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THE DESIGN OF THE HELIUM REFRIGERATOR FOR TORE SUPRA

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The special cryogenic requirements of TORE SUPRA have called for novel solutions.
- Pumping the 1,75 K (13 mb) helium bath is achieved by the use of a pair of centrifugal pumps operating at very low temperature, backed up by liquid rings pumps at room temperature.
- Four oil-lubricated screw compressors mounted in series-parallel form the main cycle helium compression set
- The Joule-Thomson expansion valve is replaced by a mechanical expansion engine working with a bi-phase exhaust.
- The control of the refrigeration system is entirely automatic.

INTRODUCTION

TORE SUPRA is a Tokamak in which the toroidal field is produced by a superconducting winding at 1.8 K and the poloidal field is produced by a conventional magnet. (1)
The two criteria influencing the design of the Tore Supra cryogenic system are :
1) the large thermal mass of the system (22 tonnes at 80 K and 160 tonnes at 4.5K and 1.8 K) and 2) maximum availability.
The cryogenic system has also to be kept cold for long periods (8000 h/y) and consequently control and maintenance operations have to be reduced to a minimum.
As the cold power demand varies greatly between day and night, a very flexible refrigeration system is required, and in addition the cyclic variations in poloidal field (period about 4 minutes) produce an equivalent variation on the cold power absorbed by the refrigerator.
To optimize the investment, the refrigerator has been designed for the most likel operating regime. When the cold power demand surpasses that available from the refrigerator, the difference is made up by boiling off liquid helium and liquid nitrogen. The cold powers available from the system are shown in the table. The figure shows the organisational structure of the refrigerator.

The design phase has now finished and assembly of the cold box will start in August 1984. Tests will take place at the end of 1985 and the system will be installed at the C.E.N. CADARACHE (France).

SATURATED HELIUM II CIRCUIT AT 1.75 K

Superfluid helium at 1.8 K and close to atmospherique pressure is used in the toroidal field windings (2). The Cold Source is created by a group of heat exchangers cooled by a saturated helium II bath boiling at 1.75 K under 0.013 bar Currently available 1.8 K refrigerators use ambient temperature pumping systems consisting of 6 to 8 stages of dry Roots pumps. In order to limit the size of the first stage pumps, the pressure drop through the heat exchangers and pipework between the saturated helium bath and the pump must be as low as possible (6 mb). This exchanger has a poor thermal transfer coefficient on the low pressure side.

In order to have a small pressure drop, the pipework cross section must be large. The usual technique is to use a tube (with or without fins) wound on a large diameter (about 850 mm).
This type of heat exchanger is difficult, therefore expensive to manufacture, and has only mediocre thermal performance. The power lost due to the temperature difference (16 K) at the warm end of the exchanger reappears at the coldest temperature. The heat load needs to be extracted from the cycle by increasing the gas flow through the compressors.

The various Roots pumps are delicate, have poor reliability and are difficult to make leaktight. Although those pumps are in principle 'dry' small amounts of oil are mixed with the compressed helium.
The total absorbed power by a turbine expander refrigerator to produce 300 W at 1.8 K, taking into account the power drawn by the compressors to compensate for the losses at the warm end of the vacuum heat exchanger, is approximatly 700 to 750 kW (3) (4).

An attractive alternative would be to use a helium compressor operating at low temperature. In this case the very low pressure vacuum heat exchanger and the reduced pressure helium circuits can be removed. However, it is important that the efficiency of the cold compressor is sufficient so as not to put too much additional load on the cycle.

L'AIR LIQUIDE has independently developed such a system and a combinaison of the two solutions was adopted for Tore Supra.
A cold centrifugal pump operating between 4.3 K and 15 K is used to compress the helium from 13 mb to 80 mb in two stages (5). Each wheel is supported by a magnetic bearing, which incorporates the pump motor. In order to limit the heat load and maintain high efficiency, the motor and bearing system operate at 80 K.
The compressed helium is warmed to 80 K by the standard process heat exchangers. From 80 K to 300 K a separate commercially available finned plate heat exchanger is used. The total pressure drop over the exchanger is 10 mb.

Ambiant temperature compression is via two liquid ring pumps (one pump would be sufficient if it were not necessary to process the gas returning from the cold box in order to absorb power at 4 K).
Liquid ring pumps are simple, robust and widely used in industry. The only modification made to the standard pump is to improve the shaft seals and to use o-rings to ensure that the pumps are leaktight.
The liquid ring is formed from the same oil as is used in the screw compressors.

This solution results in a decreased absorbed power estimated at about 450 kW to produce 300 W at 1./5 K and uses much more reliable components. Because the number of pumps operating under subatmospheric conditions is reduced (2 instead of 6 or 8) the chances of air being introduced into the system are reduced. In addition design extrapolation of this system is possible which could lead to low temperature compression at even higher pressures.

COMPRESSOR SET

Modern oil lubricated screw compressors were chosen for the following reasons :
- high reliability (MTBF > 17,000 h)
- The oil separation system is proven (L'AIR LIQUIDE has already more than 25,000 h operating experiences)
- variable throughput allowing the compressor to be matched to the operating conditions thereby saving energy
- slighty higher efficiency than reciprocating compressors.
- Total investment and civil engineering work less than that needed for dry reciprocating compressors.

The gas is compressed from 1,05 b to 18 b in two stages, with an intermediate pressure of 5 b. Each stage consists of two compressors in parallel. The number of compressors operating at any given time depends on the operating regime of the refrigerator.
A primary oil separation system is fitted to the output of each stage. A final oil removal system is used after the second stage.

TWO-PHASE EXPANSION

The expansion process used to produce liquid is usually a valve ; the gas losing energy as it is expanded through it. However, in order to increase the efficiency of the cycle a mechanical expander has been chosen for Tore Supra. This expander recovers about 600 W, which is almost all the 4.0 K heat load.
The MTBM (Mean Time Between Maintenance) of the expander is relatively low (about 3000 h), however, as it is not always needed by the refrigerator, it can be maintained during such periods.

REFRIGERATOR CONTROL SYSTEM

The refrigerator system is both extremely complex (8 compressors, 4 expanders, 12 heat exchangers) and operates in pulsed mode. In addition there are 15 different operating regimes, the transition from one to another being dependant on the mode in which the Tokamak is operating.
Additionaly, as the number of personnel involved in the experiment is to be kept to a minimum, a fully automatic control system will be used.

L'AIR LIQUIDE has already built several fully automatic standard liquefiers (6) and will use this experience in designing the refrigerator control system in collaboration with the CEA.

CONCLUSION

The design of the Tore Supra refrigerator currently being built is extremely advanced.
The reliability and efficiency of the machine indended basicly for industrial use, are both much improved when compared to conventional systems.
The techniques and design solutions employed can equally well be applied to larger systems.

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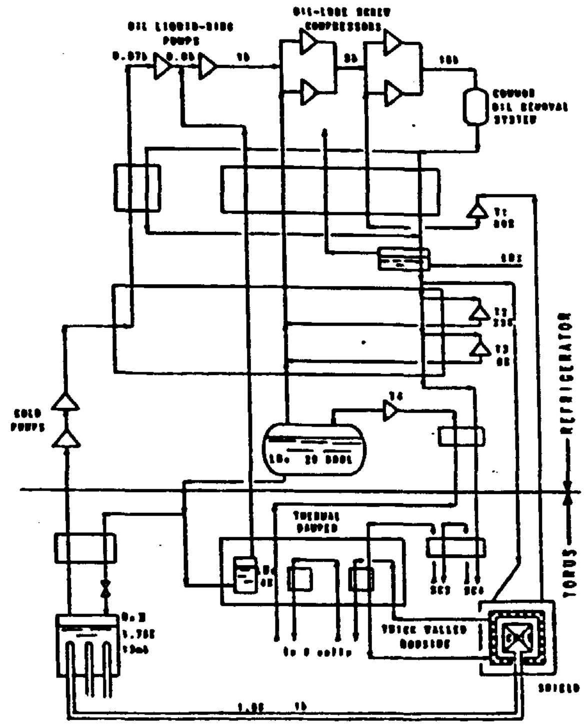
	1.75 K	4.5 K		80 K
	Power W	Power W	LHe g/s	Power W
Over power (Pulses waiting)	320	(935)	0	10700
Normal mode (Pulses waiting)	300	700	2	10700
Pulses waiting	375	385	0	10700
1.8 K Idle	333	120	.3	10700
1.8 K Bake-out	168	140	3	32100
1.8 K Liquefaction	333	170	9	10700
4.5 K Idle	-	350	3	10700
4.5 K Bake-out	-	300	3	32100
4.5 K Liquefaction	-	250	9.5	10700
80 K Idle	-	-	-	11000
Liquefaction only	-	-	[illegible]	-

TORE SUPRA REFRIGERATOR CAPABILITIES



TORE SUPRA CRYOGENIC SYSTEM SIMPLIFIED DIAGRAM