



US00RE43398E

(19) **United States**  
(12) **Reissued Patent**  
**Honkonen et al.**

(10) **Patent Number:** **US RE43,398 E**  
(45) **Date of Reissued Patent:** **May 22, 2012**

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

(75) Inventors: **Scott C. Honkonen**, Tucson, AZ (US);  
**Theodore B. Hill**, San Diego, CA (US);  
**Charles C. Hill**, San Diego, CA (US);  
**Graham Walker**, Nanaimo (CA); **Ann Valentine Walker**, legal representative, Nanaimo (CA)

(73) Assignee: **Respironics, Inc.**, Murrysville, PA (US)

(21) Appl. No.: **11/366,986**

(22) Filed: **Mar. 1, 2006**

#### Related U.S. Patent Documents

Reissue of:

(64) Patent No.: **6,698,423**  
Issued: **Mar. 2, 2004**  
Appl. No.: **09/420,892**  
Filed: **Oct. 19, 1999**

U.S. Applications:

(63) Continuation-in-part of application No. 08/876,970, filed on Jun. 16, 1997, now Pat. No. 5,979,440.

(51) **Int. Cl.**  
**A62B 7/06** (2006.01)  
**A62B 7/00** (2006.01)

(52) **U.S. Cl.** ..... **128/201.21; 128/200.24; 128/204.15; 128/204.17**

(58) **Field of Classification Search** ..... **128/200.24, 128/201.21, 204.15, 204.17, 203.25, 203.26, 128/203.27, 204.22, 204.23, 913, DIG. 27; 62/606, 615; 165/110, 174**

See application file for complete search history.

#### (56) References Cited

##### U.S. PATENT DOCUMENTS

609,499 A \* 8/1898 Chatwood et al. .... 122/485  
621,536 A \* 3/1899 Ostergren et al. .... 62/615  
621,537 A \* 3/1899 Ostergren et al. .... 62/615  
665,912 A \* 1/1901 Jolicard ..... 122/501

(Continued)

##### FOREIGN PATENT DOCUMENTS

EP 0247365 12/1987

##### OTHER PUBLICATIONS

USPTO Reexam Control No. 90/008,167.

(Continued)

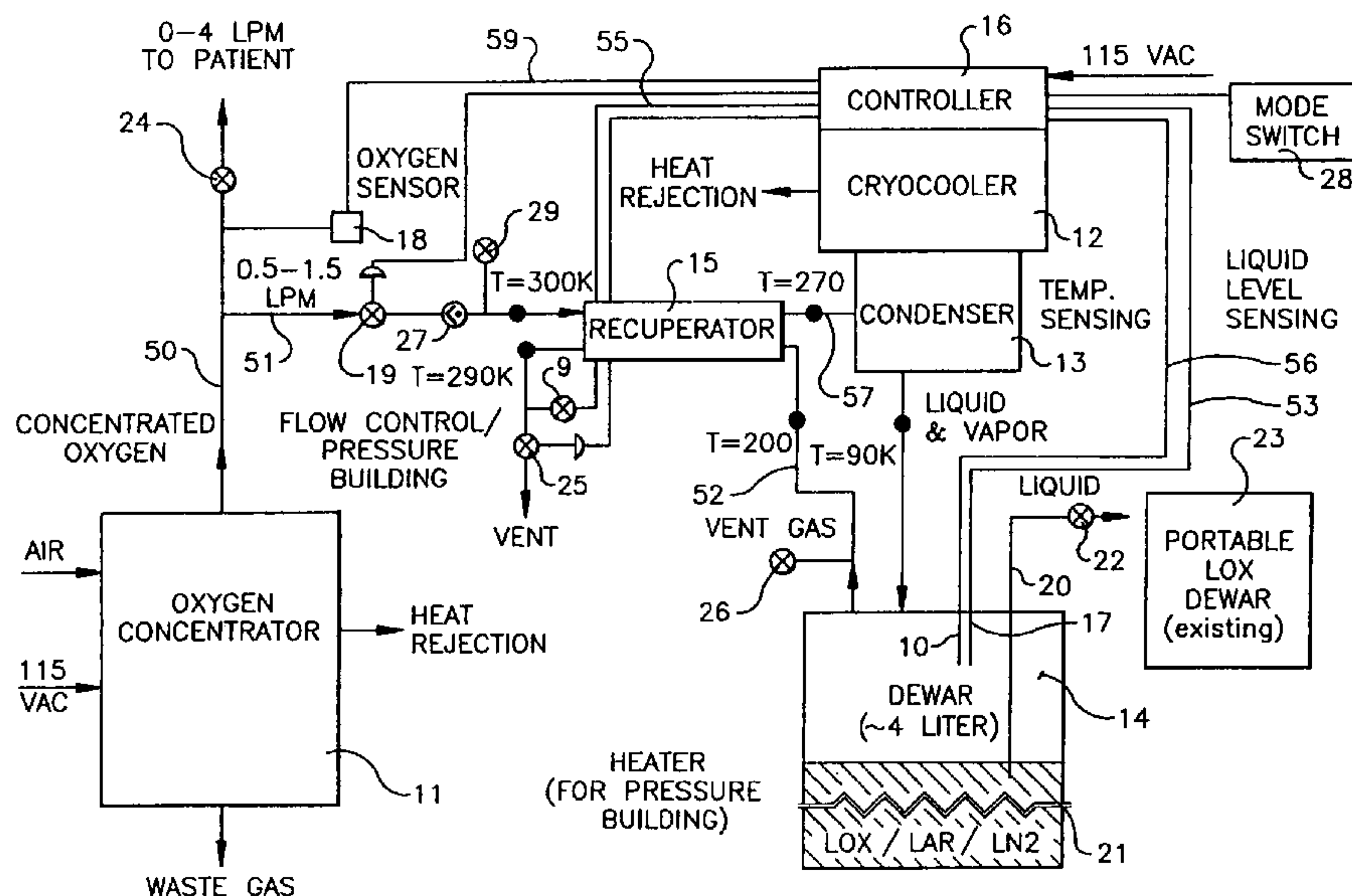
Primary Examiner — Annette Dixon

(74) Attorney, Agent, or Firm — Trenton A. Ward, Esq.; Troutman Sanders LLP

#### (57) ABSTRACT

The present invention is directed to a much safer and less expensive way of providing portable oxygen from a gas concentrator for patients who do not want to be tied to a stationary machine or restricted by present oxygen technology. The present invention involves 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. The system includes an oxygen concentrator which separates oxygen gas from the ambient air, a condenser in communication with the oxygen concentrator for receiving and liquefying the oxygen gas flow, a cryocooler associated with the condenser, and a first storage dewar in fluid communication with the condenser and adapted to store the oxygen liquefied by the condenser, the first storage dewar including means for transferring liquid oxygen from the first dewar to a second dewar for storing a quantity of oxygen suitable for moveable oxygen treatment.

**69 Claims, 21 Drawing Sheets**





# US RE43,398 E

Page 2

## U.S. PATENT DOCUMENTS

707,633	A *	8/1902	Place	62/615	4,349,357	A	9/1982	Russell	
718,572	A *	1/1903	Joly	62/615	4,360,059	A *	11/1982	Funke	165/160
879,302	A *	2/1908	Nesmith	138/38	4,404,005	A *	9/1983	Hamlin et al.	96/111
881,176	A *	3/1908	Claude	62/615	4,428,372	A	1/1984	Reysel et al.	
948,835	A *	2/1910	Walter	165/160	4,449,990	A	5/1984	Tedford, Jr.	
1,454,053	A *	5/1923	Jones	165/161	4,465,436	A	8/1984	Schonwald	
1,782,409	A *	11/1930	Chute	165/161	4,493,368	A *	1/1985	Gronnerud et al.	165/159
1,796,510	A *	3/1931	Delas et al.	165/160	4,510,760	A	4/1985	Wieland	
1,821,080	A *	9/1931	Sprong	165/183	4,513,587	A *	4/1985	Humpolik et al.	62/515
1,867,163	A *	7/1932	Loebell	165/161	4,516,424	A	5/1985	Rowland	
RE19,031	E	12/1933	Heylandt		4,529,411	A	7/1985	Goddin, Jr. et al.	
1,957,006	A *	5/1934	Wescott	165/110	4,542,010	A	9/1985	Roman et al.	
2,017,676	A *	10/1935	Girsewald et al.	165/104.19	4,545,790	A *	10/1985	Miller et al.	96/117
2,194,654	A *	3/1940	Hadamovsky	62/606	4,552,571	A	11/1985	Dechene	
2,210,031	A *	8/1940	Greene	62/117	4,561,287	A	12/1985	Rowland	
2,318,206	A *	5/1943	Eisenlohr	138/37	4,575,386	A	3/1986	Hamers	
2,384,714	A *	9/1945	Villiger	165/161	4,576,616	A	3/1986	Mottram et al.	
2,434,519	A *	1/1948	Raskin	165/110	4,583,364	A	4/1986	Wood	
2,440,245	A *	4/1948	Chevigny	165/80.4	4,587,967	A	5/1986	Chu et al.	
2,751,199	A *	6/1956	Williams	165/47	4,591,365	A	5/1986	Burr	
2,797,554	A *	7/1957	Donovan	62/509	4,602,174	A	7/1986	Redlich	
2,905,447	A *	9/1959	Huet	165/165	4,610,700	A	9/1986	Miller et al.	
2,909,903	A	10/1959	Zimmerman		4,627,860	A	12/1986	Rowland	
2,919,555	A	1/1960	Hughes et al.		4,636,226	A	1/1987	Canfora	
2,937,079	A *	5/1960	Pool	422/201	4,640,031	A	2/1987	Hoek et al.	
2,943,454	A *	7/1960	Lewis	62/50.5	4,670,223	A	6/1987	Delachapelle	
2,944,627	A	7/1960	Skarstrom		4,673,415	A	6/1987	Stanford	
2,945,354	A *	7/1960	Moskowitz	62/50.2	4,698,075	A	10/1987	Dechene	
2,958,204	A *	11/1960	Spaulding	62/48.1	4,701,187	A	10/1987	Choe et al.	
2,960,834	A *	11/1960	Patrick	62/7	4,704,146	A *	11/1987	Markbreiter et al.	62/625
2,964,919	A *	12/1960	Howlett	62/50.4	4,706,664	A	11/1987	Snook et al.	
2,969,957	A *	1/1961	Beurtheret	62/259.2	4,717,406	A	1/1988	Giacobbe	
2,970,452	A *	2/1961	Beckman et al.	62/50.2	4,765,804	A	8/1988	Lloyd-Williams et al.	
2,993,682	A *	7/1961	Huet	165/110	4,822,394	A *	4/1989	Zeigler et al.	62/632
3,055,643	A *	9/1962	Beurtheret	165/110	4,826,510	A	5/1989	McCombs	
3,097,497	A	7/1963	Fitt		4,827,643	A	5/1989	Hearst et al.	
3,117,426	A *	1/1964	Fischer et al.	62/223	4,841,732	A	6/1989	Sarcia	
3,152,589	A *	10/1964	Kugler	128/201.21	4,844,059	A	7/1989	Koch	
3,183,678	A *	5/1965	Hosford	62/50.4	4,848,447	A *	7/1989	Sladky	165/118
3,186,406	A *	6/1965	Fitt et al.	128/201.21	4,850,426	A *	7/1989	Fayolle et al.	165/111
3,199,303	A *	8/1965	Haumann et al.	62/48.1	4,867,766	A	9/1989	Campbell et al.	
3,205,670	A *	9/1965	Carolan	62/50.4	4,869,733	A	9/1989	Stanford	
3,313,091	A	4/1967	Berlin		4,870,960	A	10/1989	Hradek	
3,318,307	A	5/1967	Nicastro		4,880,443	A *	11/1989	Miller et al.	95/98
3,354,664	A *	11/1967	Van Der Ster et al.	62/606	4,899,810	A *	2/1990	Fredley	165/41
3,400,758	A *	9/1968	Man Suk Lee	165/159	4,905,685	A	3/1990	Olsson et al.	
3,552,392	A	1/1971	Dounoucos et al.		4,922,900	A	5/1990	Kiske et al.	
3,570,481	A	3/1971	Woodberry, Jr		4,948,391	A	8/1990	Noguchi	
3,572,048	A *	3/1971	Murphy	62/50.2	4,957,107	A	9/1990	Sipin	
3,707,078	A	12/1972	Cramer		4,971,609	A	11/1990	Pawlos	
3,710,854	A *	1/1973	Staub	165/111	4,979,882	A	12/1990	Wipf	
3,714,942	A	2/1973	Fischel et al.		4,983,190	A	1/1991	Verrando et al.	
3,730,178	A	5/1973	Moreland		4,991,616	A	2/1991	Fabregat	
3,749,155	A *	7/1973	Buffiere	165/147	5,002,591	A *	3/1991	Stanford	95/98
3,797,262	A *	3/1974	Eigenbrod	62/48.1	5,048,600	A *	9/1991	Stout et al.	165/110
3,807,396	A	4/1974	Fischel		5,060,480	A	10/1991	Saulnier	
3,831,594	A	8/1974	Rein		5,071,453	A	12/1991	Hradek et al.	
3,837,396	A *	9/1974	Newton	165/111	5,076,823	A	12/1991	Hansel et al.	
3,864,928	A *	2/1975	Eigenbrod	62/48.1	5,078,757	A	1/1992	Rottner et al.	
3,898,047	A	8/1975	Cramer		5,144,945	A	9/1992	Nishino et al.	
3,903,962	A *	9/1975	Newton	165/110	5,154,737	A	10/1992	Jenkins et al.	
3,924,968	A	12/1975	Gaines et al.		5,158,584	A	10/1992	Tamura	
3,935,715	A *	2/1976	Newton	62/475	5,163,297	A	11/1992	Yani et al.	
3,964,866	A	6/1976	Shelby		5,163,978	A	11/1992	Leavitt et al.	
3,983,861	A *	10/1976	Beauchaine	126/656	5,195,874	A	3/1993	Odagiri	
4,013,429	A	3/1977	Sircar et al.		5,199,423	A	4/1993	Harral et al.	
4,017,284	A	4/1977	Gifford		5,207,806	A	5/1993	Lagree et al.	
4,098,303	A *	7/1978	Gammell	141/52	5,231,835	A *	8/1993	Beddome et al.	62/615
4,181,126	A	1/1980	Hendry		5,237,987	A	8/1993	Anderson et al.	
4,194,890	A	3/1980	McCombs et al.		5,248,320	A	9/1993	Garrett et al.	
4,194,891	A *	3/1980	Earls et al.	95/98	5,271,231	A *	12/1993	Ha et al.	62/615
4,198,213	A	4/1980	Mannatt		5,342,176	A	8/1994	Redlich	
4,211,086	A *	7/1980	Leonard et al.	62/48.1	5,354,361	A	10/1994	Coffield	
4,222,750	A	9/1980	Gauthier et al.		5,388,413	A	2/1995	Major et al.	
4,253,519	A *	3/1981	Kun et al.	165/110	5,405,249	A	4/1995	Benson	
4,263,018	A	4/1981	McCombs et al.		5,454,429	A *	10/1995	Neurauter	165/109.1
4,279,127	A	7/1981	Longsworth		5,458,190	A *	10/1995	Sasaki et al.	165/110
4,331,455	A	5/1982	Sato		5,461,859	A	10/1995	Beale et al.	
					5,474,595	A	12/1995	McCombs	

5,477,689	A *	12/1995	Guillard et al. ....	62/646	6,089,226	A	7/2000	Gier	
5,490,871	A	2/1996	Coates et al.		6,132,177	A	10/2000	Loprete et al.	
5,496,153	A	3/1996	Redlich		6,212,904	B1	4/2001	Arkharov et al.	
5,499,623	A	3/1996	Pasternack		6,230,516	B1	5/2001	Andonian	
5,525,845	A	6/1996	Beale et al.		6,230,518	B1	5/2001	Hahn et al.	
5,531,807	A *	7/1996	McCombs .....	95/26	6,289,981	B1 *	9/2001	Tokizaki et al. ....	165/177
5,539,188	A	7/1996	Fallah et al.		6,302,107	B1	10/2001	Richey et al.	
5,555,655	A	9/1996	Yager et al.		6,314,957	B1	11/2001	Boissin et al.	
5,558,086	A	9/1996	Smith et al.		6,342,090	B1	1/2002	Cao	
5,558,139	A	9/1996	Snyder		6,393,802	B1	5/2002	Bowser et al.	
5,572,880	A	11/1996	Frustaci et al.		6,422,237	B1	7/2002	Engel et al.	
5,584,194	A	12/1996	Gardner		6,446,630	B1	9/2002	Todd, Jr.	
5,584,669	A	12/1996	Becker		6,513,521	B1	2/2003	Gier et al.	
5,593,291	A	1/1997	Lynn		6,520,176	B1	2/2003	Dugois et al.	
5,593,478	A	1/1997	Hill et al.		6,530,421	B1 *	3/2003	Filius et al. ....	165/109.1
5,634,517	A *	6/1997	Linden et al. ....	165/111	6,651,658	B1	11/2003	Hill et al.	
5,678,536	A	10/1997	Martin		6,681,764	B1 *	1/2004	Honkonen et al. ....	128/201.21
5,689,968	A	11/1997	Frustaci et al.		6,719,019	B2	4/2004	Cao et al.	
5,697,228	A *	12/1997	Paige .....	62/615	6,805,122	B2	10/2004	Richey et al.	
5,704,964	A	1/1998	Kaneko et al.		6,889,726	B2	5/2005	Richey, II et al.	
5,709,203	A	1/1998	Gier		6,904,913	B2	6/2005	Aylsworth et al.	
5,726,908	A	3/1998	Hosmer et al.		6,923,180	B2	8/2005	Richey, II et al.	
5,730,778	A	3/1998	Hill et al.		2005/0072423	A1	4/2005	Deane et al.	
5,823,186	A	10/1998	Rossen et al.		2005/0115630	A1	6/2005	Richey, II et al.	
5,827,358	A *	10/1998	Kulish et al. ....	96/115	2005/0136299	A1	6/2005	Richey, II et al.	
5,858,062	A	1/1999	McCulloh et al.		2005/0274142	A1	12/2005	Corey	
5,875,783	A	3/1999	Kullik		2006/0000474	A1	1/2006	Richey, II et al.	
5,893,275	A *	4/1999	Henry .....	62/615					
5,893,944	A	4/1999	Dong						
5,901,758	A	5/1999	Hwang et al.						
5,979,182	A	11/1999	Goto et al.						
5,979,440	A	11/1999	Honkonen et al.						
5,988,165	A	11/1999	Richey et al.						
6,004,378	A	12/1999	Reiss et al.						
6,012,453	A	1/2000	Tsals et al.						
6,029,473	A *	2/2000	Bravais .....	62/606					
6,035,894	A	3/2000	Weh et al.						
6,079,459	A	6/2000	Klotz et al.						

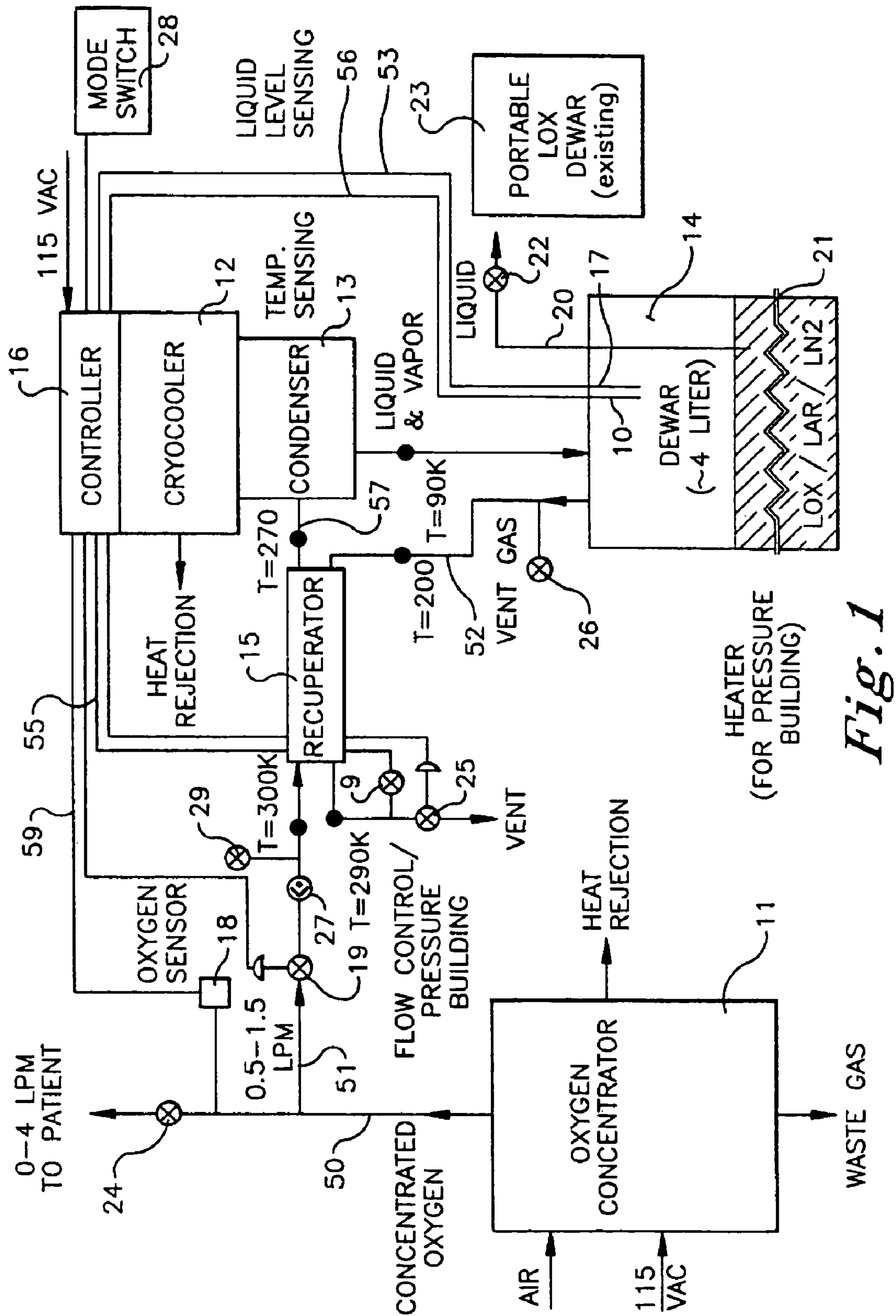
OTHER PUBLICATIONS

“Hautkondensation an feingewelten Oberflächen bei Beruckischtigun der Obrflachenspannungen”; Von Romano Gregoric, vol. V, 1954 (in German).

“Design Manual for Two-Phase Components of Spacecraft Thermal Management Systems”; PL-TR-92-3002, Crowley et al, Phillips Laboratory, Sep. 1992.

\* cited by examiner





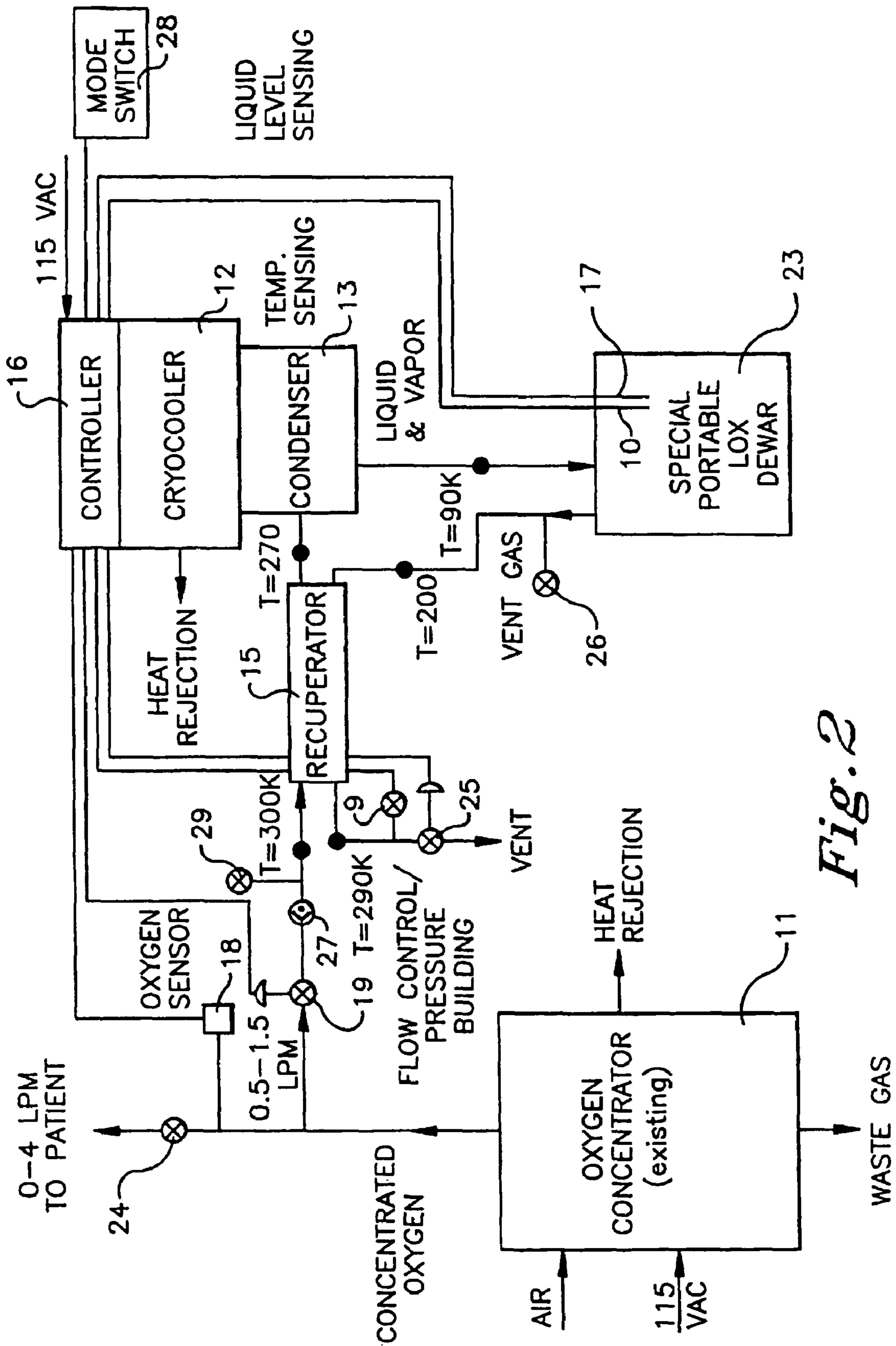
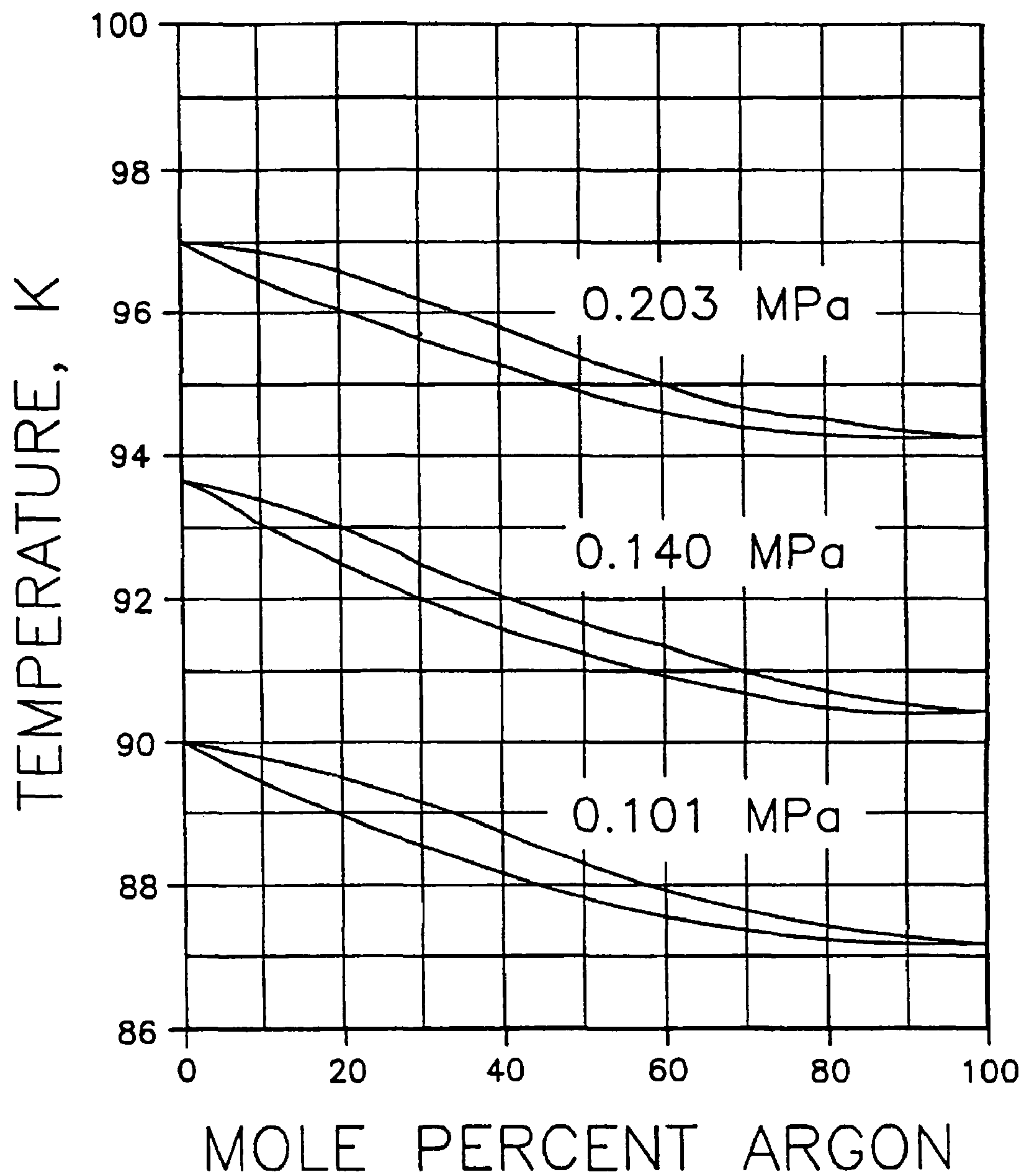
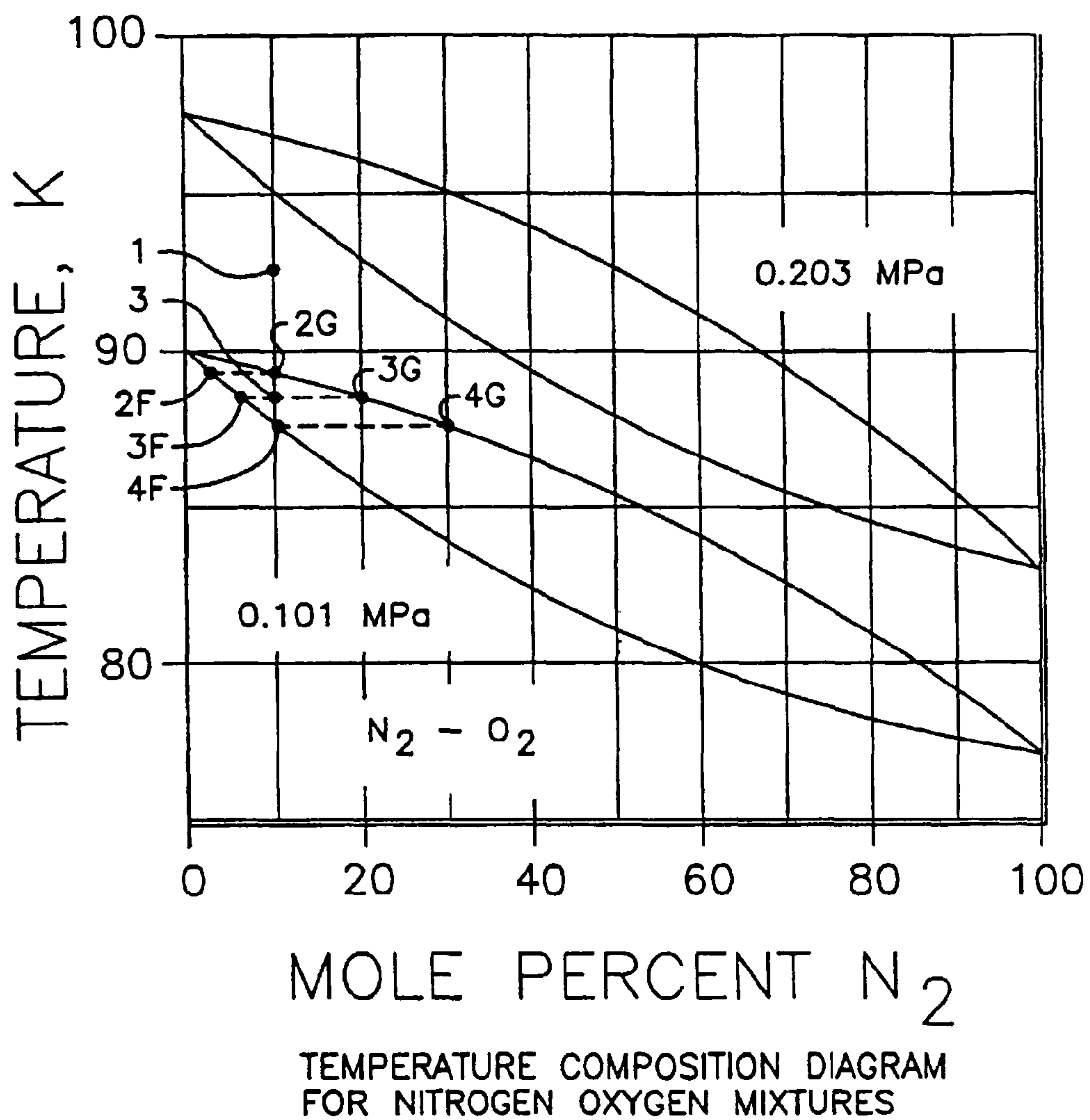


Fig. 2

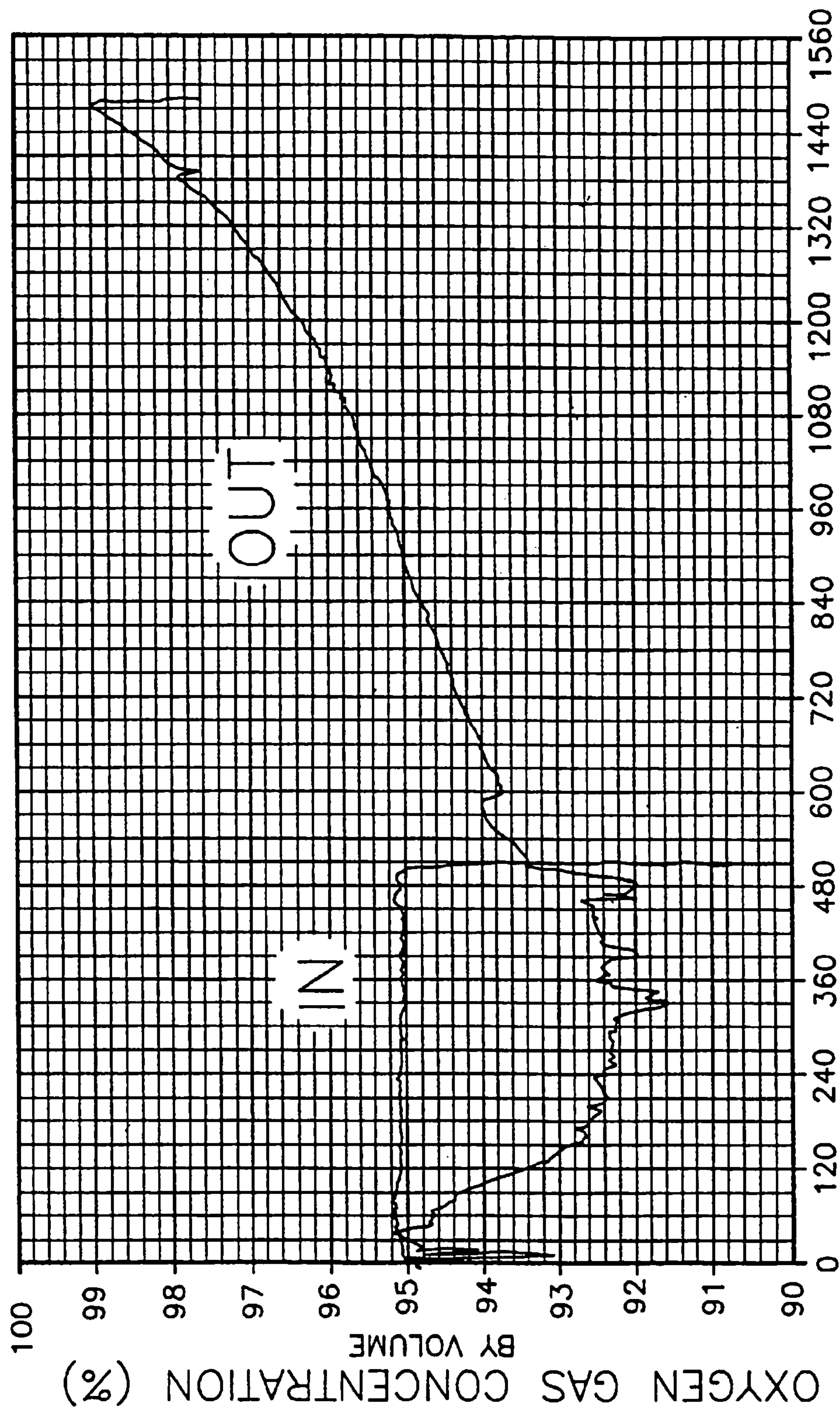


TEMPERATURE — COMPOSITION DIAGRAM  
FOR OXYGEN — ARGON MIXTURES

*Fig. 3*

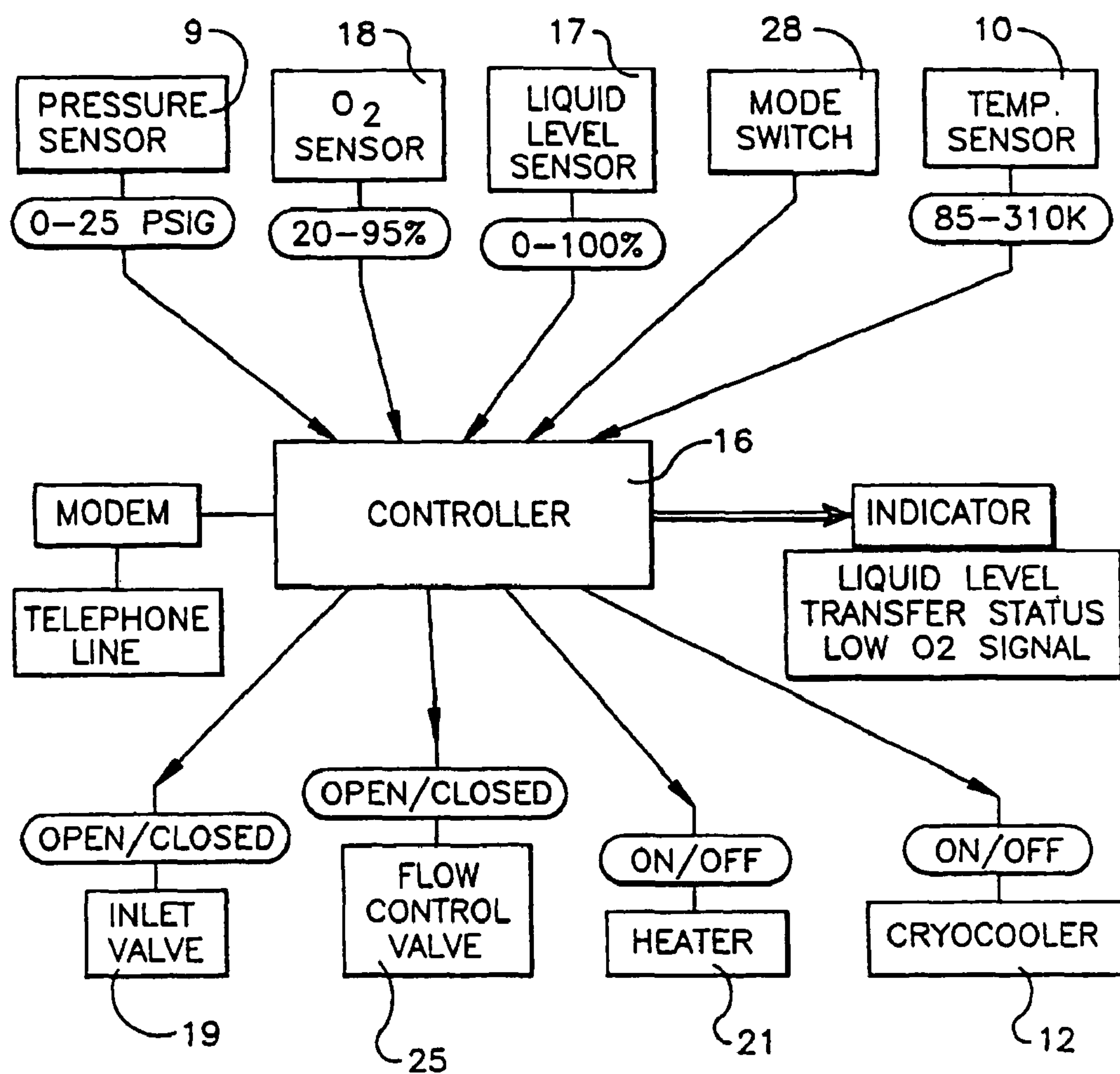
*Fig. 4*





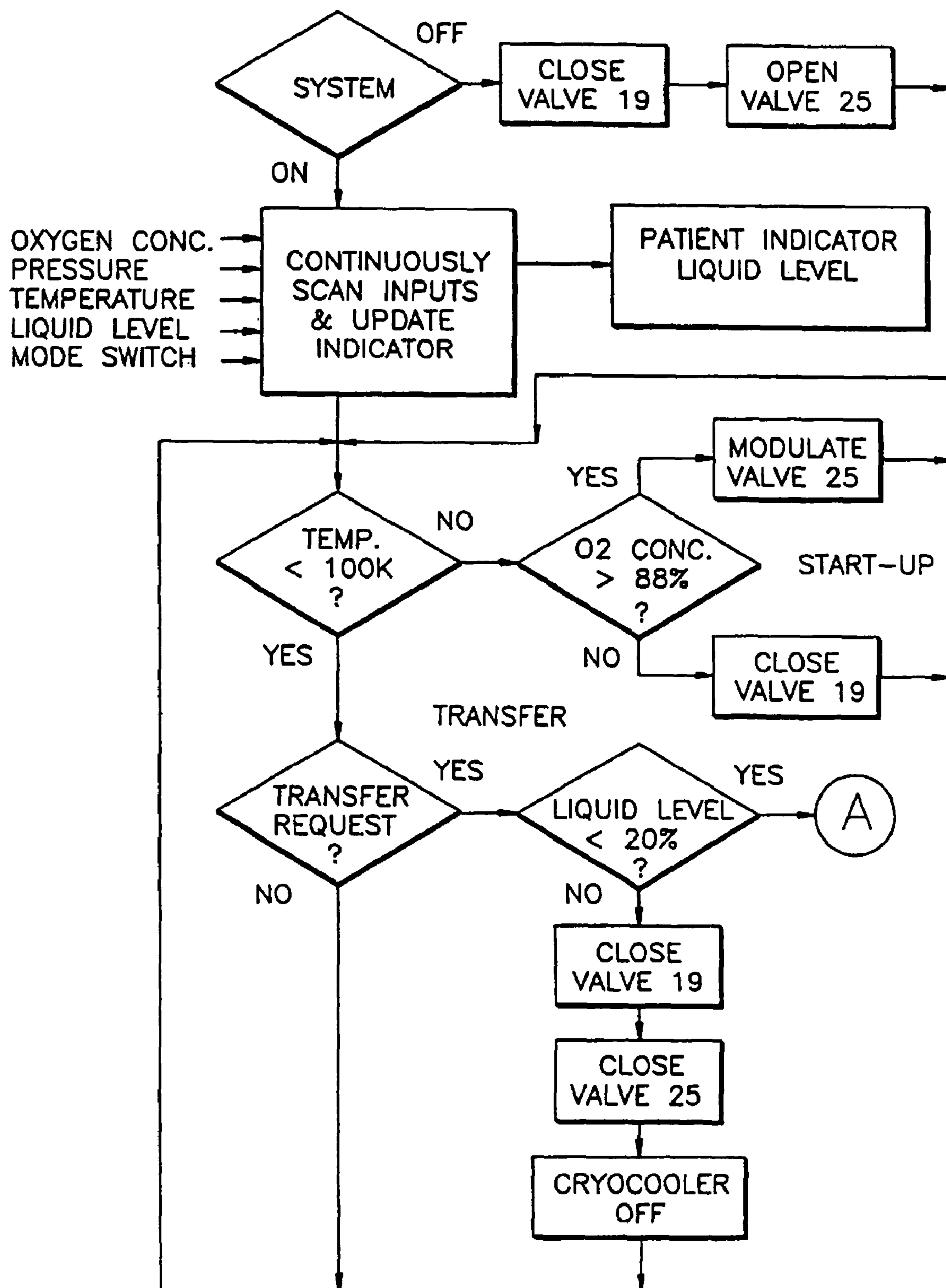
OXYGEN CONCENTRATION TEST DATA *Fig. 5*

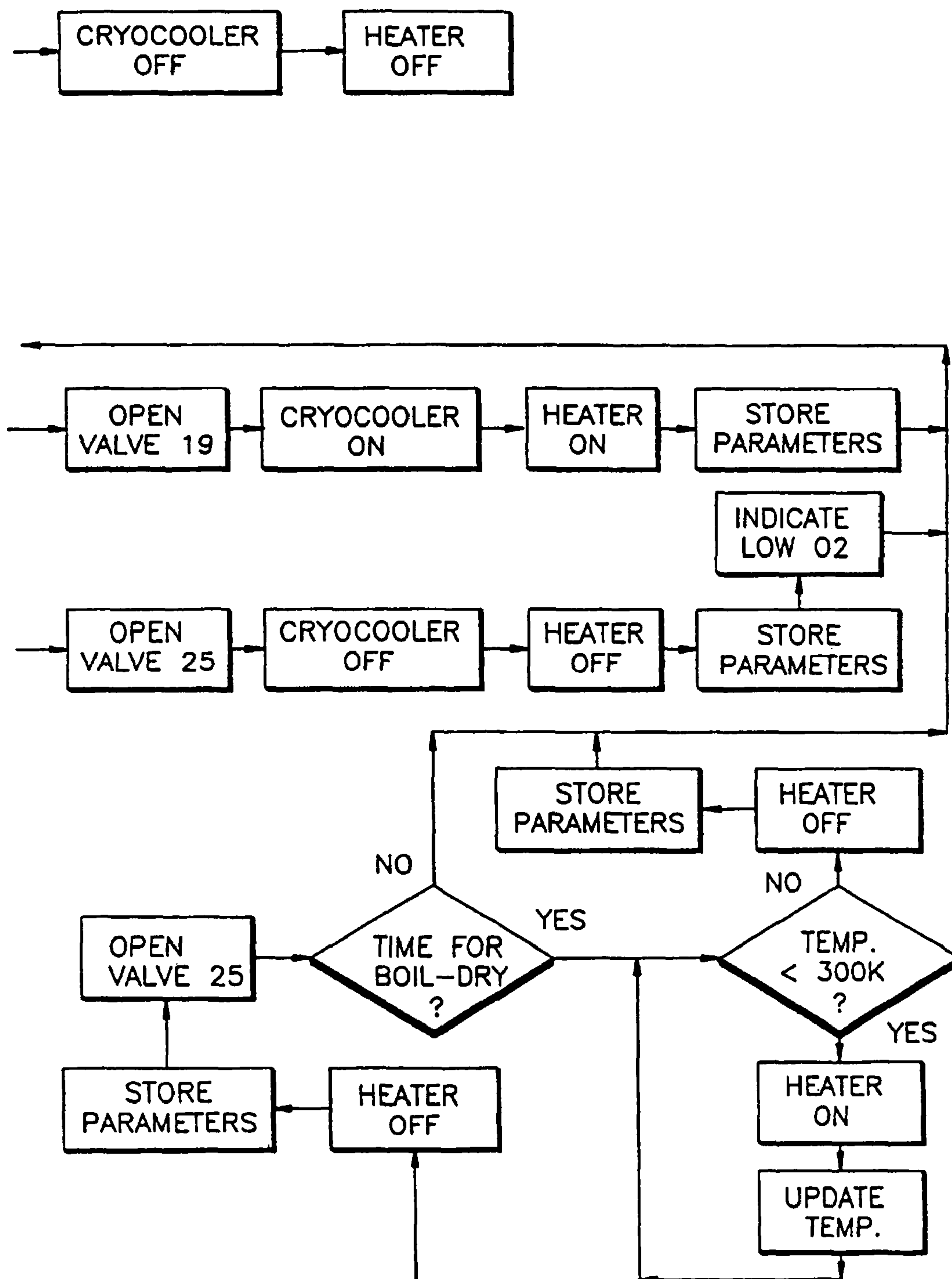




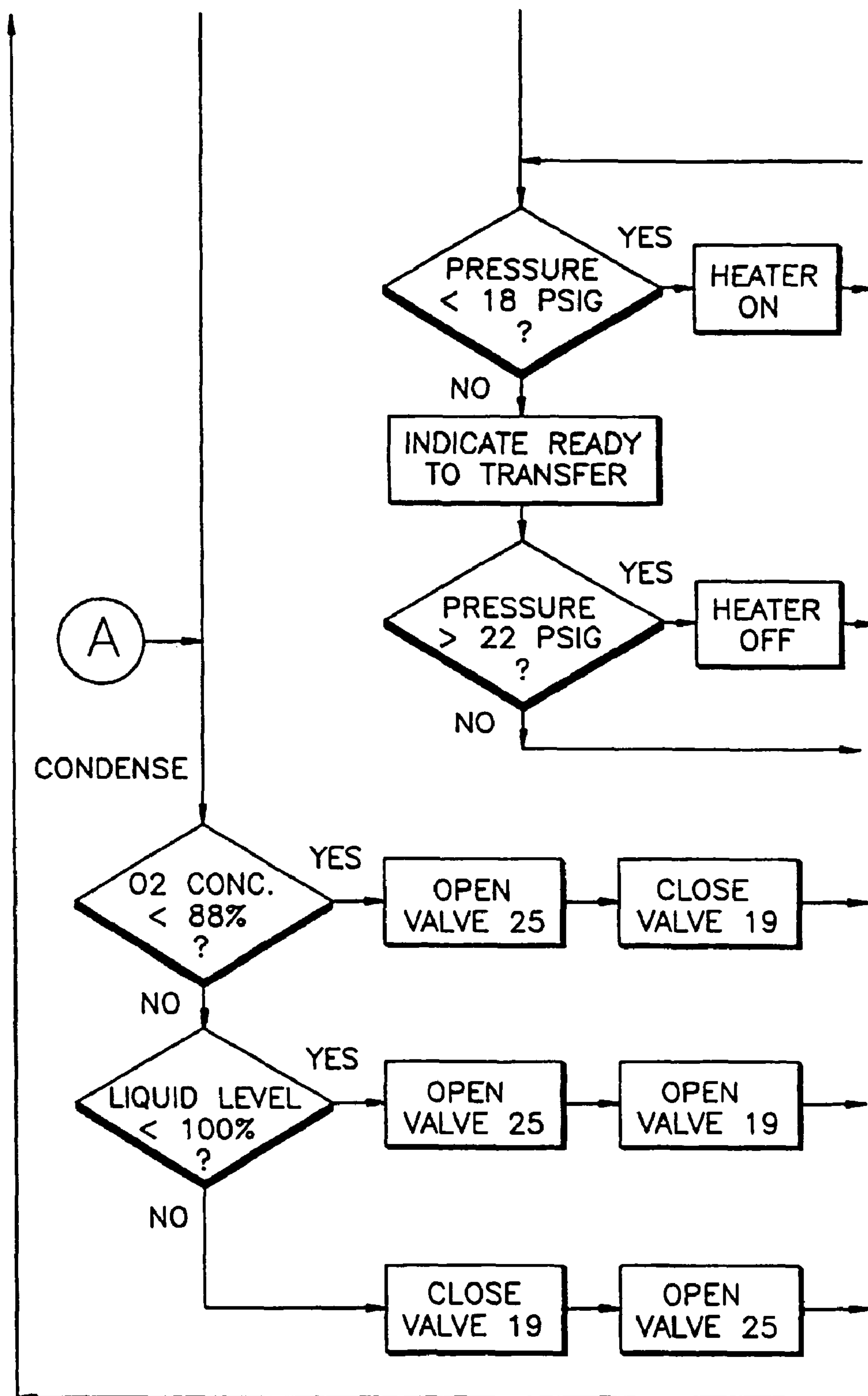
CONTROL BLOCK DIAGRAM

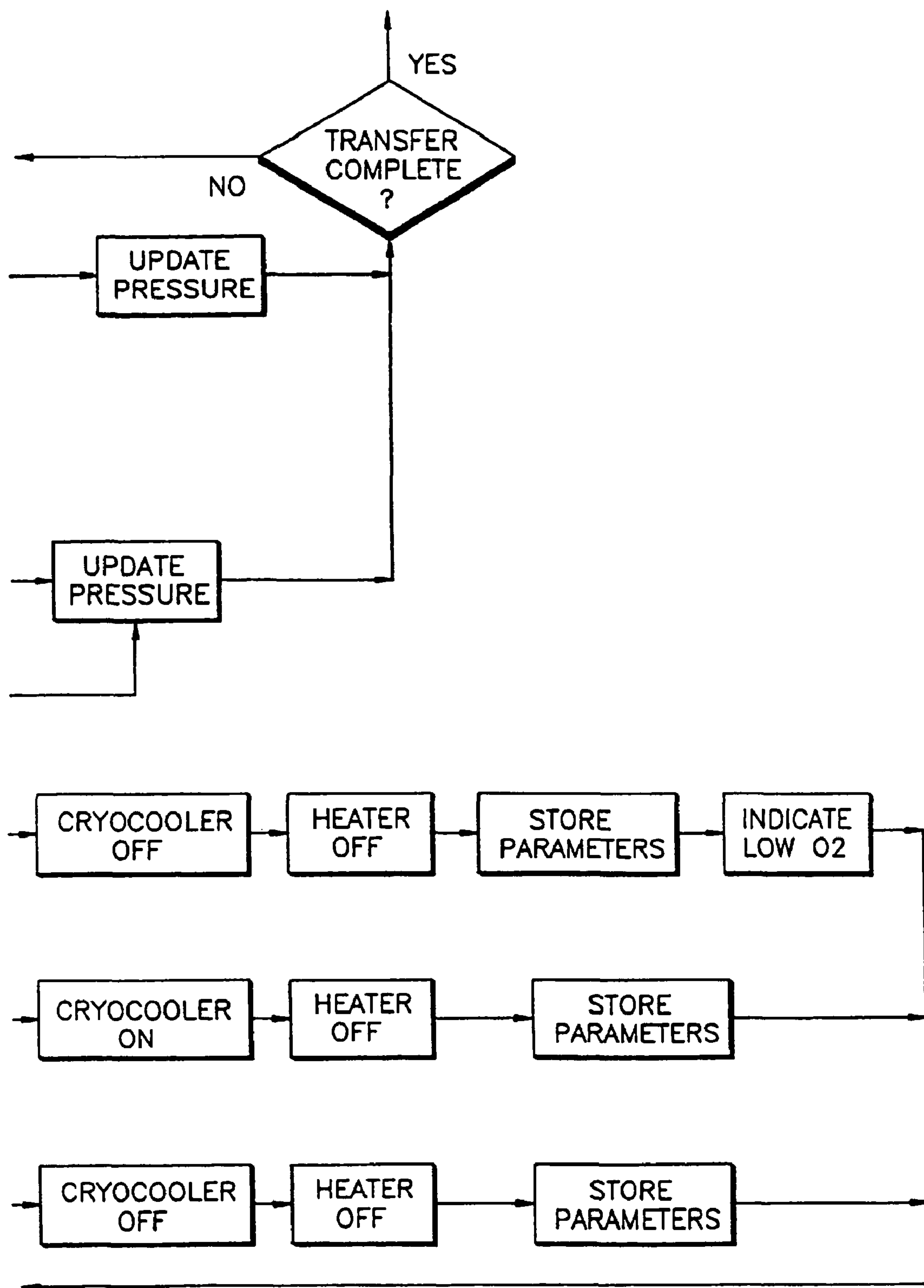
*Fig. 6*

*Fig. 7A*

*Fig. 7 B*



*Fig. 7C*

*Fig. 7 D*

*Fig. 8*

START-UP MODE  
INPUT LEVELS & 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 & 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

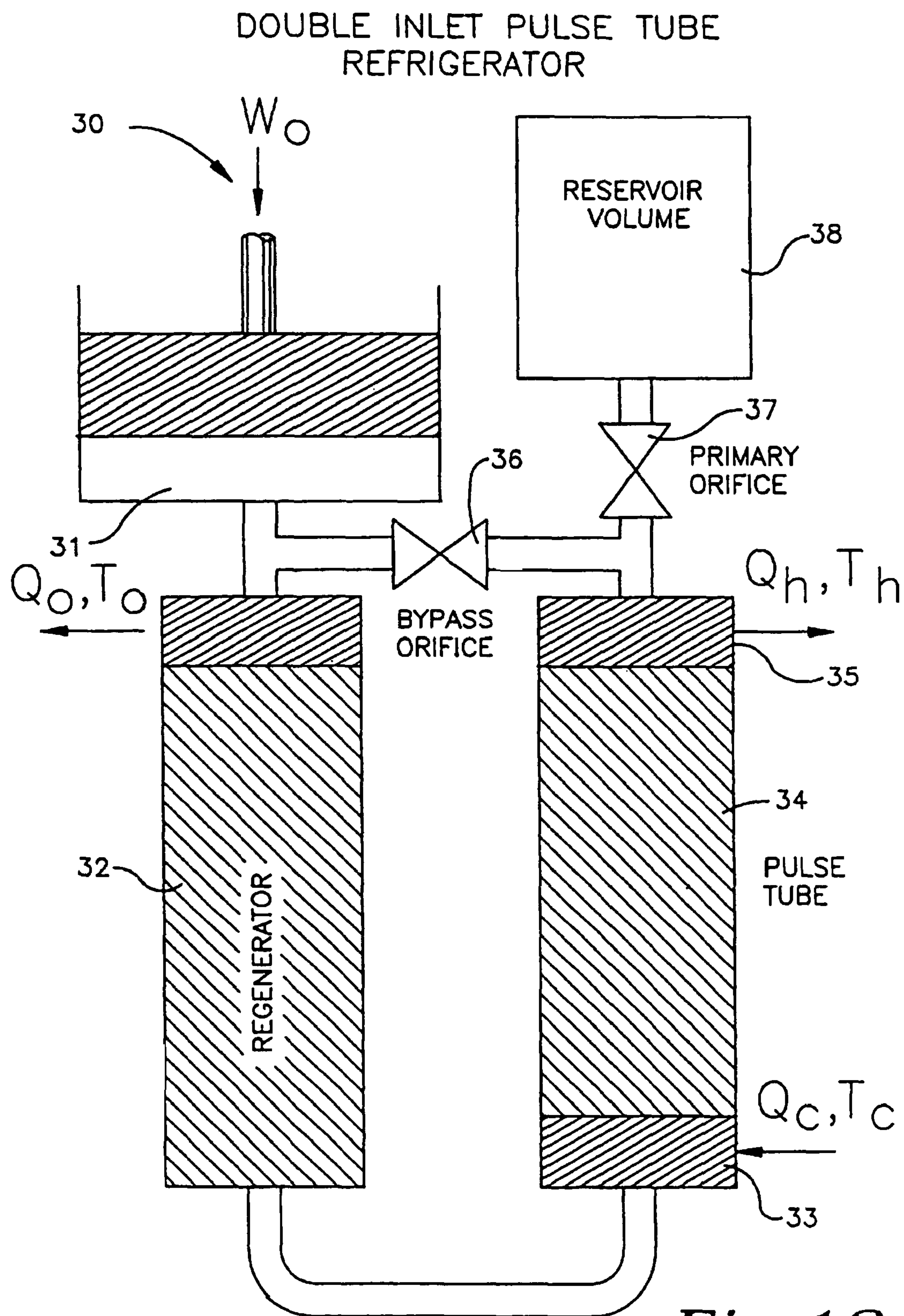


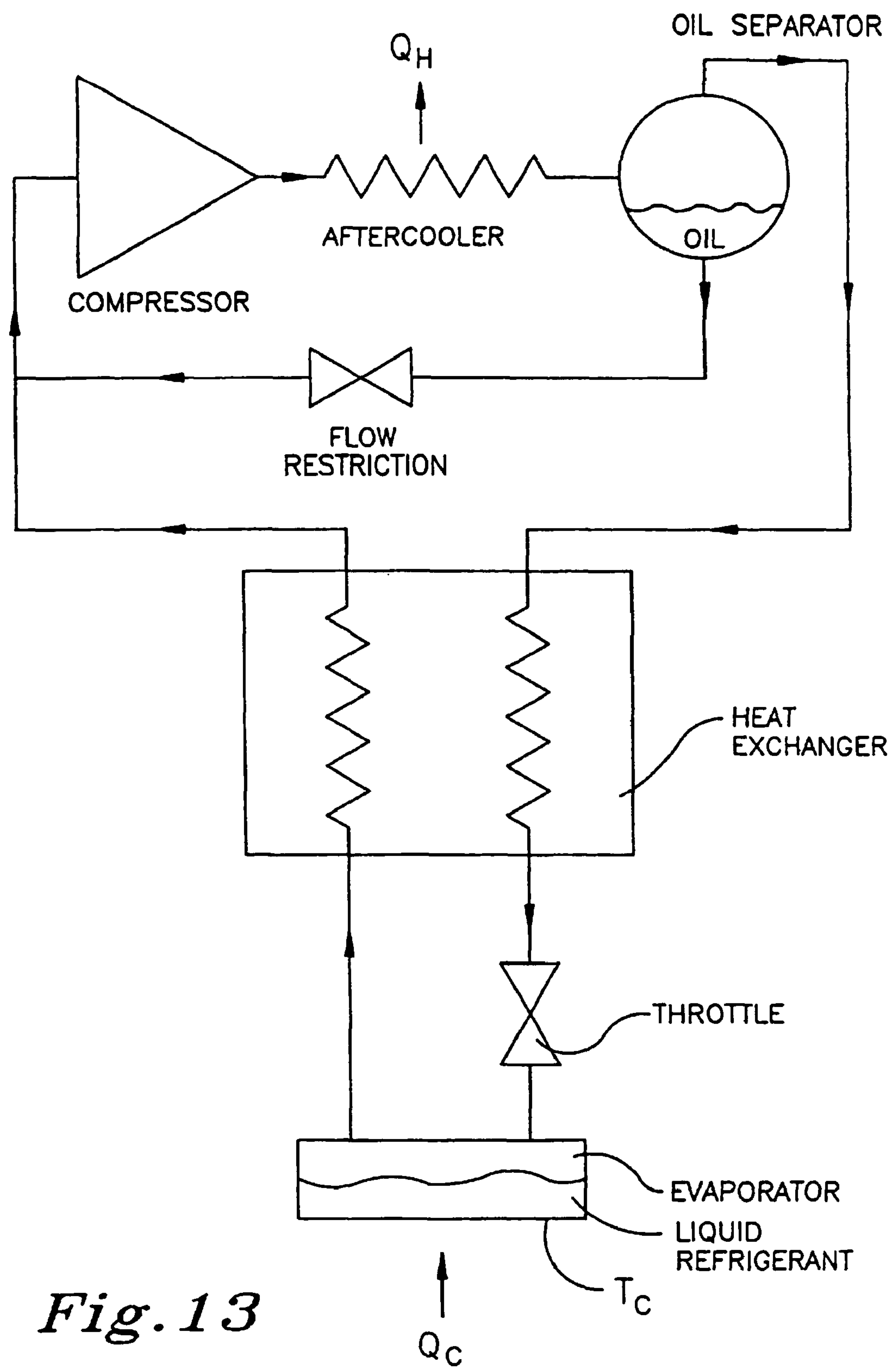
*Fig. 10*TRANSFER MODE  
INPUT LEVELS & OUTPUT STATES

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

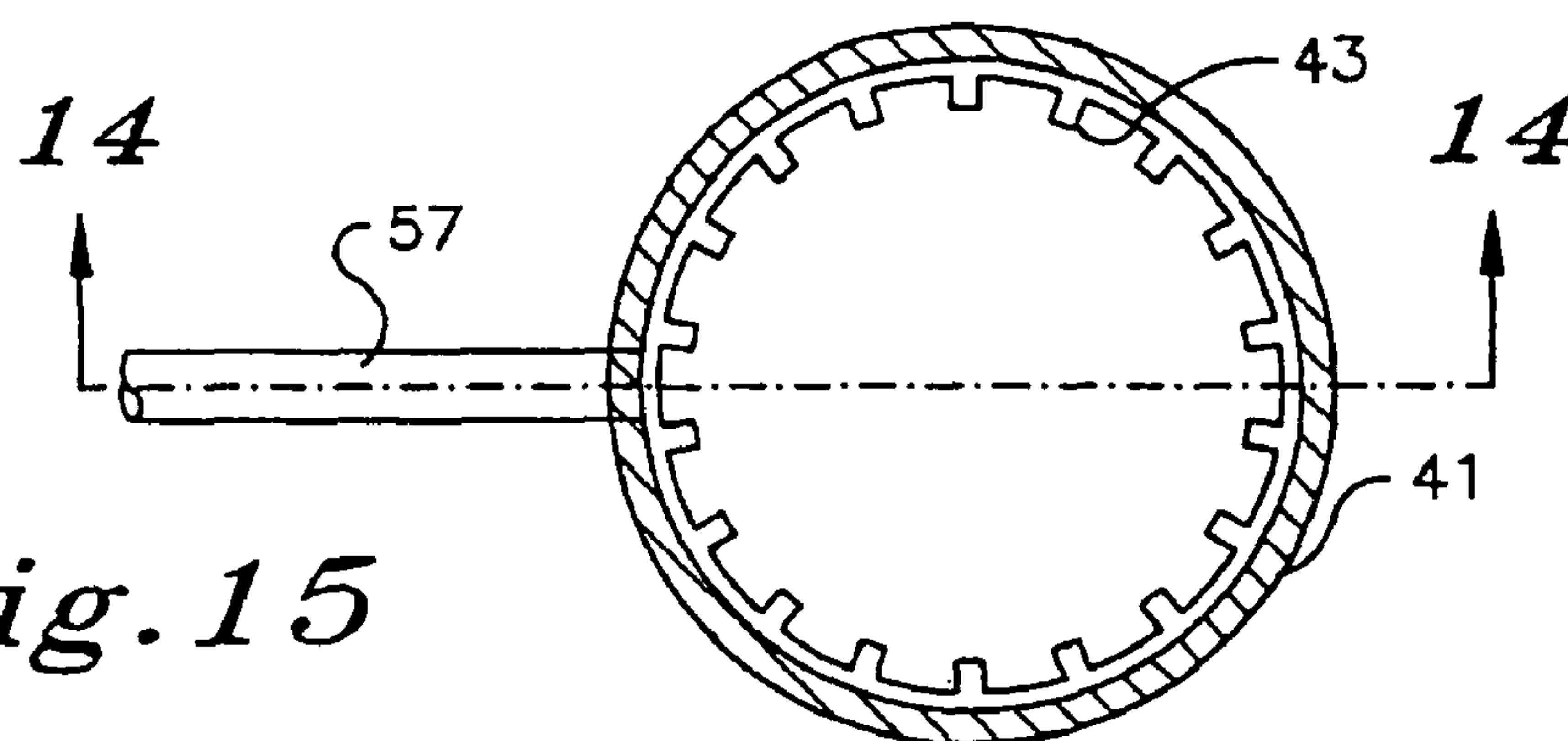
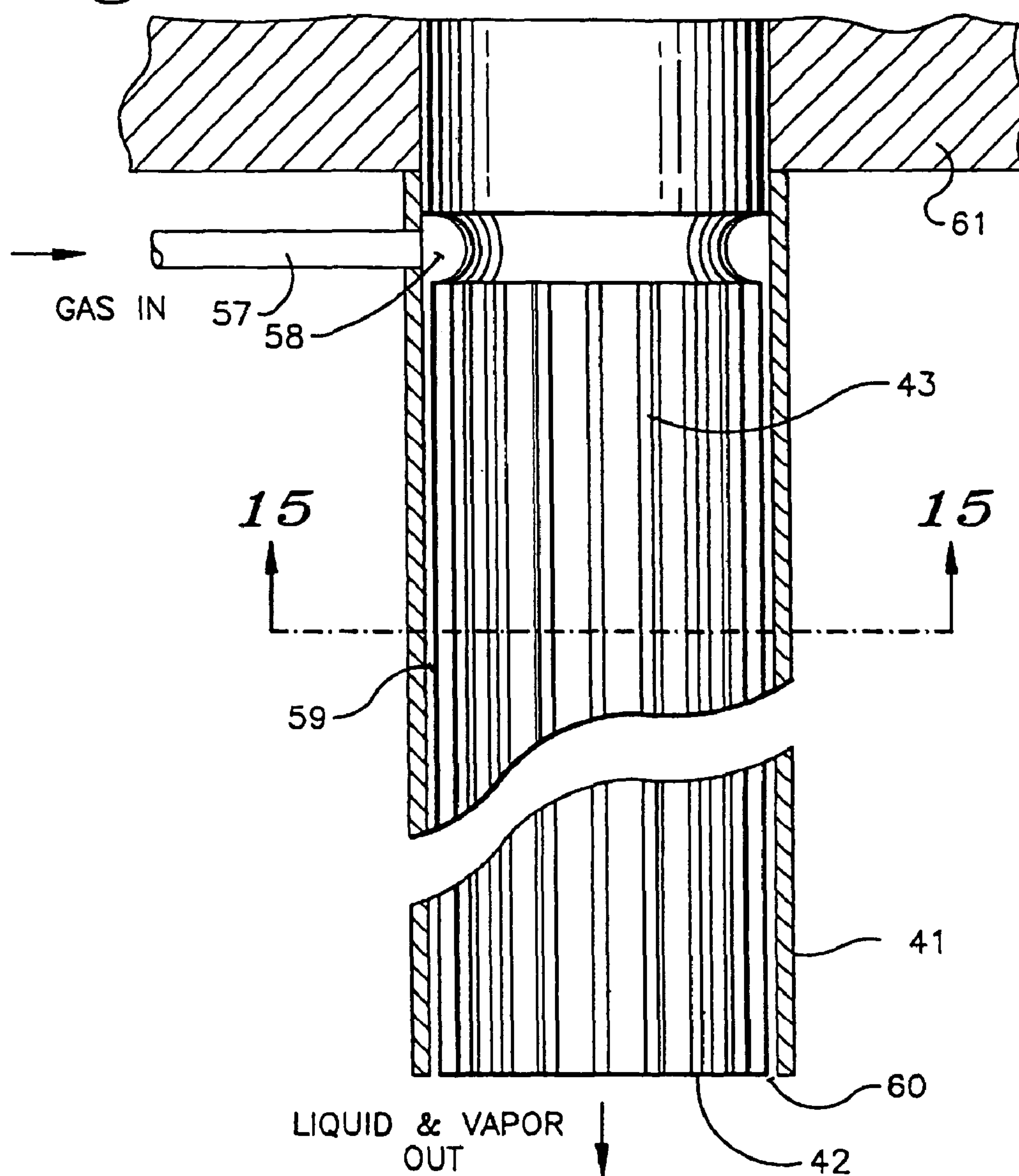
*Fig. 12*



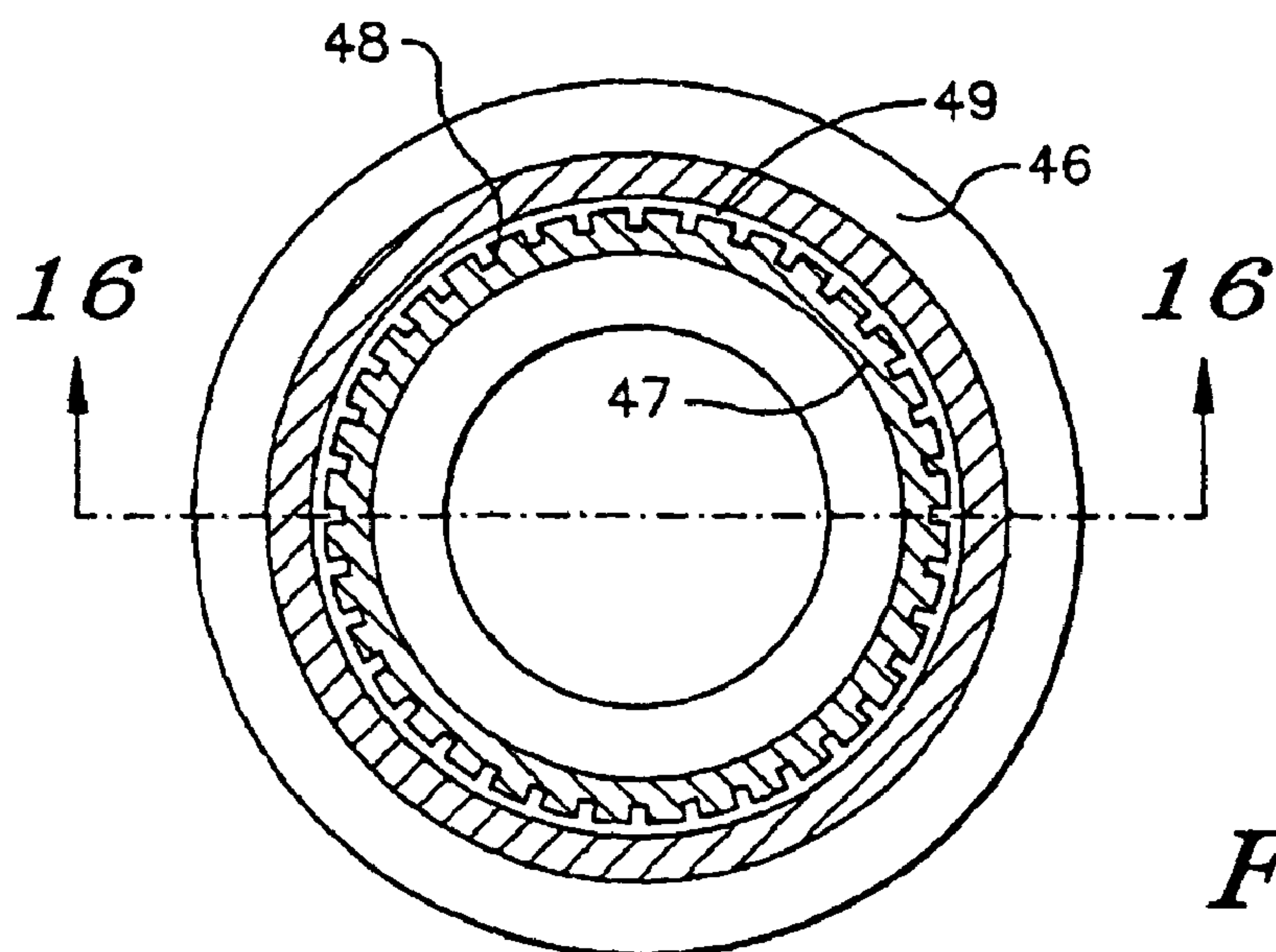
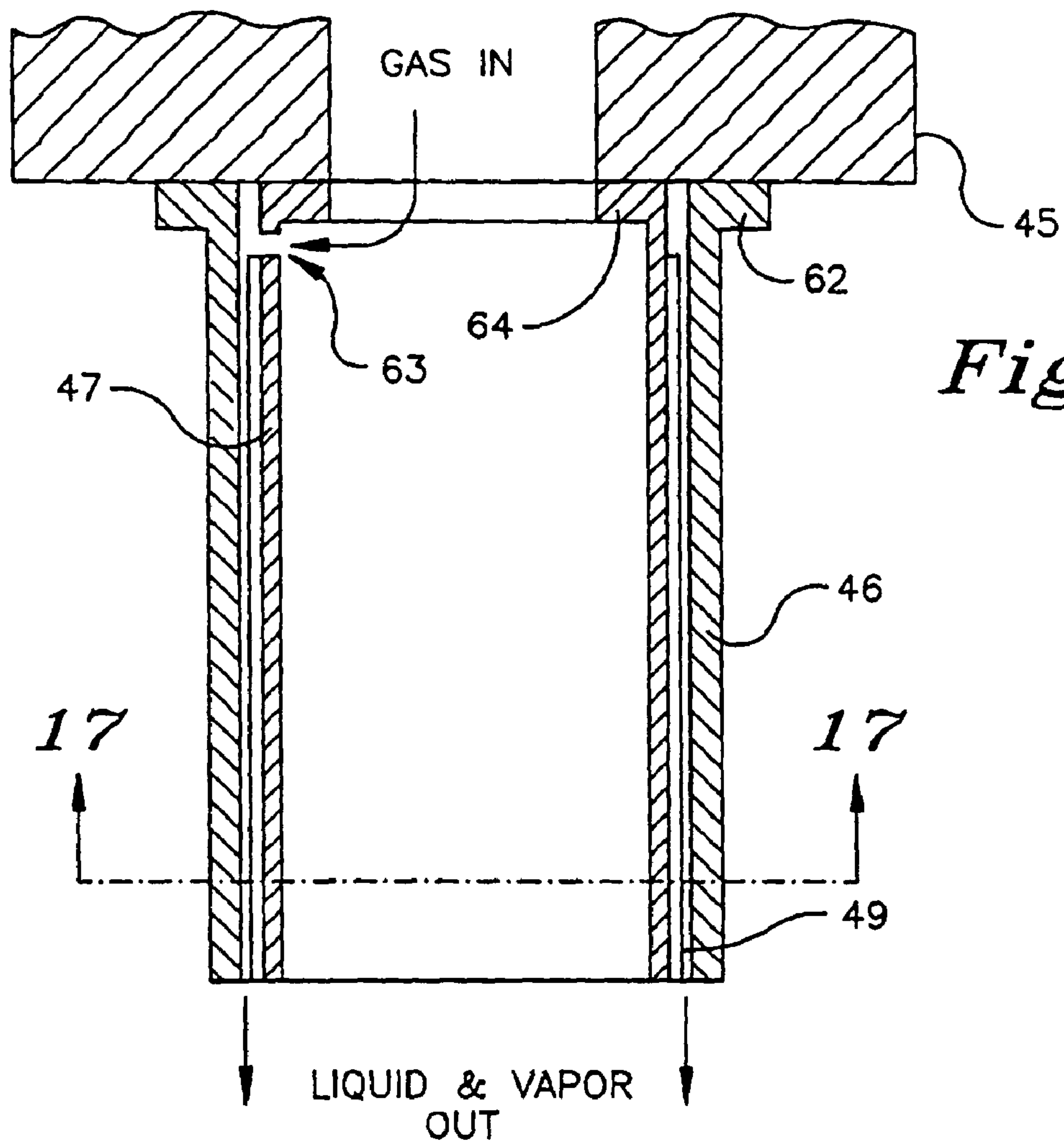
*Fig. 13*

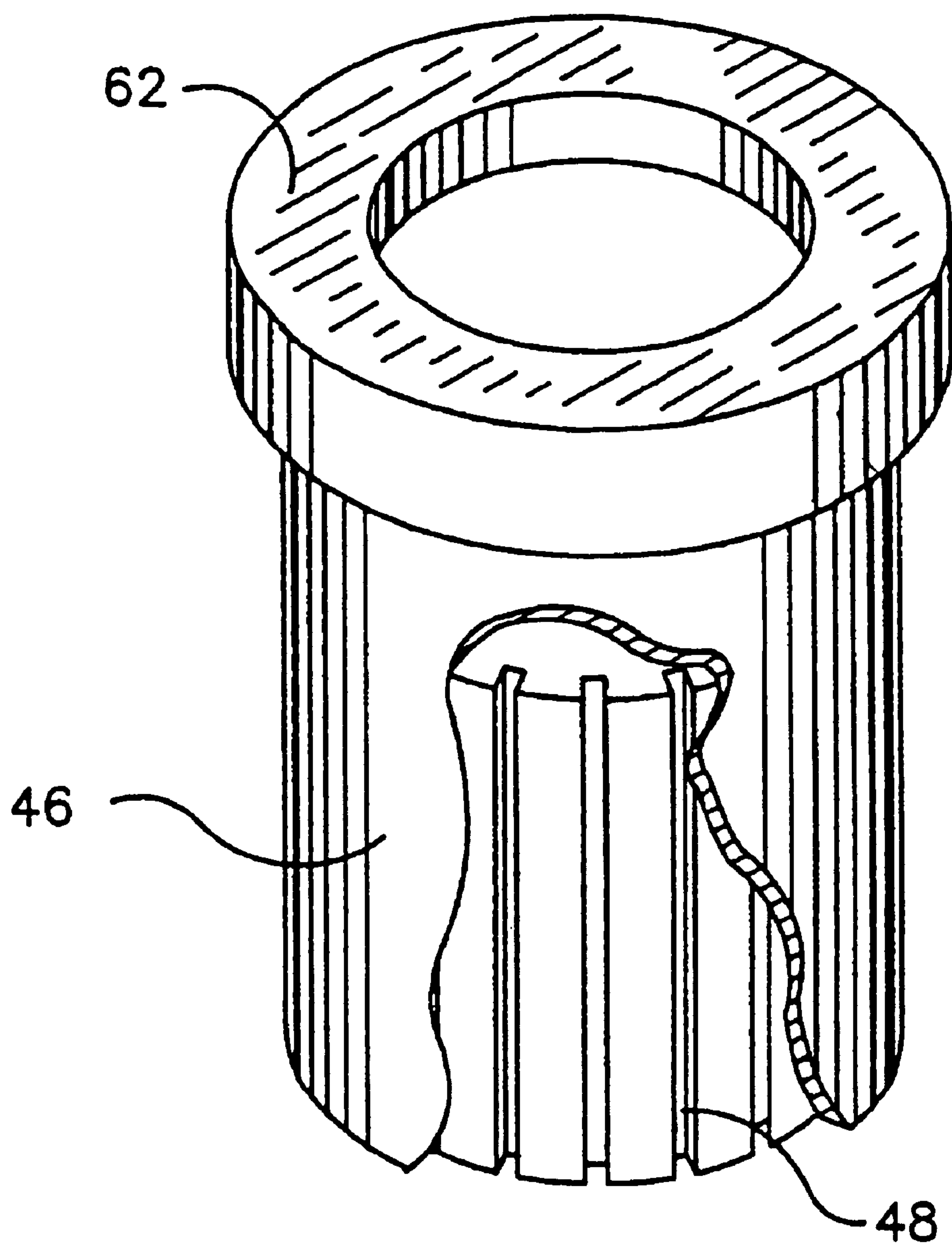


*Fig. 14*



*Fig. 15*





*Fig. 18*



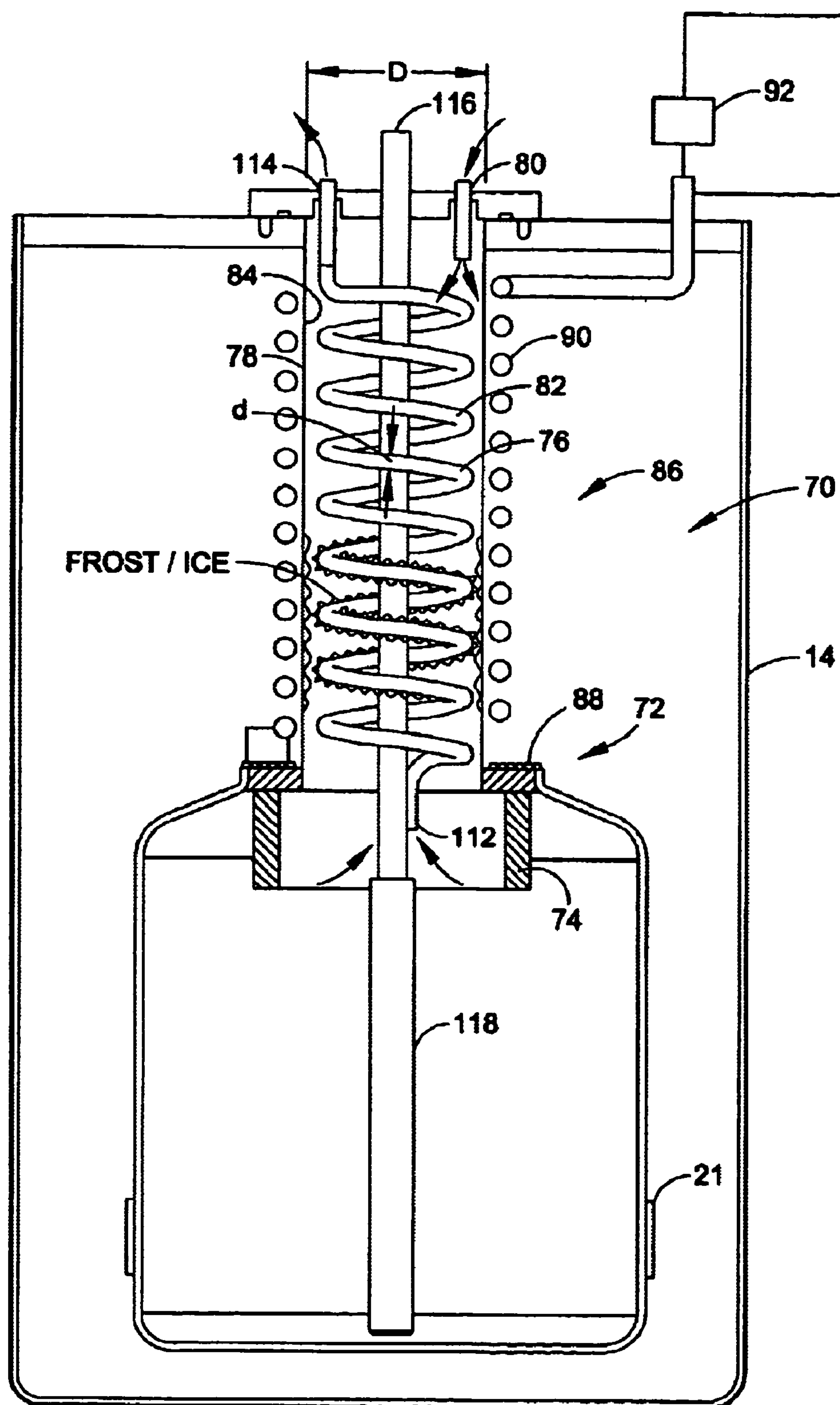


FIG. 19

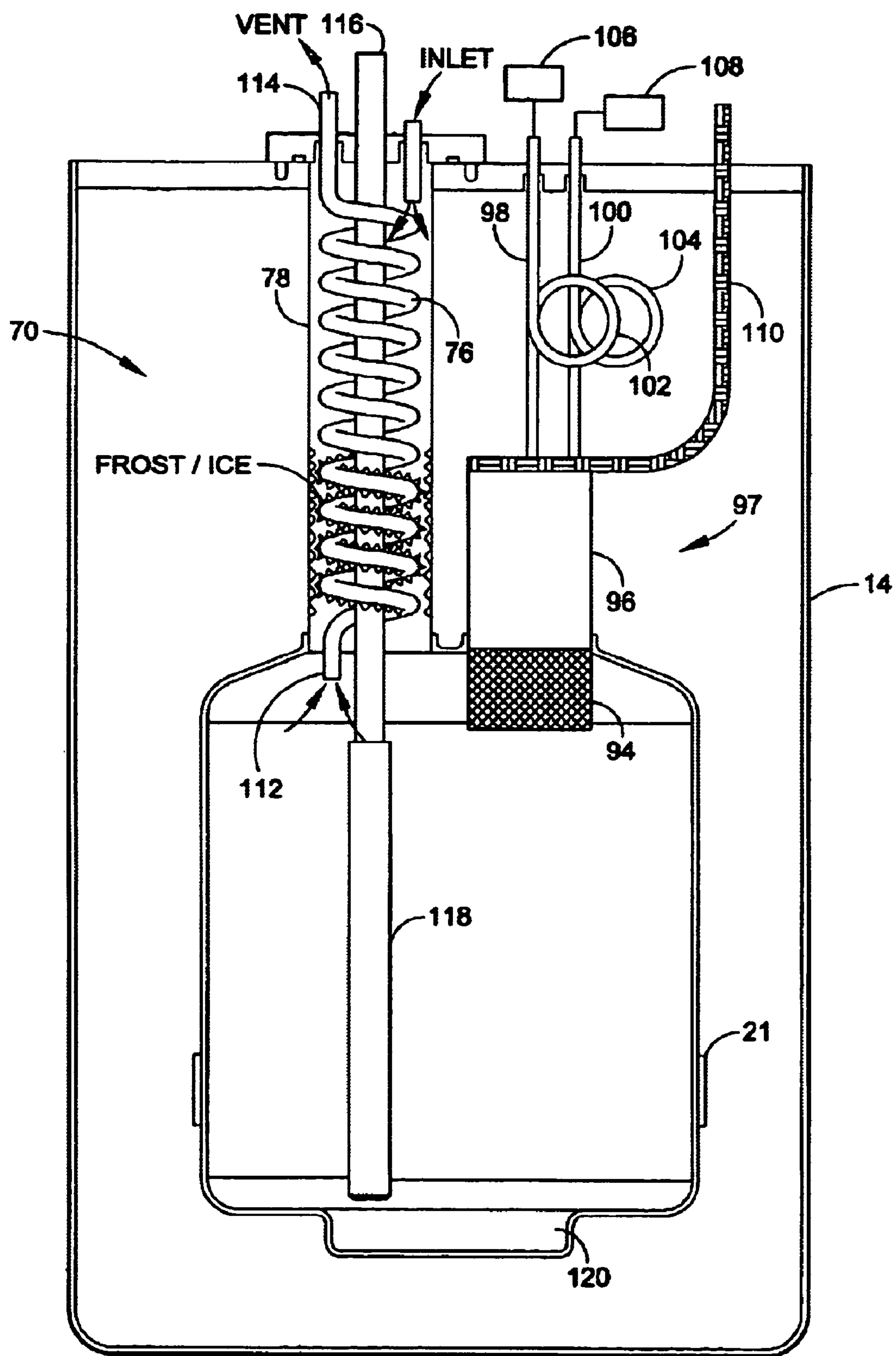


FIG. 20

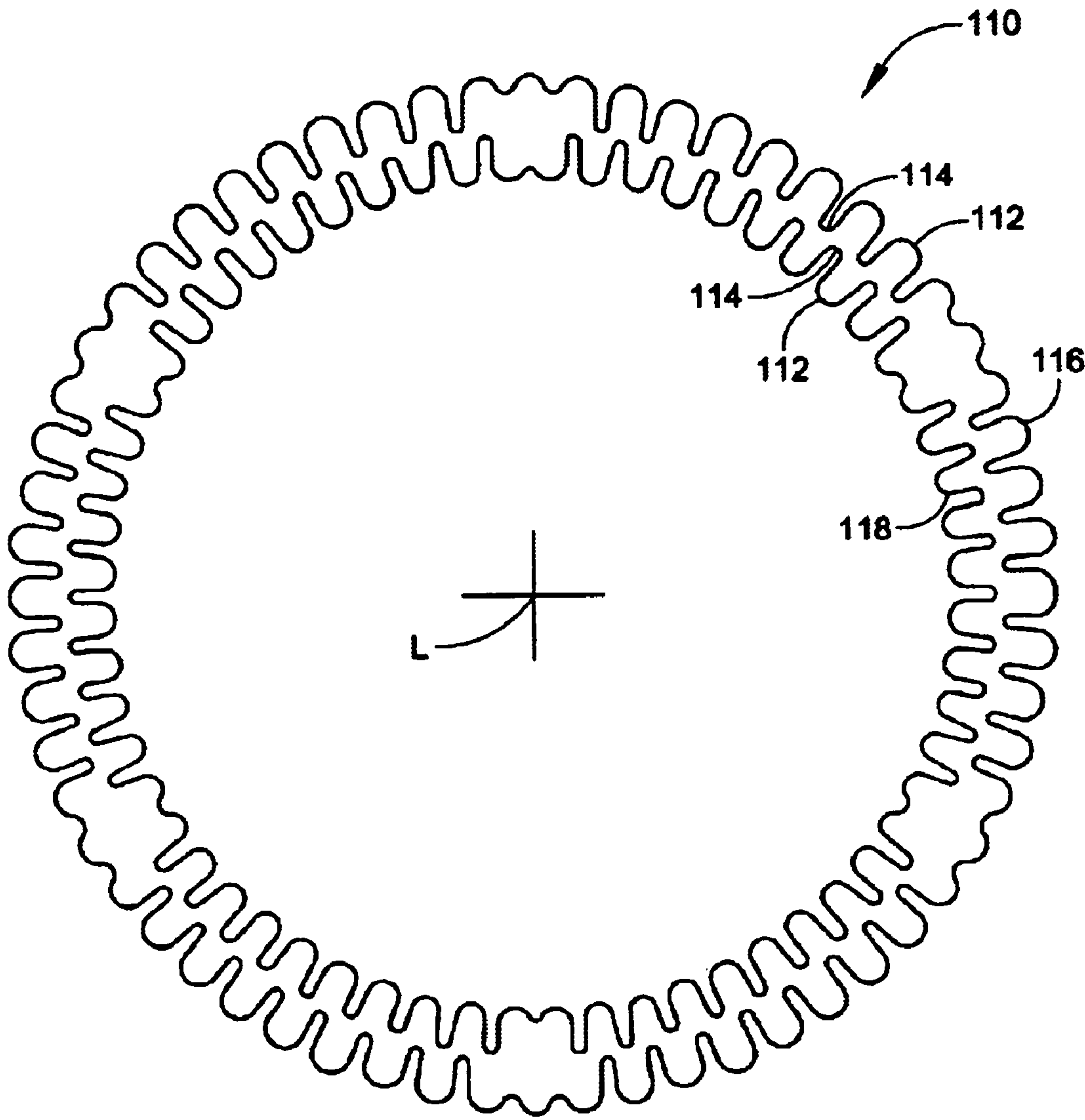
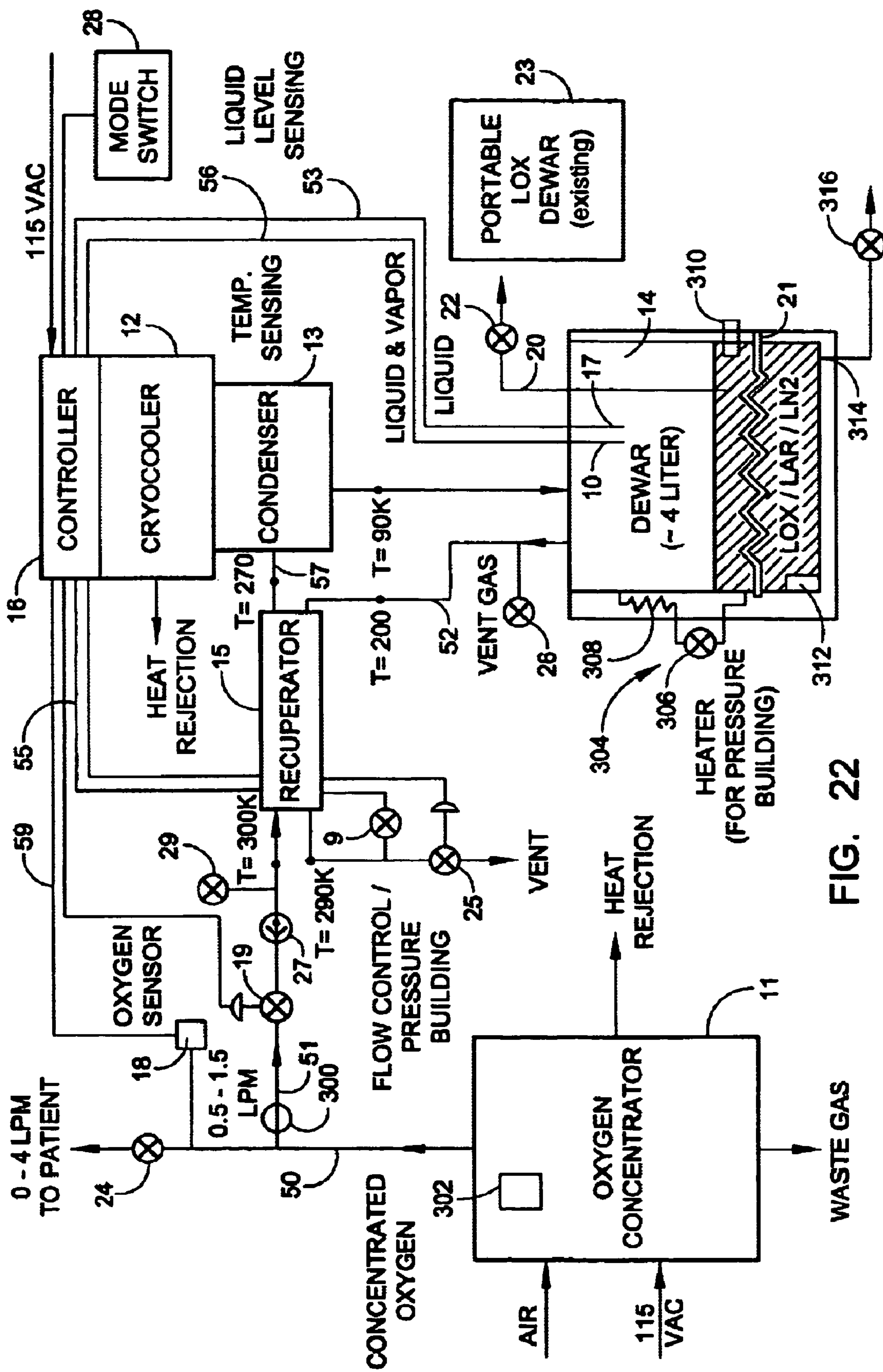


FIG. 21



**FIG. 22**



1

# METHODS AND APPARATUS TO GENERATE LIQUID AMBULATORY OXYGEN FROM AN OXYGEN CONCENTRATOR

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

## PRIOR APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 08/876,970, filed Jun. 16, 1997 now U.S. Pat. No. 5,979,440.

## BACKGROUND 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.

2

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, Calif., 1/3 hp unit costs about \$10,000 while a Haskel International, Burbank, Calif., 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. Pat. 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 THE INVENTION

An aspect of the present invention involves 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. The system includes an oxygen concentrator which separates oxygen gas from the ambient air, a condenser in communication with the oxygen concentrator for receiving and liquefying the oxygen gas flow, a cryocooler associated with the condenser, and a first storage dewar in fluid communication with the condenser and adapted to store the oxygen liquefied by the condenser, the first storage dewar including

means for transferring liquid oxygen from the first dewar to a second dewar for storing a quantity of oxygen suitable for moveable oxygen treatment.

In an embodiment of the above aspect of the invention, the liquid oxygen transferring means is adapted to increase the pressure in the first dewar.

In a further embodiment of the above aspect of the invention, the liquid transferring means includes a heater immersed within the liquid oxygen in the first dewar.

In a still further embodiment of the above aspect of the invention, the first dewar includes an inner vessel in which the liquid oxygen reside, and liquid transferring means includes a heater attached to the outer surface of inner vessel.

In another embodiment of the above aspect of the invention, the condenser is in communication with the concentrator through a line, and the liquid transferring means includes a compressor located in the line between the condenser and the concentrator.

In an additional embodiment of the above aspect of the invention, the liquid transferring means includes a high-pressure compressor in communication with the concentrator for delivering high-pressure air thereto.

In another embodiment of the above aspect of the invention, the liquid transferring means includes a vaporizer loop associated with the first dewar.

In a further embodiment of the above aspect of the invention, the liquid transferring means includes a controllable heat leak associated with the first dewar.

In a still further embodiment of the above aspect of the invention, the liquid transferring means includes a gravity-assisted dispensing mechanism.

In an additional embodiment of the above aspect of the invention, the system further includes the second storage dewar and the second storage dewar is adapted to be filled at a pressure below 20 psig.

An additional aspect of the invention involves 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. The system includes an oxygen concentrator which separates oxygen gas from the ambient air, a condenser in communication with the oxygen concentrator for receiving and liquefying the oxygen gas flow, a cryocooler associated with the condenser, and a portable dewar adapted to interface with the condenser and adapted to store the oxygen liquefied by the condenser.

Another aspect of the present invention involves a method for generating liquid oxygen in a home from a home liquid oxygen ambulatory system having an oxygen concentrator, a condenser, and cryocooler, a storage dewar and means for transferring liquid oxygen from the first dewar to a second dewar. The method includes generating a gaseous supply of oxygen using the oxygen concentrator; splitting off at least a portion of the gaseous supply to be liquefied; cooling the supply of oxygen using the condenser and cryocooler to transform the gaseous oxygen to liquid oxygen; storing the liquid oxygen in the storage dewar; and transferring the liquid oxygen in the storage dewar with the liquid oxygen transferring means to a second dewar for storing a quantity of liquid oxygen from which smaller quantities can be transferred for moveable oxygen treatment.

In an embodiment of the above aspect of the invention, transferring the liquid oxygen includes increasing the pressure in the first dewar.

In an additional embodiment of the above aspect of the invention, the liquid transferring means includes a heater immersed within the liquid oxygen in the first dewar and



## 5

transferring the liquid oxygen includes heating the liquid oxygen in the first dewar so that the pressure is increased in the first dewar.

In another embodiment of the above aspect of the invention, the first dewar includes an inner vessel in which the liquid oxygen reside, the liquid transferring means includes a heater attached to the outer surface of inner vessel, and transferring the liquid oxygen includes heating the liquid oxygen in the first dewar so that the pressure is increased in the first dewar.

In a further embodiment of the above aspect of the invention, the condenser is in communication with the concentrator through a line, and the liquid transferring means includes a compressor located in the line between the condenser and the concentrator, and transferring the liquid oxygen includes increasing the pressure of gaseous oxygen entering the condenser and the dewar with the compressor.

In a still further embodiment of the above aspect of the invention, the liquid transferring means includes a high-pressure compressor in communication with the concentrator for delivering high-pressure air thereto, and transferring the liquid oxygen includes increasing the pressure of gaseous oxygen entering the condenser and the dewar with the compressor.

In an additional embodiment of the above aspect of the invention, the liquid transferring means includes a vaporizer loop associated with the first dewar, and transferring the liquid oxygen includes heating the liquid oxygen in the first dewar with the vaporizer loop so that the pressure is increased in the first dewar.

In another embodiment of the above aspect of the invention, the liquid transferring means includes a controllable heat leak associated with the first dewar, and transferring the liquid oxygen includes heating the liquid oxygen in the first dewar so that the pressure is increased in the first dewar.

In a further embodiment of the above aspect of the invention, the liquid transferring means includes a gravity-assisted dispensing mechanism.

In a still further embodiment of the above aspect of the invention, the system further includes the second storage dewar, the second storage dewar is adapted to filled at a pressure below 20 psig.

Another aspect of the present invention involves a liquefier for a home liquid oxygen ambulatory system that is resistant to plugging. The home liquid oxygen ambulatory system includes an oxygen concentrator for delivering gaseous flow to the liquefier and a storage dewar having an inner vessel for storing liquid oxygen produced by the liquefier. The liquefier includes a condenser, a refrigerating device associated with the condenser, means for communicating incoming gaseous flow from the oxygen concentrator to the condenser, the communicating means having an inner surface with a dimension D, means for venting gaseous flow not condensed from the inner vessel, the venting means having an outer surface with an dimension d, and whereby the dimension D of the inner surface of the communicating means is significantly larger than the dimension d of the outer surface of the venting means to allow for the build-up of solid contaminants on the outer surface of the venting means without plugging up the communicating means.

In an embodiment of the above aspect of the invention, the venting means includes a recuperator comprised of a helical coil of tubing, the tubing having the outer surface with a diameter of the dimension d, whereby the incoming gas stream flows over the outer surface of the helical coil of tubing and a vent stream flows inside the helical coil of tubing.

## 6

In another embodiment of the above aspect of the invention, the outer surface of the helical coil of tubing has a cold surface to freeze out trace impurities of solid contaminants such as H<sub>2</sub>O, CO<sub>2</sub> and hydrocarbons.

In a further embodiment of the above aspect of the invention, the communicating means is comprised of a neck tube having the inner surface with a diameter of the dimension D.

In a still further embodiment of the above aspect of the invention, the liquefier further includes a liquid withdrawal tube located central to the refrigerating device, recuperator and condenser for removing liquid oxygen from the storage dewar.

In an additional embodiment of the above aspect of the invention, the refrigerating device is integral with the condenser.

In another embodiment of the above aspect of the invention, the refrigerating device, condenser and recuperator are integral with the storage dewar.

Another aspect of the invention involves a method for generating liquid oxygen in a home from a home liquid oxygen ambulatory system having an oxygen concentrator, a condenser, a cryocooler, a recuperator and a storage dewar. The method includes generating a gaseous supply of oxygen, which includes some trace impurities, using the oxygen concentrator; splitting off at least a portion of the gaseous supply to be liquefied; cooling the supply of oxygen using the condenser and cryocooler to transform the gaseous oxygen to liquid oxygen; condensing less than all of the gaseous oxygen supply flowing into the condenser; freezing out the trace impurities of the gaseous supply of oxygen and venting the non-condensed nitrogen, argon and oxygen with the recuperator; storing the liquid oxygen in the storage dewar; and periodically removing accumulated frozen impurities on the recuperator by boiling-off any stored liquid oxygen and then flow purging the system until the system has reached room temperature.

Another aspect of the invention involves a generally vertically oriented, gravity assisted condenser for use with a refrigerating device to liquefy gaseous oxygen in a home liquid oxygen ambulatory system. The condenser includes a generally vertically oriented tubular member adapted to conduct heat axially to the refrigerating device, the tubular member having outer and inner surfaces, at least one of the outer and inner surfaces having a plurality of generally vertically oriented flutes and convex fins adapted to increase the condensation rate per unit area by thinning the liquid film and drain the condensate to keep the condensate from flooding the condensation surfaces.

In an embodiment of the above aspect of the invention, the fins have a hyperbolic cosine profile.

In an additional embodiment of the above aspect of the invention, the flutes have a profile selected from the group consisting of concave, generally V-shaped, generally rectangular.

In another embodiment of the above aspect of the invention, the plurality of generally vertically oriented flutes and convex fins are located on both the outer and inner surfaces.

Another aspect of the invention involves a generally vertically oriented, gravity assisted condenser for use with a refrigerating device to liquefy gaseous oxygen in a home liquid oxygen ambulatory system. The condenser includes a generally vertically oriented tubular member adapted to conduct heat axially to the refrigerating device, the tubular member having outer and inner surfaces, at least one of the outer and inner surfaces includes means for enhancing the condensation rate per unit area by maintaining a small liquid film thickness on the condensation surfaces.



In an embodiment of the above aspect of the invention, the condensation enhancing means includes a plurality of generally vertically oriented flutes and convex fins.

In an additional embodiment of the above aspect of the invention, the fins have a hyperbolic cosine profile.

In a further embodiment of the above aspect of the invention, the flutes have a profile selected from the group consisting of concave, generally V-shaped, generally rectilinear.

In a still further embodiment of the above aspect of the invention, the plurality of generally vertically oriented flutes and convex fins are located on both the outer and inner surfaces.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 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.

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

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

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

FIG. 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.)

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

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

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

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

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

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

FIG. 12 illustrates basic components of a pulse tube refrigerator.

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

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

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

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

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

FIG. 18 is an isometric view of the embodiment of the condenser shown in FIGS. 16 and 17.

FIG. 19 is a cross-sectional view of an embodiment of a dewar having a liquefier with an integral vapor compression cycle coldhead, condenser, and recuperator, which is resistant to plugging and performance degradation caused by trace impurities in the gas stream such as water vapor, carbon dioxide and hydrocarbons.

FIG. 20 is a cross-sectional view of an alternative embodiment of a dewar having a liquefier with an integral pulse tube or Sterling cycle coldhead, condenser, and recuperator, which is resistant to plugging and performance degradation caused

by trace impurities in the gas stream such as water vapor, carbon dioxide and hydrocarbons.

FIG. 21 is an end cross-sectional view, similar to FIG. 17, of an embodiment of a condenser having shaped fins to reduce the liquid film thickness.

FIG. 22 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, similar to FIG. 1, and shows numerous means for transferring liquid oxygen from the storage dewar.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A flow chart of the preferred embodiment of the invention is set out in FIG. 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  $H_2O$ ,  $CO_2$ ,  $CO$ ,  $NO_x$ , 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 Lique-



faction Schedule for optimal operation of the liquefaction system is set out in FIGS. 7-10 and may be stored in the 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 FIG. 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 FIG. 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. Pat. Nos. 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 270 K (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 ~90 K 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: 90.18 K, 87.28 K, and 77.36 K 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 FIGS. 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 FIG. 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 89.5 K 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 FIGS. 3 and 4 for binary mixtures. Fortunately, this concern was avoided when the system was set so that only 20 to 99% 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.

FIG. 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



## 11

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 (20-99%) is liquefied, the remainder of the flow will purge the vapor with higher impurity concentration from the system. A condenser temperature of about 90 K (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 FIGS. **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 69.2-109.7 K 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 FIG. **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.

With reference to FIG. **22**, other alternative means for transferring or dispensing liquid from the dewar **14** will now be described. For simplicity, the alternative liquid transferring means are described with respect to this one Figure. It will be readily apparent to those skilled in the art that any,

## 12

combination, or all of the disclosed liquid transferring means discussed below could be used in a single home liquid oxygen ambulatory system.

An alternative means for transferring liquid by raising the pressure in the dewar **14** includes adding a compressor **300** between the oxygen concentrator **11** and the condenser **13**. The compressor **300** is preferably added in line **51**, either before or after valve **19**. The compressor **300** increases the pressure in the storage dewar **14** so that when the portable dewar **23** is engaged, liquid is forced up the dip tube **20** and into the portable dewar **23**. An additional benefit of adding a compressor **300** at this location is that it increases the pressure during liquefaction in the dewar **14**, which increases the saturation temperature. An increased saturation temperature eases the cooling requirements on the cryocooler **12**.

A further means for transferring liquid by raising the pressure in the dewar **14** includes using a high-pressure compressor **302** within the oxygen concentrator **11** instead of the typical low-pressure compressor. The high-pressure compressor **302** has the effect of increasing the pressure in the storage dewar **14** so that when the portable dewar **23** is engaged, liquid is forced up the dip tube **20**. In addition to easing the cooling requirements on the cryocooler **12**, a compressor **302** at this location slightly enhances the PSA cycle.

A still further means for transferring liquid by raising the pressure in the dewar **14** includes using a vaporizer loop **304**. In this embodiment, the dewar **14** preferably remains at low pressure while liquid is being produced. When transfer of liquid out of the dewar **14** is desired, a valve **306** is opened to allow some liquid to flow into a coil **308** to be vaporized. This would increase the pressure in the dewar **14** so that liquid could be transferred to the portable dewar **23**.

Another means for transferring liquid by raising the pressure in the dewar **14** includes a controllable heat leak such as a conductive strap **310** between ambient and the inner vessel of the dewar **14**. When transfer of liquid out of the dewar **14** is desired, the heat leak is controlled so that heat from the ambient is transferred to the liquid, causing it to vaporize. This would increase the pressure in the dewar **14** so that liquid could be transferred to the portable dewar **23**.

Another means for transferring liquid by raising the pressure in the dewar **14** includes a controllable pump **312** that is actuated when transfer of liquid out of the dewar **14** is desired.

An additional means for transferring liquid without raising the pressure in the dewar **14** includes incorporating a gravity-assisted dispensing mechanism **314** such as a controllable spigot (analogous to those used to dispense liquids from a large insulated cooler) near the bottom of the dewar **14**. Unlike the alternative means for transferring liquid from the storage dewar **14** described above, which expel liquid out of the dip tube **20**, the gravity-assisted dispensing mechanism eliminates the need for the dip tube **20**. The gravity-assisted dispensing mechanism **314** preferably includes a quick disconnect valve **316** or other flow control means, similar to disconnect valve **22** described above, located on the end of the mechanism **314** to allow for connection of a portable dewar **23**.

An additional means for transferring liquid without raising the pressure in the dewar **14** includes incorporating a portable dewar **23** adapted to be filled from a pressure less than 20 psig, which is the standard for currently available home stationary liquid dewars. For example, the portable dewar **23** may be adapted to be filled from a pressure such as 5 psig.

A further means for transferring liquid without raising the pressure in the dewar **14** involves replacing the storage dewar **14** with a specially designed portable dewar **23** such as that



## 13

described above with respect to FIG. 2, which interfaces with the rest of the home liquid oxygen ambulatory system.

In order to eliminate accumulation of solid water and hydrocarbons which may be supplied in trace amounts from the oxygen concentrator, the dewar 14, recuperator 15, and condenser 13 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 until all the liquid has boiled-off as evidenced by, for example, the temperature sensor 10 being above 125 K. The heater will boil-off the remaining liquid in the dewar 14 and with it any trace amounts of water and hydrocarbons which are condensed and solidified in the liquid oxygen or on the cold surfaces. Once valve 19 is reopened, the flow of concentrated oxygen gas purges and removes most of the water vapor and hydrocarbons from the liquefier. The heater 21 will remain turned on until the dewar temperature, measured by temperature sensor 10, has warmed to about 300 K. Any remaining water vapor will be flushed out by gaseous oxygen during the subsequent cooldown.

The dewpoint/frostpoint of the gas stream provided by the oxygen concentrator is below  $-55^{\circ}\text{C}$ . Although the mass of water flowing into the liquefier is quite small, the ice/frost formed at such a cold temperature has a very low density and hence, can take a appreciable volume of space that can lead to plugging of the liquefier. Therefore, the design of the recuperator 15 and/or condenser 13 must be able to allow for accumulation of frost without plugging.

With reference to FIG. 19, an embodiment of a liquefier 70, which is resistant to plugging, will now be described. Elements similar to those previously described are referred to with the reference numerals and are not described in further detail. The liquefier 70 includes an integral coldhead 72, condenser 74 and a recuperator 76 located generally within a dewar 14. Incoming gaseous flow enters a neck tube 78 via an inlet 80 as shown by the arrows. The gaseous flow includes mostly oxygen gas along with a small amount of water vapor and other trace impurities. The gaseous flow is pre-cooled as it passes the helical recuperator 76. Water vapor in the gaseous flow freezes out on surfaces at temperature below its frostpoint such as outer surface 82 of the recuperator 76 and inner surface 84 of the neck tube 78. The neck tube 78 has an inner diameter or dimension D and the helical recuperator 76 is constructed of a tube having an outer diameter or dimension d. By making inner diameter D of the neck tube 78 significantly larger than the outer diameter d of the helical recuperator tube 76 at locations along the neck tube 78 where incoming gaseous flow is present, the liquefier 70 allows for accumulation of frost on the inner surface 84 of the neck tube 78 or outer surface 82 of the recuperator 76 without plugging. This extends the period of time required between boil-dries without causing plugging in the liquefier 70.

Oxygen from the gaseous flow condenses into liquid oxygen at the condenser 74. The condenser 74 is shown in conjunction with a vapor compression cycle cryocooler 86 (evaporator 88, tube-in-tube heat exchanger 90, compressor 92) as its associated refrigerating mechanism. It will be readily understood by those skilled in the art that other refrigerating mechanisms may be used in conjunction with the condenser such as, but not by way of limitation, pulse tube, Stirling, etc. For example, with reference to FIG. 20, in an alternative embodiment of the invention, a condenser 94 may

## 14

be used in conjunction with a coldhead 96 from a pulse tube cryocooler 97 to liquefy the incoming flow. The cryocooler 97 includes copper tubes 98, 100 that provide strain relief via respective coils 102, 104. Copper tube 98 connects the coldhead 96 to a compressor 106 and copper tube 100 connects the coldhead 96 to a reservoir volume 108. A flexible copper braid 110 provides a heat conduction path if needed to reject heat from the coldhead 96.

Excess gaseous flow not condensed becomes vent gas that is removed from the liquefier 70 via the recuperator 76. Vent gas enters the recuperator 76 through inlet 112, as shown by the arrows, flows through the helical recuperator 76 (providing the aforementioned pre-cooling) and preferably exits to the atmosphere through outlet 114.

The dewar 14 may include a central liquid withdrawal tube 116 for withdrawing liquid oxygen from the dewar 14. The central liquid withdrawal tube 116 may include an integral liquid level sensor 118 for monitoring the level of the liquid oxygen in the dewar 14. A heater 21 may be attached to the outer surface of the inner vessel of the dewar 14 to assist in transferring liquid oxygen from the dewar 14.

A getter cup 120 such as those used in commercial cryogenic dewars may be attached to the inner vessel of the dewar 14 to maintain a high vacuum in the dewar 14.

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 FIG. 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 90 K, 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.

FIG. 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.).

FIGS. 7A-D show a logic flow chart for the controller for the normal operation modes. This can also be referred to as



## 15

the "input/output control schedule." 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 FIG. 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. FIGS. 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, FIG. 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 FIGS. 6 through 8 and as depicted in FIG. 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 FIG. 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 FIG. 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 FIG. 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 FIG. 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 FIG. 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, FIG. 11 indicates the boil-dry mode, with valve **25** open to allow the vapor to escape, and the various parameters relating thereto.

FIG. 12 shows a schematic of a pulse tube refrigerator, the preferred embodiment of the cryocooler **12** in FIG. 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 U.S. Pat. Nos. 5,488,830; 5,412,952 and 5,295,355 the disclosure of which are hereby incorporated by reference. FIG. 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 FIG. 12 is comprised of a pressure oscillator **30**, primary heat rejecter **31**, regenerator **32**, heat acceptor **33**, pulse tube **34**, orifice rejecter **35**, bypass orifice **36**, primary orifice **37**, and reser-

## 16

voir 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 rejecter **35** where it is rejected at near ambient temperature. Although FIG. 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.

FIG. 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 U.S. Pat. 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 FIG. 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 FIG. 1 is shown in FIGS. 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 20-99% 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.



17

FIGS. 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, FIG. 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 FIG. 18.

FIG. 21 is a cross-sectional view, similar to the views in FIGS. 15 and 17, of another embodiment of a generally vertically oriented gravity assisted condenser 110. The condenser 110 includes fins 112 and corresponding flutes 114 that extend vertically the longitudinal length of the condenser 110 on both an exterior side 116 and an interior side 118 of the condenser 110, generally parallel with a vertical longitudinal axis L of the condenser 110. The vertical longitudinally elongated fins 112 and flutes 114 enhance condensation by using surface tension forces to maintain a small liquid film thickness on the condensation surface. A small liquid film thickness,  $\delta$ , allows for better condensation performance because the heat transfer coefficient ( $h$ ) is equal to  $k/\delta$  ( $h=k/\delta$ ). The fins 112 preferably have a convex surface with a hyperbolic cosine profile to provide a uniform liquid film thickness and maximize condensation; however, other simpler convex curved surfaces that are more easily manufactured can be used with only slightly less performance. A convex surface for the fins 112 produces a small liquid film thickness and a concave surface for the flute 114 supports or receives a larger liquid film thickness. Thus, the convex surfaces of the fins 112 can be drained by concave surfaces of the flutes 114. Thus, the flutes 114 serve as drainage channels to keep the condensate from flooding the condensation surfaces. By making a condenser 110 with both vertical longitudinally elongated convex and concave portions, the overall condensation rates can be increased many fold even though the surface area is only increased a little.

In an alternative embodiment of the invention, the flutes 114 may have a profile that is other than convex such as, but not by way of limitation, generally rectilinear or generally V-shaped.

In a further embodiment of the invention, the fins 112 and flutes 114 may exist on only the exterior side 116 or interior side 118 of the condenser 110. Alternatively, the condenser 110 may have fins 112 and flutes 114 on the interior and/or the exterior and the condenser 110 is used in conjunction with another condensing device such as another condenser located within the interior 118 and/or around the exterior 116 of the condenser 110.

Prior art (U.S. Pat. Nos. 4,253,519, 4,216,819) has been limited to horizontal externally fluted tubes with purely radial conduction through the tube wall. In contrast, the condenser 110 of the present invention may include fins 112 and flutes 114 on both sides 116, 118. Also, heat is conducted axially in the condenser 110 of the present invention.

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

18

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.

What is claimed is:

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] a pressure swing adsorption system is condensed into liquid oxygen, comprising:

- (a) [an oxygen concentrator] a pressure swing adsorption system comprising a molecular sieve bed which [separates oxygen gas from] receives the ambient air as an input and provides an output of oxygen-enriched gas;
- (b) a condenser in communication with said [oxygen concentrator] pressure swing adsorption system for receiving and liquefying [the oxygen gas flow] the output from the pressure swing adsorption system;
- (c) a cryocooler associated with said condenser; and
- (d) a first storage dewar in fluid communication with said condenser and adapted to store the oxygen liquefied by the condenser, the first storage dewar including means for transferring liquid oxygen from the first dewar to a second dewar for storing a quantity of oxygen suitable for moveable oxygen treatment, wherein said liquid oxygen transferring means is adapted to increase the pressure in said first dewar.

2. The system of claim 1, wherein said liquid transferring means includes a heater immersed within the liquid oxygen in said first dewar.

3. The system of claim 1, wherein said first dewar includes an inner vessel in which said liquid oxygen reside, and liquid transferring means includes a heater attached to the outer surface of inner vessel.

4. The system of claim 1, wherein said condenser is in communication with said [concentrator] pressure swing adsorption system through a line, and said liquid transferring means includes a compressor located in said line between said condenser and said [concentrator] pressure swing adsorption system.

5. The system of claim 1, wherein said liquid transferring means includes a high-pressure compressor in communication with said concentrator for delivering high-pressure air thereto.]

6. The system of claim 1, wherein said liquid transferring means includes a vaporizer loop associated with said first dewar.

7. The system of claim 1, wherein said liquid transferring means includes a controllable heat leak associated with said first dewar.

8. The system of claim 1, wherein said liquid transferring means includes a gravity-assisted dispensing mechanism.

9. The system of claim 1, wherein said system further includes said second storage dewar and said second storage dewar is adapted to be filled at a pressure below 20 psig.

10. A method for generating liquid oxygen in a home from a home liquid oxygen ambulatory system having [an oxygen concentrator] a pressure swing adsorption system comprising a molecular sieve bed, a condenser, and cryocooler, a storage dewar and means for transferring liquid oxygen from the first dewar to a second dewar, comprising:

- (a) generating a gaseous supply of oxygen using the [oxygen concentrator] pressure swing adsorption system



19

*which receives the ambient air as an input and provides an output of oxygen-enriched gas;*

(b) splitting off at least a portion of the gaseous supply to be liquefied;

(c) cooling said supply of oxygen using the condenser and cryocooler to transform the gaseous oxygen to liquid oxygen;

(d) storing the liquid oxygen in the storage dewar;

(e) transferring the liquid oxygen in the storage dewar with the liquid oxygen transferring means to a second dewar by increasing the pressure in said first dewar for storing a quantity of liquid oxygen from which smaller quantities can be transferred for moveable oxygen treatment.

11. The method of claim 10, wherein said liquid transferring means includes a heater immersed within the liquid oxygen in said first dewar and transferring the liquid oxygen includes heating the liquid oxygen in said first dewar so that the pressure is increased in said first dewar.

12. The method of claim 10, wherein said first dewar includes an inner vessel in which said liquid oxygen reside, said liquid transferring means includes a heater attached to the outer surface of inner vessel, and transferring the liquid oxygen includes heating the liquid oxygen in said first dewar so that the pressure is increased in said first dewar.

13. The method of claim 10, wherein said condenser is in communication with said [concentrator] *pressure swing adsorption system* through a line, and said liquid transferring means includes a compressor located in said line between said condenser and said [concentrator] *pressure swing adsorption system*, and transferring the liquid oxygen includes increasing the pressure of gaseous oxygen entering said condenser and said dewar with said compressor.

14. The method of claim 10, wherein said liquid transferring means includes a high-pressure compressor in communication with said concentrator for delivering high-pressure air thereto, and transferring the liquid oxygen includes increasing the pressure of gaseous oxygen entering said condenser and said dewar with said compressor.]

15. The method of claim 10, wherein said liquid transferring means includes a vaporizer loop associated with said first dewar, and transferring the liquid oxygen includes heating the liquid oxygen in said first dewar with said vaporizer loop so that the pressure is increased in said first dewar.

16. The method of claim 10, wherein said liquid transferring means includes a controllable heat leak associated with said first dewar, and transferring the liquid oxygen includes heating the liquid oxygen in said first dewar so that the pressure is increased in said first dewar.

17. The method of claim 10, wherein said liquid transferring means includes a gravity-assisted dispensing mechanism.

18. The method of claim 10, wherein said system further includes said second storage dewar, said second storage dewar is adapted to filled at a pressure below 20 psig.

19. A liquefier for a home liquid oxygen ambulatory system that is resistant to plugging, the home liquid oxygen ambulatory system having [an oxygen concentrator] *a pressure swing adsorption system comprising a molecular sieve bed* for delivering gaseous flow to the liquefier and a storage dewar having an inner vessel for storing liquid oxygen produced by the liquefier, comprising:

a condenser;

a refrigerating mechanism associated with said condenser;

means for communicating incoming gaseous flow from the

[oxygen concentrator] *pressure swing adsorption system which receives the ambient air as an input and*

20

*provides an output of oxygen-enriched gas* to the condenser, said communicating means having an inner surface with a dimension D;

means for venting gaseous flow not condensed from the inner vessel, said venting means having an outer surface with a dimension d and disposed within said communicating means; and

whereby the dimension D of the inner surface of the communicating means is significantly larger than the dimension d of the outer surface of the venting means to allow for the build-up of solid contaminants on the outer surface of the venting means without plugging up the communicating means.

20. The liquefier of claim 19, wherein said venting means includes a recuperator comprised of a helical coil of tubing, the tubing having said outer surface with a diameter of said dimension d, whereby the incoming gas stream flows over the outer surface of said helical coil of tubing and a vent stream flows inside said helical coil of tubing.

21. The liquefier of claim 20, wherein said outer surface of said helical coil of tubing has a cold surface to freeze out trace impurities of solid contaminants such as H<sub>2</sub>O, CO<sub>2</sub> and hydrocarbons.

22. The liquefier of claim 19, wherein said communicating means is comprised of a neck tube having said inner surface with a diameter of said dimension D.

23. The liquefier of claim 19, wherein refrigerating mechanism is integral with the condenser.

24. The liquefier of claim 19, wherein the refrigerating mechanism and condenser are integral with said storage dewar.

25. A method for generating liquid oxygen in a home from a home liquid oxygen ambulatory system having [an oxygen concentrator] *a pressure swing adsorption system comprising a molecular sieve bed*, a condenser, a cryocooler, a recuperator and a storage dewar, comprising:

(a) generating a gaseous supply of oxygen, which includes some trace impurities, using the [oxygen concentrator] *pressure swing adsorption system which receives the ambient air as an input and provides an output of the gaseous supply of oxygen;*

(b) splitting off at least a portion of the gaseous supply to be liquefied;

(c) cooling said supply of oxygen using the condenser and cryocooler to transform the gaseous oxygen to liquid oxygen;

(d) condensing less than all of the gaseous oxygen supply flowing into the condenser;

(e) freezing out the trace impurities of the gaseous supply of oxygen and venting the excess gaseous oxygen with said recuperator;

(f) storing the liquid oxygen in the storage dewar; and

(g) periodically removing accumulated frozen impurities on said recuperator by boiling-off any stored liquid oxygen and then flow purging the system until the system has reached room temperature.

26. A generally vertically oriented, gravity assisted condenser for use with a refrigerating mechanism to liquefy gaseous oxygen in a home liquid oxygen ambulatory system, comprising:

a generally vertically oriented tubular member adapted to conduct heat axially to said refrigerating mechanism, the tubular member having a geometric center and outer and inner surfaces, at least one of said outer and inner surfaces having a plurality of generally vertically oriented flutes and convex fins adapted to increase the condensation rate per unit area by thinning the liquid



## 21

film and drain the condensate to keep the condensate from flooding the condensation surfaces, wherein the flutes and convex fins are circumferentially spaced with respect to each other and not radially aligned with each other relative to the geometric center of the tubular member.]

[27. The condenser of claim 26, wherein the fins have a hyperbolic cosine profile.]

[28. The condenser of claim 26, wherein said plurality of generally vertically oriented flutes and convex fins are located on said inner surface.]

[29. The condenser of claim 26, wherein said plurality of generally vertically oriented flutes and convex fins are located on both said outer and inner surfaces.]

[30. A generally vertically oriented, gravity assisted condenser for use with a refrigerating mechanism to liquefy gaseous oxygen in a home liquid oxygen ambulatory system, comprising:

a generally vertically oriented tubular member adapted to conduct heat axially to said refrigerating mechanism, the tubular member having outer and inner surfaces, at least one of said outer and inner surfaces includes means for enhancing the condensation rate per unit area by maintaining a small liquid film thickness on the condensation surfaces, said condensation enhancing means including a plurality of generally vertically oriented flutes and convex fins located on both said outer and inner surfaces.]

31. An apparatus for supplying oxygen-enriched gas to a patient in a home environment and for use in an ambulatory environment, comprising:

a compressor adapted to receive ambient air and produce compressed air;

a pressure swing adsorption system comprising a molecular sieve bed adapted to produce oxygen-enriched gas, the pressure swing adsorption system having an inlet adapted to receive the compressed air from the compressor and an outlet adapted to provide the oxygen-enriched gas;

a first outlet flow line operatively coupled to the outlet and adapted to deliver a first portion of the oxygen-enriched gas to a patient;

a second outlet flow line operatively coupled to the outlet and adapted to deliver a second portion of the oxygen-enriched gas to a storage vessel; and

a valve positioned and operable to terminate the delivery of the second portion of the oxygen-enriched gas to the storage vessel responsive to an oxygen concentration of the oxygen-enriched gas being below a predetermined value, wherein the first outlet flow line remains substantially unimpeded so as to maintain the delivery of the first portion of the oxygen-enriched gas to the patient even during termination of the second portion of the oxygen-enriched gas to the storage vessel.

32. The apparatus of claim 31, wherein an oxygen concentration of the first portion of the oxygen-enriched gas is at least 80%.

33. The apparatus of claim 31, further comprising an oxygen sensor adapted to sense a concentration of oxygen-enriched gas produced by the pressure swing adsorption system, wherein the valve closes to prevent delivery of the second portion of the oxygen-enriched gas to the storage vessel responsive to the oxygen sensor sensing that the oxygen concentration of the oxygen-enriched gas is below the predetermined value.

34. The apparatus of claim 33, wherein the predetermined value is 88%.

## 22

35. The apparatus of claim 33, wherein the oxygen sensor is operatively coupled to the second outlet flow line.

36. The apparatus of claim 31, wherein the valve is positioned between the outlet of the pressure swing adsorption system and the storage vessel.

37. The apparatus of claim 31, further comprising a third outlet flow line having (a) a first end operatively coupled to the outlet of the pressure swing adsorption system, and (b) a second end, wherein the first outlet flow line and the second outlet flow line are coupled to a second end of the third outlet flow line.

38. The apparatus of claim 31, further comprising a product storage tank adapted to receive the oxygen-enriched gas from the pressure swing adsorption system, and wherein an outlet of the product tank corresponds to the outlet of the pressure swing adsorption system.

39. The apparatus of claim 31, wherein the pressure swing adsorption system is an oxygen concentrator.

40. The apparatus of claim 31, further comprising a liquefier adapted to liquefy at least a portion the second portion of the oxygen-enriched gas, and wherein the storage vessel stores the liquefied oxygen.

41. A process for supplying oxygen-enriched gas to a patient and to a storage vessel comprising the steps of:

generating an oxygen product utilizing a pressure swing adsorption system comprising a molecular sieve bed; directing a first portion of the oxygen product to a patient; directing a second portion of the oxygen product to a storage vessel;

monitoring an oxygen concentration of the oxygen product; and

interrupting delivery of the second portion of the oxygen product to the storage vessel responsive to the oxygen concentration being below a predetermined value, wherein directing the first portion of the oxygen product to the patient continues while the delivery of the second portion of the oxygen product is interrupted.

42. The process of claim 41, wherein the oxygen product is an oxygen-enriched gas.

43. The process of claim 41, wherein the predetermined value is 88%.

44. The process of claim 41, further comprising: liquefying at least a portion of the second portion of the oxygen product directed to the storage vessel; and storing the liquefied oxygen product in the storage vessel.

45. The process of claim 41, further including the step of pressurizing the second portion of the oxygen product directed to the storage vessel to a pressure greater than the pressure of the first portion of the oxygen product directed to the patient.

46. The process of claim 41, wherein the pressure swing adsorption system is an oxygen concentrator.

47. The process of claim 41, further including the step of transferring the oxygen product from the storage vessel to a portable storage vessel.

48. An apparatus for providing oxygen-enriched gas to a patient in a home environment and an ambulatory environment comprising:

a pressure swing adsorption system comprising a molecular sieve bed adapted to generate oxygen-enriched gas; a first outlet flow line operatively coupled to the pressure swing adsorption system to direct a first portion of the oxygen-enriched gas from the pressure swing adsorption system to a patient;

a storage vessel; and a second outlet flow line operatively coupled to the pressure swing adsorption system to direct a second portion



23

of the oxygen-enriched gas from the pressure swing adsorption system to the storage vessel;  
 a compressor in fluid communication with the second outlet flow line, wherein the compressor is adapted to compress the second portion of oxygen-enriched gas prior to delivery to the storage vessel; and  
 a coupling operatively coupled to the storage vessel, wherein the coupling is adapted to be connected with a portable tank to enable filling of the portable tank from the storage vessel.

49. The apparatus of claim 48, further comprising a liquefier adapted to liquefy at least a portion of the second portion of the oxygen-enriched gas directed to the storage vessel, and wherein the storage vessel stores the liquefied oxygen.

50. That apparatus of claim 48, wherein the pressure swing adsorption system is an oxygen concentrator.

51. A process for supplying oxygen-enriched gas to a patient and to a portable storage container comprising the steps of:  
 generating an oxygen product utilizing a pressure swing adsorption system comprising a molecular sieve bed;  
 directing a first portion of the oxygen product to a patient;  
 directing a second portion of the oxygen product to a storage vessel; and  
 filling a portable storage container with a content of the storage vessel.

52. The process of claim 51, wherein the oxygen product is an oxygen-enriched gas.

53. The process of claim 51, further comprising:  
 liquefying at least a portion the second portion of the oxygen product directed to the storage vessel; and  
 storing the liquefied oxygen product in the storage vessel, and wherein filling the portable storage container includes providing the liquefied oxygen product as the content from the storage vessel to the portable storage container.

54. The process of claim 51, wherein the pressure swing adsorption system is an oxygen concentrator.

55. The process of claim 51, wherein the first portion of oxygen product is delivered simultaneously to the patient while the second portion of oxygen product is directed to the storage vessel.

56. The process of claim 55, wherein the flow of the second portion of oxygen product is terminated if the oxygen product is measured to be below a predetermined concentration level.

57. The process of claim 56, wherein the predetermined concentration level is 88%.

58. An apparatus for filling a portable tank with an oxygen product, comprising:  
 a pressure swing adsorption system comprising a molecular sieve bed adapted to generate oxygen-enriched gas;  
 a storage vessel;  
 an outlet flow line operatively coupled to the pressure swing adsorption system to direct at least a portion of the oxygen-enriched gas from the pressure swing adsorption system to the storage vessel;  
 a compressor to receive the oxygen-enriched gas from the pressure swing adsorption system from the outlet flow line, wherein the compressor is adapted to compress the portion of the oxygen-enriched gas prior to delivery to the storage vessel; and  
 a coupling operatively coupled to the storage vessel, wherein the coupling is adapted to be connected with a portable tank suitable for human transport to enable filling of the portable tank with a content from the storage vessel.

24

59. The apparatus of claim 58, further comprising a liquefier adapted to liquefy at least a portion the oxygen-enriched gas directed to the storage vessel, and wherein the storage vessel stores the liquefied oxygen.

60. The apparatus of claim 58, wherein the pressure swing adsorption system is an oxygen concentrator.

61. A method of filling a portable tank for portable transport by a patient with an oxygen product, the method comprising the steps of:  
 generating an oxygen product gas utilizing a pressure swing adsorption system comprising a molecular sieve bed which receives the ambient air as an input and provides an output of the oxygen product gas at a first pressure;  
 pressurizing the oxygen product gas to a second pressure subsequent to the generation, the second pressure being greater than the first pressure;  
 directing the oxygen product at the second pressure to a storage vessel; and  
 filling a portable tank of sufficient size for portability by a patient with a content of the storage vessel.

62. The method of claim 61, further comprising:  
 liquefying at least a portion the oxygen product after the compressing step; and  
 storing the liquefied oxygen product in the storage vessel, and wherein filling the portable tank includes providing the liquefied oxygen product as the content from the storage vessel to the portable tank.

63. The method of claim 61, wherein the pressure swing adsorption system is an oxygen concentrator.

64. The method of claim 61 further including monitoring a purity of the oxygen product and terminating the direction of oxygen product to the storage vessel responsive to the purity being below a predetermined level.

65. A method of producing and storing liquid oxygen in an oxygen patient's residence, comprising:  
 providing a liquid oxygen producing apparatus;  
 placing the liquid oxygen producing apparatus in a location at which a user of liquid oxygen resides;  
 producing liquid oxygen at the location utilizing a pressure swing adsorption system comprising a molecular sieve bed which receives the ambient air as an input and provides an output of oxygen-enriched gas; and  
 delivering oxygen-enriched gas produced by the pressure swing adsorption system to a patient.

66. The method of claim 65, further including monitoring a purity of the oxygen-enriched gas to determine whether a level of purity is suitable for human consumption.

67. The method of claim 65, wherein the delivering step is conducted while the liquid oxygen producing apparatus is producing the liquid oxygen.

68. The method of claim 65, wherein producing the liquid oxygen is terminated responsive to an oxygen concentration level of the oxygen-enriched gas produced by the pressure swing adsorption system being below a predetermined level.

69. The method of claim 65, further comprising storing the liquid oxygen in a dewar and transferring the liquid oxygen from the dewar to a portable storage device.

70. A home liquid oxygen ambulatory system for supplying an ambulatory portable supply of oxygen comprising:  
 a pressure swing adsorption system comprising a molecular sieve bed adapted to separate oxygen from ambient air for human consumption;  
 a liquefier adapted to receive oxygen from the pressure swing adsorption system and liquefying the oxygen;



## 25

a first storage dewar in fluid communication with the liquefier and adapted to store oxygen liquefied by the liquefier;

a second portable storage dewar adapted to store a quantity of oxygen suitable for ambulatory moveable oxygen treatment;

a monitor for measuring an oxygen concentration of oxygen from the pressure swing adsorption system; and

a controller receiving signals from the monitor, and adapted to terminate the liquefying of the oxygen responsive to the oxygen concentration being below a predetermined level.

71. The apparatus of claim 70, wherein the predetermined level of oxygen concentration is at least 88% oxygen purity.

72. The apparatus of claim 70, further including a pressure inducer adapted to increase the pressure within the first dewar for facilitating in the transfer of liquid oxygen from the first dewar to the second portable dewar.

73. The apparatus of claim 70, further comprising a flow line from the pressure swing adsorption system to a person so as to deliver oxygen from the pressure swing adsorption system to a patient simultaneous to the delivery of oxygen to the liquefier.

## 26

74. The apparatus of claim 70 including a valve operationally controlled by the controller, wherein the valve terminates the flow of oxygen to the liquefier responsive to the oxygen concentration being below a predetermined level.

75. A method for generating liquid oxygen in a home comprising:

generating a gaseous supply of oxygen for human consumption using a pressure swing adsorption system comprising a molecular sieve bed which receives the ambient air as an input and provides an output of the gaseous supply of oxygen;

monitoring a purity of the gaseous oxygen supply to determine if the level of purity is suitable for human consumption;

liquefying the gaseous supply of oxygen responsive to the level of purity being above a predetermined level;

storing the liquid oxygen in a first storage dewar;

transferring the liquid oxygen in the first storage dewar to a portable second storage.

76. The method of claim 75, wherein at least a portion of the gaseous supply of oxygen from the pressure swing adsorption system is delivered to a person for consumption.

\* \* \* \* \*