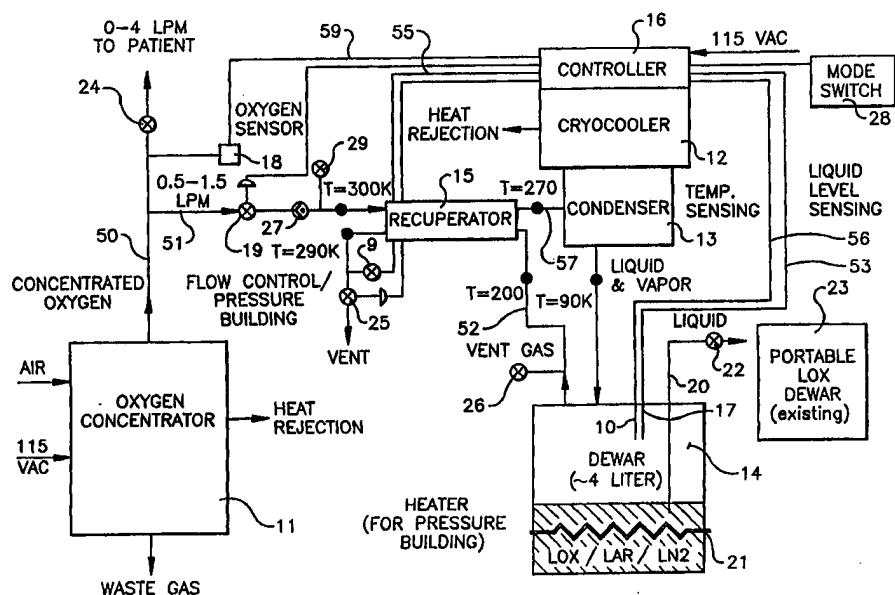


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(54) Title: METHODS AND APPARATUS TO GENERATE LIQUID AMBULATORY OXYGEN FROM AN OXYGEN CONCENTRATOR



(57) Abstract

In one preferred embodiment, the present invention splits off some of the excess capacity gas flow from a gas concentrator (11) which is then stored (14) via liquefaction. The stored gas can then be used as a portable supply. A portion of the oxygen gas flow generated by the oxygen concentrator is channeled to a condenser (13) which receives and liquefies the oxygen gas using cryocooler (12). A storage dewar (14) is used for storing the oxygen liquefied by the condenser. Liquid is then selectively transferred to a smaller portable dewar (23). A controller can be used for monitoring the parameters of liquefaction, including oxygen concentration, the amount of liquid oxygen in the dewar, and for controlling the parameters of liquid oxygen generation and transfer.

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DESCRIPTIONMETHODS AND APPARATUS TO GENERATE LIQUID AMBULATORY  
OXYGEN FROM AN OXYGEN CONCENTRATORBackground of the Invention

The field of this invention relates to using an oxygen concentrator to create a portable supply of supplementary oxygen for ambulatory respiratory patients so that they can lead normal and productive lives -- as the typical primary oxygen sources are too bulky to carry or require excessive power to operate.

There is a burgeoning need for home and ambulatory oxygen. Supplemental oxygen is necessary for patients suffering from lung disorders; for example, pulmonary fibrosis, sarcoidosis, or occupational lung disease. For such patients, oxygen therapy is an increasingly beneficial, life-giving development. While not a cure for lung disease, supplemental oxygen increases blood oxygenation, which reverses hypoxemia. This therapy prevents long-term effects of oxygen deficiency on organ systems -- in particular, the heart, brain and kidneys.

Oxygen treatment is also prescribed for Chronic Obstructive Pulmonary Disease (COPD), which afflicts about 25 million people in the U.S., and for other ailments that weaken the respiratory system, such as heart disease and AIDS. Supplemental oxygen therapy is also prescribed for asthma and emphysema.

The normal prescription for COPD patients requires supplemental oxygen flow via nasal cannula or mask twenty four hours per day. The average patient prescription is

two liters per minute of high concentration oxygen to increase the oxygen level of the total air inspired by the patient from the normal 21% to about 40%. While the average oxygen flow requirement is two liters per minute, the average oxygen concentrator has a capacity of four to six liters of oxygen per minute. This extra capacity is occasionally necessary for certain patients who have developed more severe problems but they are not generally able to leave the home (as ambulatory patients) and do not require a portable oxygen supply.

There are currently three modalities for supplemental medical oxygen: high pressure gas cylinders, cryogenic liquid in vacuum insulated containers or thermos bottles commonly called "dewars," and oxygen concentrators. Some patients require in-home oxygen only while others require in-home as well as ambulatory oxygen depending on their prescription. All three modalities are used for in-home use, although oxygen concentrators are preferred because they do not require dewar refilling or exchange of empty cylinders with full ones.

Only small high pressure gas bottles and small liquid dewars are portable enough to be used for ambulatory needs (outside the home). Either modality may be used for both in-home and ambulatory use or may be combined with an oxygen concentrator which would provide in-home use.

As we describe below, the above-described current methods and apparatus have proven cumbersome and unwieldy and there has been a long-felt need for improved means to supply the demand for portable/ambulatory oxygen.

For people who need to have oxygen but who need to operate away from an oxygen-generating or oxygen-storage source such as a stationary oxygen system (or even a portable system which cannot be easily carried), the two most prescribed options generally available to patients are: (a) to carry with them small cylinders typically in a wheeled stroller; and (b) to carry portable containers typically on a shoulder sling. Both these gaseous oxygen and liquid oxygen options have substantial drawbacks. But from a medical view, both have the ability to increase the productive life of a patient.

The major drawback of the gaseous oxygen option is that the small cylinders of gaseous oxygen can only provide gas for a short duration. Oxygen conserving devices that limit the flow of oxygen to the time of inhalation may be used. However, the conserving devices add to the cost of the service and providers have been reluctant to add it because there often is no health insurance reimbursement. Indeed, the insurance reimbursement for medical oxygen treatment appears to be shrinking.

Another drawback of the gaseous oxygen option is the source of or refill requirement for oxygen once the oxygen has been depleted from the cylinder. These small gas cylinders must be picked up and refilled by the home care provider at a specialized facility. This requires regular visits to a patient's home by a provider and a substantial investment in small cylinders for the provider because so many are left at the patient's home and refilling facility. Although it is technically possible to refill these cylinders in the patient's home using a commercial

oxygen concentrator that extracts oxygen from the air, this task would typically require an on-site oxygen compressor to boost the output pressure of the concentrator to a high level in order to fill the cylinders. Additionally, attempting to compress the oxygen in pressurized canisters in the home is dangerous, especially for untrained people. This approach of course presents several safety concerns for in-home use. For example, in order to put enough of this gas in a portable container, it must typically be compressed to high pressure (~2000 psi). Compressing oxygen from 5 psi (the typical output of an oxygen concentrator) to 2000 psi will produce a large amount of heat. (Enough to raise the temperature 165°C per stage based on three adiabatic compression stages with intercooling.) This heat, combined with the oxygen which becomes more reactive at higher pressures, sets up a potential combustion hazard in the compressor in the patient's home. Thus, utilizing and storing a high pressure gas system in the patient's home is dangerous and not a practical solution.

The convenience and safety issues are not the only drawbacks of this compressed oxygen approach. Another drawback is that the compressors or pressure boosters needed are costly because they require special care and materials needed for high pressure oxygen compatibility.

For example, a Rix Industries, Benicia, CA, 1/3 hp unit costs about \$10,000 while a Haskel International, Burbank, CA, air-powered booster costs about \$2200 in addition to requiring a compressed air supply to drive it. Litton Industries and others also make oxygen pressure boosters.

Turning now to the liquid oxygen storage option, its main drawback is that it requires a base reservoir -- a stationary reservoir base unit about the size of a standard beer keg -- which has to be refilled about once a week. The liquid oxygen can then be obtained from a base unit and transferred to portable dewars which can be used by ambulatory patients. Also, with the liquid oxygen option, there is substantial waste, as a certain amount of oxygen is lost during the transfer to the portable containers and from evaporation. It is estimated that 20% of the entire contents of the base cylinder will be lost in the course of two weeks because of losses in transfer and normal evaporation. These units will typically boil dry over a period of 30 to 60 days even if no oxygen is withdrawn.

There are other complications. Typically, supplemental oxygen is supplied to the patient by a home care provider, in exchange for which it receives a fixed monetary payment from insurance companies or Medicare regardless of the modality. Oxygen concentrators for use in the home are preferred and are the least expensive option for the home care provider. For outside the home use however, only small high pressure gas bottles and small liquid dewars are portable enough to be used for ambulatory needs. One of these two modalities may be used for both in-home and ambulatory use or may be combined with an oxygen concentrator which would provide in-home use. In either case, the home care provider must make costly weekly or biweekly trips to the patient's home to replenish the oxygen. One of the objects of this invention is to eliminate these costly "milk runs."

Portable oxygen concentrators are commercially available for providing patients with gaseous oxygen. These devices are "portable" solely in the sense that they can be carried to another point of use such as in an automobile or in an airplane. At present, there are no home oxygen concentrators commercially available that can provide liquid oxygen. One type of medical oxygen concentrator takes in air and passes it through a molecular sieve bed, operating on a pressure swing adsorption cycle, which strips most of the nitrogen out, producing a stream of ~90% oxygen, for example, as shown in U.S. Patent Nos. 4,826,510 and 4,971,609 (which are incorporated herein by reference). While, as set out in the Information Disclosure Statement, complex oxygen liquefaction systems have been disclosed for use by the military in jet aircraft, and while large-scale commercial plants have been disclosed, this technology has not yet found its way into the home to help individual patients and to benefit the general public. A truly portable oxygen concentrator has not yet been perfected and this event is unlikely, at least in the near future, because the power requirements are too large to be provided by a lightweight battery pack.

Since liquid oxygen requires periodic delivery and home oxygen concentrators are not commercially available that would create liquid oxygen, there has existed a long-felt need for a device or method having the capability to concentrate oxygen from the air, liquefy it, and transfer it into portable dewars in a home environment, and for a home oxygen concentrator unit which allows excess flow capacity from the concentrator to be stored by either compression or liquefaction for later use.

Summary of Invention

The present invention presents a much safer and less expensive way of providing portable oxygen for patients who do not want to be tied to a stationary machine or restricted by present oxygen technology. In one preferred embodiment, the present invention splits off some of the excess capacity gas flow from a PSA (pressure swing adsorption) or membrane gas concentrator which has a relatively stable base load. This small portion of the excess flow capacity, about one liter per minute (01LPM) is stored via liquefaction. The stored gas can then be used as a portable supply away from the location of the gas concentrator. The daily six hour range capacity for a two liter per minute patient can be accumulated by liquefying a one liter per minute gas flow for less than 24 hours. Therefore, the entire daily requirement for mobility can be produced every day if needed.

A summary of one of the many representative embodiments of the present invention is disclosed including a home liquid oxygen ambulatory system for supplying a portable supply of oxygen, where a portion of the gaseous oxygen output obtained from an oxygen concentrator is condensed into liquid oxygen, comprising:

(a) an oxygen concentrator which separates oxygen gas from the ambient air; (b) an outlet flow line to transfer flow of oxygen gas from said oxygen concentrator for patient use; (c) a valve placed in the outlet flow line for splitting off a portion of the oxygen gas flow generated by the oxygen generator; (d) a generally vertically oriented, gravity assisted, condenser for receiving and liquefying the split off portion of the

oxygen gas flow; (e) a cryocooler associated with said condenser; (f) a first storage dewar in fluid communication with said condenser for storing the oxygen liquefied by the condenser, the first storage dewar having an outlet selectively engageable to and in fluid communication with at least one second smaller dewar and a fluid path for supplying liquid oxygen from the first dewar to the second dewar; (g) a heater for heating said first storage dewar; (h) a controller for monitoring (i) oxygen concentration of the oxygen gas flowing from said concentrator, and (j) the amount of liquid oxygen in said first dewar, and for controlling the parameters of liquid oxygen generation and transfer from said first storage dewar.

Another representative embodiment is the feature where the flow rate into the condenser is chosen to exceed the capacity of the condenser. In particular, only 20 to 90% of the incoming flow into the condenser is condensed to minimize the liquefaction of argon, nitrogen and trace gases, and to purge the system.

Additionally, the controller may control condenser parameters so that the condenser temperature varies in the range from approximately 69.2 to 109.7K, the condenser pressure varies from approximately 5 to 65 psia, and the concentrations of gas into the condenser varies with the oxygen range being 80 to 100%, the nitrogen range being 0 to 20%, and the argon range being 0 to 7%.

A unique condenser design is also disclosed where the condenser is in thermal contact with a cryocooler for use in liquefying oxygen and comprises: (a) an inlet conduit

for receiving oxygen; (b) an outer member; (c) an inner member; (d) a passage defined by said outer and inner members; (e) said inner member having radial slots to passages; (f) means for circulating said oxygen in said condenser.

Also disclosed is a representative method for controlling a home ambulatory liquid oxygen system comprised of an oxygen concentrator, a controller having a microprocessor, a condenser, a cryocooler and a storage dewar, where all or only a portion of the oxygen flow is utilized for liquefaction, comprising: (a) providing the microprocessor with a database and control functions; (b) sensing the parameters relating to the concentration and supply of gaseous oxygen, the level of liquid oxygen in the dewar, and the pressure of the condenser; (c) providing the microprocessor with these sensed parameters and having the microprocessor calculate optimal conditions; (d) controlling servomechanisms to regulate the system so that optimal conditions are realized as a function of said calculations.

The feature is also described wherein the liquid dewar will be periodically boiled dry to eliminate any small amounts of water and hydrocarbons that may pass through the gas concentrator.

The above-summarized apparatus and methods, more specifically set out in the claims, fill long-felt needs without posing any new safety issues to the patient in that, for example, there are no potentially dangerous canisters of high pressure compressed oxygen. The end result is that patients can ultimately use equipment with

which they are familiar. For example, patients on liquid oxygen currently perform liquid transfers from large (30-50 liquid liter) dewars to small (0.5-1.2 liquid liter -- corresponding to six hours of support) portable dewars.

The present invention will provide a means of supplying ambulatory oxygen for a lower life cycle cost than the conventional method. Unlike industrial or military use liquefiers, which can take up whole rooms, the claimed oxygen liquefier (not including the oxygen concentrator) weighs less than 60 pounds and takes up less than six cubic feet of volume. There are currently about 700,000 patients in the United States using ambulatory oxygen with an average yearly cost of about \$1,960 per patient. The estimated annual cost of oxygen per patient with the present invention is about \$540.

#### Brief Description of the Drawings

Figure 1 is a block diagram of the invention in the medical oxygen preferred embodiment where gaseous oxygen is split off and liquefied for storage in a stationary dewar or container.

Figure 2 shows another preferred embodiment of the invention for ambulatory supplemental oxygen using a portable LOX dewar.

Figure 3 shows a typical temperature-composition diagram for oxygen-argon mixtures at typical dewar pressures.

Figure 4 shows a typical temperature-composition diagram for nitrogen-oxygen mixtures at typical dewar pressures.

Figure 5 shows typical oxygen concentration test data for gas streams into the condenser and out of the dewar during liquefaction, and out of the dewar as the

liquid is re-vaporized. (Oxygen source is a PSA oxygen concentrator.)

Figure 6 shows the controller block diagram for operation of the system.

Figures 7A through 7D are flow charts showing the controller logic.

Figure 8 shows the controller input levels and output states for the start-up mode of the preferred embodiment.

Figure 9 shows the controller input levels and output states for the condense mode of the preferred embodiment.

Figure 10 shows the controller input levels and output states for the transfer mode of the preferred embodiment.

Figure 11 shows the controller input levels and output state for the boil dry mode of the preferred embodiment.

Figure 12 illustrates basic components of a pulse tube refrigerator.

Figure 13 illustrates another embodiment of a cryocooler which may be used in the subject invention.

Figure 14 is a side cross-sectional view of the preferred embodiment of the condenser.

Figure 15 is an end cross-sectional view of the preferred embodiment of the condenser corresponding to Figure 14.

Figure 16 shows a side cross-sectional view of another preferred embodiment of the condenser.

Figure 17 shows an end cross-sectional view of another preferred embodiment of the condenser corresponding to Figure 16.

Figure 18 is an isometric view of the embodiment of the condenser shown in Figures 16 and 17.

Detailed Description of the Preferred Embodiment

A flow chart of the preferred embodiment of the invention is set out in Figure 1. Its main components include an oxygen concentrator 11, a cryocooler 12, a condenser 13, and a storage/collection dewar or vacuum insulated container 14. In the preferred embodiment, the oxygen concentrator 11 operates on a pressure swing adsorption cycle and essentially strips all or most of the nitrogen from air along with other minor components such as H<sub>2</sub>O, CO<sub>2</sub>, CO, NO<sub>x</sub>, etc. The result is a stream of dry gas with high oxygen concentration (~92%) flowing in fluid outlet 50. A portion of the gas from this output in fluid outlet 50 is routed to a condenser 13 in association with a cryocooler (or cryogenic refrigerator) 12 through flow lines 51 and 57. The cryocooler provides cooling of the condenser heat exchanger 13 to liquefaction temperatures, causing the oxygen in contact therewith to go from the gaseous to the liquid phase. The condenser 13 typically must be insulated from ambient heating and may in practice even be located inside the dewar 14. In order to lessen the load on the cryocooler 12, a recuperator 15 may be used to pre-cool the incoming stream utilizing the vent flow through line 52 out of the dewar as a cooling medium. In practice, this recuperator 15 may also be located within the dewar 14 to reduce ambient heating.

Controller 16 may be equipped with a microprocessor, adequate memory, software and ancillary equipment comprising a computer which can be used to monitor and control the operation of the system. The controller 16 may be provided with signals from liquid level sensor 17, oxygen sensor 18, pressure transducer 9, and temperature sensor 10 via lines 53, 59, 55 and 56, respectively.

These signals are sensed and processed by the computer, with the controller operating valve 19, valve 25, heater 21, and cryocooler 12, in accordance with predetermined programs.

The controller also provides output indicators for the patient. The liquid level in the dewar is continuously displayed and the patient is alerted when the oxygen concentration is low and when the system is ready for them to transfer liquid to a portable dewar. A modem or wireless link may be included to enable remote monitoring of the key parameters of the system by the home care provider as well as information which is useful for repair, maintenance, billing, and statistical studies of patients for the medical oxygenation market. Key system parameters of interest include the number of liquid transfers performed, the oxygen concentration history, number of run hours on the cryocooler, and time of the last boil-dry as well as number of boil dries performed.

The controller may include a computer and/or a microprocessor located either integrally with the liquefaction system claimed herein or remotely therefrom but in communication therewith using either a modem and telephone lines or with a wireless interface. The computer and/or microprocessor may include memory having a database, or may be remotely connected to a memory or database using a network. An Optimal Liquefaction Schedule for optimal operation of the liquefaction system is set out in Figures 7-10 and may be stored in said controller using the memory and database. The controller can sense optimum parameters of the system and optimally control, including by activating servomechanisms, liquefaction and transfer of liquid oxygen.

Dewar 14 is equipped with a dip tube 20 and heater 21. Heater 21 is used to build pressure in the dewar in order to expel liquid out the dip tube 20 when so desired.

A quick disconnect valve 22 or other flow control means is located on the end of the dip tube. This allows connection of a portable LOX dewar 23, which can then be carried by the patient requiring a mobile/ambulatory supply of oxygen.

In another embodiment of this system shown in Figure 2, the dewar 14 could be eliminated and replaced with a portable dewar 23 which is modified slightly from those existing today. The new portable dewar would interface with the condenser 13, recuperator 15, and controller 16. This embodiment requires a slightly different control scheme from that given for the preferred embodiment as the transfer and boil-dry modes are eliminated. Any small amount of accumulated water and hydrocarbons are eliminated from the portable dewar 23 after each use by allowing it to warm to room temperature before reuse.

In operation, in the preferred embodiment of Figure 1, where a pressure swing adsorption (PSA) system is used, air is drawn into the oxygen concentrator 11, where it is compressed by an oilless compressor, cooled, and passed through molecular sieve beds operating on the pressure swing adsorption cycle, as shown in U.S. Patents 5,366,541; 5,112,367; 5,268,021 and Re. 35,009, which are incorporated herein by reference. This PSA system produces a 5-6 liters per minute (LPM) gas stream with high oxygen concentration at 3-7 pounds per square inch gauge (psig). The composition of this gas stream varies

but is typically 90-95% oxygen, 5-6% argon, 0-4% nitrogen, <15 parts per million (ppm) water vapor, and <1 ppm hydrocarbons. Exhaust from the PSA cycle (80-84% nitrogen, 15-19% oxygen, 0.6-0.8% argon, and trace amounts of water vapor, carbon dioxide and hydrocarbons) is vented into the atmosphere as waste gas. In the preferred embodiment, the high concentration oxygen stream in fluid outlet 50 is split with 0-4 lpm going through control valve 24, for patient consumption, and 0.5-1.5 lpm through line 51 and control valve 19 for liquefaction. Oxygen sensor 18, monitors the oxygen concentration produced by oxygen concentrator 11. If the oxygen concentration falls below 88%, controller 16 will close valve 19 and turn off the cryocooler 12.

Even though 88% oxygen is adequate as supplemental oxygen therapy, if this was liquefied, as will be described below, the initial revaporized stream may have a reduced oxygen content because of the close boiling points of the components of the mixture. The temperature of the split gas stream entering the recuperator 15 is about room temperature. It is cooled to about 270K (or colder) by the vent gas from the dewar flowing through the other side of the recuperator via line 52. The recuperator 15 reduces the load on the cryocooler by using the cold vent gas to pre-cool the oxygen-rich gas stream flowing into the condenser 13. From the recuperator 15 the high oxygen concentration stream flows through a line 57 to the condenser 13, which is cooled to ~90K by the cryocooler 12.

The condenser 13 provides cold surfaces to further cool and condense the flow. It is important to note that

the gas passing through the condenser 13 is a mixture of oxygen, argon, and nitrogen. The normal boiling points of these components are: 90.18K, 87.28K, and 77.36K respectively. Because of the close boiling points of the components of this mixture, there was initial skepticism because of the concern that all the nitrogen and argon would condense along with the oxygen. If this concern was realized, when this liquid mixture was revaporized, the lower boiling point components; i.e., nitrogen and argon, would boil off first, resulting in flow with high concentrations of nitrogen, argon and a much lower oxygen concentration than that which was supplied to the condenser -- which would make the process of oxygen treatment ineffective or a failure.

This concern is explained in Figures 3 and 4 which are temperature composition diagrams for binary mixtures of oxygen-argon and oxygen-nitrogen. In these diagrams taken from K.D. Timmerhaus and T.M. Flynn, *Cryogenic Process Engineering*, Plenum Press, 1989, pp. 296-297, the upper curve at a given pressure defines the dew point and the lower curve defines the bubble point. Looking at Figure 4 for a pressure of 0.101 MPa, if there is a gas mixture with 10 mole percent nitrogen (point 1), condensation will start when the gas has cooled to the dew point curve (point 2g) which is at a temperature of about 89.5K in this case. Because oxygen has a higher boiling point than nitrogen, the initial liquid formed (point 2f) will have only 7.4 mole percent nitrogen. If the temperature is lowered to point 3, the liquid will have the composition of point 3f while the remaining vapor will

have the composition of point 3g. As the temperature is lowered further to point 4f or below, all of the mixture liquefies and the composition is 10 mole percent nitrogen, the same as at point 1. If this liquid is heated, the nitrogen which has a lower boiling point will vaporize first. Thus, the composition of the first vapor formed will be that of point 4g or about 30 mole percent. As the remaining liquid boils, the mole percent of nitrogen in the vapor drops back to 10 mole percent when point 2g is reached. It is believed that the composition swings with a ternary mixture of oxygen, argon and nitrogen will be even more pronounced than those shown in Figures 3 and 4 for binary mixtures. Fortunately, this concern was avoided when the system was set so that only 20 to 90% of the incoming flow to the condenser was actually condensed and when the condenser was controlled in accordance with the parameters as explained herein. This is believed to work because the excess flow operates to purge the vapor with higher impurity concentration from the system and avoid the aforementioned problem. Instead, the results realized were that a high concentration stream of oxygen could be liquefied and stored as set out in the portable ambulatory device claimed herein.

Figure 5 shows typical oxygen concentration test data for condensing and re-vaporizing part of the product outlet stream from the oxygen concentrator 11 in the preferred embodiment. For the first 120 minutes after the system was turned on, the system was cooling down without any net liquid accumulation in the dewar 14. From this point up to about 500 minutes, condensation continued with liquid accumulation. During this time phase, the inlet stream to the condenser 13 had an oxygen concentration of

95%, while the vent flow through line 52 had an oxygen concentration of only 92-93%. After 500 minutes the inlet stream and condenser cooling were stopped. The oxygen concentration of the re-vaporized liquid increased as the liquid boiled off due to the lower boiling point components (argon and nitrogen) boiling off first. This change in oxygen concentration presents no problem for medical ambulatory use because the oxygen concentration remains above 85%.

Because of the aforementioned mixture problem, it is important and even critical not to let the amount of argon and nitrogen in the liquid become too high or when it is revaporized, the oxygen concentration will initially be much lower than that conventionally used in supplemental oxygen therapy (>85%). This can be accomplished by selecting the proper condenser temperature, which is a function of pressure, and by not condensing all of the incoming flow. If only part of the incoming flow (20-90%) is liquefied, the remainder of the flow will purge the vapor with higher impurity concentration from the system.

A condenser temperature of about 90K (for 17 psia) minimizes the amount of argon and nitrogen liquefied without overly diminishing the yield of oxygen. Hence there will be both liquid and vapor leaving the condenser.

The liquid will fall into the dewar 14 and collect. The vapor which has not condensed is vented to the atmosphere through line 52 and the recuperator 15.

The amount of incoming flow liquefied is controlled by setting the mass flow rate relative to the cooling capacity of the cryocooler. The parameters of the condenser and/or cryocooler can be stored in the memory of

the controller and/or computer and the controller regulating the incoming flow depending on the parameters stored and/or sensed. Having a mass flow rate which exceeds the cooling capacity of the cryocooler/condenser combination, prevents the incoming flow from being completely liquefied. The mass flow rate is controlled by the amount of flow restriction between inlet valve 19 and flow control valve 25. This includes the flow losses of the valves themselves as well as those in the recuperator, condenser, and all of the interconnecting plumbing.

The pressure in the dewar 14 is maintained slightly above ambient pressure while the cryocooler is operating by valve 25. It is desirable to keep the pressure in the condenser as high as possible because this increases the condensation temperature (as shown in figures 3 and 4) which eases the requirements on the cryocooler. Once again this can be controlled by the controller and/or the computer, microprocessor and memory system.

This pressure regulating function of the solenoid on-off valve 25 is accomplished by the pressure transducer 9 and controller 16. Alternately, a back pressure regulating valve (such as a Tescom BB-3 series) or a suitable servomechanism may be used in lieu of the actively controlled solenoid. Liquid keeps accumulating in the dewar 14 until the liquid level sensor 17 signals the controller that the dewar is full or until the oxygen sensor 18 signals that the oxygen concentration of fluid exiting the oxygen concentrator 11 is too low.

In the best mode, operating parameters for optimal operation of the system for the condenser should be that

the condenser surface temperature should be in the range from 69.2-109.7K and pressure should be in the range from 5-65 psia. The gas concentrations into the condenser for medical use should have oxygen in the range of 80-100%, nitrogen from 0-20%, and argon from 0-7%.

In order to transfer liquid from the dewar 14; e.g. to fill a portable LOX dewar 23, the pressure in the dewar 14 must be increased so that liquid can be forced up the dip tube 20. As shown in Figure 1, heater 21 is used for this purpose. Heater 21 may be immersed in the liquid oxygen or attached to the outer surface of the inner vessel. The controller 16 ensures that the cryocooler 12 is turned off and valve 25 is closed before the heater 21 is energized. The heater 21 remains turned on until the pressure, measured by pressure transducer 9, reaches about 22 psig.

In order to eliminate accumulation of solid water and hydrocarbons which may be supplied in trace amounts from the oxygen concentrator, the dewar 14 will be warmed to room temperature periodically (preferably after about 30 fillings of a portable dewar, or every two months). This procedure is accomplished most economically when the inventory of liquid in the storage dewar is low; e.g. shortly after liquid transfer and a portable dewar has been filled. In this "boil-dry" mode, valve 19 will be closed, the cryocooler 12 is turned-off, valve 25 is open, and heater 21 is energized. The heater will boil-off the remaining liquid in the dewar and with it any trace amounts of water and hydrocarbons which are condensed and solidified in the liquid oxygen or on the cold surfaces. The heater 21 will remain turned on until the dewar

temperature, measured by temperature sensor 10, has warmed to about 300K. Any remaining water vapor will be flushed out by gaseous oxygen during the subsequent cool-down.

At initial start-up or after a periodic boil-dry phase, the dewar, condenser, recuperator, and all associated hardware are at room temperature and must be cooled down. This is accomplished in the **start-up** mode, where valve 19 (see Figure 1) is open, the heater is off, the cryocooler is on, and valve 25 is modulated to control the pressure/flow rate. It is desired to keep the pressure and hence the density of the gas as high as possible while maintaining the flow rate.

The higher density gas will have better heat transfer with the dewar walls and associated hardware. It is noted that higher flow rates will enhance the convection heat transfer but may exceed the cooling capacity. Based on the cooling characteristics of the cryocooler between room temperature and 90K, the flow rate can be changed to minimize the cool-down time.

The dewar 14 is equipped with at least one relief valve 26 as a safety feature. Another relief valve 29 is provided and in communication with the inlet gas stream 51, before flowing into the recuperator 15. This serves as a back-up for relief valve 26 as well as providing a means to eliminate accumulated water from the recuperator 15 during periods when the cryocooler 12 is off, if valve 25 is closed. A check valve 27 is also provided to prevent backflow into the oxygen concentrator in the event of a malfunction.

Figure 6 provides a block diagram of the controller 16 control system with sensor input value ranges and output states. It also shows interfaces to an indicator and a modem or wireless interface. The mode switch 28 may be used by the patient to request the system to prepare for a liquid transfer to a portable dewar. The indicator then provides a visual signal that the system is building pressure in the dewar. Once the pressure has reached the desired value, a visual and/or audio signal is given to alert the patient that the system is ready to transfer liquid. The controller may also be programmed to perform an unattended liquid transfer. The modem, telephone line or wireless interface connections are optional hardware that may be added to the controller to enable remote monitoring of the system by the home care provider (e.g., to assist with maintenance and repair) or insurance companies or health providers/administrators (e.g., to assess if patients are using enough ambulatory oxygen to justify payments, etc.).

Figures 7A-D show a logic flow chart for the controller for the normal operation modes. This can also be referred to as the  $\square$ input/output control schedule.  $\square$  The mode switch 28 can also be used by a repair or factory technician to put the controller in a calibration mode which serves as a method to check and reset the program. As shown in Figure 6, the indicator provides liquid level readout, transfer request status, and low oxygen concentration information to the patient. All of the sensors are continuously scanned to provide the controller with the latest information. Figures 8 through 11 provide detailed output states as a function

of input levels for the normal operating modes (start-up, condense, transfer, and boil-dry), which can be referred to as the □Optimal Liquefaction Operational Schedule.□

For example, Figure 8 relates to the start-up mode; i.e., when the system is first turned on or after the boil-dry cycle. As shown in Figures 6 through 8 and as depicted in Figure 1, at start-up mode, the liquid sensor 17 shows zero liquid volume in the dewar and, when the oxygen sensor 18 shows an oxygen concentration greater than 88%, valve 19 is open, heater 21 is off, cryocooler 12 is on, and the indicator or the controller indicates a cool-down state. Valve 25 is modulated to control pressure.

Once the system attains a cool enough temperature, steady state or normal operational condense mode is used. As shown in Figure 9, the input to the controller 16 is such that when the oxygen sensor indicates oxygen concentration being greater than 88% and when the other criteria in the left-hand column of Figure 9 are achieved, the output states set out in the right portion of the chart are attained. For example, when the level of the dewar is sensed as being full, the liquid level sensor indicates a level of approximately 100%, causing closure of valves 19 and 25, keeping the heater off, turning the cryocooler off, and having the indicator signal that the dewar is full.

The transfer mode in Figure 10 is the stage where one can fill the portable thermos bottles or dewars 23 from the main storage dewar 14. The top portion of

Figure 10, for example, shows controller readouts where, if the liquid sensor indicates a liquid level of less than 20%, then the conclusion is computed that there is not enough liquid to transfer into the portable dewar from the main dewar as shown. When the operator wants to increase the pressure in the storage dewar to force the liquid oxygen into the portable dewar, the heater is activated, and when the pressure sensor indicates that the pressure exceeds 22 psig, as shown on the last line in the left-hand column of Figure 10, the heater 21 is then turned off and the controller readout or indicator shows that the transfer of liquid oxygen can be made to the portable dewar. Finally, Figure 11 indicates the boil-dry mode, with valve 25 open to allow the vapor to escape, and the various parameters relating thereto.

Figure 12 shows a schematic of a pulse tube refrigerator, the preferred embodiment of the cryocooler 12 in Figure 1. Because the cooling load on the condenser is small (7-15W), the pulse tube refrigerator is preferred for use in the subject ambulatory oxygen system because of its good efficiency with only one moving part, the pressure oscillator. Pulse tube refrigerators are shown in US Patent Nos. 5,488,830; 5,412,952 and 5,295,355 the disclosure of which are hereby incorporated by reference. Figure 11 depicts a pulse tube refrigerator of the double inlet type. Other types of pulse tube refrigerators (PTR) could also be used such as the basic PTR or the inertance tube PTR (Zhu et al., 9<sup>th</sup> International Cryocooler Conference, NH, June 1996).

The double inlet pulse tube refrigerator as shown in Figure 12 is comprised of a pressure oscillator 30, primary heat rejector 31, regenerator 32, heat acceptor 33, pulse tube 34, orifice rejector 35, bypass orifice 36, primary orifice 37, and reservoir volume 38. The preferred refrigerant gas in the PTR closed and pressurized circuit is helium but various other gases such as neon or hydrogen could also be used. In operation, the PTR essentially pumps heat accepted at low temperature in the heat acceptor 33 to the orifice heat rejector 35 where it is rejected at near ambient temperature. Although Figure 12 depicts a □U-tube□ configuration of the PTR, in-line and coaxial configurations are other possible options. Depicted therein is a piston type pressure oscillator, but other types are possible such as those utilizing diaphragms or bellows.

Figure 13 shows a schematic of another embodiment of the cryocooler. This is a vapor compression cycle cryocooler using a mixed gas refrigerant such as shown in US Patent No. 5,579,654; a 1969 German Patent by Fuderer & Andrija; British Patent No. 1,336,892. Other types of cryocoolers will work as long as they meet the important criteria of small size, convenience and low cost. In Figure 13, the refrigerant is compressed by the compressor to high pressure. Then it is cooled by the aftercooler with heat  $Q_h$  being rejected to the environment. Oil is separated in the oil separator. Oil flows back to the compressor inlet through a flow restriction. The refrigerant gas flows to a heat exchanger where it is cooled by the returning cold stream. Some components of the mixture may condense in

this process. The liquid/gas refrigerant mixture flows through a throttle valve where its pressure is reduced and its temperature drops. This cold refrigerant enters the evaporator where the heat load  $Q_c$  is absorbed and some liquid is boiled into vapor. This vapor flows up the cold side of the heat exchanger absorbing heat from the incoming stream. Then it flows back to the compressor. Heat  $Q_c$  is accepted at cold temperature  $T_c$ . This is where the condenser would interface with the cryocooler.

It is noted that with this type of cryocooler, it may be possible to remove some of the heat from the oxygen stream at a temperature warmer than  $T_c$ .

One possible geometry of the generally vertically oriented, gravity assisted condenser 13 in Figure 1 is shown in Figures 14 and 15. The incoming gas from the oxygen concentrator flows from conduit 57 to chamber 58 and then is distributed through an annular passage 59 between the outer tube 41 and inner rod 42. The inner rod 42 is made of a high thermal conductivity material such as OFHC (Oxygen Free High Conductivity) copper, to minimize the temperature gradient between the surface on which the oxygen condenses (13) and the cryocooler 12. The cold end of the cryocooler is shown by cross-hatched member 61. Due to surface tension, the axial slots or grooves 43 will draw in liquid as it condenses. This will enhance heat transfer from the incoming gas by preventing a liquid film from forming over the entire condenser surface. Condensed liquid will drip off the bottom of the rod 42 while non-condensed gases flow out the end of the annulus 60. It is possible to liquefy

all of the incoming flow to the condenser provided the cryocooler has sufficient cooling capacity and temperature capability. However, in order to minimize the amount of nitrogen and argon condensed, the preferred embodiment only condenses between 20-90% of the incoming flow. The incoming flow rate can be determined by the appropriate sizing of flow restrictions downstream of and by controlling valve 19.

As mentioned previously, the mass flow rate is chosen to exceed the cooling capacity of the condenser/cryocooler so that only part of the incoming flow is liquefied. Also, the pressure in the condenser is maintained as high as possible while maintaining the desired flow rate. The higher pressure increases the condensation temperature which in turn reduces the requirements on the cryocooler.

Figures 16 and 17 show another embodiment of the condenser that allows easier integration with the mixed gas refrigerant cryocooler. This configuration also allows access to the liquid in the dewar through the center of the condenser. The cold end of the cryocooler 45 is in thermal contact with an outer tube 46 and an inner tube 47, both of which are made of a high thermal conductivity material such as OFHC copper and which utilize flanges 62 and 64 to interface with the cryocooler. The inner tube has axial slots or grooves 48 cut into its outer surface (see, Figure 17) to increase the surface area and to wick condensed liquid, preventing a liquid film from forming over its entire surface. Gas enters the condenser through port 63. The liquid and vapor flow down through an annular passage

49. An isometric view of this embodiment is shown in Figure 18.

Thus, an improved home/ambulatory liquid oxygen system is disclosed. While the embodiments and applications of this invention have been shown and described, and while the best mode contemplated at the present time by the inventors has been described, it should be apparent to those skilled in the art that many more modifications are possible, including with regard to scaled-up industrial applications, without departing from the inventive concepts therein. Both product and process claims have been included and in the process claims it is understood that the sequence of some of the claims can vary and still be within the scope of this invention. The invention therefore can be expanded, and is not to be restricted except as defined in the appended claims and reasonable equivalence departing therefrom.

CLAIMS

1. A home liquid oxygen ambulatory system for supplying a portable supply of oxygen, where a portion of the gaseous oxygen output obtained from an oxygen concentrator is condensed into liquid oxygen, comprising:
  - (a) an oxygen concentrator which separates oxygen gas from the ambient air;
  - (b) an outlet flow line to transfer flow of oxygen gas from said oxygen concentrator for patient use;
  - (c) a valve placed in the outlet flow line for splitting off a portion of the oxygen gas flow generated by the oxygen generator;
  - (d) a condenser for receiving and liquefying the split off portion of the oxygen gas flow;
  - (e) a cryocooler associated with said condenser;
  - (f) a first storage dewar in fluid communication with said condenser for storing the oxygen liquefied by the condenser, the first storage dewar having an outlet selectively engageable to and in fluid communication with at least one second smaller dewar and a fluid path for supplying liquid oxygen from the first dewar to the second dewar;
  - (g) a heater for heating said first storage dewar;

(h) a controller for monitoring (i) oxygen concentration of the oxygen gas flowing from said concentrator, and (ii) the amount of liquid oxygen in said first dewar, and for controlling the parameters of liquid oxygen generation and transfer from said first storage dewar.

2. The liquid oxygen system of claim 1 wherein the oxygen concentrator is a pressure swing adsorption (PSA) type oxygen concentrator.

3. The liquid oxygen system of claim 1 wherein the flow rate into the condenser is chosen to exceed the capacity of the condenser.

4. The liquid oxygen system of claim 1 wherein only 20 to 90% of the split off portion flowing into the condenser is condensed to minimize the liquefaction of argon, nitrogen and trace gases.

5. The liquid oxygen system of claim 1 wherein the controller controls condenser parameters so that the condenser temperature varies in the range from approximately 69.2 to 109.7K, the condenser pressure varies from approximately 5 to 65 psia, and the concentrations of gas into the condenser varies approximately as follows:

oxygen: 80 to 100%

nitrogen: 0 to 20%

argon: 0 to 7%

6. The liquid oxygen system of claim 1 wherein vent gas from the first storage dewar is recovered and used to pre-cool the gas into the condenser.

7. The liquid oxygen system of claim 1 wherein the condenser is in thermal contact with the cryocooler and comprises:

- (a) an inlet conduit for receiving the split off portion of oxygen;
- (b) an outer member;
- (c) an inner member having a chamber in communication with said inlet conduit;
- (d) a passage defined by said outer and inner members;
- (e) said inner member having axial slots; and
- (f) means for circulating said oxygen in said passage defined by said inner and outer members;

8. The liquid oxygen system of claim 1 wherein a generally vertically oriented, gravity assisted condenser for use in liquefaction of oxygen from its gaseous to its liquid phase comprises:

- (a) an inlet for receiving a stream of gaseous oxygen;
- (b) an outer member;
- (c) an inner member;
- (d) a passage defined by said inner and outer members, the inlet being in communication with said passage;

- (e) the inner member having axial slots to enhance heat transfer and to avoid liquid film build-up; and
- (f) at least one of said members being in thermal contact with said cryocooler.

9. The liquid oxygen system of claim 1, further comprising a recuperator interfaced between the oxygen concentrator and the condenser.

10. The liquid oxygen system of claim 1, wherein the controller senses pressure in said first dewar and controls said heater in response thereto.

11. The liquid oxygen system of claim 1 wherein the first storage dewar will be periodically boiled dry to eliminate any trace gases that may pass through the gas concentrator.

12. The liquid oxygen system of claim 1, wherein the condenser comprises a generally vertically oriented, gravity assisted, circular housing with an inner center grooved core defining an annulus and with axial slits to wick away the condensed liquid.

13. The liquid oxygen system of claim 1 wherein the controller is located remotely from the oxygen source.

14. The liquid oxygen system of claim 1 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of

liquid oxygen generation and transfer remotely using a modem.

15. The liquid oxygen system of claim 1 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of liquid oxygen generation and transfer remotely using a wireless interface.

16. A control system for a home ambulatory liquid oxygen system having an oxygen concentrator, condenser, cryocooler, a heater and a storage dewar, the control system comprising:

- (a) an oxygen concentration sensor which senses the concentration of oxygen gas generated by the oxygen concentrator and generates a first signal in response thereto;
- (b) a liquid level sensor which senses the liquid level in the dewar and generates a second signal in response thereto;
- (c) a temperature sensor which senses the temperature in the dewar and generates a third signal in response thereto;
- (d) a microprocessor for receiving the first, second and third signals for computing the flow concentration of gaseous oxygen out of the concentrator and into the condenser, the level of liquid oxygen in the dewar, the temperature in the dewar and for controlling the transfer of liquid oxygen from said storage dewar.

17. The control system in claim 16 wherein the microprocessor is located remotely from the home ambulatory system and connected to the sensors and controllers using a modem.

18. The control system in claim 16 wherein the microprocessor is located remotely from the home ambulatory system and connected to the sensors and controllers using a wireless interface.

19. The control system in claim 16 wherein the actual flow rate into the condenser is chosen to exceed the designed flow capacity of the condenser allowing the excess flow to purge the system.

20. The liquid oxygen system of claim 16 wherein only 20 to 90% of the incoming flow into the condenser is condensed to minimize the liquefaction of argon, nitrogen and trace gases.

21. The apparatus of claim 16 wherein the controller controls condenser parameters so that the condenser temperature varies in the range from approximately 69.2 to 109.7K, the condenser pressure varies from approximately 5 to 65 psia, and the concentrations of gas into the condenser varies approximately as follows:

oxygen: 80 to 100%

nitrogen: 0 to 20%

argon: 0 to 7%

22. An ambulatory liquid oxygen system where liquid oxygen is formed from gaseous oxygen obtained from an oxygen concentrator comprising:

- (a) an oxygen concentrator which separates oxygen gas from the air line;
- (b) a first output line from said oxygen concentrator for delivering oxygen gas from said concentrator;
- (c) a first valve placed in said first output line to control the output flow of oxygen;
- (d) a condenser in cooperation with a cryocooler for providing cooling for said condenser;
- (e) a second output line in communication between the first valve and the condenser for delivering the oxygen gas from the concentrator output to the condenser for cooling to form liquid oxygen;
- (f) a storage dewar for storing liquid oxygen liquefied by the condenser;
- (g) a third output line in communication between said condenser and storage dewar for delivering liquid oxygen from the condenser to the storage dewar;
- (h) a heater for heating liquid oxygen in said dewar;
- (i) an oxygen sensor to measure the oxygen concentration of flow from said concentrator;
- (j) a liquid level sensor in said dewar;
- (k) a temperature sensor in said dewar;

- (1) a pressure sensor in communication with said dewar; and
- (m) a controller for receiving output from the oxygen sensor, liquid level sensor, temperature sensor and pressure sensor, and for controlling the flow of input gaseous oxygen to the condenser and for controlling liquefaction and transfer from the storage dewar in accordance with the sensed conditions.

23. The system of claim 22 wherein the oxygen concentrator is of the Pressure Swing Adsorption (PSA) type.

24. The system of claim 22 wherein the condenser parameters are maintained as follows:

temperature from approximately 69.2 to 109.7K;  
pressure from approximately 5 to 65 psia;  
gas concentrations into condenser:  
oxygen from approximately 80 to 100%,  
nitrogen from approximately 0 to 20%, and  
argon from approximately 0 to 7%

25. The system of claim 22 further comprising a recuperator between the oxygen concentrator and condenser for pre-cooling the flow of gas into the condenser.

26. The liquid oxygen system of claim 22 wherein the flow rate into the condenser is chosen to exceed the designated capacity of the condenser.

27. The liquid oxygen system of claim 22 wherein only 20 to 90% of the incoming flow to the condenser is condensed to minimize the liquefaction argon, nitrogen and trace gases.

28. The liquid oxygen system of claim 22 wherein the generally vertically oriented, gravity assisted condenser is in contact with the cryocooler and comprises:

- (a) an inlet for receiving gaseous oxygen;
- (b) an outer tubular member;
- (c) an inner member;
- (d) a passage defined by said outer and inner members;
- (e) said inner member having axial slots cut into its outer surface;
- (f) means for circulating said oxygen in said passage; and
- (g) an outlet for releasing liquid oxygen,

wherein when said oxygen gas enters said condenser at said inlet and passes through said passage, condensation takes place causing a transition from gas to liquid phase.

29. The liquid oxygen system of claim 22 where the generally vertically oriented, gravity assisted, condenser comprises:

- (a) an inlet for receiving a stream of oxygen;
- (b) an outer member;

- (c) an inner member;
- (d) passage defined by said inner and outer members;
- (e) the inner member having axial slots to enhance heat transfer and to avoid liquid film build-up; and
- (f) an outlet for the oxygen which is liquefied.

30. The liquid oxygen system in claim 22 wherein the controller is located remotely from the oxygen generator.

31. The liquid oxygen system in claim 22 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of liquid oxygen generation and transfer remotely using a modem.

32. The liquid oxygen system in claim 22 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of liquid oxygen generation and transfer remotely using a wireless interface.

33. A method for controlling an ambulatory oxygen generator and oxygen liquefier having an oxygen concentrator, a condenser, a storage dewar and a controller comprising the following steps:

- (a) generating a gaseous supply of oxygen using the oxygen concentrator for supplying oxygen to a patient;
- (b) splitting off a portion of the gaseous supply to be liquefied;
- (c) cooling said split-off supply of oxygen using the condenser to transform the oxygen from gaseous phase to liquid phase;
- (d) storing the liquid oxygen in the storage dewar;
- (e) sensing a concentration of oxygen being supplied by the oxygen concentrator, the level of liquid oxygen in said dewar and the temperature and pressure in said dewar; and
- (f) the controller calculating conditions and controlling the operation of the above system to allow for liquefaction and operative transfer of liquid oxygen to a portable dewar.

34. A method for controlling a home ambulatory liquid oxygen system comprised of an oxygen generator, a controller having a microprocessor, a condenser, a cryocooler and a storage dewar, where all or only a portion of the oxygen flow is utilized for liquefaction, comprising:

- (a) providing the microprocessor with a database and control functions;
- (b) sensing the parameters relating to the concentration and supply of gaseous

oxygen, the level of liquid oxygen in the dewar, and the pressure of the condenser;

- (c) providing the microprocessor with these sensed parameters and having the microprocessor calculate optimal conditions;
- (d) controlling servomechanisms to regulate the system so that optimal conditions are realized as a function of said calculations.

35. An ambulatory home oxygen concentrator liquefaction system comprising:

- (a) an oxygen concentrator which can isolate oxygen gas from the air;
- (b) a first output means from the concentrator to channel the oxygen which is isolated;
- (c) a second means to split off all or a portion of the gaseous oxygen from the output means of said concentrator for liquefaction;
- (d) a condenser which can cause gaseous oxygen to change phase into liquid oxygen;
- (e) means to channel the oxygen stream from said output means to a condenser;
- (f) means to liquefy said oxygen stream in said condenser using a cryocooler; and
- (g) means to collect the condensed liquid oxygen using a first dewar, wherein said first dewar includes a heater which can

be used to effectuate the transfer of liquid oxygen from the first dewar to a second dewar for storing a quantity of liquid oxygen from which smaller quantities can be transferred for moveable oxygen treatment.

36. The apparatus of claim 35 wherein the oxygen concentrator is a pressure swing adsorption (PSA) type oxygen concentrator.

37. The liquid oxygen system of claim 35 wherein the flow rate into the condenser is chosen to exceed the capacity of the condenser.

38. The liquid oxygen system of claim 35 wherein only 20 to 90% of the incoming flow to the condenser is condensed to minimize the liquefaction argon, nitrogen and trace gases.

39. The apparatus of claim 35 wherein the controller controls condenser parameters or ranges so that the condenser temperature varies in the range from approximately 69.2 to 109.7K and the condenser pressure varies from approximately 5 to 65 psia, and the concentrations of gas into the condenser varies approximately as follows:

Oxygen: 80 to 100%

Nitrogen: 0 to 20%

Argon: 0 to 7%

40. The apparatus of claim 35 wherein vent gas from the storage dewar is recovered and used to pre-cool the gas into the condenser.

41. The apparatus of claim 35, further comprising a recuperator interfaced between the oxygen concentrator and the condenser.

42. The apparatus of claim 35, further comprising a controller which senses pressure in the first dewar and controls said heater in response thereto.

43. The system set forth in claim 35 wherein the liquid dewar will be periodically boiled dry to eliminate any trace gases that may pass through the gas concentrator.

44. The apparatus of claim 35, wherein the generally vertically oriented, gravity assisted condenser comprises a circular housing with an inner center grooved core defining an annulus and with axial slits to wick away the condensed liquid.

45. The liquid oxygen system in claim 42 wherein the controller is located remotely from the oxygen generator.

46. The liquid oxygen system in claim 42 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of liquid oxygen generation and transfer remotely using a modem.

47. The liquid oxygen system in claim 42 wherein the controller monitors the oxygen concentration and amount of liquid oxygen and controls the parameters of liquid oxygen generation and transfer remotely using a wireless interface.

48. A controller for a home ambulatory liquid oxygen system having a computer, an oxygen concentrator, condenser, and storage dewar comprising:

- (a) means for sensing the oxygen pressure of flow out of the concentrator;
- (b) means for sensing the oxygen concentration of flow out of the concentrator;
- (c) means for sensing the liquid level in the dewar;
- (d) means for sensing flow parameters at the condenser;
- (e) means for sensing the temperature at the dewar;
- (f) means for controlling input of gaseous oxygen to the condenser;
- (g) means for initiating and controlling the output of liquid oxygen from the storage dewar;
- (h) a programmable control means coupled to each means for sensing, said programmable control means to be used for storing at least one required input/output control schedule, for processing the inputted signals and for actuating one or more control means.

49. A system for liquefying oxygen utilizing an oxygen concentrator, condenser, cryocooler and storage dewar comprising:

- (a) a first flow control means for channeling off gaseous fluid flow from an oxygen concentrator;
- (b) a second flow control means for advancing said gaseous fluid to a condenser;
- (c) means for cooling said condenser to change the phase of said oxygen flow from gas to liquid;
- (d) a conduit for transferring the liquid oxygen from the condenser to a storage dewar;
- (e) a third flow control means for advancing the flow of liquid oxygen out of the storage dewar;
- (f) a controller for sensing the oxygen concentration of flow into the condenser, for sensing the liquid level in the storage dewar, and for controlling said first, second, and third flow control means;
- (g) programmable control means in said controller coupled to each of said flow control means, for storing flow delivery and liquefaction parameters for use by the controller in optimizing liquefaction of oxygen.

50. The liquid oxygen system of claim 49 wherein the flow rate into the condenser is controlled to exceed the capacity of the condenser.

51. The liquid oxygen system of claim 49 wherein only 20 to 90% of the incoming flow to the condenser is condensed to minimize the liquefaction argon, nitrogen and trace gases.

52. The liquid oxygen system of claim 49 wherein contact with a cryocooler for use in liquefying oxygen comprises:

- (a) an inlet for receiving gaseous oxygen;
- (b) an outer tubular member;
- (c) a generally vertically oriented inner member;
- (d) a passage defined by said outer and inner members;
- (e) said generally vertically oriented inner member having axial slots cut into its outer surface;
- (f) means for circulating said oxygen in said passage; and
- (g) an outlet for releasing liquid oxygen;

wherein when said oxygen gas enters said condenser at said inlet and passes through said passage, condensation takes place causing a transition from gas to liquid phase.

53. The liquid oxygen system of claim 49 where the generally vertically oriented, gravity assisted condenser for use in liquefaction of oxygen from its

gaseous to its liquid phase and for use with a cryocooler comprises:

- (a) an inlet for receiving a stream of oxygen;
- (b) an outer member;
- (c) an inner member;
- (d) passage defined by said inner and outer members;
- (e) the inner member having axial slots to enhance heat transfer and to avoid liquid film build-up
- (f) an outlet for the oxygen which is liquefied.

54. A generally vertically oriented, gravity assisted condenser in thermal contact with a cryocooler for use in liquefying oxygen comprising:

- (a) an inlet for receiving gaseous oxygen;
- (b) an outer tubular member;
- (c) an inner member;
- (d) a passage defined by said outer and inner members;
- (e) said inner member having axial slots cut into its outer surface;
- (f) means for circulating said oxygen in said passage; and
- (g) an outlet for said liquid oxygen;

wherein when said oxygen gas enters said condenser at said inlet and passes through said passage, condensation takes place causing a transition from gas to liquid phase.

55. A generally vertically oriented, gravity assisted condenser for use in liquefaction of oxygen from its gaseous to its liquid phase and for use with a cryocooler comprising:

- (a) an inlet for receiving a stream of oxygen;
- (b) an outer member;
- (c) an inner member;
- (d) passage defined by said inner and outer members;
- (e) the inner member having axial slots to enhance heat transfer and to avoid liquid film build-up; and
- (f) an outlet for the liquid oxygen to exit the condenser.

56. A home liquefaction system including an oxygen concentrator, controller with a programmable control means, condenser, cryocooler and storage dewar comprising:

- (a) an oxygen concentrator which separates oxygen gas from the air;
- (b) a first flow line from said oxygen concentrator for delivering oxygen gas from said concentrator;
- (c) a first valve placed in said first flow line to control the output flow of oxygen;

- (d) a condenser in cooperation with a cryocooler for providing cooling for said condenser;
- (e) a second flow line in communication between the first valve and the condenser for delivering the oxygen gas from the concentrator output to the condenser for cooling to form liquid oxygen;
- (f) a storage dewar for storing liquid oxygen liquefied by the condenser;
- (g) a third flow line in communication between said condenser and storage dewar for delivering liquid oxygen from the condenser to the storage dewar;
- (h) a heater for heating liquid oxygen in said dewar;
- (i) an oxygen sensor to measure the oxygen concentration of flow from said concentrator;
- (j) a liquid level sensor in said dewar;
- (k) a temperature sensor in said dewar;
- (l) a pressure sensor for sensing pressure in said dewar;
- (m) a second valve for regulating flow of liquid oxygen from said dewar;
- (n) a controller for receiving output from the oxygen sensor, liquid level sensor, temperature sensor and pressure sensor, and having means for storing at least one parameter from the Optimum Liquefaction Schedule, for controlling the flow of input gaseous oxygen to the condenser, and for optimizing liquefaction and

transfer from the storage dewar in accordance with the sensed conditions.

57. The apparatus of claim 56 wherein said programmable control means including means for storing information relating to optimum condenser parameters and for displaying an indicium of the modes of operation prior to activating any of said flow control means.

58. A system as in claim 56 wherein said programmable control means includes means for scheduling intermittent actuation of one or more of said valves so as to permit the system to be operated in accordance with the Optimum Liquefaction Schedule;

59. A system as in claim 56 including means for adjusting actuation of selected flows and conditions so as to optimize condenser parameters in response to said programmable control means and Optimum Liquefaction Schedule.

60. A system as in claim 56 including means for visually displaying controller parameters.

61. A system in claim 56 including means for transferring said liquid oxygen from said storage dewar to the delivery port at a controllable rate and including means to actuate said means in accordance with a predetermined Optimum Liquefaction Schedule;

62. An oxygen liquefaction system utilizing a concentrator to increase the oxygen concentration of an oxygen enriched product gas comprising:

- (a) a first output line for transporting said product gas from said concentrator;
- (b) a first valve for selectively withdrawing all or a portion of said product gas from said conduit to be liquefied;
- (c) flow rate sensor independent of said first valve for sensing the rate of withdrawal of the product gas from said conduit to be liquefied and for communicating the sensed rate of withdrawal of said product gas to a modem;
- (d) an oxygen sensor for sensing the oxygen concentration in said oxygen enriched product gas selectively withdrawn for liquefaction and for communicating the sensed oxygen concentration in said product gas to a first modem;
- (e) a condenser for receiving the product gas withdrawn from said first flow control means;
- (f) a second output line from said first flow control means oxygen concentrator for delivering oxygen gas from said concentrator for a first use;
- (g) a second flow rate sensor in said second output line;
- (h) a second oxygen sensor in said second output line;
- (i) a cryocooler for providing cooling for said condenser;

- (j) a storage dewar for storing liquid oxygen liquefied by the condenser;
- (k) a third output line in communication between said condenser and storage dewar for delivering liquid oxygen from the condenser to the storage dewar;
- (l) a heater for heating liquid oxygen in said dewar;
- (m) a liquid level sensor for sensing the level in said dewar;
- (n) a temperature sensor for sensing the temperature in said dewar;
- (o) a pressure sensor for sensing the pressure in said dewar;
- (p) a second modem for receiving quantitative signals communicated from said flow rate sensing means and said oxygen sensing means and for transmitting said signals to a remote controller; and
- (q) a remote controller in telephonic communication with said first and second modems for receiving transmitted signals from said modems and having means for displaying the liquefaction parameters in the liquefaction process.

63. The oxygen liquefaction system of claim 62 wherein the concentrator increases the oxygen concentration of an oxygen enriched product gas recovered therefrom using a plurality of molecular sieve beds for receiving atmospheric air for selectively adsorbing nitrogen therefrom, an electric motor driven compressor including means for providing line voltage

for operating said compressor, and a valve cooperating with said compressor for alternately charging said sieve beds with atmospheric air and timing means for switching said valve to alternately charge said sieve beds according to a timing cycle.

64. The oxygen liquefaction system of claim 62 wherein said flow rate sensors comprise a pressure transducer for measuring product gas pressure therein.

65. The system of claim 64 including a microprocessor cooperating with said pressure transducers and having means for determining the rate of flow of product gas into the condenser in response to pressure sensings therein.

66. The system of claim 65 wherein said test apparatus includes visual display means for displaying the product gas flow rate and the oxygen concentration into the condenser and the pressure and temperature in the storage dewar.

67. The system of claim 62 wherein said remote control apparatus includes means for selectively signaling said modem to transmit said signals from said liquefaction apparatus.

68. The system of claim 62 including a microprocessor having means for receiving the sensed rate of product gas withdrawal and oxygen concentration in said product gas from said oxygen sensor, the pressure, temperature, and liquid level in the storage dewar, and having memory means provided with minimum

selected parameters at different conditions, means for comparing the sensed parameters with the minimum selected parameters, and means for signaling said modem to transmit said signals to said controller when said sensed parameters fall below said minimum selected parameters.

69. The oxygen concentrator of claim 68 wherein said first modem is connected to said microprocessor and said second remote modem is connected to said controller at a remote location, and wherein said modems are in telephonic communication.

70. The concentrator of claim 69 wherein said microprocessor includes means for signaling said first modem to transmit said signals to said controller when said sensed oxygen concentration or liquefaction falls below said minimum selected parameters.

71. The apparatus of claim 70 wherein said microprocessor cooperates with said first means and said second means and wherein said controller includes selective digital display means for displaying liquefaction parameters.

72. The system in claim 70 wherein the entry system not including the oxygen concentrator weighs no more than about 60 pounds and takes up less than about six cubic feet of volume.

73. An ambulatory liquid oxygen system where liquid oxygen is formed from gaseous oxygen obtained from an oxygen concentrator comprising:

- (a) an oxygen concentrator which separates oxygen gas from the air;
- (b) a first output means from said oxygen concentrator for delivering oxygen gas from said concentrator;
- (c) a first valve placed in said first output means to control the output flow of oxygen;
- (d) a condenser in cooperation with a cryocooler for providing cooling for said condenser;
- (e) a second output line in communication between the first valve and the condenser for delivering the oxygen gas from the concentrator output to the condenser for cooling to form liquid oxygen;
- (f) a storage dewar for storing liquid oxygen liquefied by the condenser;
- (g) a third output line in communication between said condenser and storage dewar for delivering liquid oxygen from the condenser to the storage dewar;
- (h) a heater for heating liquid oxygen in said dewar;
- (i) an oxygen sensor to measure the oxygen concentration of flow from said concentrator;
- (j) a liquid level sensor in said dewar;
- (k) a temperature sensor in said dewar;
- (l) a pressure sensor in communication with said dewar;

(m) a controller for receiving output from the oxygen sensor, liquid level sensor, temperature sensor and pressure sensor, and for controlling the flow of input gaseous oxygen to the condenser and for optimizing liquefaction and transfer from the storage dewar in accordance with the sensed conditions.

74. An ambulatory home oxygen concentrator liquefaction system comprising:

- (a) an oxygen concentrator which can isolate oxygen gas from the air;
- (b) a first output means from the concentrator to channel the oxygen which is isolated;
- (c) a second means to split off all or a portion of the gaseous oxygen from the output means of said concentrator for liquefaction;
- (d) a condenser which can cause gaseous oxygen to change phase into liquid oxygen;
- (e) means to channel the oxygen stream from said output means to a condenser;
- (f) means to liquefy said oxygen stream in said condenser using a cryocooler;
- (g) means to collect the condensed liquid oxygen using a dewar;
- (h) wherein said dewar includes a heater which can be used to effectuate the transfer of liquid oxygen from the dewar

for storing a quantity of liquid oxygen from which smaller quantities can be transferred for moveable oxygen treatment.

75. A system for liquefying oxygen utilizing an oxygen concentrator, condenser, cryocooler and storage dewar comprising:

- (a) a first flow control means for channeling off gaseous fluid flow from an oxygen concentrator;
- (b) a second flow control means for advancing said gaseous fluid to a condenser;
- (c) means for cooling said condenser to change the phase of said oxygen flow from gas to liquid;
- (d) a conduit for transferring the liquid oxygen from the condenser to a storage dewar;
- (e) a third flow control means for advancing the flow of liquid oxygen out of the storage dewar;
- (f) a controller for sensing the oxygen concentration of flow into the condenser, for sensing the liquid level in the storage dewar, and for controlling said first, second, and third flow control means;
- (g) programmable control means in said controller coupled to each of said flow control means, for storing flow delivery and liquefaction parameters for use by

the controller in optimizing liquefaction of oxygen.

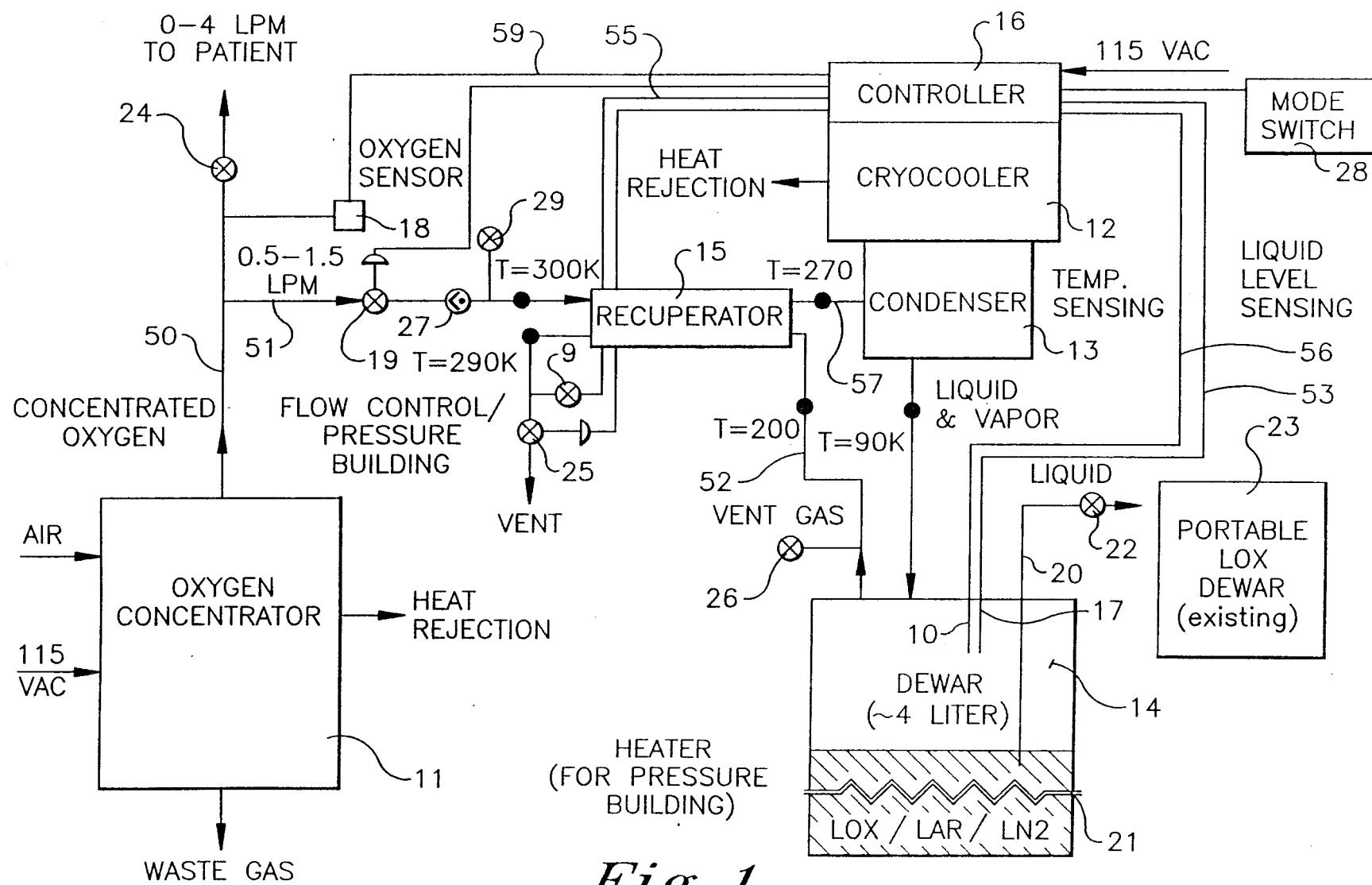


Fig. 1

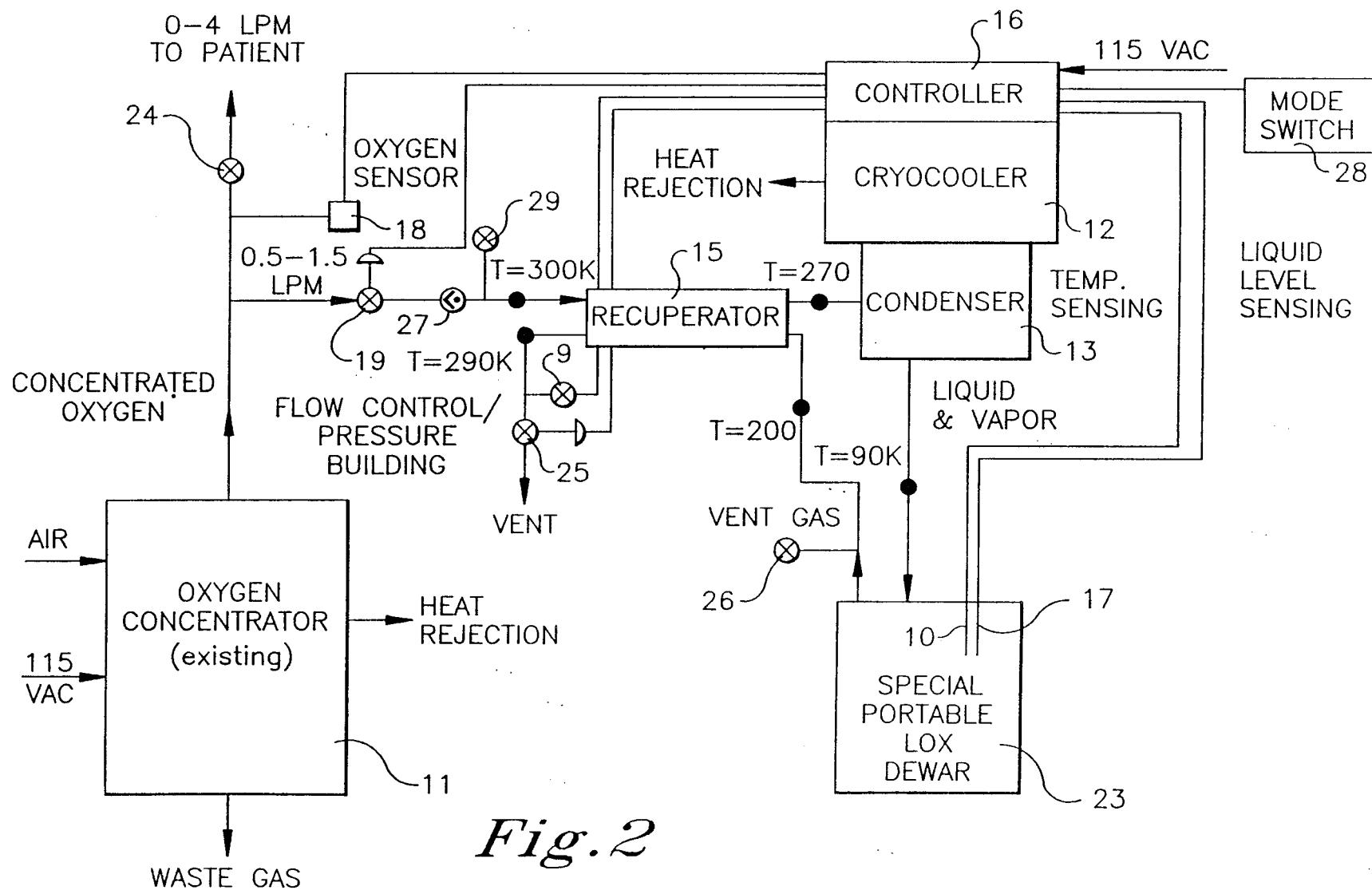
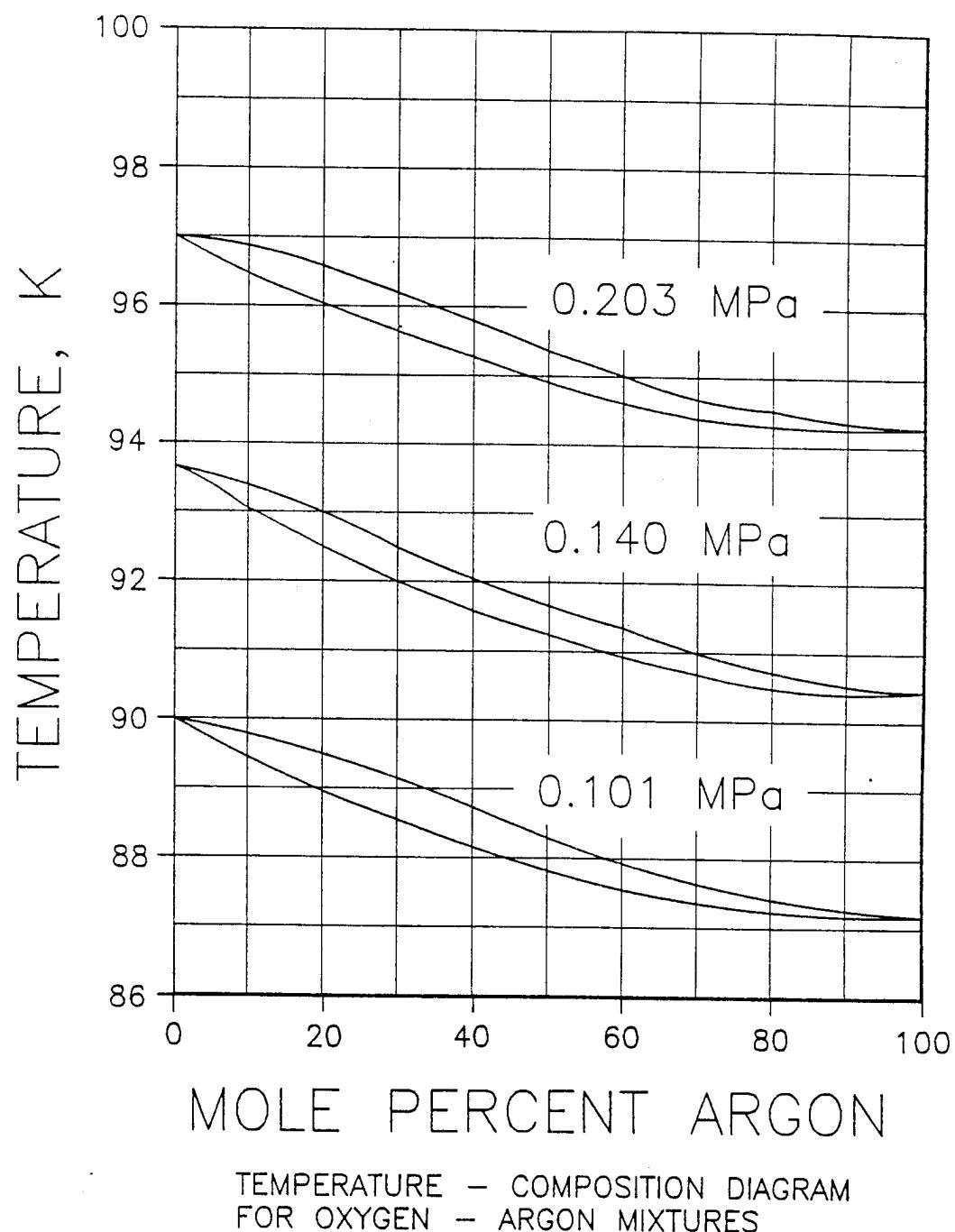


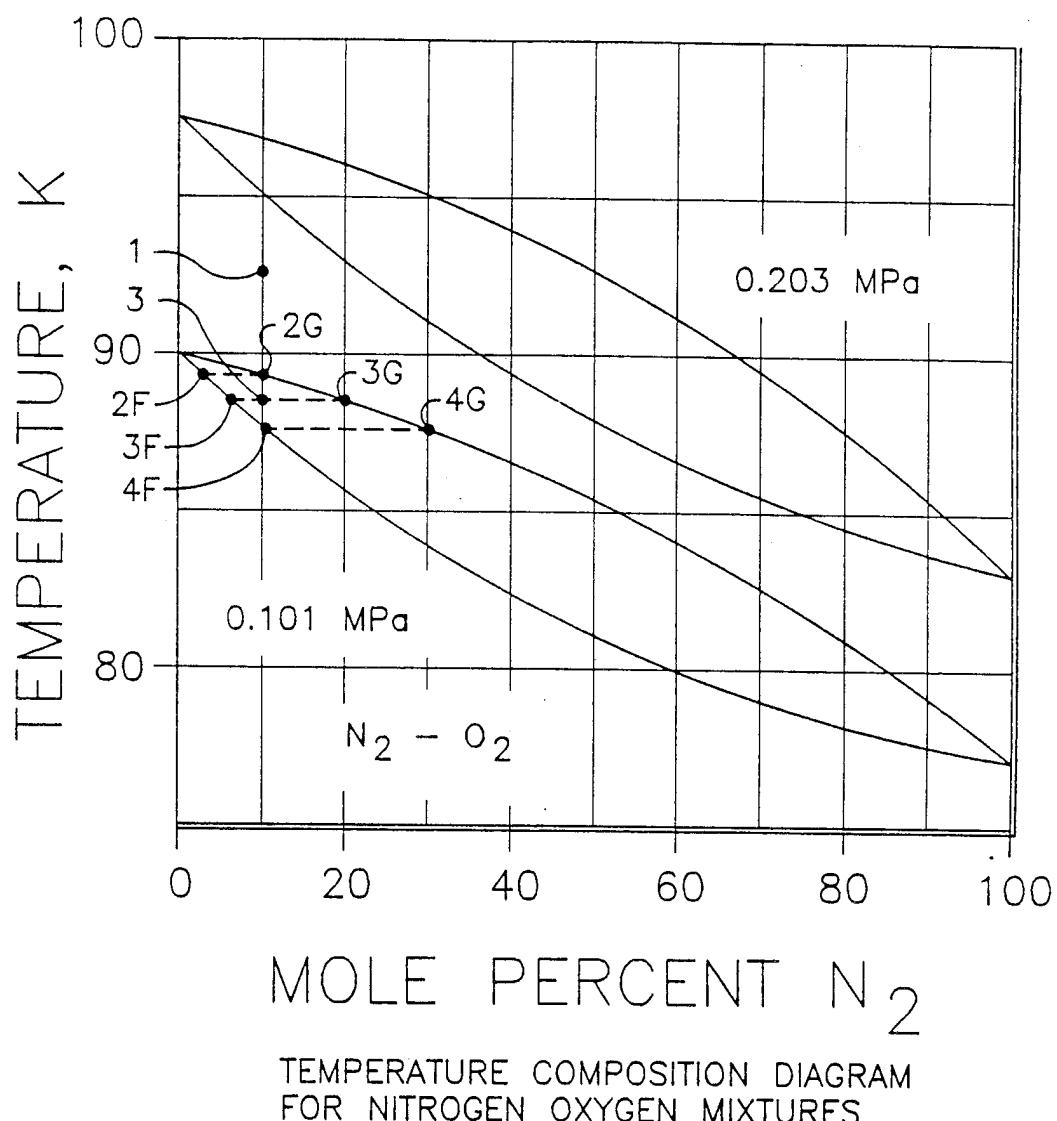
Fig. 2

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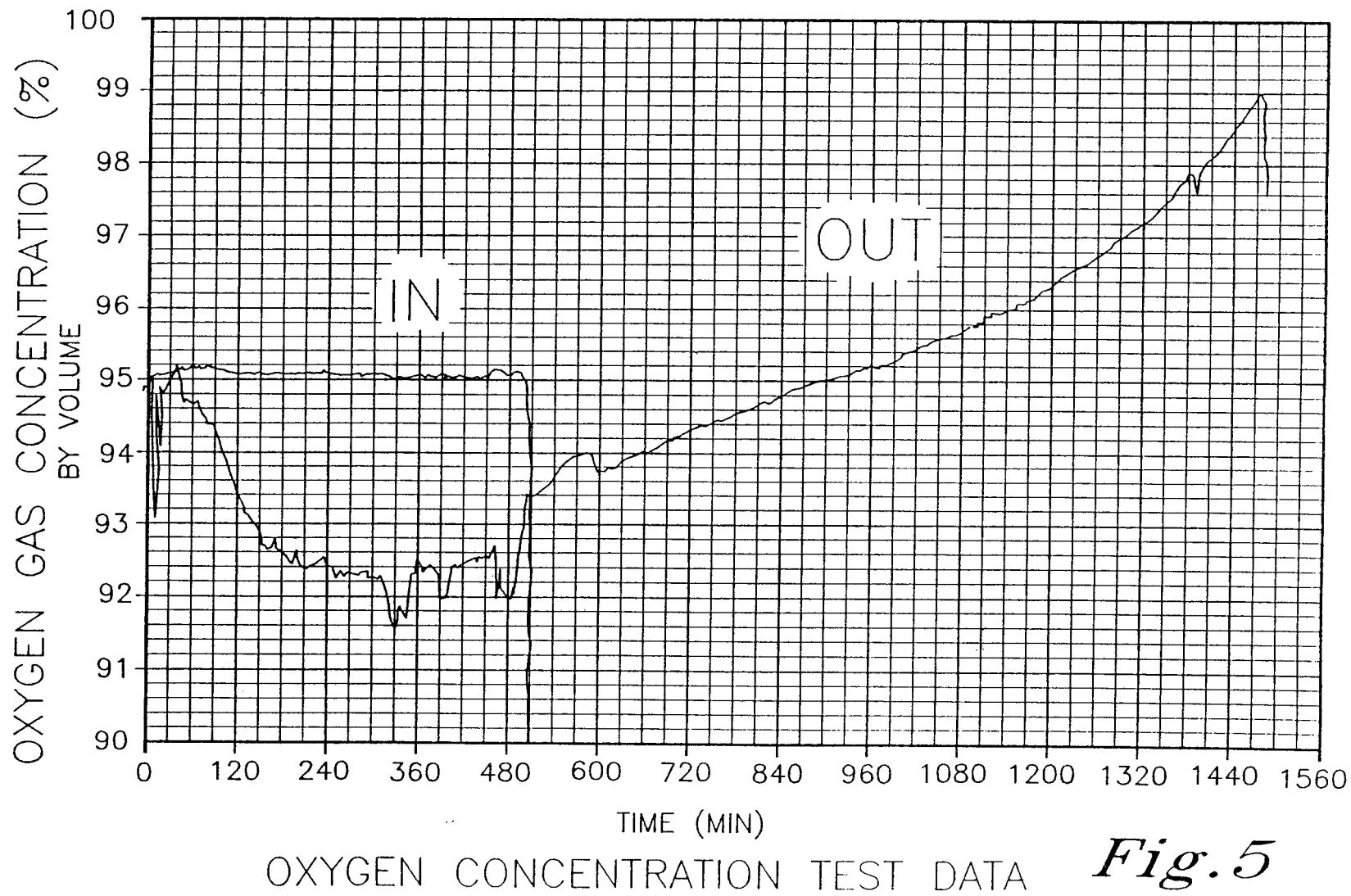


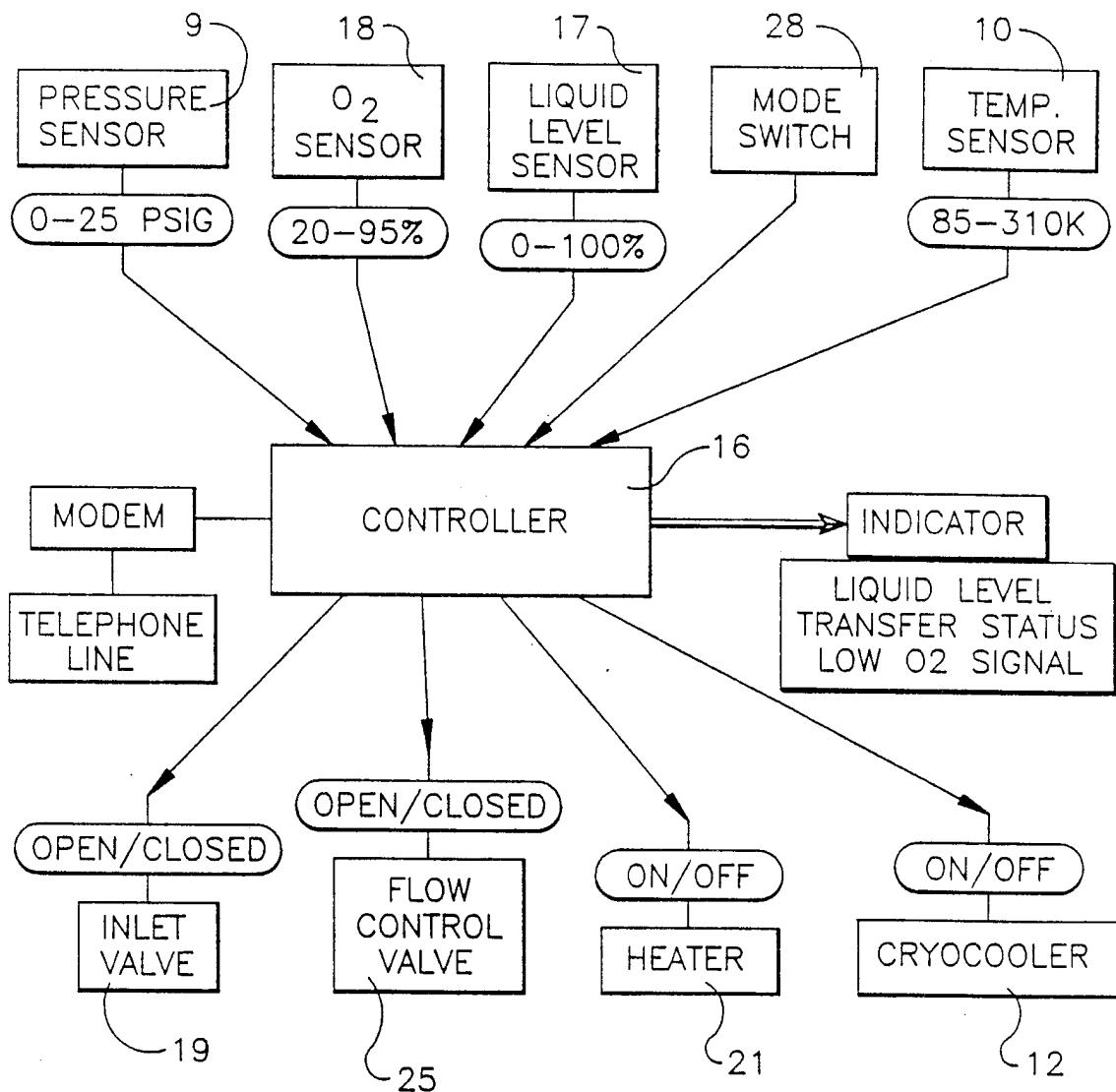
*Fig. 3*

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*Fig. 4*



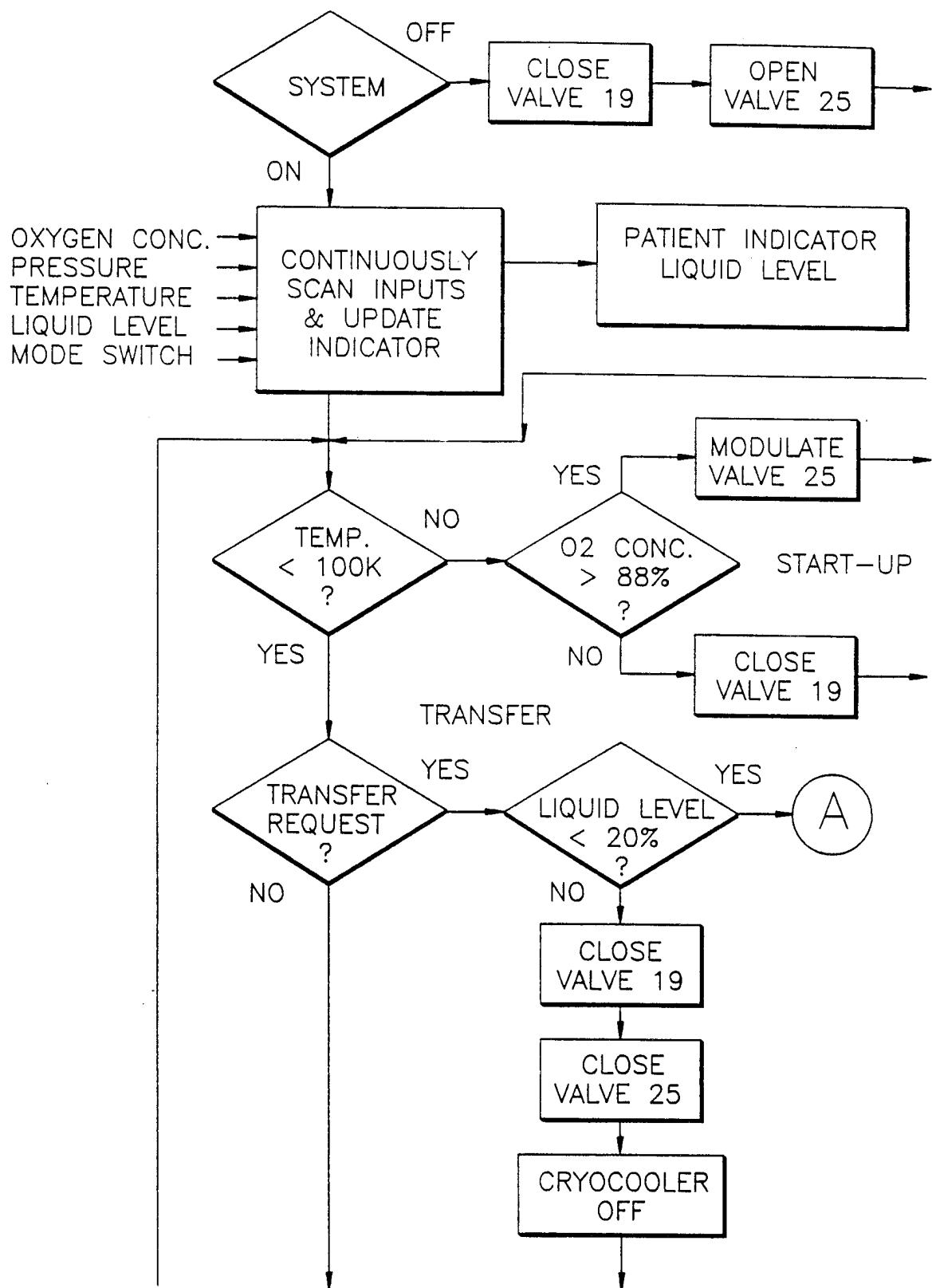


CONTROL BLOCK DIAGRAM

*Fig. 6*

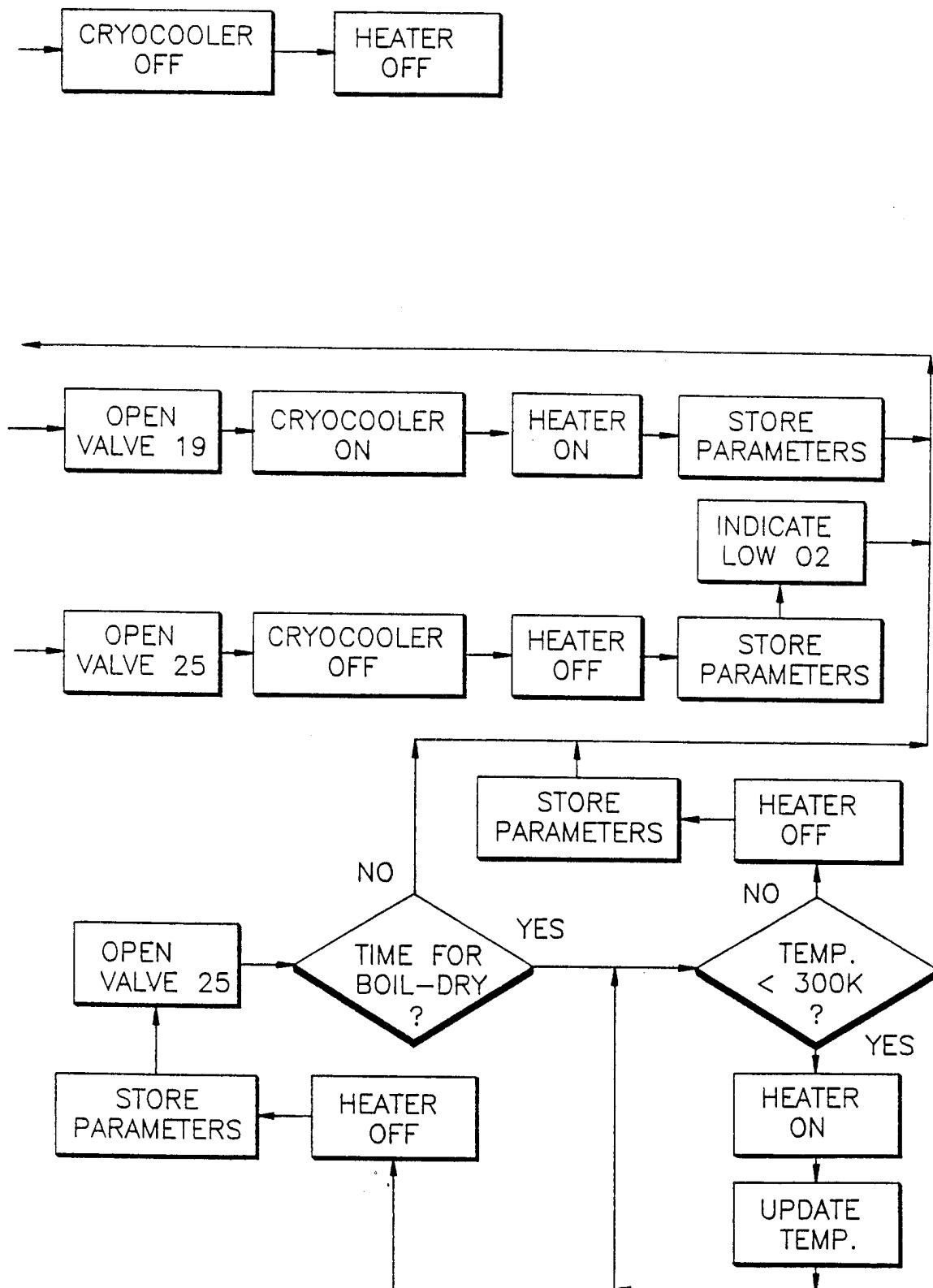
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Fig. 7A



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Fig. 7B



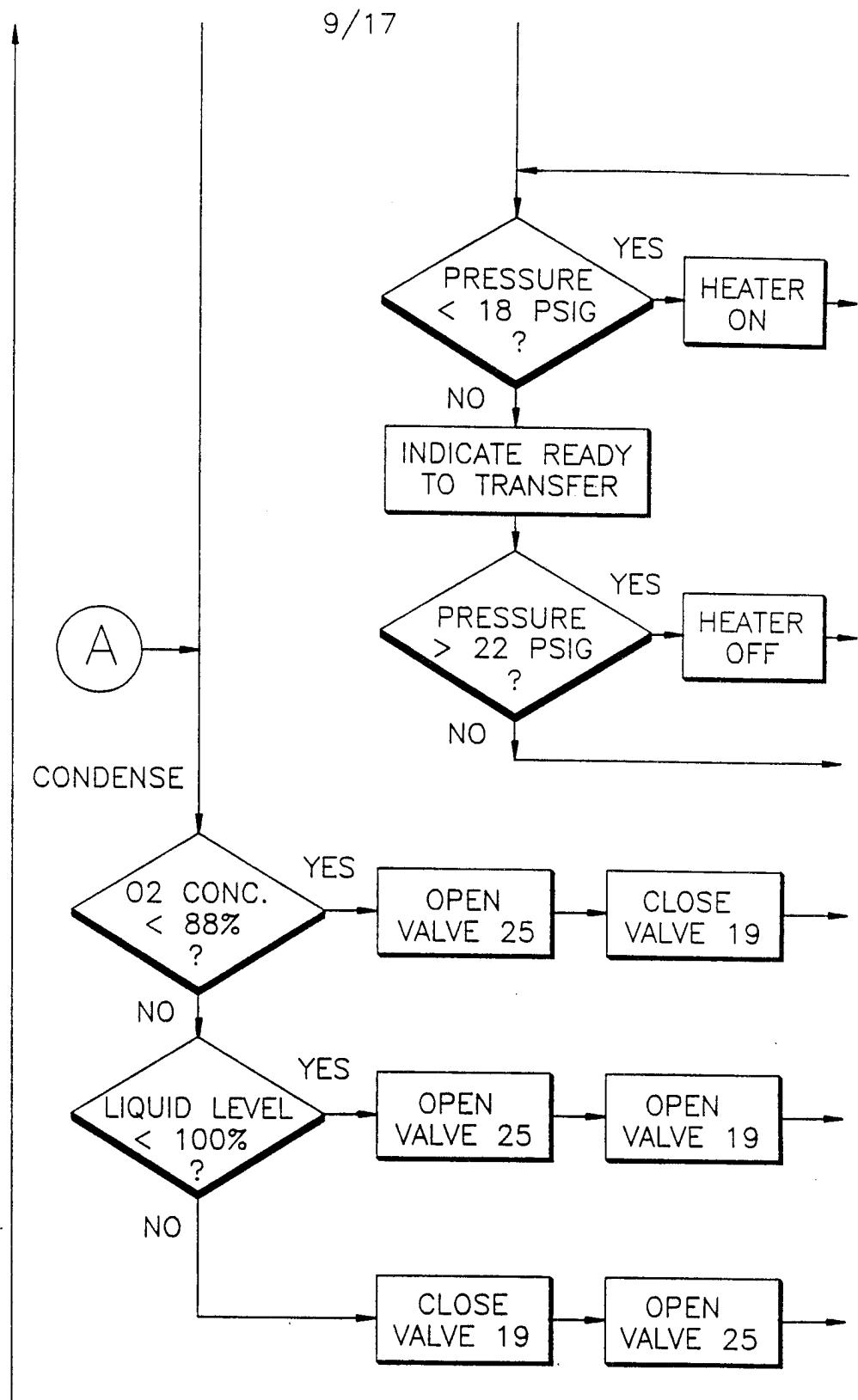


Fig. 7C

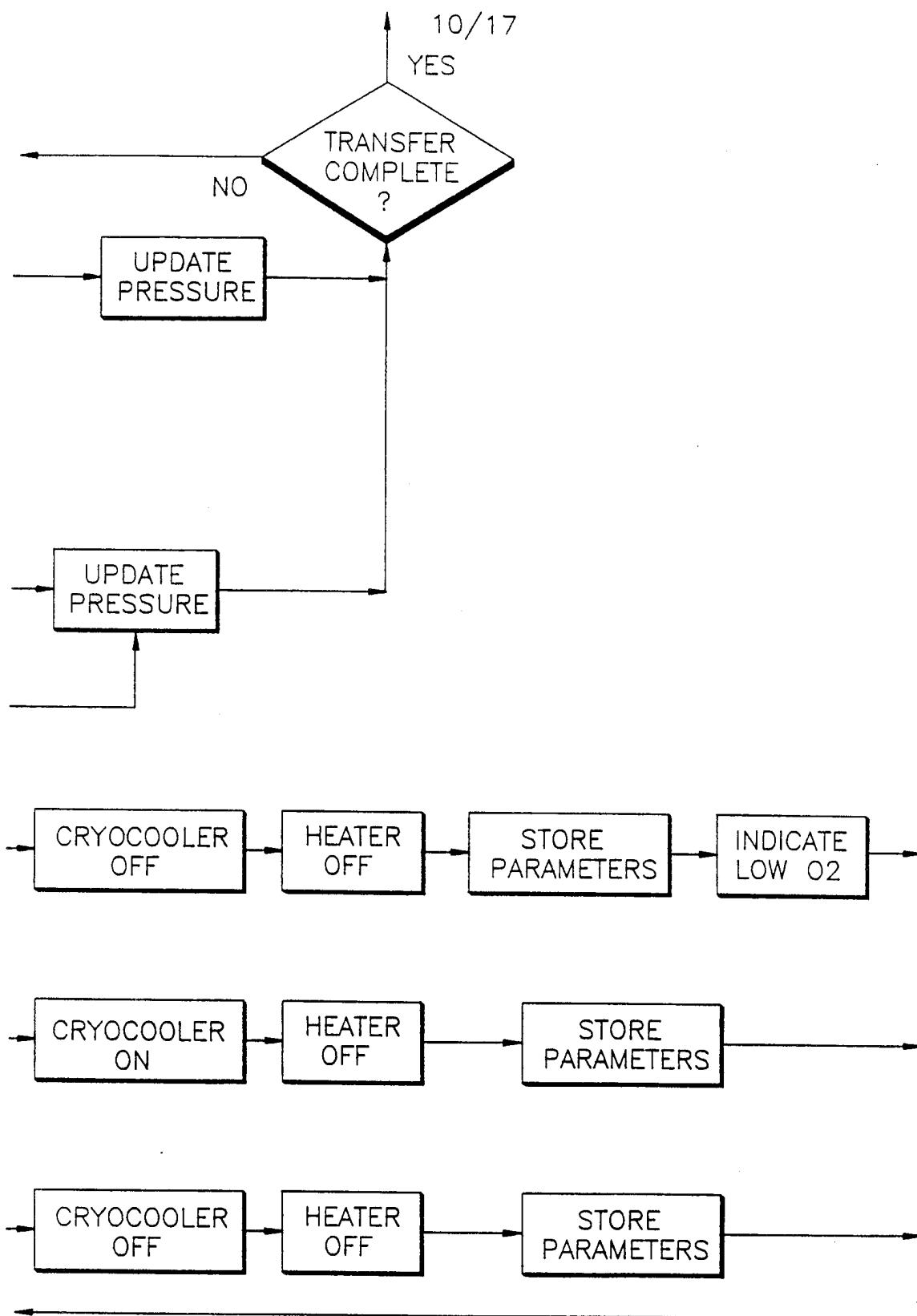


Fig. 7D

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*Fig. 8*

## START-UP MODE

## INPUT LEVELS &amp; OUTPUT STATES

INPUT	LEVEL	OUTPUT	STATE
OXYGEN SENSOR	>88%	VALVE 19	OPEN
LIQUID LEVEL SENSOR	0%	VALVE 25	OPEN/CLOSED *
		HEATER	OFF
		CRYOCOOLER	ON
		INDICATOR	COOLDOWN

\* MODULATED TO CONTROL PRESSURE

*Fig. 9*

## CONDENSE MODE

## INPUT LEVELS &amp; OUTPUT STATES

INPUT	LEVEL	OUTPUT	STATE
OXYGEN SENSOR	>88%	VALVE 19	OPEN
LIQUID LEVEL SENSOR	<100%	VALVE 25	OPEN
		HEATER	OFF
		CRYOCOOLER	ON
		INDICATOR	CONDENSE
OXYGEN SENSOR	≤88%	VALVE 19	CLOSED
LIQUID LEVEL SENSOR	<100%	VALVE 25	OPEN
		HEATER	OFF
		CRYOCOOLER	OFF
		INDICATOR	O <sub>2</sub> LOW
OXYGEN SENSOR	>88%	VALVE 19	CLOSED
LIQUID LEVEL SENSOR	≥100%	VALVE 25	OPEN
		HEATER	OFF
		CRYOCOOLER	OFF
		INDICATOR	FULL

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*Fig. 10* TRANSFER MODE  
INPUT LEVELS & OUTPUT STATES

INPUT	LEVEL	OUTPUT	STATE
OXYGEN SENSOR LIQUID LEVEL SENSOR	20-95% <20%	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED OPEN OFF OFF LIQ. LOW
OXYGEN SENSOR LIQUID LEVEL SENSOR PRESSURE SENSOR	20-95% ≥20% <18 PSIG	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED CLOSED ON OFF WAIT
OXYGEN SENSOR LIQUID LEVEL SENSOR PRESSURE SENSOR	20-95% ≥20% >18 PSIG	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED CLOSED ON OFF TRANSFER
OXYGEN SENSOR LIQUID LEVEL SENSOR PRESSURE SENSOR	20-95% ≥20% >22 PSIG	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED CLOSED OFF OFF TRANSFER

*Fig. 11* BOIL-DRY MODE  
INPUT LEVELS & OUTPUT STATES

INPUT	LEVEL	OUTPUT	STATE
OXYGEN SENSOR LIQUID LEVEL SENSOR TEMPERATURE SENSOR	20-95% <100% <300K	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED OPEN ON OFF BOIL-DRY
OXYGEN SENSOR LIQUID LEVEL SENSOR TEMPERATURE SENSOR	20-95% 0-100% ≥300K	VALVE 19 VALVE 25 HEATER CRYOCOOLER INDICATOR	CLOSED OPEN OFF OFF WARM

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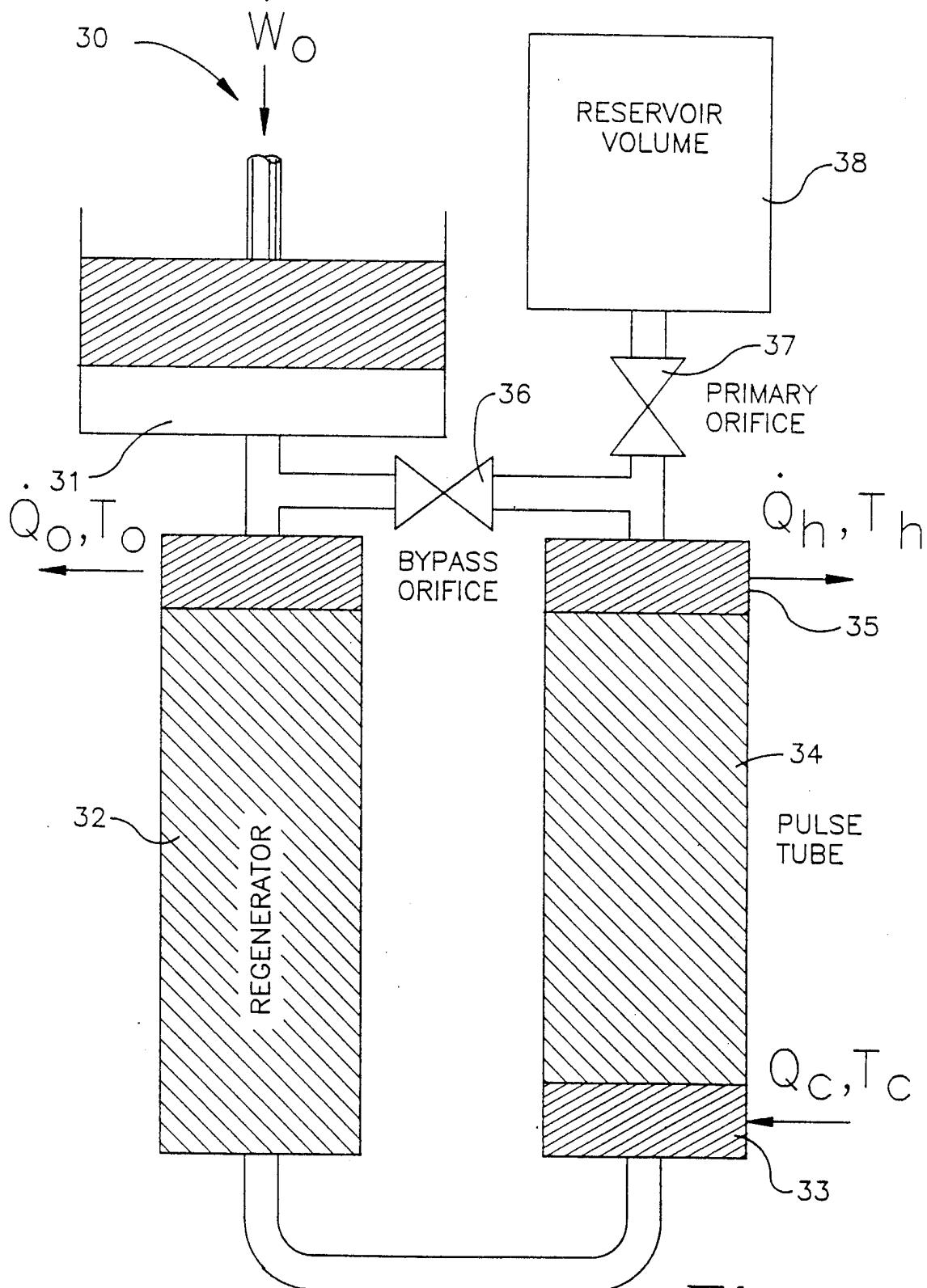
DOUBLE INLET PULSE TUBE  
REFRIGERATOR

Fig. 12

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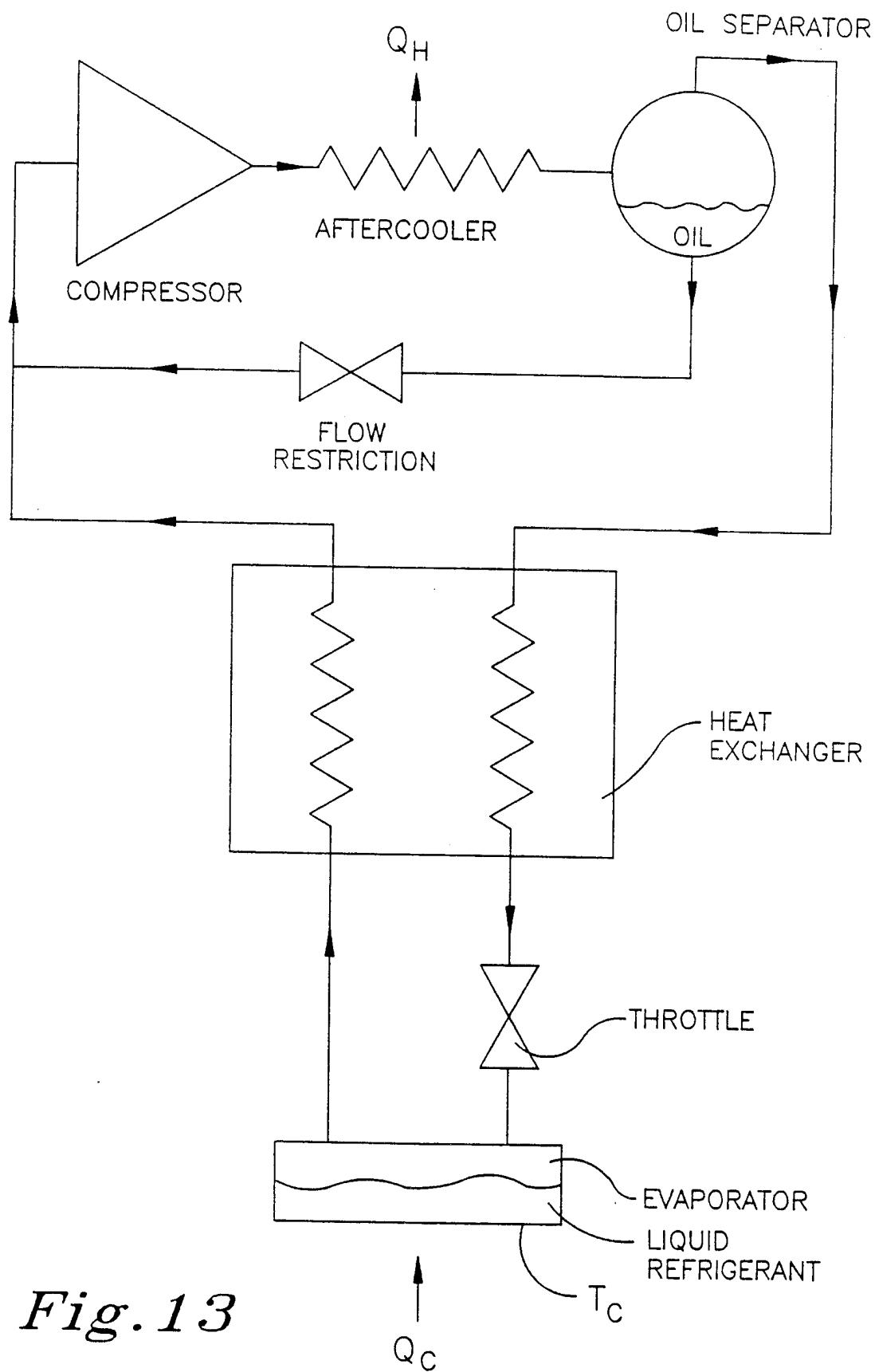


Fig. 13

Fig. 14

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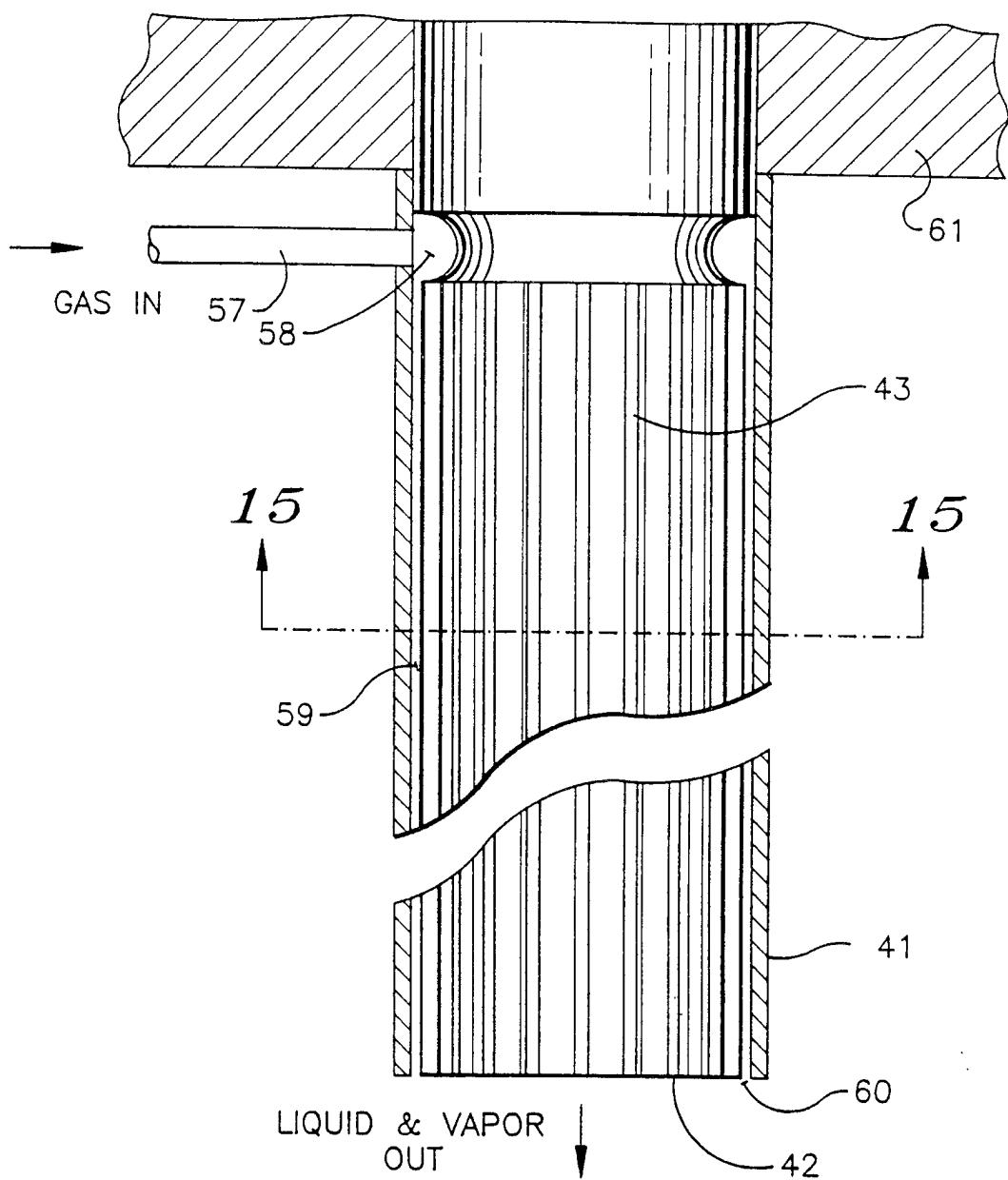
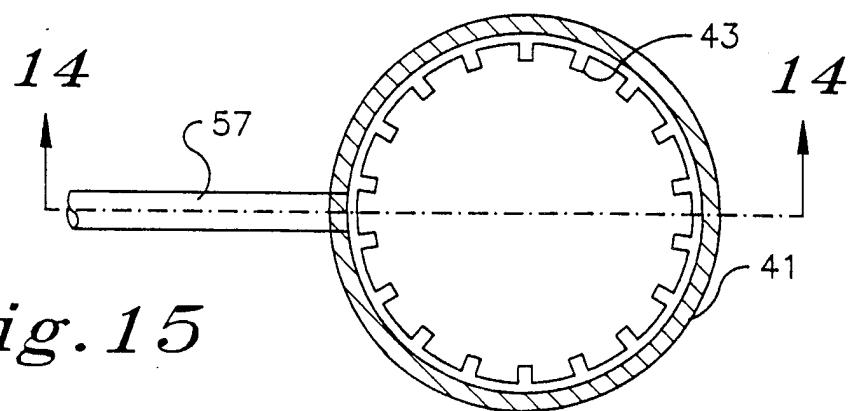


Fig. 15



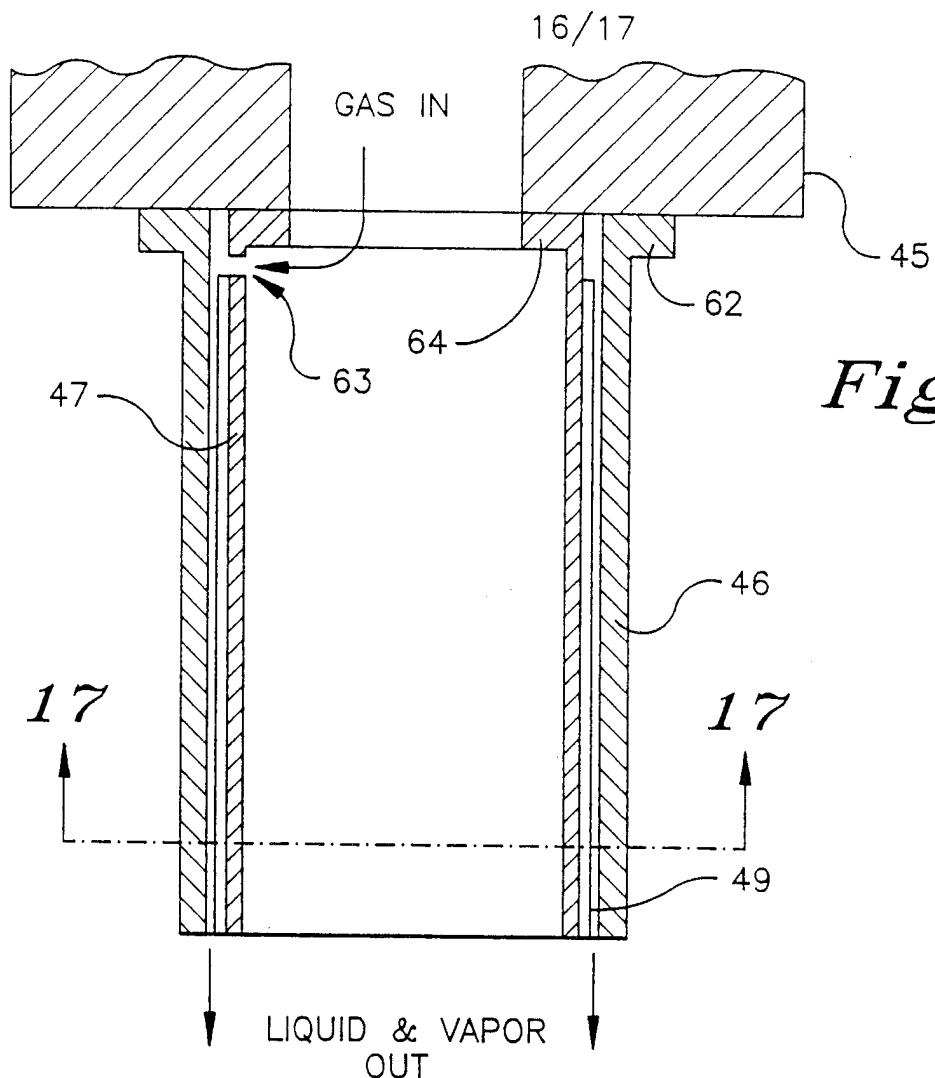


Fig. 16

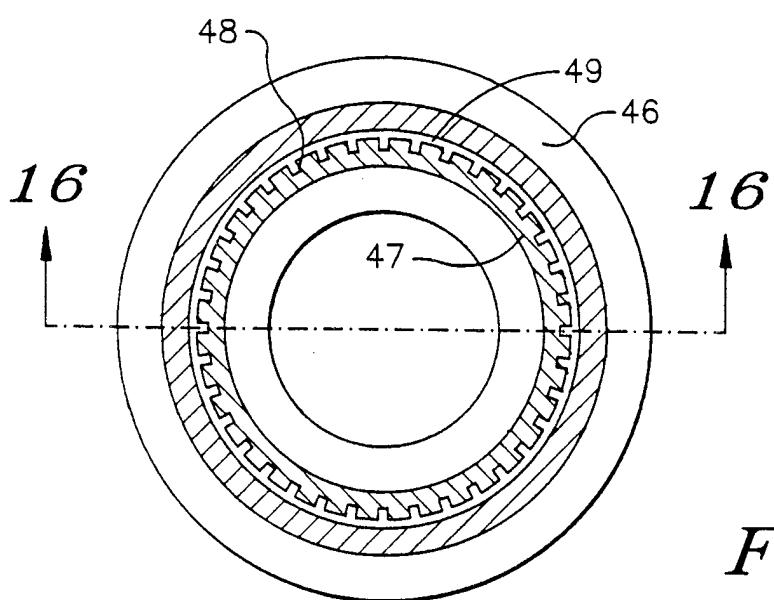
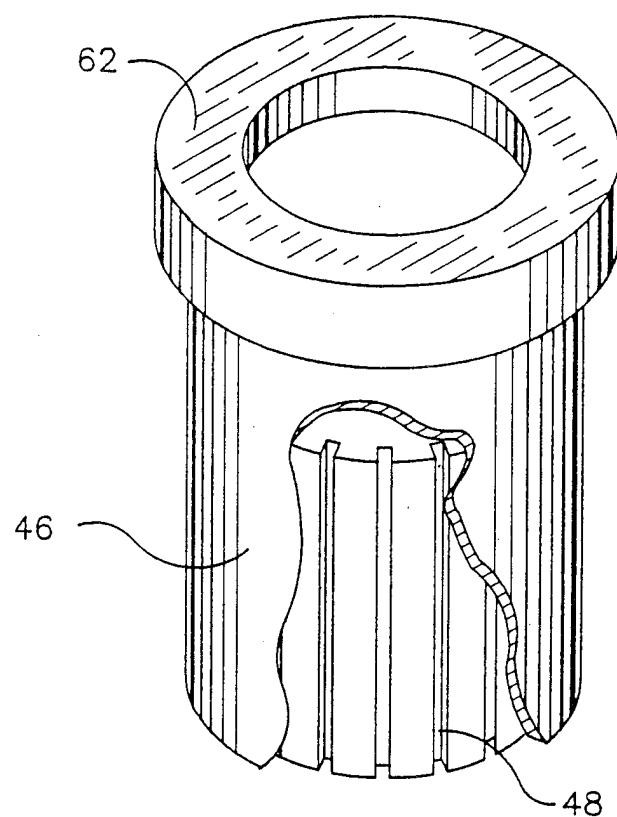


Fig. 17

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*Fig. 18*

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US 98/11154

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 6 F25J3/06

B01D8/00

B01D5/00

F28D7/10

F25J3/00

According to International Patent Classification(IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 F25J B01D F28D F28B F28F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 870 960 A (HRADEK RICHARD W) 3 October 1989 ----	1-48, 56-61, 73,74
A	US 4 627 860 A (ROWLAND ROBERT O) 9 December 1986 ----	1-48, 56-61, 73,74
A	GB 1 416 163 A (BOC INTERNATIONAL LTD) 3 December 1975 ----	49-53, 62-72,75
A	US 5 584 194 A (GARDNER THOMAS W) 17 December 1996 ----	49-53, 62-72,75
A	US 5 163 297 A (YANI MASAYOSHI ET AL) 17 November 1992 ----	54,55 -/-

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Patent family members are listed in annex.

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Date of the actual completion of the international search

Date of mailing of the international search report

17 September 1998

25/09/1998

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## INTERNATIONAL SEARCH REPORT

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PCT/US 98/11154

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

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