulated and used by most present day self-contained underwater breathing apparatus. Furthermore, the system efficiency is extremely high because of the closed circuit arrangement, which insures that only replenishment oxygen need be added during operation of the system.

The large cryogen reservoir comprising the storage vessel 60 represents a stable cryogenic source. Most effective use is made of this stable source, however, by utilizing an efficient counter-current heat exchanger 72 to limit heat gains in lowering the temperature of the expired mixture to the cryogenic level, while raising the adjusted mixture to a respirable level. Furthermore, the heat exchanger 72 is used to extract solidified CO₂ during the cooling of the incoming gases, and provides another advantageous aspect of the system.

Injection of helium to compensate for pressure differentials between system pressure and the hyperbaric environment, and the use of a helium tank 67 within the cryogen have additional advantages. A large volume of helium may be maintained at the low cryogen temperature. At least several times the normal useful quantity of inert gas is made available in this fashion. Although the helium provides a high percentage of the gas mixture at substantial pressures, it is not utilized physiologically and therefore a substantially lesser amount is needed. In practical systems in accordance with the invention, the useful work cycle for a diver is extended appreciably. An operating period of five hours can readily be achieved without the employment of masses or sizes of equipment so large as to limit a diver's work product.

In addition, use is made of the heat generated in the operation of the receiver system 102 to provide a part of the heat supply inevitably needed in underwater environments. The presence of large amounts of helium in a breathable mixture greatly increases the rate at which heat is lost by an individual. Thus the utilization of generated heat to supply the conduits 108 in the diver's suit supplies a basic need for such environments and increases the overall efficiency of the present system.

4. Variation of the Liquid Oxygen Purity

The useful range of partial pressure for oxygen, for purposes of human life support, has been stated as approximately 0.2 to 1.0 atmosphere. As the total respired medium is brought into thermal vapor pressure equilibrium with liquid oxygen in order to achieve the desired oxygen partial pressure, it follows that the temperature range for the pure oxygen liquid, corresponding to the safe oxygen levels cited in accordance with the data of FIG. 2, is approximately 77° K. to 90° K. The same temperature control range therefore applies to the surrounding cryogen. If, on the other hand, the

liquid oxygen is diluted with another cryogenic fluid, the former's vapor pressure is correspondingly diluted, all else remaining equal. Specifically, the partial pressure of a gas in thermal equilibrium with its liquid phase, irrespective of the ambient pressure of foreign gases in direct combination with the liquid, is proportional to the product of the subject gas partial pressure (obtaining for the pure liquid) and the fractional molar concentration of the substance in question in the liquid state. Thus, for example, whereas the partial pressure of oxygen gas in equilibrium with pure liquid oxygen at 90° K. is 0.98 atmospheres, the partial pressure for a 50 percent molar concentration of liquid oxygen (diluted, e.g., with 50 percent molar liquid nitrogen) at the same temperature of 90° K. is reduced by one-half, to 0.49 atmospheres. So long as the dilution remains fixed the respective partial pressures of the liquid constituents are invariant.

This physical principle is applicable with advantage to the cryogenically controlled system. Thus, the liquid oxygen may be diluted with another cryogenic fluid provided the vapor pressure of the diluting fluid which results thereby is tolerable for human breathing. The operating temperature of the cryogenic fluids is consequently collectively raised from that which would be employed with pure liquid oxygen, in order to provide the same level of oxygen partial pressure in the breathing medium. If the dilution is used, consideration must be given to the progressive dilution of oxygen liquid as the latter is selectively extracted from the solution by evaporation. If allowed to continue, the level of oxygen partial pressure would be altered even if temperature were held fixed. The effects of dilution may be suppressed by carrying a larger supply of liquid, so that the rate of oxygen consumption, when compared with the period of use, is not sufficient to alter the oxygen partial pressure level beyond tolerable limits. Also adjustments may be made periodically as oxygen liquid is consumed, to raise the operating temperature and offset the oxygen level decrement. The principal advantage of oxygen liquid dilution, if only for abbreviated periods of use, is the higher operating temperature of the surrounding cryogen which allows the latter a correspondingly higher operating pressure. In those cases where the cryogen pressure exceeds that of the ambient environment, system use in a positive pressure environment, without the need of an exhaust compressor or other type of receiver system, save for the environment itself may be permitted.

5. Heat Exchanger System

FIGS. 5 and 6 illustrate the general organization and particular details of a heat exchanger system having high efficiency and extreme compactness but using elements that can be readily fabricated and easily assembled. The heat exchanger is of the counter-current type, and solves the problem of headering, i.e., directing the gases into separated passageways without a complex maze of interconnections.

As best seen in FIG. 6, which is a greatly enlarged view of a segment of the heat exchanger, in which relative dimensions are not to scale in order to show the elements more clearly, the basic heat exchanger elements comprise thin corrugated membranes 110, with the corrugations running parallel and lengthwise along the membrane. Of the order of 50 corrugations per inch may be employed for use in the present system, and the peak-to-valley dimension may be of the order

of approximately 30 mils, with a membrane of the order of 0.002 inches to thickness. The membrane 110 itself is preferably of a thermosetting plastic of one of the types conveniently used in thermoforming such as the material sold under the trademark "Lexan." The corrugated configuration can be achieved by shaping the plastic between dies after bringing it above the plastic flow temperature. The waviness or repetitive deviation of the membrane 110 from its median plane to define gas passageways need not follow the generally sinusoidal form that is associated with the term "corrugation." Instead, the membrane 110 may deviate to define grooves, or peaks and valleys, in any desired periodic or even aperiodic fashion.

As to this basic heat exchanger element, a hot gas that is to be cooled is passed on one side of the membrane 110, and cold gas that is to be heated is passed on the other side of the membrane 110 in the opposite direction. Heat conduction then occurs through the thickness of the membrane. While the passage of oppositely flowing gases on different sides of an intervening separator is known for liquid and other systems, the present system is unique in at least several respects. The passageways defined by the grooves are small, and the membrane 110 is a poor heat conductor but very thin. Thermal energy is therefore readily transferable between the gases in the adjacent passageways through the membrane thickness. An advantage accrues due to the use of the corrugated membrane as the periodic surface of separation between the counter flowing gases rather than as heat conducting fins, characteristic of earlier designs. The heat transfer efficiency and amount of heat transfer surface per unit volume are thereby greatly increased. In fact, the primary limitation on the interchange of heat energy is not the minute insulative effect interposed by the membrane but the heat energy transfer within the gas itself. At the same time, however, the relatively low thermal conductivity of the membrane 110 insures that heat will not be conducted along its length parallel to the gas flow directions. Unlike prior art heat exchange systems, therefore, the opposite hot and cold ends are not interconnected by a highly conductive medium comprising the heat exchange member itself and acting in the nature of a heat sink tending to reside at a median temperature along its entire length and thereby reducing the efficiency of the heat exchanger. Because of the insulative properties of the heat exchanger material, it is possible to employ a large cross-sectional area to length ratio without significant loss of efficiency. The pneumatic impedance of the passageway system is low, providing a low pressure differential and permitting greater ease of breathing.

For separation of the gases, and for headering purposes, the peaks and valleys on opposite sides of the membrane 110 are affixed respectively to an intermediate thin lamination 112 and a relatively thicker spacer 114. As may be seen in both FIGS. 5 and 6, the intermediate laminations are disposed between a pair of membranes 110, and run the full length of the heat exchange structure. The spacers 114, however, are discontinuous along the length of the heat exchanger, and the spacers 114 and intervening open volumes are utilized for several purposes.

It is convenient for purposes of illustration and description to regard the laminated structure comprising a pair of membranes 110 between a pair of thicker

spacers 114 as a heat exchanger entity. This entity is then bounded by the thicker spacers 114, and includes an adjacent and coextensive pair of membranes 110 between which the intermediate thin lamination 112 is interposed for the full length of the heat exchanger. The laminations 112 and the spacer 114 may, as with the membranes 110, be of a suitable plastic material. Regarding the thin lamination 112 as the center of the structure, the interior adjacent passageways whose sides are bounded by the lamination 112 and the two adjacent membranes 110 provide flow paths from one end of the heat exchanger to the other. What may be termed the exterior passageways within the entity are the passageways defined between the opposite sides of the membranes 110 and the outer spacers 114. A first gas or mixture passing in one direction along the length of the heat exchanger within the interior passageways is therefore completely separated from a second gas or mixture passing along the exterior passageways. If leakage occurs due to improper bonding between the membrane and the intermediate lamination 112, there is neither a substantial temperature differential between the gases nor a mixing of unlike gases. The open volumes between the separate thicker spacers 114 provide access to all of the exterior passageways of an entity from a side of the heat exchanger. These outer open volumes communicate with the outer passageways on the lower side (as seen in FIG. 5) of the upper entity, and the upper side of the next lower heat exchanger entity. All of these open volumes communicate with common side manifolds or headers positioned at two or more regions along the heat exchanger. The necessary separation between the gas mixtures is provided by sealing surfaces 120 closing off the exterior passageways at the ends of the system, and by sealing membranes 121 closing off the interior passageways at the side header regions.

As may be seen in both FIGS. 5 and 6, therefore, gases in the interior passageways moving in a first direction (from right to left in FIGS. 5 and 6) pass from one end header 118 to the opposite header 116. The second gas mixture passing in the opposite flow direction is fed from one side heater 122 through the heat exchanger, to the opposite side heater 124.

The greatly simplified and idealized representation of FIG. 5 therefore shows a complete heat exchange structure 72 built up of successive laminations of the basic heat exchange entities until the desired cross-sectional areas for flow of the two gas mixtures are attained. It will be appreciated that the continued lamination of additional elements does not in any way change or further complicate the headering arrangement and that many hundreds of entities may be utilized. In a practical example, a heat exchanger having external dimensions of approximately 6 inches by 6 inches by 2 feet provides the needed heat transfer capacity for an individual life support system. This system operates between the breathable temperature range and at approximately the cryogenic range, transferring approximately 500 B.T.U. per minute with approximately 98 percent actual efficiency, and with a total heat exchanger volume of the order of one-half cubic foot. The gas passageways are linear, and as noted, a substantial cross-sectional area is made available for gas flow, together with an extremely large heat transfer area. Thus, a low pressure differential exists within the system. This arrangement is further characterized by

the fact that standardized heat exchange sections may be assembled of selected length and cross-sectional areas. For greater capacity or efficiency, these may be series or parallel connected simply by appropriate interconnection between the heat exchange headers.

The heat exchanger structure is also arranged to provide an additional heat transfer function, extracting heat from the principal counter-current gases with high efficiency. It will be appreciated that a temperature drop or rise may be augmented simply by insertion of an available high or low temperature source in close contact with the heat transfer entities, in view of the unrestricted interior volumes between the entities and headers. Apart from this obvious expedient, however, it is desirable in the present example to provide heat extraction from the counter flowing gas mixtures without substantially impeding gas flow and by utilizing a substantial heat exchange area. To this end, low temperature gases from a boil-off manifold 125 are passed through a tortuous conduit 126 interposed between the facing sets of exterior passageways in adjacent heat exchanger entities, and between the side headers 122, 124. The gases in the exterior passageways are kept separated by thin interior laminations 127. A tertiary heat exchange is thus effected, utilizing the boil-off gases as a heat sink that acts substantially upon both counter-flowing gases through that gas flowing in the second direction within the heat exchanger, between the side headers 122, 124.

6. Pressure and Temperature Control

Because the cryogenic reservoir, containing the gas-liquid interface volume, is not itself invested with the breathing medium, the partial pressure which exists therein by virtue of the temperature which also obtains is the total pressure in the cryogenic container. In view of the fundamentally isomorphic relationship which exists between temperature and partial pressure for any fluid in equilibrium with its vapor in and enclosed volume it is possible to control the temperature of the cryogenic fluid by mechanically regulating the back pressure of the cryogenic container. The partial pressure of oxygen vapor is obscured, in the mechanical sense, by the presence of the supportive breathing medium, consisting of appropriately proportioned inert gases, precluding, thereby, direct mechanical control of oxygen pressure. The latter is, nevertheless, indirectly regulated by equilibrium with its related liquid, the temperature of which, is identified with that of the cryogenic fluid and may be controlled as a consequence of control of the cryogenic fluid.

The arrangement of FIG. 7 illustrates one suitable arrangement of a receiver for boil-off gases and a control system for maintaining the oxygen partial pressure constant or within a selected range in the system of FIGS. 3 and 4. Portions of the system may be conventional and accordingly have been illustrated in block diagram or idealized form. Other portions of the system are shown in FIGS. 3 and 4 and accordingly are omitted herein.

The controlling mechanical force for regulating the boil-off exhaust rate to the receiver system 102 is generated by the pressure of a gas within a thermal sensor tube 130. The thermal sensor tube 130 has a sealed end 131 disposed within the liquid oxygen 63 in the liquid-oxygen tank 62, with a sufficient pressure of gas, e.g., nitrogen initially being contained within the sealed tubing to insure that a portion of the internal gas is lique-

fied within the coiled length 131 of tubing immersed in the liquid oxygen bath. The immersed length is appropriately coiled or otherwise formed to maintain contact with the liquid oxygen 63 in all orientations.

The tubing extends outside the liquid oxygen tank 62 into communication with a venting control valve 100. Gas pressure within the tube is in communication with a diaphragm 134 bearing against an axially slidable piston 136 having a radial vent 138 which moves as the piston 136 slides. The radial vent 138 opens and closes an exhaust conduit 139 for the compressor 105. A spring 140 normally opposes opening of the radial vent 138, with a force dependent upon the setting of an adjustable control knob 103.

The thermal sensor tube 130 generates a mechanical force that is substantially completely determined solely by the liquid oxygen temperature. The sealed end 131 of tubing maintained within the liquid oxygen bath insures that the liquefied nitrogen within the sealed tube assumes the liquid oxygen temperature. Therefore, the nitrogen partial pressure in the enclosed volume constituting the remainder of the tube represents the total gas pressure within the tube, and is directly dependent upon thermodynamic equilibrium between the gas and the liquid in the interface region. Relatively small variations in the absolute level of the liquid oxygen temperature nevertheless represent large relative pressure variations, and the pressure within the tube therefore covers a wide dynamic range, providing accurate and substantially linear control forces to operate the diaphragm 134. Because substantially perfect communication of pressure within the confined gas may be assumed and because that pressure is dominated by the liquefaction equilibrium condition at one end the desired force may be transmitted through a long tube, and the tube may pass through widely varying temperature zones, such as the cryogenic reservoir and the associated positive pressure environment. This closed loop temperature control system is not only extremely simple and free from reliance upon components or functional units subject to failure, but also effects the necessary temperature sensing and transduction to an amplified mechanical force at very low cost.

7. System Operating in Negative Pressure Environments

A different form of closed circuit life support system is illustrated in FIG. 8, this form having particular applicability to enclosed environments for life support in superatmospheric or space conditions. A life containment structure 150 may comprise one or several individual pressure suits, or an enclosed volume. In either event, the life containment structure 150 forms part of a closed circuit system for satisfying physiological needs for oxygen. A supply of liquid oxygen is maintained in an enclosed and insulated tank 152 that defines an enclosed volume within which gaseous oxygen is maintained at saturation and in thermodynamic equilibrium with the liquid oxygen. Gases are circulated through the life containment structure 150 via an inlet-outlet system including outlet terminal 153 and an inlet terminal 154 with the inlet terminal communicating with the enclosed volume within the liquid oxygen tank 152.

This system advantageously employs what may be regarded as the infinite heat sink capacity of a superatmospheric or outer space environment, and does not require a receiver system or a cryogen or other means

for controlling the gas mixture. Instead, a pump 156 circulates the gas through a cleansing system 157 and the remainder of the system. A sensor 158, which may be of the sensor tube type or a different form of thermally responsive sensor, operates a controllable bypass valve 159 to circulate gases through the system so as to tend to maintain a selected range of oxygen partial pressure. The circulation path from the pump 156 includes a cryogenic refrigerator 161 operating in conjunction with counter-current heat exchanger 160 and a bypass path, both coupled into the liquid oxygen tank 152. In space applications, an extended length of conduit and fins providing an adequate area of heat exchange surface with the environment is sufficient as a cold source, if insulated from radiant energy, because the environment is at approximately 4° K. and therefore represents an infinitely great negative heat capacity factor. Otherwise, a conventional power operated cryogenic refrigerator may be used. The heat exchanger 160 receives gases from the enclosed volume within the tank 152 for effecting heat transfer with the incoming gases.

When the life containment structure 150 operates without substantial physiological demand for oxygen, the only change in the temperature of the liquid oxygen in the tank 152 results from heat losses to or intake from the surrounding environment. As the oxygen in the structure 150 is lost through leakage and physiological use, without regard to variations in circulation flow rate, however, the valve 159 is operated to by-pass the cryogenic refrigerator 161 to the extent that the liquid oxygen temperature is maintained in the selected range.

The cleansing system for the contaminated gases may conveniently be incorporated in the cryogenic refrigerator 161 or heat exchanger 160 with collected water vapor and carbon dioxide being ejected into the environment. The use of a by-pass system is merely one expedient that may be employed. Variable cooling may also be achieved by using variable flow rates, or by varying the efficiency of the cryogenic refrigerator, as by varying the length of flow within a conduit system. Alternatively flow may be divided in controlled fashion between heating and cooling paths.

It is common to utilize a 100 per cent oxygen supply and a pressure of the order of 0.35 atmospheres. The flammable nature of pure oxygen, however, indicates the need for an inert component for quenching purposes in the gas mixture. The inert gas may be provided from a source 162 through a pressure regulator 164 open to the life containment structure 150. Thus, with an oxygen partial pressure of approximately 0.35 atmospheres, a total pressure of 0.50 atmospheres (or any other selected value) may be achieved by injection of the needed additional gas via the pressure regulator 164. In any such system the quenching gas should be such that it does not liquefy at the range of partial pressures utilized. Nitrogen and helium are satisfactory for the example given.

It will also be recognized, moreover, that the partial pressure of the inert gas may itself be controlled directly, with oxygen pressure being adjusted by a pressure regulator, to provide the converse of the system of FIG. 8.

Control of the partial pressure of oxygen can moreover be utilized in an open circuit system, even though such a system is wasteful of a supply of breathable gas

mixture. Furthermore, the added efficiency achieved by the use of heat exchanger mechanisms can either be realized in other ways, or need not be utilized in the system.

Although a number of alternative forms and modifications of systems in accordance with the invention have been described, it will be appreciated that the invention is not limited thereto but encompasses all variations and modifications falling within the scope of the appended claims.

What is claimed is:

1. A life support system providing a safe respirable breathing mixture in an otherwise hostile environment comprising:

15 a closed circuit gas circulating system operatively responsive to the pressure of the environment of the life support system and including a supply of liquid oxygen;

means for maintaining said liquid oxygen supply within a selected temperature region, including temperature sensing means responsive to the temperature of the liquid oxygen; and,

means coupled to the gas circulating system for passing the gases into communication with said liquid oxygen and to the life support system as a safe respirable breathing mixture, including at least one heat exchanger.

2. The invention as set forth in claim 1 above, wherein the system in addition includes means responsive to the pressure of the environment of the life support system for injecting an inert gas to provide the respirable breathing mixture at a pressure within a selected pressure range.

3. A life support system providing a safe respirable breathing mixture in an otherwise hostile environment comprising:

35 a closed circuit gas circulating system operatively responsive to the pressure of the environment of the life support system and including a supply of liquid oxygen;

means for maintaining said liquid oxygen supply within a selected temperature region, including cryogenic refrigerator means receiving at least a portion of the gases;

means coupled to the gas circulating system for passing the gases into communication with said liquid oxygen into the life support system as a safe respirable breathing mixture; and

means responsive to the liquid oxygen temperature for operating said cryogenic refrigerator means to control the temperature of the liquid oxygen supply.

4. A system for providing oxygen content control for an oxygen demand system comprising:

55 a substantially enclosed vessel containing liquid oxygen;

a cryogenic reservoir encompassing said vessel; means supplying inert gas disposed within said cryogenic reservoir, and;

means coupled to said oxygen demand system for passing gases requiring oxygen content control through said substantially enclosed vessel in communication with said liquid oxygen, said means including means for selectively varying the pressure of the gases.

5. A system for providing oxygen content control for an oxygen demand system comprising:

a substantially enclosed vessel containing liquid oxygen that only partially fills the vessel to define a gas containment volume;

a cryogenic reservoir encompassing said vessel;

means coupled to said oxygen demand system for passing gases requiring oxygen content control through said substantially enclosed vessel in communication with said liquid oxygen; and,

conduit means coupled to said means for passing gases through said substantially enclosed vessel for confining said gases in a tortuous path in heat exchange relationship within said cryogenic reservoir prior to entering said vessel.

6. The invention as set forth in claim 5 above, wherein in addition said conduit means comprises a pair of conduits passing in generally arcuate paths through said cryogenic reservoir and terminating within said vessel in oppositely disposed ports both normally within the gas containment volume.

7. A system for providing oxygen content control for an oxygen demand system comprising:

a substantially enclosed vessel containing liquid oxygen;

a cryogenic reservoir encompassing said vessel;

means coupled to said oxygen demand system for passing gases requiring oxygen content control through said substantially enclosed vessel in communication with said liquid oxygen; and,

means coupled to said cryogenic reservoir for regulating the rate of cryogen boil-off therefrom in response to the temperature of the liquid oxygen.

8. The invention as set forth in claim 7 above, wherein in addition said system includes cryogen boil-off conduit means coupled into said cryogenic reservoir, said conduit means comprising a plurality of individual conduits having terminal ports disposed at different spaced regions within said cryogenic reservoir.

9. The invention as set forth in claim 8 above, wherein said conduit means comprises four individual conduits, and said conduits have extended tortuous lengths disposed in mutually exclusive paths, each of said conduits extending in two mutually orthogonal directions through spans that are more than half of the corresponding dimension of said cryogenic reservoir, and wherein said system additionally includes manifold means coupling said four conduits together at a common region.

10. A system for providing efficient oxygen utilization from a liquid oxygen supply used for breathing purposes, and including means providing expiratory and inspiratory flows, comprising:

a heat exchanger coupled to receive expiratory flows and to provide inspiratory flows;

a substantially enclosed vessel containing liquid oxygen;

a cryogenic reservoir encompassing said vessel;

means coupling expiratory flows of gases from said heat exchanger to said substantially enclosed vessel; and,

means coupling inspiratory flows of gases from said substantially enclosed vessel to said heat exchanger.

11. The invention as set forth in claim 10 above, wherein said heat exchanger has a heat transfer efficiency in excess of 90 percent and wherein expiratory

and inspiratory gases are passed in counter-current relation.

12. The invention as set forth in claim 10 above, wherein said system further includes means coupled to said cryogenic reservoir for regulating the cryogen boil off, and wherein the cryogen boil off is passed in heat transfer relation to said heat exchanger.

13. A life support system comprising:

a conduit system for receiving contaminated gases along an inlet conduit and for providing a breathable mixture along an outlet conduit, said gases being subject to ambient pressure variations;

means responsive to said ambient pressure variations for injecting inert breathing gas into said inlet conduit to equalize pressure to the ambient level;

liquid oxygen supply means including an oxygen chamber providing a liquid oxygen-gas mixture interface;

cryogenic means in heat transfer relationship to said liquid oxygen supply means, and including means for maintaining the liquid oxygen in a selected temperature range; and,

additional conduit means including heat exchanger means coupling said inlet conduit means through said oxygen chamber to said outlet conduit means, said heat exchanger means being coupled to pass incoming gases in counter-current relation to outlet gases, and said heat exchanger means further including CO₂ precipitator means in the coupling between said inlet conduit means and said oxygen chamber.

14. A life support system for an hyperbaric environment comprising:

a conduit system for receiving contaminated expiratory gases along an inlet conduit and for providing a breathable inspiratory mixture along an outlet conduit, the hyperbaric environment providing pressure variations affecting such gases;

means responsive to said pressure variations for injecting inert breathing gas into said inlet conduit to equalize pressure to the hyperbaric environment level;

liquid oxygen supply means including an interface chamber providing an interface region between the liquid oxygen and a gas mixture;

cryogenic means in heat transfer relationship to said liquid oxygen supply means for maintaining the liquid oxygen in a temperature range from approximately 77° K. to approximately 90° K.;

heat exchanger means coupling said inlet conduit means through said interface chamber to said outlet conduit means, said heat exchanger means having a heat exchange efficiency in excess of approximately 90 percent, and passing expiratory gases in countercurrent relationship to inspiratory gases, said heat exchanger means cooling expiratory gases to below the precipitation temperature of CO₂, and further including CO₂ precipitate collector means; and,

means disposed along the inlet conduit of said conduit system for removing water vapor from expiratory gases prior to said heat exchanger means.

15. The invention as set forth in claim 14 above, wherein said cryogenic means comprises a supply of a cryogen substantially encompassing said liquid oxygen supply means, and means for regulating the tempera-

ture of said cryogen, and wherein said means for removing water vapor comprises a desiccant chamber.

16. The invention as set forth in claim 15 above, wherein in addition means are disposed within said interface chamber in contact with the liquid oxygen for providing an increased liquid oxygen surface area; and,

wherein in addition isothermal conduit means are coupled to pass expiratory gases between said heat exchanger means and the interface chamber, said isothermal conduit means passing in heat transfer relationship through said cryogen.

17. A self-contained life support system comprising:

- a substantially enclosed cryogen vessel;
- a liquid oxygen vessel disposed within said cryogen vessel; said liquid oxygen vessel being less than full of liquid to define a substantially enclosed gas containment volume in communication with the liquid oxygen;
- a high efficiency counter-current flow heat exchanger for gases mechanically coupled to said cryogen vessel, said heat exchanger having a passageway system for expiratory gases and a passageway system for inspiratory gases each having an inlet and outlet end, said heat exchanger further cooling expiratory gases below the CO₂ precipitation temperature;
- a respiratory mechanism for system users;
- a first conduit coupling said respiratory mechanism to the inlet end of said heat exchanger passageway system for expiratory gases;
- a second conduit coupling the outlet end of said heat exchanger passageway system for expiratory gases to the gas containment volume within said liquid oxygen vessel;
- a third conduit coupling the gas containment volume within said liquid oxygen vessel to the inlet end of said heat exchanger passageway system for inspiratory gases;
- a fourth conduit coupling the outlet end of said heat exchanger passageway system for inspiratory gases to said respiratory mechanism;
- a pressure operable control valve system coupled to vent gas from said cryogen vessel; and,
- a pressure generating control device in communication with the liquid oxygen in the liquid oxygen vessel and responsive to the temperature thereof for exerting variable pressure thereon to vent gas from said cryogen to maintain the temperature of the liquid oxygen substantially within a selected range.

18. The invention as set forth in claim 17 above, and including in addition a vessel for a pressurized inert gas disposed within said cryogen vessel;

- a pressure regulator coupled to receive the inert gas and to inject the inert gas into said first conduit in response to environmental pressure changes;
- a water removal chamber coupled into said first conduit; and,
- a CO₂ precipitation chamber coupled to the heat exchanger passageway system for expiratory gases at the region at which the expiratory gases are approximately at precipitation temperature.

19. The invention as set forth in claim 18 above, wherein said pressurized inert gas is helium, wherein said cryogen is nitrogen, wherein the selected range is approximately 77° K. to approximately 90° K., and

wherein the water removal chamber comprises a desiccant chamber.

20. The invention as set forth in claim 18 above, wherein the CO₂ precipitation chamber is disposed at approximately three-fourths of the length of the heat exchanger system from the inlet end for expiratory gases.

21. The invention as set forth in claim 20 above, wherein said boil-off conduit comprises a manifold and a plurality of individual inlet lines each following an extended path within said cryogen vessel from inlet openings at different regions within said vessel and each coupled to the manifold.

22. The invention as set forth in claim 21 above, wherein said cryogen vessel comprises a double-walled insulated vessel of generally cylindrical shape with hemispherical ends, and wherein said individual inlet lines for said boil-off conduit extend in reentrant paths in at least two orthogonal directions within said cryogen vessel, the limits of said paths spanning more than half of the corresponding dimension of the cryogen vessel to block passage of liquid therein.

23. The invention as set forth in claim 18 above, wherein said system further includes a boil-off conduit coupling the cryogen to said control valve, said conduit passing in heat exchange relationship to said heat exchanger; and,

wherein said second conduit passes in an extended path through said cryogen in said cryogen vessel and terminates in oppositely disposed outlets normally within the gas containment volume within said liquid oxygen vessel.

24. The invention as set forth in claim 18 above, wherein said system further includes a high surface area wicking member disposed within the liquid oxygen vessel and extending into the liquid oxygen to facilitate thermodynamic equilibrium and attainment of oxygen vapor saturation.

25. The invention as set forth in claim 18 above, wherein said system further includes a boil-off gas receiver coupled to said pressure operable control valve, and wherein said control valve includes adjustable means for varying the pressure response thereof.

26. A system for controlling the partial pressure of a selected gas comprising:

- at least one reservoir maintaining a supply of the liquid of the selected gas and defining a gas containment volume in communication with the liquid;
- conduit means having a first closed end in heat exchange relation with the liquid within the reservoir means, said conduit means including an enclosed gas-liquid interface of a second selected gas, the liquid being adjacent the closed end thereof; and,

means responsive to pressure variations in the gas in the conduit means for controlling the temperature of the liquid in said reservoir means.

27. A system for controlling the partial pressure of a selected gas comprising:

- at least one source of the selected gas in the liquid phase;
- at least one enclosed reservoir disposed adjacent said source and containing said selected gas, the gas in the reservoir being in communication and thermodynamic equilibrium with said liquid phase;
- means responsive to the temperature of said source for controlling the temperature of said source,

thereby to control the partial pressure of the selected gas; and,
means for passing foreign gases into and adjusted gases out of said at least one enclosed reservoir for the selected gas without altering the partial pressure of said selected gas.

28. A system for providing gas at a selected partial pressure, irrespective of ambient and gas mixture variations, comprising:

at least one storage vessel maintaining a liquid supply of the selected gas, and including an enclosed reservoir for maintaining a gas mixture containing the selected gas in communication and thermodynamic equilibrium with the liquid;

a liquid reservoir encompassing said storage vessel and in heat exchange relation therewith;

sensing means disposed in the liquid supply of selected gas and responsive to the temperature thereof; and,

control means coupled to said liquid reservoir and responsive to said sensing means for controlling the back pressure within said liquid reservoir to tend to maintain the temperature of the liquids in a selected range.

29. The invention as set forth in claim 28 above, wherein said sensing means comprises conduit means having an enclosed end in heat exchange relation with the liquid supply in said storage means and containing a gas-liquid interface of a selected constituent, with the liquid being disposed in heat exchange relation with said liquid supply.

30. The method of adjusting the constituents of a gaseous mixture for life support purposes comprising the steps of substantially cleansing the gaseous mixture of water vapor, toxic hydrocarbons and carbon dioxide, cooling the cleansed gases to a cryogenic level, establishing thermodynamic equilibrium between the cooled gases and liquid oxygen maintained in a selected temperature range, with the oxygen vapor at saturation, and reheating the gases to breathable temperature.

31. The method of life support in a positive pressure environment comprising the steps of circulating contaminated gases through a cryogenic environment containing liquid oxygen to adjust at least the gaseous oxygen partial pressure by establishing thermodynamic equilibrium of the gaseous mixture containing oxygen with the liquid oxygen, with the gaseous oxygen at saturation, and returning the adjusted gases to the life support system.

32. The method of adjusting the constituents of a gaseous mixture for life support purposes in a positive pressure environment comprising the steps of cooling breathed gases to precipitate CO₂, saturating the cooled gases with oxygen vapor in association with liquid oxygen, maintaining the liquid oxygen in a selected temperature range and subsequently heating the gases back to a breathable temperature.

33. The method of adjusting the partial pressure of one selected gas in a gas mixture comprising the steps of bringing the gas mixture into communication with the liquid of the selected gas, maintaining the liquid in a selected temperature range to provide thermodynamic equilibrium between the gas mixture and the liquid, with the vapor of the liquid at saturation, and substantially increasing the temperature of the liquid of the selected gas by diluting the liquid with at least a second liquid.

34. The method of adjusting the partial pressure of one selected gas in a gas mixture comprising the steps of bringing the gas mixture in communication with the liquid of the selected gas, maintaining the liquid in a selected temperature range to provide thermodynamic equilibrium between the gas mixture and the liquid, with the vapor of the liquid at saturation, and compensating for ambient pressure variations by diluting the liquid with at least one other liquid while maintaining the liquid mixture in a different temperature range.

35. A system for maintaining a selected gas in a chosen partial pressure range within an enclosed operative volume maintained at a positive pressure relative to a superatmospheric or space environment, comprising:

a storage vessel providing a liquid source of the selected gas, said storage vessel also defining a substantially enclosed gas-containment chamber in communication with the liquid, such as to establish thermodynamic equilibrium between the gas and liquid forms;

conduit means circulating gas from and to the gas containment chamber;

means operatively coupled to the liquid in the storage vessel for sensing the temperature thereof; and, refrigerator means coupled in the conduit means and responsive to the sensed temperatures for cooling the circulating gas to tend to maintain the gas and liquid temperatures within said storage vessel within a selected range.

36. The invention as set forth in claim 35 above, wherein said selected gas is oxygen, and the chosen partial pressure range comprises approximately 0.2 to 1 atmospheres and wherein said refrigerator means at least partially comprises means in heat exchange relationship with the environment.

37. The invention as set forth in claim 36 above, wherein said system further includes heat exchanger means coupled into said conduit means adjoining said storage vessel for heating and cooling the gases between breathable and cryogenic gases.

38. A system for maintaining a breathable oxygen mixture containing a selected proportion of an inert gas within an enclosed operative volume comprising:

a source of liquid oxygen, including means defining a substantially enclosed gas containment chamber in communication with the liquid oxygen;

means for maintaining the liquid oxygen in a selected temperature range to provide a chosen range of oxygen vapor partial pressures;

conduit means circulating gas from and to the enclosed operative volume through the gas chamber; and,

means providing a regulated source of the inert gas for establishing a desired total pressure within the enclosed operative volume.

39. A system for separating CO₂ from a gas mixture comprising:

a first source of gases within a temperature range below the precipitation temperature of CO₂;

a second source of gases containing CO₂ and within a temperature range above the precipitation temperatures of CO₂;

at least one heat exchanger coupled to said first and second sources of gases for passing said gases in heat exchange relation with one another, said at least one heat exchanger providing substantially

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linear gas flow with low pressure gradient and having sufficient length and area to cool gases from said second source to below the precipitation temperature of CO₂ through passing said gases in said heat exchange relation with one another;

and at least one CO₂ collector having an enclosed volume open to gases from said second source passing along said at least one heat exchanger, said enclosed volume communicating with the region along said at least one heat exchanger at which CO₂ precipitates.

40. The invention as set forth in claim 39 above, wherein said at least one heat exchanger is divided into two sections, and wherein said CO₂ collector means is disposed between said sections, and includes an outlet conduit and an inlet conduit within an enclosed chamber, with the outlet and inlet conduits being disposed in overlapping relation, and further including screen means covering said outlet conduit.

41. A system for life support comprising:
a cryogenic system for adjusting the oxygen partial pressure in a breathable gas mixture;

at least one cryogen reservoir for liquid temperature control cryogen coupled to said cryogenic system in heat exchange relation therewith for stabilizing the temperature thereof;

means coupled to said at least one cryogen reservoir for reacting exothermically with gases boiled off therefrom due to heat absorption from said cryogenic system; and

heat transmitting means for providing heat for life support purposes from said means for reacting exothermically.

42. A system for life support of a respiring user in a hyperbaric environment comprising:

a cryogenic system for adjusting the oxygen partial pressure in a gas mixture for breathing;

a reservoir containing a liquid cryogen at cryogenic temperature in heat exchange relation with at least

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part of said cryogenic system for stabilizing the temperature thereof;

receiving means coupled to said cryogenic reservoir for receiving cryogen evaporated due to heat exchange with said cryogenic system and containing exothermic means for reacting exothermically with said evaporated cryogen, said receiving means isolating the liquid cryogen from the hyperbaric environment; and

means in heat transfer relation with said receiving means for supplying heat to said user for life support.

43. The invention as set forth in claim 42 wherein said system further includes heat conduit means for transferring heat to said respiring user from said means for supplying heat, said heat conduit means being in heat transfer relation to said means for supplying heat.

44. A simulation system for extracting oxygen from a separate system operating to tend to maintain a chosen breathable gas mixture comprising:

means including a liquid oxygen supply maintained in a selected temperature region within a substantially enclosed volume;

means receiving the gas mixture from the separate system for passing the gas mixture in communication with the vapor of the oxygen supply;

means for returning the gas mixture to the separate system;

wherein the selected temperature range provides an oxygen vapor partial pressure below the range of a breathable mixture;

means coupled to the means for returning for adding gaseous contaminants to the gas mixture; and, heat exchanger means for passing the received and returning gas mixtures in counter-current relationship.

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