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TURBO EXPANDER FOR SATELLITE REFRIGERATOR

**PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
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FOR

**FERMI NATIONAL ACCELERATOR LABORATORY
BATAVIA, ILLINOIS**

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TURBO EXPANDER FOR SATELLITE REFRIGERATOR1. INTRODUCTION:

Presently, satellite refrigerators are equipped with reciprocating expansion engines. The question has arisen whether turbines could replace these engines in order to achieve greater reliability. This report evaluates the feasibility of equipping the satellite refrigerator with turbo expanders.

2. SATELLITE REFRIGERATOR PROCESS:

Figure 1 shows the process flow sheet of the satellite refrigerator cold box (below 80°K). Tables I, II, and III give the significant process points for satellite operation, refrigerator operation, and liquefier operation, respectively.

The values of the tables have been calculated on the basis of the following performance data of the expanders:

a) Warm Expander:

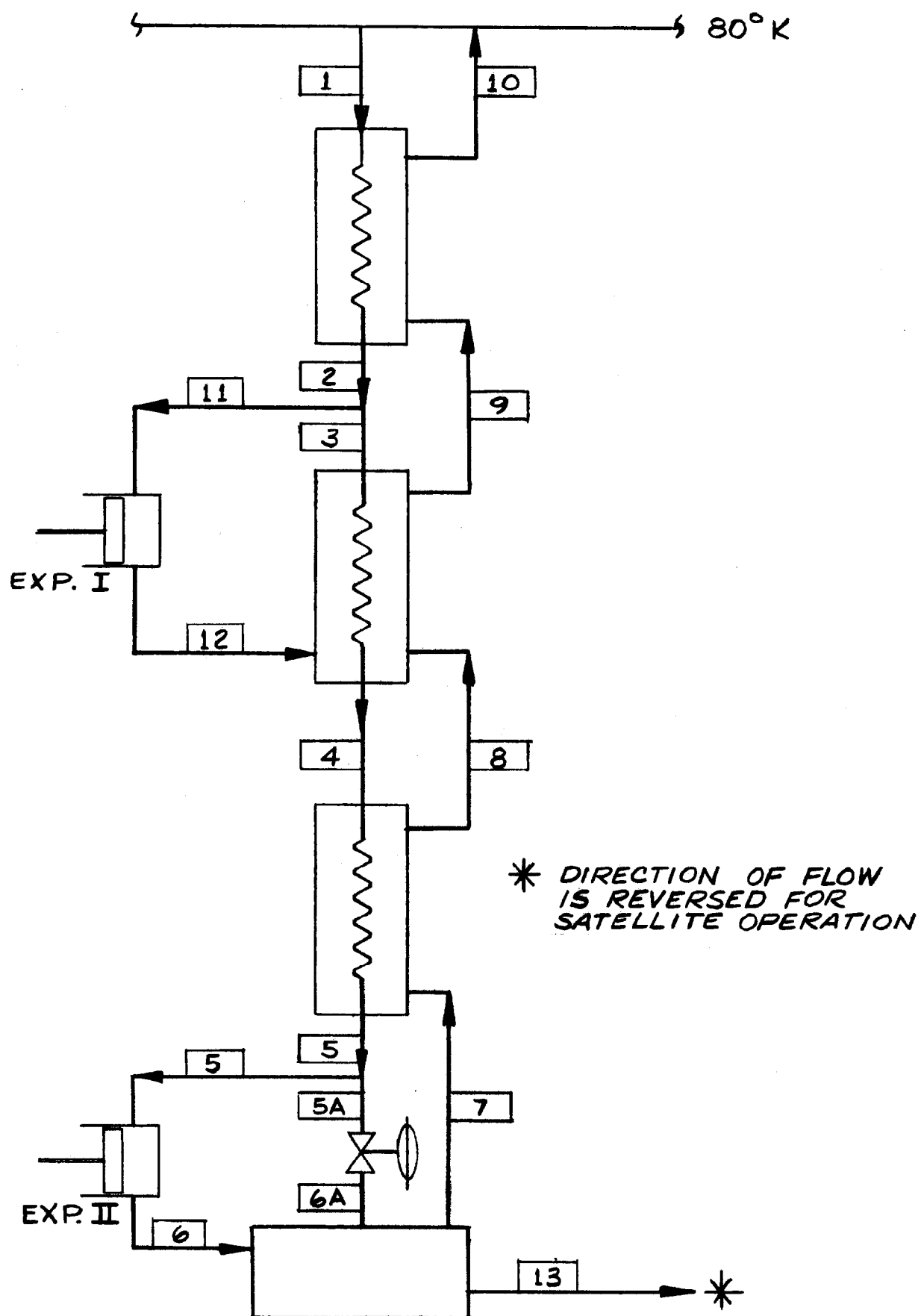
Inlet Pressure	=	20.0 atm
Discharge Pressure	=	1.4 atm
Efficiency	=	62%

b) Wet Expander/Liquefier Mode:

Inlet Pressure	=	20.0 atm
Inlet Temperature	=	8.15°K
Discharge Pressure	=	1.8 atm
Efficiency	=	56%

c) Wet Expander/Satellite Mode:

Inlet Pressure	=	20 atm
Inlet Temperature	=	5.24°K
Discharge Pressure	=	1.8 ata
Efficiency	=	57%

FIGURE - 1

T A B L E I

<u>Point</u>	<u>Pres. ata</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
1	20.8	80	434.4	46.1
2	20.5	25.07	138.8	46.1
3	20.5	25.07	138.8	46.1
4	20.1	15.6	77.76	46.1
5	20.0	5.24	21.84	46.1
6	1.8	4.75	13.1	46.1
7	1.22	4.4	29.94	50.0
8	1.19	13.15	81.55	50.0
9	1.16	23.8	137.84	50.0
10	1.11	76.2	410.42	50.0
11	20.0	25.07	138.8	-0-
12	-	-	-	-0-
*13	1.22	4.4	11.91	3.9

T A B L E I I

<u>Point</u>	<u>Pres. ata</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
1	20.8	81	439.6	50.0
2	20.5	30	166.9	50.0
3	20.5	30	166.9	35.06
4	20.1	18	96.67	35.06
5	20.0	5.7	23.34	35.06
6	1.8	4.9	14.4	35.06
7	1.22	4.4	29.94	35.06

TABLE II (Continued)

<u>Point</u>	<u>Pres. ata</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
8	1.20	17.25	103.27	35.06
9	-	-	-	50.0
10	1.11	79	425.2	50.0
11	20.5	30	166.9	14.94
12	1.20	17.25	103.27	14.94
13	-	-	-	-0-

TABLE III

<u>Point</u>	<u>Pres. ata</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
1	20.8	80	434.4	50.0
2	20.0	25.07	138.8	50.0
3	20.0	25.07	138.8	13.34
4	20.0	14.7	75.86	13.34
5	20.0	8.15	33.66	13.34
6	1.8	4.9	24.66	13.34
7	1.22	4.4	29.94	9.68
8	1.20	14.4	88.1	9.68
9	1.20	17.8	106.22	46.34
10	1.11	79	425.2	46.34
11	20.0	25.07	138.8	36.66
12	1.20	14.4	88.1	36.66
13	1.22	4.4	10.80	3.66

3. The following operations with the satellite refrigerator are considered:

- a) Cooldown of the magnet string.
- b) Liquefaction operation.
- c) Satellite refrigerator operation.
- d) Refrigerator operation.
- e) Standby of the magnet string and/or satellite refrigerator.

In order to evaluate the five operating modes, it is useful to briefly review the operation and equipment used during the five modes of operation listed above. In order to understand these various modes, the flow sheet of Figure 2 of the satellite refrigerator, magnets, and central helium liquefier should be considered. Detailed flow sheets of the components of the system of Figure 2 are shown on the following drawings: #1650-ME-91468 and #1650-ME-91469.

Figure 2 shows three essentially independent systems, as follows:

- 1) The CHL (central helium liquefier) consisting of compressors and cold box makes liquid helium into the 5,000 gal liquid helium dewar. High pressure gas flows through lines 1 and 2 to the cold box, low pressure gas returns through lines 6 and 7. Gas to be liquefied is added to the system through lines 9 and 10 (warm) and line 8 (cold). These three sources of gas are generated from:
 - a) Lead flow of the magnets is returned through line 9 as low pressure warm gas.
 - b) The satellite refrigerator unbalanced flow of the cold box (see Table I) is first compressed by the satellite compressor and then returned as ambient temperature gas through control valve V5 and line 10 to the CHL compressor discharge line.
 - c) Cold helium gas of 4.4°K and 1.2 ata is returned from the vapor space of the pump dewar to the cold vapor return line from the 5,000 gal dewar. This vapor represents the losses suffered in pumping liquid helium around the accelerator through liquid helium transfer line 12 which is approximately 4 miles long.

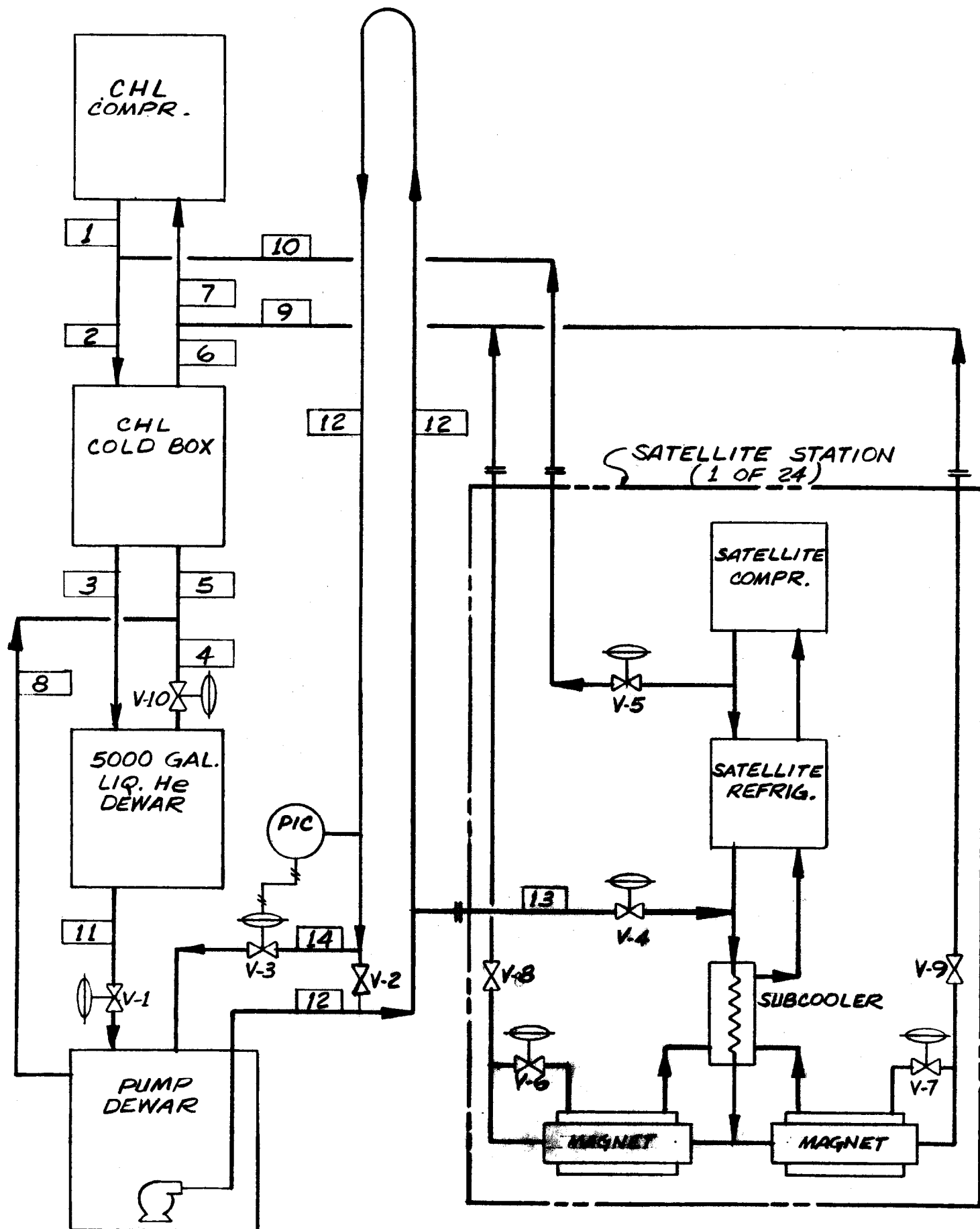


FIGURE - 2

- 2) The pump dewar with liquid helium circulation pump and 4 mile long transfer line 12 around the accelerator ring provides a sufficiently large source of liquid helium under pressure to the satellite refrigerators. A constant pressure in the liquid helium supply line is maintained at the inlet of valve 4. This is accomplished by pumping more than the maximum requirement for liquid helium and returning the excess through valve V3 to the pump dewar.

In case circuit 12 is interrupted (bad transfer line section), valve V3 will be closed and valve V2 opened to maintain supply of liquid helium to all satellite stations.

- 3) Twenty-four (24) satellite refrigerators with compressors and cold boxes provide 600-800 W of refrigeration at 4.4°K to the magnets of the accelerator. In order to generate this much refrigeration with modest flow rates in compressors and cold boxes, liquid helium is added through valve V4, refrigeration is extracted from this liquid in the satellite refrigerator cold box, and the warm gas is returned to the CHL through valve V5 and line 10.

Each of the three systems can operate by itself, provided that:

- a) The CHL receives gas for liquefaction from another source than the satellite refrigerators.
- b) The pump dewar receives liquid from the storage dewar to replenish losses.
- c) The satellite refrigerators receive some gas or liquid to make up for losses in the system.

Cooldown Operation:

In order to remove all but .5% of the heat from copper and stainless steel of the magnet structures, it is only necessary to cool the magnets to a temperature of 20°K. After reaching 20°K, some 575,000 joules (40,000 lb of steel) remain to be removed per satellite station. Only 50 liters of liquid helium are required to do this.

To cool quickly to 20°K, the satellite refrigerator needs to provide a high flow rate of helium gas at 20°K. This will be achieved by operation of the warm expander at the highest possible flow rate. The satellite refrigerator will use liquid nitrogen under these conditions. The benefit of using the wet expander under these conditions

is insignificant and the machine should be bypassed. Time required to cool a string of magnets is of the order of 30 hrs. To cool the rest of the way and fill requires approximately 10 hrs.

Liquefaction Operation:

To liquefy at the highest rate, both warm and cold expanders should be used.

Satellite Operation:

Only the wet engine operates. There is no need for a warm expander.

Refrigerator Operation:

Both warm and cold engines are required for full output.

Magnet String Standby Operation:

It is assumed that the magnets will not be pulsed. If it is not necessary to maintain the magnets full of liquid, warm engine operation is not required until the liquid in the magnet has been consumed. This may be a period of 16-24 hrs, dependent on heat leak of the magnet string.

Table IV summarizes the engine requirements for the various modes of operation and the number of hours in a year for each operation. It is assumed that there will be four complete cooldowns per year. Non-operation of the CHL is assumed to be for a total period of 24 days divided into 6 equal periods of continuous non-operating time. Standby time will be treated to mean drifting to 80°K when the magnets are not used for long periods of time. Satellite refrigerator operation is then not required.

T A B L E I V

<u>Function</u>	<u>Warm Expander</u>	<u>Cold Expander</u>
Cooldown (4X)		
a) To 20°K	120 hrs	-
b) Fill	-	40 hrs
Liquefier	-	-
Satellite	-	6,000 hrs
Refrigerator	400 hrs	400 hrs
Standby	100 hrs	100 hrs

Standby time while maintaining the magnets full of liquid will be considered as refrigerator time. Typically, these periods will be short relative to standby time with the magnets drifting up to 80°K. Assume a total of 100 hrs per year.

Table IV suggests that the real important engine for full performance operation is the cold or wet engine. The warm engine is used only for a total of 610 hrs per year and the longest continuous operation involving a warm engine is of the order of 100 hrs.

4. Replacement of the Warm Reciprocating Engine with a Turbine:

It is assumed that Fermilab does not want to engage in turbine development and that commercially-available turbines will be considered. Following are the sources potentially capable of providing turbines:

a) Sulzer Brothers, Wintherthur, Switzerland.-

To our knowledge Sulzer has an exclusive agreement with Helix of Waltham, Mass. This agreement gives Helix the sole right to market the Sulzer turbines as part of their helium refrigeration equipment. To date, Sulzer turbines have not been sold as modules to be included in refrigeration systems designed and built by others than Helix in the U.S.A.

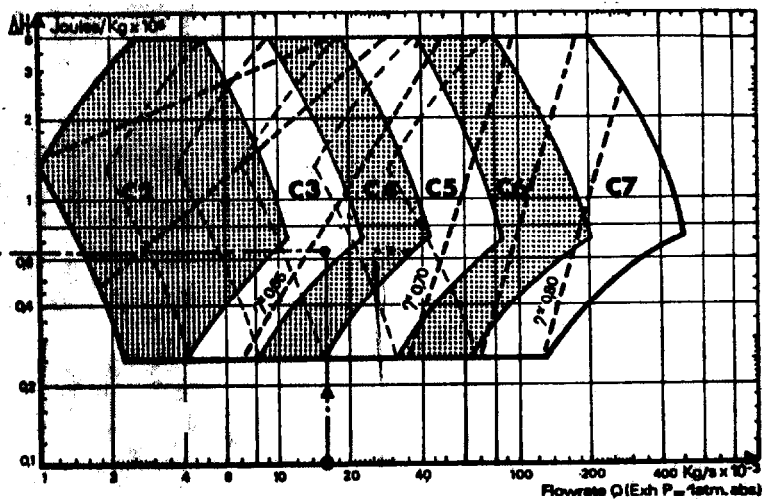
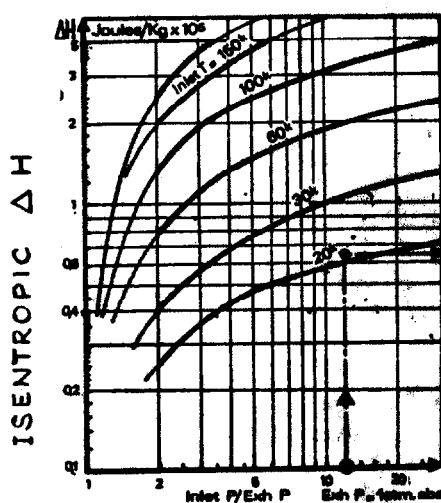
b) B.O.C., Great Britain.-

B.O.C. markets its gas bearing turbines through Cryoproducts, Guilderland, N.Y. To date, B.O.C. turbines have not been sold as modules to be included in refrigeration systems designed and built by others than Cryoproducts in the U.S.A.

c) L'Air Liquide, Sassenage, France.-

L'Air Liquide will sell complete gas bearing turbine modules to any one interested in incorporating these units in helium refrigeration equipment.

It appears then that L'Air Liquide is the only potential supplier of turbine modules for the satellite refrigerators. L'Air Liquide provides sales literature describing their turbine modules. Part of this literature is included as Figure 3. Figure 3 indicates that the L'Air Liquide turbines can handle a fairly high pressure ratio. This is useful, since the satellite refrigerator cold boxes have been designed for a high pressure to the warm expander of about 20 atm.



Choix de la taille C_n de la turbine en fonction de $\Delta H_s = f(P_{ad}/P_{exh}, T_{ad})$ et de Q
 Choice of C_n turbines size as a function $\Delta H_s = f(\text{Inlet } P/\text{Exh } P, \text{ Inlet } T)$ and Q

Figure 3a

Figure 3b

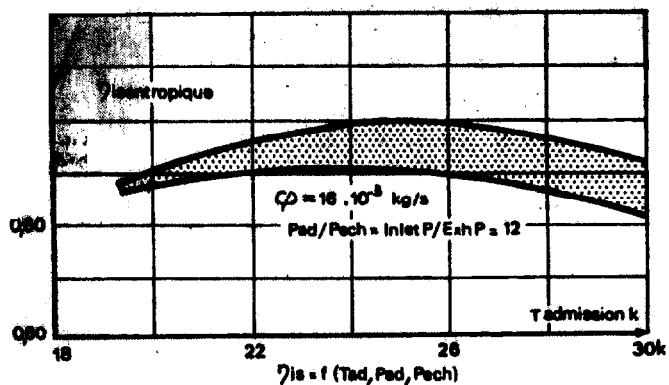


Figure 3c

FIGURE 3

Table V provides the process data of a satellite refrigerator heat exchanger column equipped with a L'Air Liquide turbine in lieu of a warm reciprocating expander operating in the liquefier mode. A comparison of Table V with Table III shows a reduction of liquefaction capability from 3.66 g/sec (105 liters/hr) to 3.38 g/sec (97 liters/hr). Refrigeration is provided by the turbine at an inlet pressure of 20 atm, an exhaust pressure of 1.20 atm, and an efficiency of .55. In the refrigeration mode, flow rate through the turbine need only be 14.06 g/sec. Table VI provides the data. It has been assumed that turbine efficiency is only .50.

T A B L E V

Point	Pres. atm	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
1	20.8	80	434.4	50.0
2	20.0	25.09	138.4	50.0
3	20.0	25.09	138.4	12.596
4	20.0	15.2	79.0	12.596
5	20.0	8.16	33.81	12.596
6	1.8	4.91	24.81	12.596
7	1.22	4.4	29.94	9.217
8	1.20	15.04	91.7	9.217
9	1.20	18.1	107.75	46.621
10	1.11	79	425.2	46.621
11	20.0	25.09	138.4	37.404
12	1.20	15.04	91.7	37.404
13	1.22	4.4	10.8	3.379

TABLE VI

<u>Point</u>	<u>Pres. ata</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
1	20.8	80	434.4	50
2	20.0	30	166.9	50
3	20.0	30	166.9	35.94
4	20.0	19.7	107.1	35.94
5	20.0	5.4	22.32	35.94
6	1.8	4.9	14.32	35.94
7	1.22	4.4	29.94	35.94
8	1.20	19.4	114.72	35.94
9	1.20	27.8	157.7	50
10	1.11	79	425.2	50
11	20.0	30	166.9	14.06
12	1.2	19.4	114.72	14.06
13	1.22	4.4	10.8	-0-

It appears that replacement of the warm reciprocating expansion engine with a turbine does not lead to a very large deterioration of the performance of the system when operating in the liquefaction or refrigeration mode. The replacement of the warm expander module with a turbine module is done externally to the cold box. There are no changes required in the cold box.

It should be pointed out that the satellite refrigerators will be capable of larger rates of liquefaction and refrigeration with a higher efficiency of either turbine or reciprocating expander. Only the reciprocating expander has the potential for a substantial increase in efficiency.

5. Replacement of the Wet Reciprocating Expander with a Turbine:

To our knowledge, there are no turbines operating at the required process conditions of points 5 and 6 of Tables I, II, and III. It does not appear feasible to use a turbine for these conditions, because volume flow rates in and out of the machine are so very small. For instance, process points 5 and 6 of Table I represent volume flow rates of 300 and 440 cc/sec, respectively. A turbine with its nozzles handling these flow rates would be extremely small.

6. Summary:

- a) The warm expansion engine may be replaced with a turbine without suffering serious consequences for the performance of the unit. Turbine efficiency will be low, and the required flow rate varies by a factor of 2.5. Liquefier operation requires the high flow rate. The difference in anticipated performance between turbine and engine is small, because efficiency of the reciprocating expander has been assumed to be a low value of 60-64%.
- b) The wet engine cannot be replaced with a turbine, because the actual volume flow rates through the machine are very small. At this time, there are no known turbines which can efficiently handle these small flow rates.
- c) The design of the cold box does not need to be changed for a change of dry reciprocating expander to a turbine.
- d) For doubler operation (complete system), it is anticipated that the warm expander will be used for continuous periods of less than one week. Also, with reasonably good overall system performance, the warm expander will operate for less than 10% of the time.
- e) The wet expander needs to be used all the time for complete doubler operation. Its reliability needs to be such that 4,000 to 5,000 hours of trouble-free operation will be achieved between scheduled maintenance periods.