CRYOGENIC REFRIGERATION FOR COLD NEUTRON SOURCES

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INTRODUCTION

Neutron moderation by means of a fluid at cryogenic temperature is a very interesting way to get cold neutrons. Today, a number of nuclear research reactors are using this technology. This paper deals with thermodynamics and technology which are used for cooling Cold Neutron Sources.

THE MAIN FEATURES OF A COLD NEUTRON SOURCE

The moderator fluid is generally hydrogen or deuterium. In order to reach a higher density it can be in a liquid phase at a nearby atmospheric pressure or in a gaseous phase, under pressure, for example hydrogen at 15 b (see table 1).
In both cases, it is important, for safety reasons, to keep a very high moderator fluid purity.

	HYDROGEN	DEUTERIUM
	Liquid	Liquid
Boiling temperature at 1.013 b (K)	20.38	23.57
Density at 1.013 b (kg/m^3)	70.97	162.40
	Triple point	Triple point
Pressure (b)	0.072	0.0171
Temperature (K)	13.95	18.72
	Gaseous	
Density at 15 bar and 25 K (kg/m^3)	66.99	

Table 1. Some properties of hydrogen and deuterium at cryogenic temperatures.

The moderator cell is made out of a material which can withstand a very high neutron flux for a long period of time without any damage. Very special alloys made out aluminium or "exotic" materials are used for this purpose. The moderator fluid circuits must be perfectly leak tight. A conditioning system allows thorough purging of the circuits prior to filling them with very pure moderator fluid.
The cold parts of the Cold Neutron Source must be correctly insulated in order to avoid ice deposition on the walls and also to reduce the amount of thermal power to be extracted from the system. A double-wall technology supplemented by vacuum and, when possible, multi-layer insulation copes nicely with such a requirement.

HOW TO COOL THE MODERATOR FLUID ?

The neutron beam deposits thermal power into the moderator fluid and the cell material. This power is to be removed in order to keep the moderator fluid at the design temperature and pressure. This the duty of the cryogenic refrigerator.
The cryogenic refrigerator is not operated with the moderator fluid as a cycle working fluid, because large quantities of dangerous and sometimes very expensive moderator material

should be handled which might be polluted either during the compression process or by some circuit leak.

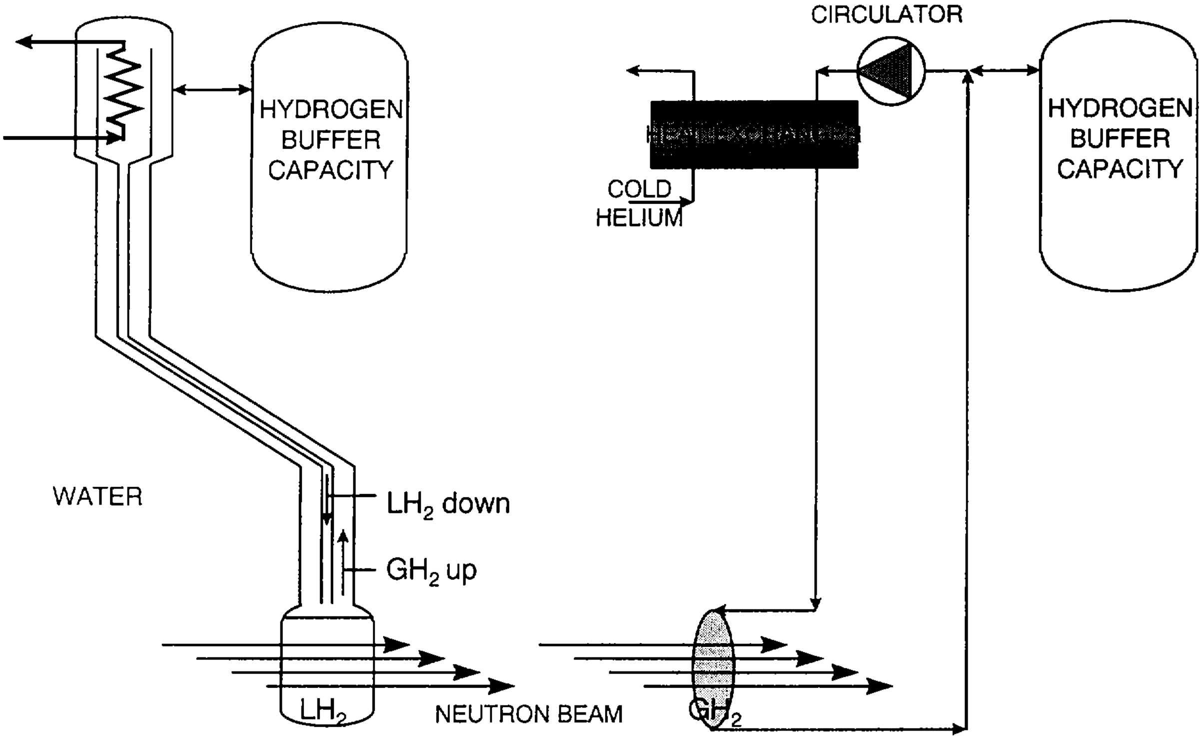


Figure 1. Examples of liquid and gaseous moderator cooled with helium (double wall insulation not shown).

A refrigerator operated with a fluid different from the moderator, makes possible to confine the moderator fluid in a perfectly closed. Thermal power is transferred from the moderator fluid to the working fluid by means of a heat exchanger. Circulation of the moderator fluid is done by a natural phenomenon like a thermal or by means of a circulator which can be operating at room temperature or at cryogenic temperature (see Figure 1). As the moderator circuit is a closed one, room must be provided to allow the fluid to expand when the system is warmed up to room temperature. This is the duty of a room temperature buffer capacity. All Cold Neutron Sources are cooled by a helium refrigerator.

WHICH DUTY DOES A CNS REFRIGERATOR HAS TO PERFORM ?

The CNS refrigerator has to :

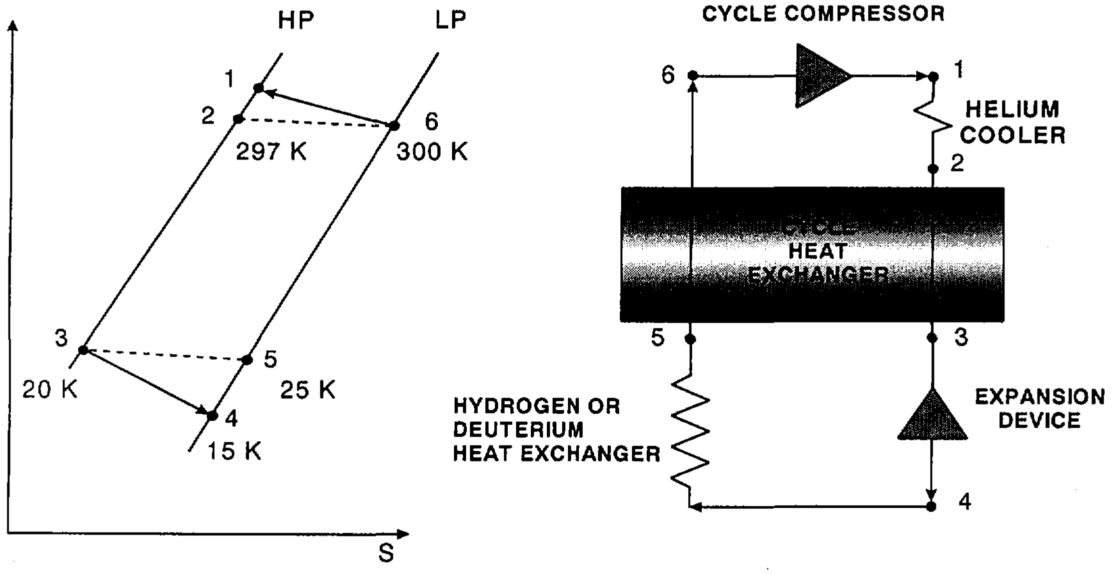
- cool the system from room temperature down to LH_2 or LD_2 temperature,
- keep it cold for long periods of time,
- avoid any pollution of the moderator fluid,
- control cryogenic power according to power dissipated by the reactor,
- avoid freezing of the moderator fluid,
- perform all these duties automatically,
- keep the refrigerator operating in order to prevent the reactor to be stopped, if a short electrical break down happens.

Among cryogenic thermodynamical cycles, the Brayton cycle operating with helium is the best suited for such a duty. For low power, a Stirling cycle can also be used.

THE HELIUM BRAYTON CYCLE

The Brayton cycle gas follows six steps through the cycle components (see Figure 2) :

STEPS	COMPONENT
• room temperature compression (6 - 1),	cycle compressor,
• cooling down by water or air (1 - 2),	helium cooler,
• cooling down by counter current exchange (2 - 3),	cycle heat exchanger,
• expansion with extraction of energy (3 - 4),	expansion device,
• absorption of the useful heat load (4 - 5),	H2 or D2 heat exchanger,
• warming up by counter current exchange (5 - 1),	cycle heat exchanger.



TEMPERATURE/ENTROPY DIAGRAMME FLOW DIAGRAMME

Figure 2. The Brayton cycle

By selecting a cycle low pressure higher than atmospheric pressure, the size, and therefore the cost of the compressor, are minimised. Allowing the cycle pressures to "float" makes possible to adapt the cryogenic power to the needs of the Cold Neutron Source : the cryogenic power roughly varies as the suction pressure of the cycle compressor. However, for situations where the cryogenic power demand is very low, for example when the reactor is not operating while the moderator cell is cold, some power is to be injected into the helium cycle in order to avoid turning the moderator fluid into solid.

The cycle compressor.

Two severe constraints govern the compression of helium : as a monatomic gas, it has a higher heat of compression than other gases and it must not be polluted in order not to plug the refrigerator heat exchangers. On top of that, the compressor must be reliable. The present solution for helium compression is the oil lubricated screw compressor. Such a machine has only two screws as moving parts (see Figure 3) therefore it has a very high reliability. Some screw lubricated compressors have been operated for more than 40000 hours without maintenance ! Maintenance is light. The isothermal efficiency is reasonable : around 0.50 at full load.

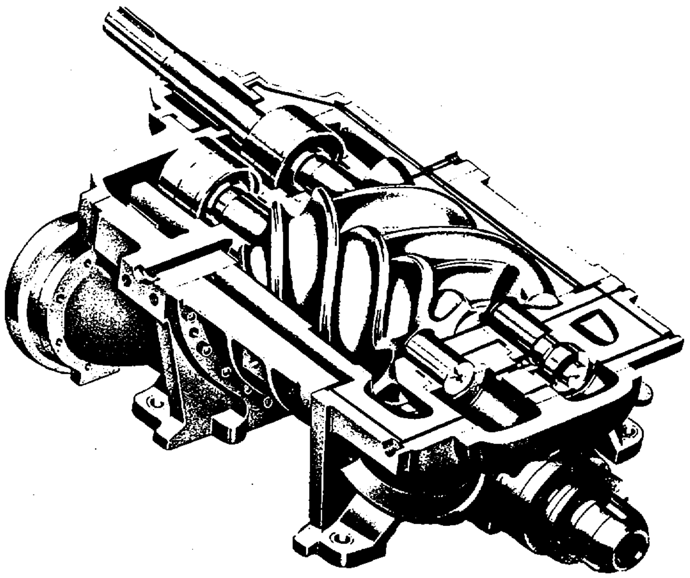


Figure 3. A screw compressor (Mycom)

A large quantity of oil is injected into the screw compressor. During the compression process, the oil limits the helium leakage between the screws, thus improves the volumetric efficiency, and absorbs the heat of compression, allowing a reduction of the increase of temperature of helium, thus improves the isothermal efficiency. At the discharge side of the compressor, the mixture of helium and oil is roughly separated in a bulk oil separator (see Figure 4). The separated oil is cooled, compressed in a pump and further injected into the compressor. At the discharge side of the bulk oil separator, the oil exists in two states : aerosols and vapour. The very big surface between oil and helium allows oil vapour to be released into helium. The oil is selected in order to have a very low vapour pressure. On top of that, it is specially processed under vacuum and temperature in order to release light components, air and water. The helium is cooled and processed into coalescers which separate the aerosols. Oil vapour is adsorbed into a room temperature adsorber filled with special activated charcoal, followed by a filter.

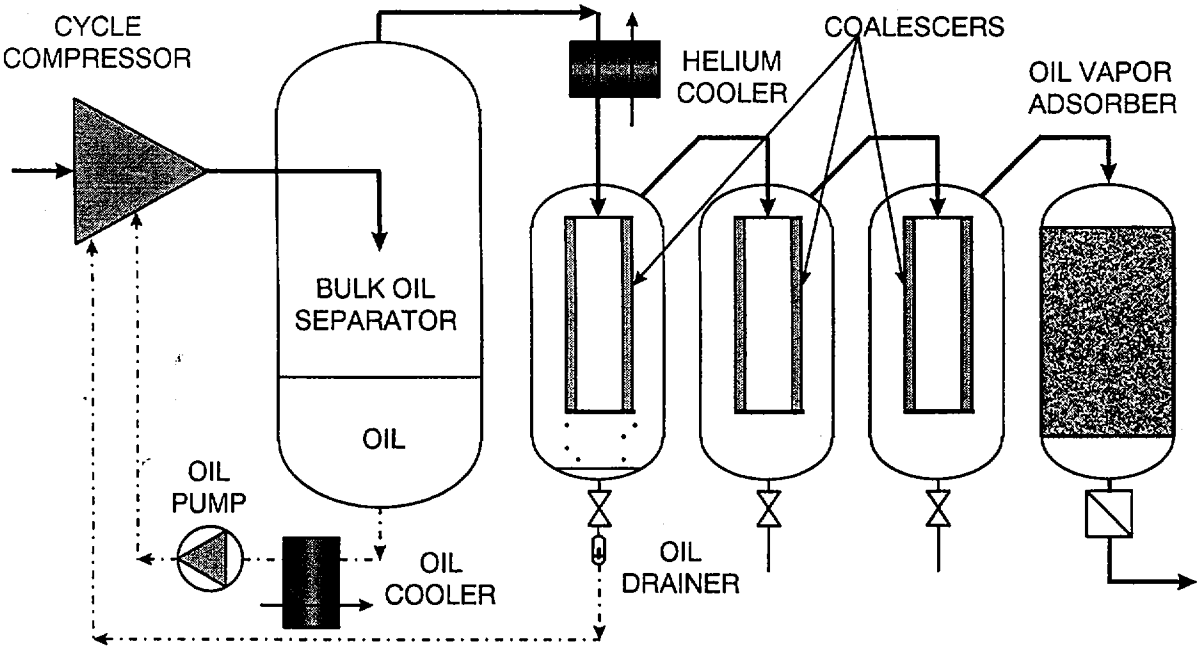


Figure 4 The oil removal system

The cycle cryogenic heat exchanger

Most of the heat exchangers are of the brazed aluminium alloy plate and fin type which are industrially made by quantities, compact and very efficient (see Figure 5).

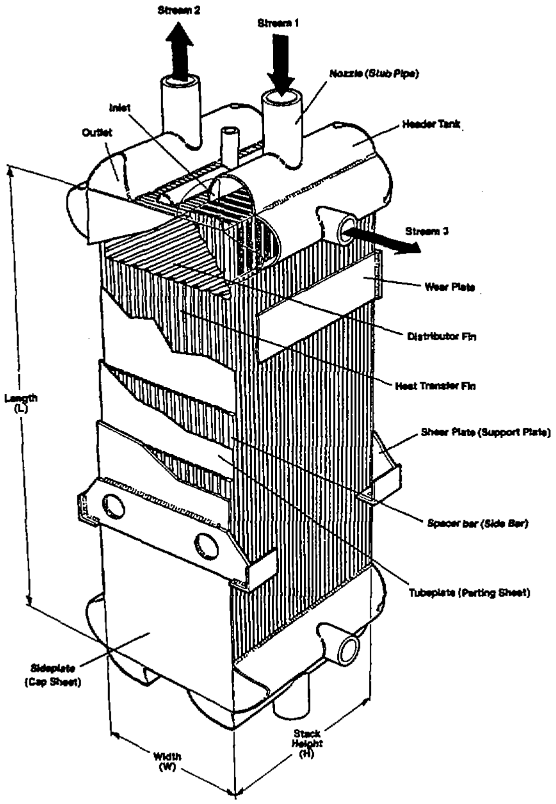


Figure 5. A typical brazed plate and fin heat exchanger (Marston)

The expansion device

The reciprocating expander has been the first equipment used for cryogenic expansion of gases. It is favoured by operators of small plants because it is locally serviceable. However it has many limitations like mass flow rate, power, rotational speed and reliability.

The industrial solution comes with cryogenic expansion turbines. In order to cope with high tip speeds specific of helium expansion, their rotational speed is high, namely from 50000 rpm for big turbines up to 600000 rpm for small ones. Therefore, they require a special gas lubricated bearing system which can be of the dynamic or static type. The gas bearing system is pollution-free because it uses the cycle gas as lubrication means. The dynamic bearings are sustained by the gas which is self-compressed in the bearings. As a result, the sustaining strength is strongly depending on the speed. Dynamic bearings have a low capacity to react to fast variations of load. Driving turbines fitted with such bearings is somewhat delicate and the power which can be extracted is limited. The static bearings need a small amount of pressurised gas provided by the cycle compressor (see Figure 6), but their sustaining strength, which can be adapted by changing the pressure of the feed gas, is independent of the rotational speed. They are more robust in a general way. Presently, static gas bearing turbines have no limitation in power, they can reach up to 200 kW. Gas bearing cryogenic expansion turbines have very good isentropic efficiencies, up to 80 %. No maintenance is needed on the expansion turbine itself because there is no friction. However, checking the monitoring system equipment must be done regularly. The MTBF of industrial cryogenic expansion turbines is, presently (1998), as high as 38000 hours[1].

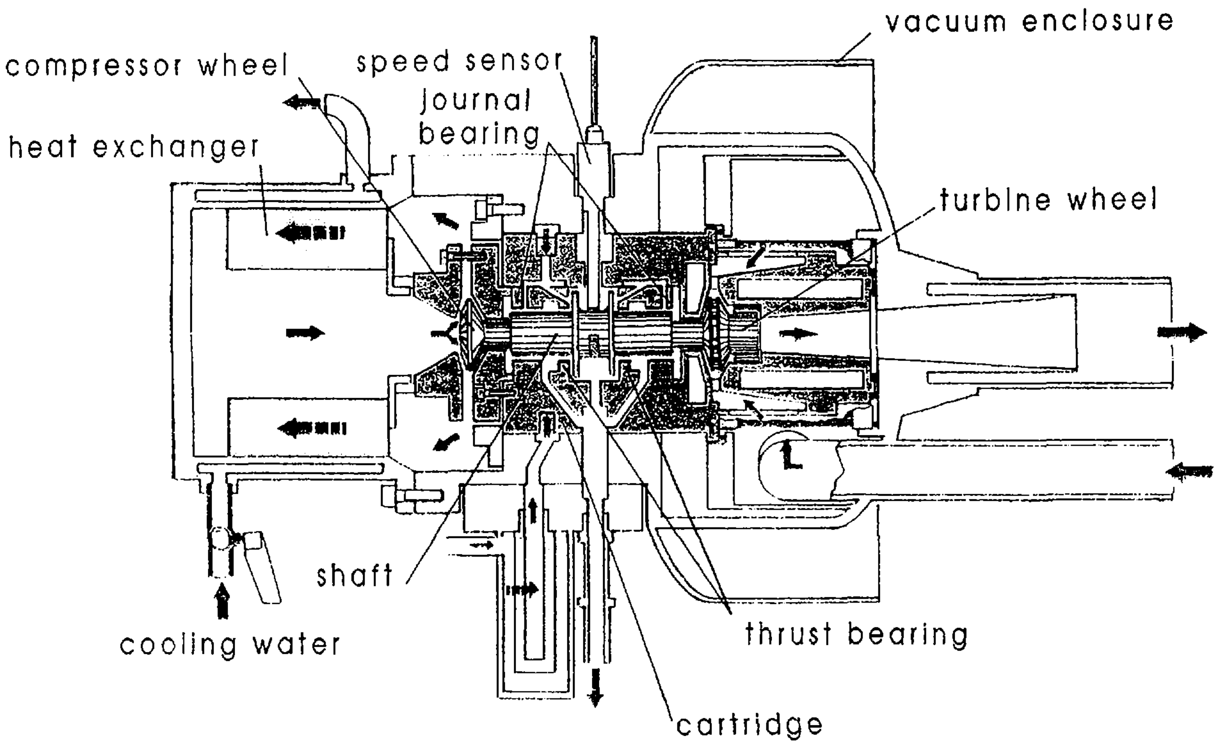


Figure 6. A static gas bearing cryogenic expansion turbine (Air Liquide)

The moderator/helium heat exchanger

This heat exchanger must be efficient in order to reduce the temperature difference between cold helium and the moderator fluid and avoid any possible leak between the moderator fluid and helium. Stainless steel heat exchangers or specially designed brazed plate and fin aluminium alloy can be used.

THE STRUCTURE OF A HELIUM REFRIGERATOR

The compression station

The compression station incorporates the screw compressor, its electric motor, helium and oil coolers, the oil management system and the monitoring system. All these components are assembled onto a common frame. A cycle helium buffer capacity is connected to the high and low pressure sides by means of control valves. It releases helium into the refrigerator at the time of cooling and recovers helium from the refrigerator at the time of warming.

There are two solutions to keep the refrigerator "alive" for short periods of time, during electrical break downs. For a few tenths of second, a fly wheel can be integrated on the motor/compressor shaft. For a few tens of second, a special buffer capacity delivers to the high pressure piping of the refrigerator a sufficient helium flow to supplement or even replace the compressor flow. This helium is vented to the air at the low pressure side of the cycle until electrical power resumes. When the length of the electrical break down is too long, the plant is stopped according to the emergency procedure.

The cold box

The cold box is mainly a cylindrical enclosure which houses all components operating at low temperatures : heat exchangers, expanders, cryogenic extended-stem valves, adsorbers, filters and connecting pipes. The cylindrical cold box can be vertical or horizontal. Thermal insulation is achieved by the use of multi-layer insulation supplemented by high vacuum. A dedicated vacuum pumping set maintains a pressure lower than 10^{-3} Pa in the cold box. The connection between the cold box and the moderator/helium heat exchanger is made by means of vacuum insulated jacketed transfer lines.

The process control system

The process control system drives the plant automatically, according to the control programme for all transient and steady regimes : cool down, adaptation of the cryogenic power to the reactor needs, either on a stand-by situation were the reactor is not yet running or during full power operation and warming up. Prior to start up, the control system checks all parameters, make sure that all conditions are correct to reach nominal operation. If some abnormal situation occurs, the control system can react in different ways :

- if it is possible, it will correct the situation ; example : control a pressure,
- if not possible, it will make an action to keep the refrigerator running, even at lower power, and give a warning to the operator in order he can correct the situation ; example : if the cooling water becomes too warm,
- if the situation degrades, it will bring the refrigerator to a stop ; example : if instrument air pressure is too low, the emergency stop procedure is launched.

An electrical power or cooling water or instrument air break down obviously brings the refrigerator to a stop. As soon as the defective utility is back, the refrigerator starts automatically. Reports are issued by the control system, either to confirm that important steps have been correctly passed or on abnormal situations. Of course, the operator can also monitor any parameter of the plant at any time. Consequently, such a control system makes possible, to actuate the refrigerator with a simple "ON/OFF" command from the main control panel of the reactor or from the reactor central process controller.

The conditioning system of the moderator fluid circuits

This part of the Cold Neutron Source is not cryogenic. However, as it is connected to the cryogenic system and designed according to same principles as leak tightness, vacuum technology and automatic process control, it is generally built by the refrigerator manufacturer.

EFFICIENCY AND RELIABILITY OF A CNS HELIUM REFRIGERATOR

For helium Brayton cycle refrigerators ranging from 1 to 10 kW at about 20 K, the ratio of power supplied by the electrical net versus cryogenic power ranges from 80 to 110.
Reliability is among the most important characteristic feature the rector team expects from the Cold Neutron Source refrigerator. Modern refrigerators have a high reliability[2,3] by themselves (the ILL refrigerator has been responsible for 0.1 % in the non availability of the reactor in 11 years of operation). However, it is trivial to remind anyone that utilities as electrical power, cooling water, instrument air participate heavily to the overall reliability of a plant[4]. The quality of the control programme is also of paramount importance.

EXAMPLE : ORPHEE CNS REFRIGERATOR

The Orphée research reactor is located at Saclay, south of Paris, France. Its thermal power is 14 MW. Two cold neutron sources are cooled with a new 1800 W @ 20 K helium Brayton cycle refrigerator which replaced an older one[5]. For historical reasons, the helium cycle is fed with two screw compressors operating in parallel. They absorb 236 kW. The cold box is horizontal, fitted with one turbine, located nearby the pool (see Figure 7). Two separate transfer lines link the cold box to the hydrogen condensers which are immersed into the pool. A special buffer capacity allows uninterrupted operation of the refrigerator when an electrical power break down shorter than 20 seconds happens.

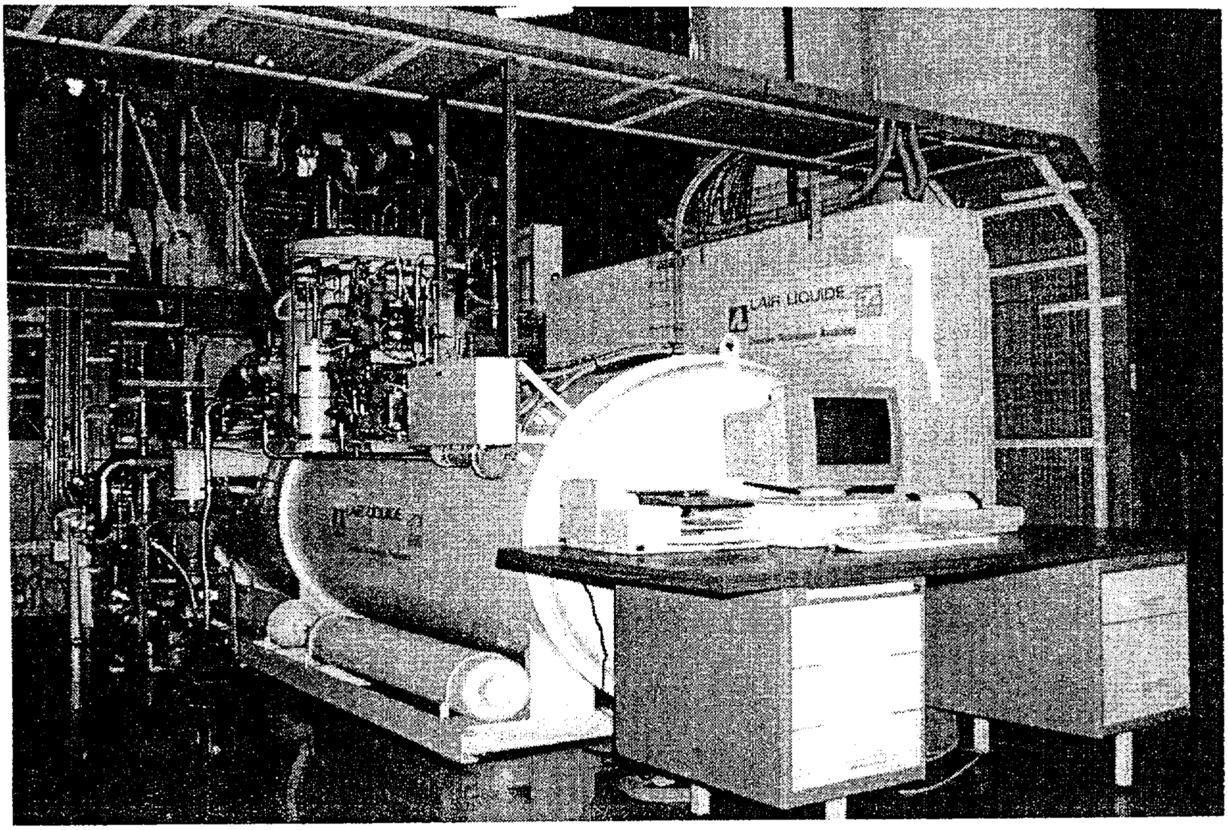


Figure 7. The Orphée refrigerator cold box.

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