Cryogenics

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ABSTRACT

The paper reviews some physical properties of materials at low temperatures and the general techniques which are used to produce and maintain temperatures in the liquid-hydrogen and liquid-helium region. Applications of low-temperature technology encountered in high-energy physics are described, with particular reference to refrigeration, hydrogen and polarized targets, liquid hydrogen bubble chambers, superconducting devices and condensation cryopumping.

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The technology of low temperature has been developed and exploited industrially over the last 100 years or so, down to temperatures of about 80 K, principally for the separation of air into its constituents. Although the use of temperatures at this level is widespread in high-energy physics, liquid nitrogen being a convenient and relatively cheap source of cold, the technology involved is in no way novel and will not concern us here. On the other hand, it can be convincingly argued that, for temperatures in the liquid hydrogen and helium region, cryogenic engineering as we know it today has arisen in response to the needs of space research, high-energy physics, and plasma physics. In Europe, in particular, the principal stimulus has been high-energy physics.

The increasing use of low temperatures is illustrated by the consumption of cryogenic liquids at CERN during the last decade (Fig. 1). These data represent something of an understatement in fact, since they only show the quantities distributed in transport dewars. The recent fall in hydrogen consumption and the levelling-off of helium consumption is merely a consequence of the increasing use of large closed-circuit refrigerators.

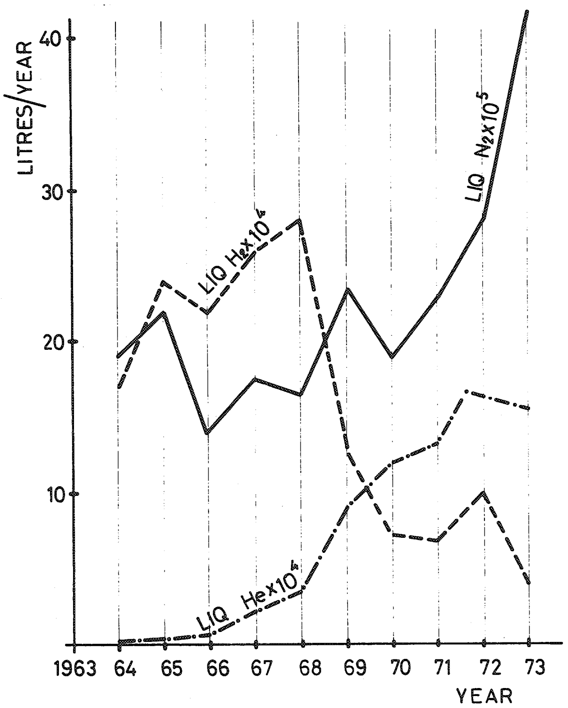

Fig. 1 Consumption of cryogenic liquids at CERN

1. GENERAL LOW-TEMPERATURE TECHNOLOGY

The fundamental problem of low-temperature technology can be stated quite simply. In Fig. 2 the lower curve shows the theoretical minimum power required to produce one watt of refrigeration at a given temperature. This is inversely proportional to the temperature of refrigeration and so tends to infinity as absolute zero is approached. Real refrigerators are less efficient than this, of course. The two upper curves give a rough idea of the range of power requirements encountered in practice. We are interested here in the low-temperature end of these curves (below about 30 K), and it is clear how important it is to limit heat dissipation and improve the efficiency of thermal insulation as the temperature decreases.

Many of the cryogenic techniques are common to applications throughout our temperature range. It may be useful to summarize these and take a brief look at some of the peculiar properties of the materials we use.

The cold parts of almost all cryogenic systems working below 30 K are surrounded by high vacuum to suppress *convection* completely and reduce gas conduction to insignificant proportions. There remains thermal *radiation* across the vacuum space and this is potentially quite important. Figure 3 shows the maximum possible radiation from room temperature

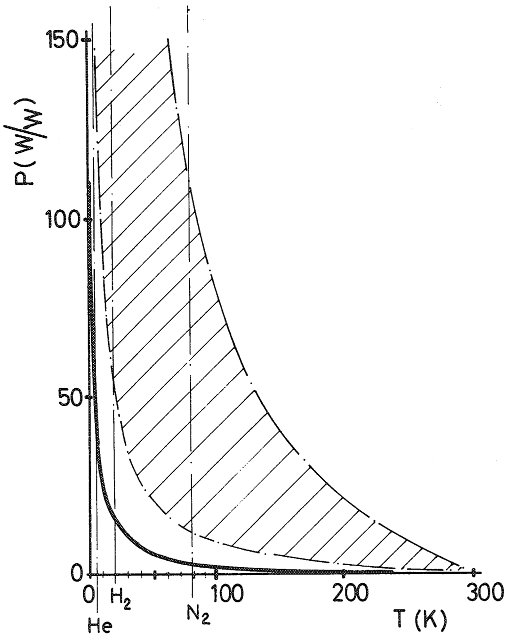

Fig. 2 Refrigeration power requirements as a function of temperature

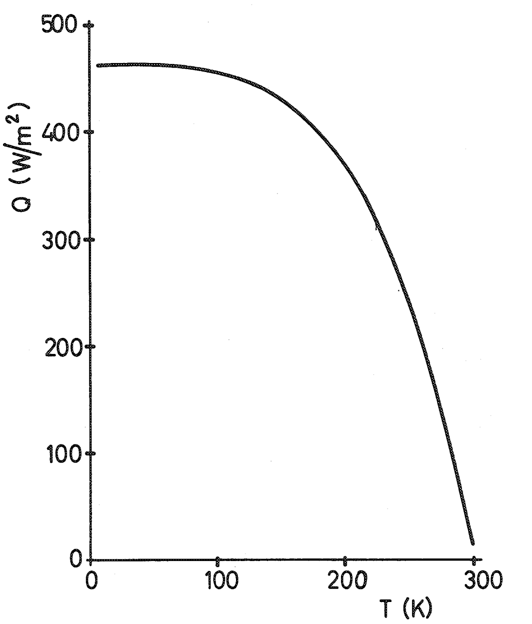

Fig. 3 Black-body thermal radiation from 300 K to a surface at temperature T

(taken as 300 K) as a function of the temperature of the cold surface. Since this radiation is proportional to the difference of the fourth powers of the two surface temperatures, it rises rapidly to a value which is very sensitive to the temperature of the warm surface. Fortunately, the radiant heat flux can be reduced by several orders of magnitude. The surfaces may be coated with metals which strongly reflect in the infra-red. Extra reflecting surfaces may be interposed in the vacuum space, for example in the form of multiple layers of thin aluminized plastic foil. In addition, some of these surfaces may be cooled at an intermediate temperature. Combinations of such techniques are used in most cryogenic systems below 30 K, depending on the degree of complication which is justified.

Solid *conduction* is minimized by using the smallest permissible cross-section of materials with high ratio of strength to thermal conductivity; stainless steels, titanium alloy, and glass-reinforced plastics are typical. Figure 4 shows the variation of thermal conductivity of some common materials at low temperatures. Thermal contact resistance in a high vacuum is also sometimes used to reduce the heat conducted through supports, the aim being to introduce as many contacts as possible. For example, chains are used as tensile supports and piles of metal or plastic foils in compression. Heat transmission may be reduced by more than an order of magnitude in this way.

The variation of electrical resistivity for some typical metals is illustrated in Fig. 5. High purity metals, whose resistivity at room temperatures is largely of thermal origin, can

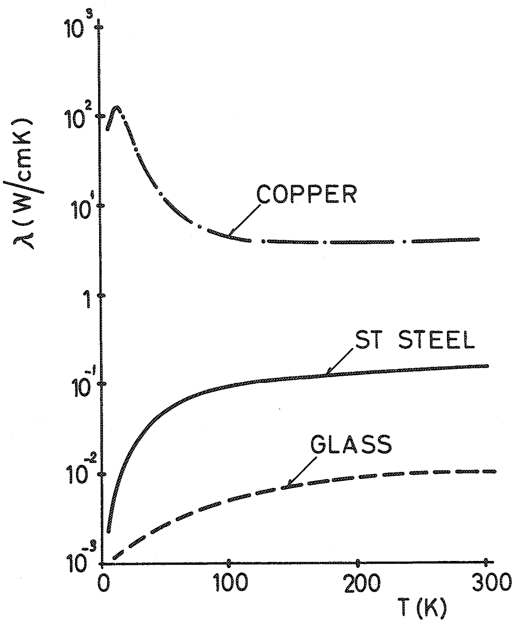

Fig. 4 Thermal conductivity of copper, stainless steel, and glass as a function of temperature

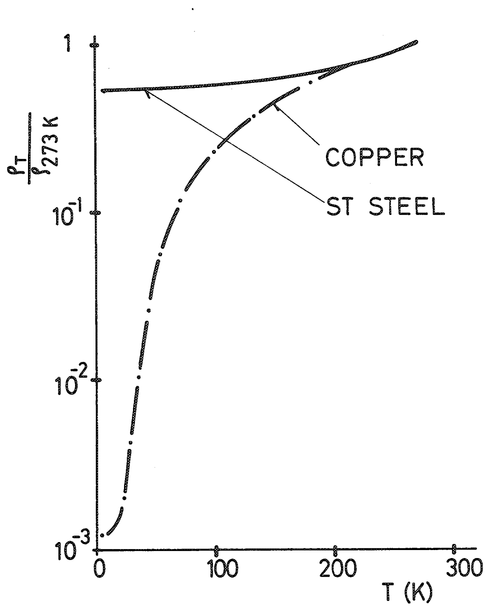

Fig. 5 Normalized electrical resistivity of copper and stainless steel as a function of temperature

show reductions in excess of four orders of magnitude at low temperature, while that of alloys with many chemical and physical lattice defects remains largely unchanged.

One of the properties of solids which changes most strikingly is specific heat. Figure 6 gives some examples. It is often difficult to appreciate the effect of these large changes. For example, a block of copper at 4 K has less thermal inertia than the same volume of air at room temperature.

Figure 7 shows the thermal contraction of some solids at low temperature. Combinations of different materials may cause permanent deformation or even fracture of the assembly when cooled down, if precautions are not taken. Furthermore, some materials become brittle at low

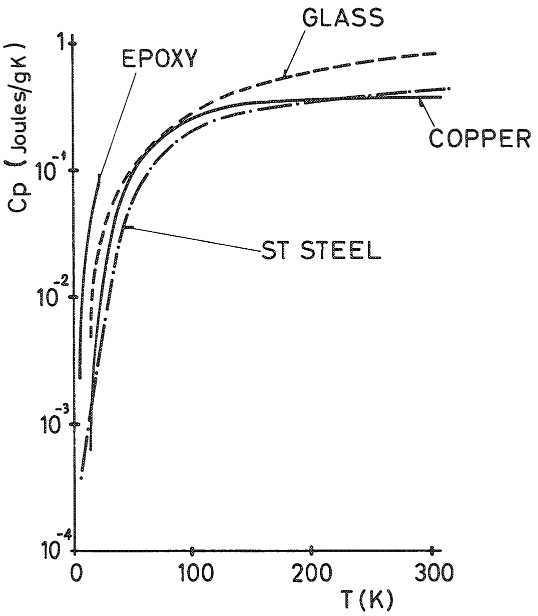

Fig. 6 Specific heat of copper, stainless steel, epoxy, and glass as a function of temperature

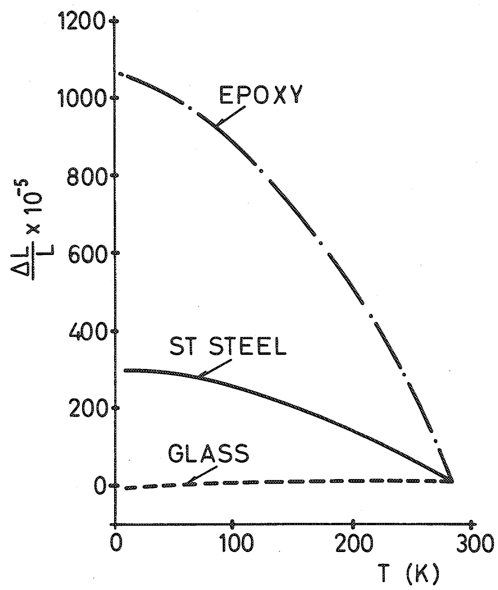

Fig. 7 Thermal contraction of stainless steel, epoxy, and glass as a function of temperature

temperatures; unfortunately these include the ferritic iron alloys, so we are deprived of the use of irons and low-alloy steels at least for stress-bearing components. High nickel-chromium stainless steels may be used since they have an austenitic structure and remain ductile.

2. HYDROGEN TARGETS

Hydrogen is of great importance as a target material in high-energy physics since its nucleus is the simplest of all elements, consisting of a single proton. It is clearly essential that the target present the maximum density of hydrogen and the minimum mass of other materials which make up the container. This condition is most easily satisfied by using liquid hydrogen at a pressure only slightly above atmospheric and a temperature of about 20 K. The flask separating the liquid from the vacuum may then be a very light structure. In the case of small targets, plastic walls, a few tenths of a millimetre thick, are sufficient, and allow hydrogen-to-container mass ratios in the beam direction of the order of 50.

Originally all targets were filled and replenished by liquid hydrogen supplied from a central liquefier in transport dewars, but the dangers resulting from the relatively large quantity of hydrogen in the dewars and from the high combustibility of hydrogen-air mixtures require stringent safety precautions. At present, where possible, an alternative system consists of a sealed hydrogen circuit in which the target flask is permanently connected to a reservoir large enough to contain the small charge of liquid hydrogen as gas at room temperature and about 2 atm pressure. The hydrogen is condensed into the flask and kept liquid during operation either by a small refrigerator or by cold helium vapour generated by evaporating liquid helium at 4.2 K. The liquid helium is supplied in transport dewars from a central liquefier and the gas is returned via the site helium-recovery system. It may appear illogical to provide refrigeration at 20 K with liquid at 4.2 K, but considerations of power

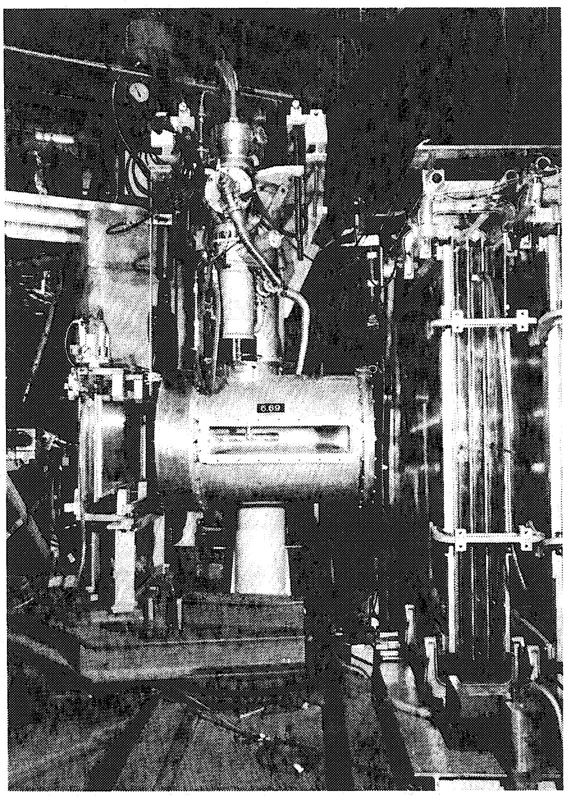

Fig. 8 A typical liquid-hydrogen target

consumption are of no consequence on the scale involved here, and the considerable practical advantages of a system essentially not dependent on moving parts and providing a great degree of flexibility in operation make the method most attractive for small targets. Refrigerator cooling is often used when the thermal load on the target is relatively high or when access to the target is limited. A typical refrigerator-cooled target is shown in Fig. 8. The refrigerator in this instance is a cryogenerator capable of absorbing some 90 W at 20 K.

3. BUBBLE CHAMBERS

Bubble chambers rely on the principle, first demonstrated by D.A. Glaser in 1952, that a fast charged particle passing through a superheated liquid ionizes the liquid and so deposits a small fraction of its energy as heat in the immediate vicinity of its path. This can initiate local boiling and make the trajectory of the charged particle visible by the train of bubbles it leaves in its track. If a magnetic field is applied to the chamber, the radius of the resulting curvature of the track can be used to derive the momentum of the particle.

When an incident charged particle interacts with a nucleus of the liquid, the resulting charged secondary particles also leave tracks, and if all particles are charged a complete kinematic analysis of the interaction is possible. Neutral particles do not leave tracks. They may, however, identify themselves by producing charged particles within the chamber.

In principle any transparent liquid can be used for a bubble chamber, but liquid hydrogen or deuterium have the advantages already noted for hydrogen targets of presenting the highest densities of simple nuclei, i.e. protons or quasi-free neutrons.

In a typical hydrogen bubble chamber the liquid is held at a pressure of, say, 5 atm. The temperature of the liquid is maintained just below the boiling point corresponding to the applied pressure, say 26 K. Some 20 msec before the particles are expected to arrive in the chamber, the pressure of the liquid is reduced to, say, 2 atm. Since the temperature of the liquid is now about 3°K above the boiling point at the new pressure, it is super-heated and track-sensitive. The chamber is held in this state until the bubbles have grown to a visible size and have been photographed stereoscopically. The liquid is then recompressed to its original pressure and the bubbles recondense.

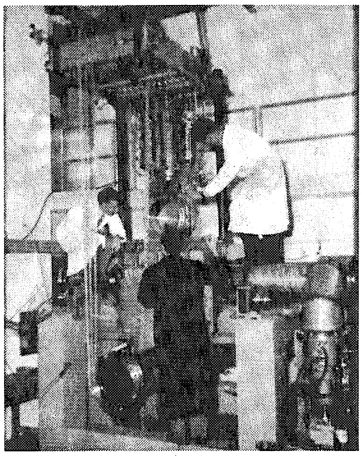

Fig. 9 The CERN 30 cm Hydrogen Bubble Chamber

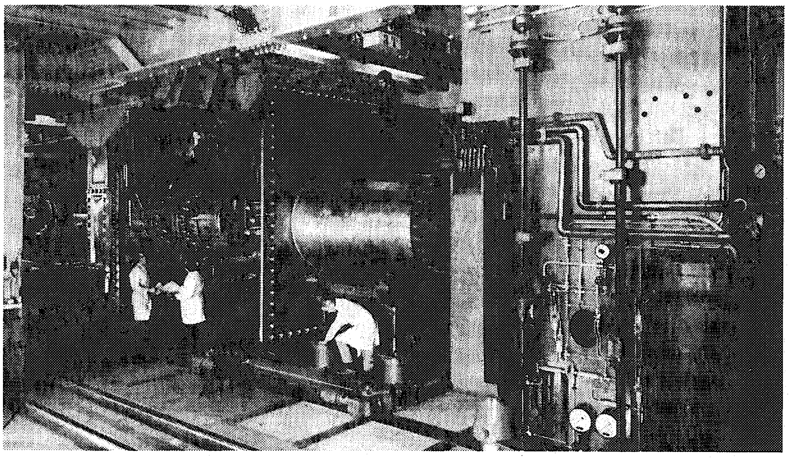

Fig. 10 The CERN 2 m Hydrogen Bubble Chamber

Early hydrogen bubble chambers, about 20 years ago, had dimensions of tens of centimetres (Fig. 9). By the early sixties, the increase in the energy of the incident particles and improved understanding of the technology had led to the construction of hydrogen chambers with dimensions of about 2 m (Fig. 10). These chambers were near the limit of the practicable with the technique which was used at the time. The optical system required at least one wall of the chamber to be made of a thick glass slab which had to contain a maximum pressure of some 10 atm under shock loading.

This type of window imposes a number of limitations. One example is the difference in contraction in the long direction between the window and the metallic chamber body of about 4 mm. The solution to this problem is to make the seal between the window and the chamber body when they are cold, by inflating a special gasket with high-pressure helium gas. This applies sufficient force to soft metal seals, trapped between the window and the body, to make a vacuum-tight joint. In addition, the low thermal conductivity of glass limits the speed of cool-down if high thermal stresses are to be avoided.

Although such chambers give excellent results and have been developed to a high degree of reliability, problems of this type become more severe as the size increases. Nevertheless, as the energy of available incident beams and interest in neutrino physics grew, chambers with both larger volume and higher magnetic fields were required. The use of retrodirective reflecting materials, such as "Scotchlite", and wide-angle optics allowed the large flat windows to be replaced by smaller and much more rigid hemispherical "fish eyes". The development of superconducting magnets provided double the field over much larger volumes with considerably reduced power consumption. For example, the useful volume of BEBC (Fig. 11) is about 35 times that of the CERN 2 m chamber and it has more than twice the magnetic field. Four large hydrogen bubble chambers with some or all of these features have been built in recent years -- two of them in Europe.

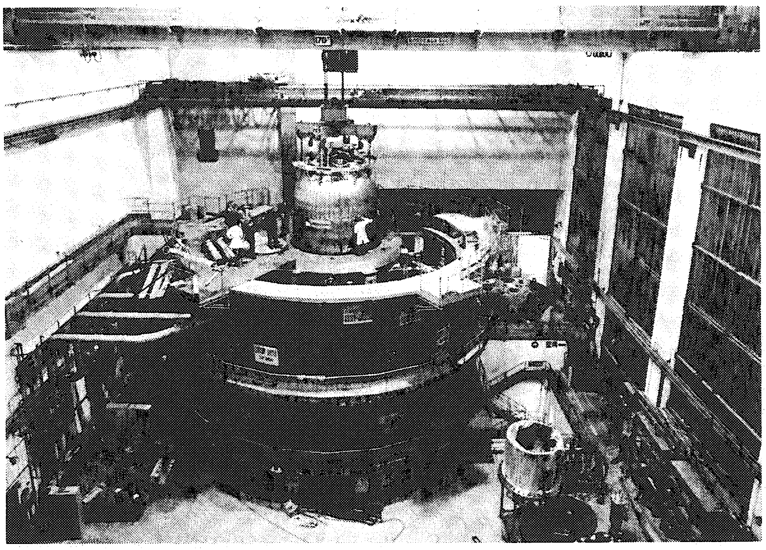

Fig. 11
The Big European Bubble Chamber (BEBC) during construction

The pistons used in some of these large chambers to produce the pressure cycling now often have diameters of about 2 m. They are required to move at high speed, and the magnetic field in their vicinity is both high and inhomogeneous. This can lead to eddy-current heating if the piston is metallic. Special glass-fibre reinforced plastic structures which must be impervious to hydrogen at about 20 K have been applied.

However, not all modern hydrogen bubble chambers are very large. A good deal of effort is currently being devoted to developing quite small chambers with very high repetition rates. Instead of expanding about once per second as do the large chambers, these rapid cycling chambers operate at some 60 Hz. When used in conjunction with electronic detectors, which can decide when an interesting interaction has occurred and instruct the cameras to photograph it, these chambers provide a considerable increase in speed and efficiency, especially in detecting rare events.

4. SUPERCONDUCTING DEVICES

Although some superconductors have critical temperatures slightly above 20 K, no practical material has useful properties above the triple point of hydrogen, so it is necessary to use helium for cooling. Two temperature levels are of interest in practice, about 4.2 K (the normal boiling point of helium) and something less than 2 K.

The size of superconducting apparatus used in high-energy physics varies enormously. Volumes range from a few litres to tens of cubic metres, and weights from some kilogrammes to several hundred tons, so it is not surprising that the techniques used for cooling such equipment and keeping it cold are diverse. Basically, however, the choice lies between cooling by evaporating liquid helium, recovering the gas at room temperature for subsequent reliquefaction, and using a closed-cycle refrigerator which furnishes a continuous supply of liquid and recovers the vapour at the boiling temperature. There is apparently a considerable advantage in using closed-cycle refrigeration since a given installation can absorb five or six times more heat in this mode than it can when the gas is recovered at room temperature. The advantage is only a real one, however, if the heat is generated at the lowest temperature of the system. When the heat originates at higher temperatures, as in the case of heat inleak from room temperature, it is more efficient to absorb as much as possible in warming the cold vapour to room temperature. For example, the heat conducted from room temperature to 4 K down a bar of, say, stainless steel, can be reduced by a factor of more than 30 by using the vapour generated by this heat leak to cool the bar in counter current. Losses due to thermal radiation can, in principle, be reduced by even greater amounts by using screens cooled by the cold vapour. These features are peculiar to helium and are a consequence of the high ratio of the sensible heat of the gas to the latent heat of vaporization (about 70). Hydrogen, for instance, with a sensible-to-latent heat ratio of about 10, gives an economy factor of less than four in heat conduction with counter-current cooling. The use of cooling by evaporating liquid in open cycle involves considerable complication of the design if its potentialities are to be fully realized, but it allows increased flexibility of operation since the instantaneous cooling power available is not limited by the refrigerator nor is the reliability of the cooling at the mercy of such things as power failure. In practice, the use of this system is restricted to equipment with fairly low over-all consumption; for example, beam deflection and focusing magnets, which have typical heat loads of a few watts. A system with a total heat load of 4 W has an autonomy of about three days when supplied from a 500 ℓ dewar, so the manpower requirements for transporting and changing dewars are not excessive, but such systems do require efficient transfer lines, as losses here can easily make up a significant proportion of the total heat load. The solution adopted is to use cold vapour for cooling a radiation shield around the liquid line.

The very large superconducting magnets certainly require a committed refrigeration system for each installation. The great mass of the coils and containers, which must be cooled down in a carefully controlled manner, must be taken on strong and rigid supports, with all the conductive heat inleak this entails. Cold surfaces in excess of 100 m^2 are subjected to thermal radiation, and the heat generated by leads for several thousand ampères is far from negligible. The resulting heat loads can exceed 1 kW, and large refrigeration systems have been developed by the manufacturers of such equipment.

The superconducting magnet for the Omega spectrometer at CERN has the distinction of being cooled by the circulation inside the conductor of helium at about 4.5 K, but above the critical pressure (2.2 atm). Heat is absorbed by a monophase fluid, and the thermal instabilities associated with cooling by boiling liquid are avoided. The supercritical helium is circulated in the coil by the refrigerator. Unfortunately the pressure drop in the windings entails a rise in the fluid temperature, and the helium must be repeatedly recooled by heat exchange with a bath of liquid helium.

High-frequency superconducting devices such as radio-frequency particle separators and linear accelerators are invariably operated at about 1.8 K, which corresponds to a vapour pressure of 12.5 Torr. The increase in electrical performance below this temperature does not justify the rapidly increasing cost of refrigeration. These installations represent the first large-scale applications at such low temperatures, and they require the most stringent control of the operating conditions, for example the system pressure must be kept constant to ±0.1 Torr.

5. CONDENSATION CRYOPUMPS

These pumps are used in ultra high vacuum systems to condense the residual gas on a surface maintained at 4 K or less. The vapour pressures of all substances other than helium are extremely low at these temperatures. With careful design, ultimate pressures of the order of 10^{-13} Torr can be obtained.

One of the principal requirements is for a very low rate of evaporation of the liquid helium with which the pump reservoir is filled. For example, the pumps installed at the CERN Intersecting Storage Rings are inaccessible for periods of some three weeks, and the pumps are required to have an autonomy of more than one month with an initial charge of ten litres of liquid. The fact that the pumps must be bakeable at 300°C forbids the use of aluminized plastic foil insulation, so radiative heating is reduced by screens cooled by liquid nitrogen at either 77 K or just above the triple point (63 K), and the use of carefully prepared low-emmissivity surfaces. The helium in the pump is generally at either 4.2 K or about 2.3 K, these temperatures, like those in the screen, being determined by the required operating conditions of the pump. Recent test results at CERN suggest that autonomies of the order of a year can be obtained with these pumps by the addition of a gas-cooled intermediate screen and the optimization of the dimensions of other components.

6. POLARIZED TARGETS

For some high-energy physics experiments it is beneficial to bombard targets in which the nuclei have predetermined orientation. Such devices are called polarized targets. In practice, the polarization method used consists of cooling the target material -- usually a hydrogen-rich hydrocarbon containing a paramagnetic impurity -- to about 0.5 K in a uniform magnetic field of some 25 kG and applying microwave radiation of an appropriate frequency. When the microwave radiation is stopped, the target material slowly depolarizes in some hours. This depolarization time can be increased to the order of 1000 hours by cooling the target to 0.05 K as the microwave radiation is removed.

Several cryostats for polarized targets, developed in collaboration between CERN and CEA, Saclay, are in use at CERN. These absorb between 20 and 200 mW at about 0.5 K by the evaporation of the helium isotope ^{3}He at a pressure of about 10^{-1} Torr in a closed-circuit system. Precooling at either 1 K or 2.7 K is by evaporation of ^{4}He under reduced pressure in open circuit.

The very low temperatures needed for long depolarization time are well below the range of the ^{3}He evaporation system. They are, however, within the range of the helium dilution refrigerator. Two such refrigerators have been developed for this purpose in a collaboration between CERN and the Helsinki University of Technology. The first (Fig. 12) has a minimum operating temperature of about 0.02 K and produces 10 mW of refrigeration at 0.5 K. This is about ten times the refrigeration power of commercially available units. The second is even more powerful, producing 100 mW at 0.5 K and being capable of cooling the target from this temperature to less than 0.1 K in about five minutes. Both these units have the distinction of working in the horizontal position and need to be very compact to enter between the poles of the magnet used during polarization.

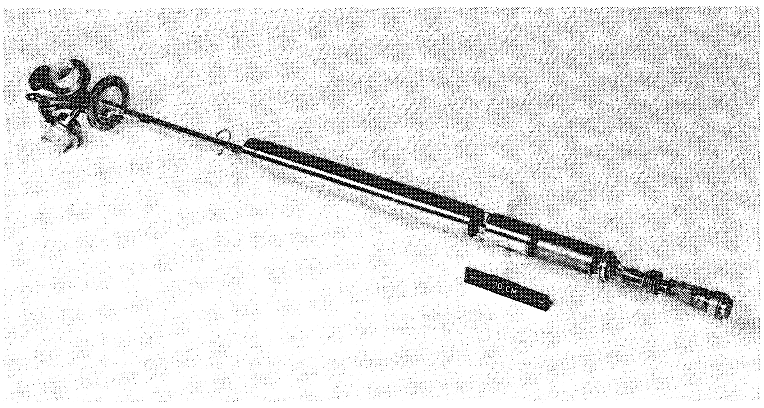

Fig. 12
Dilution refrigerator for polarized targets

7. REFRIGERATION

When one contemplates the large and sophisticated low-temperature refrigeration installations in routine operation in modern research institutes, it is sometimes difficult to realize that only some 20 years ago the ability to liquefy hydrogen and especially helium was something quite rare. If the stimulus for this rapid advance has come from high-energy physics and similar fields of activity, nearly all the development effort has been provided by industry, and this effort has been considerable. European industry, in particular, has a strong position in this field, since it can call upon several experienced manufacturers of low-temperature refrigerators. Let us look very briefly at some of the techniques they use.

The fluids we are interested in cannot be compressed into the liquid state at room temperature, so if they are to be liquefied they must either be condensed by a colder fluid or cooled at high pressure to a temperature close to the liquid state before expansion. In either case the necessary precooling is usually produced by expanding a high-pressure gas in some sort of engine which extracts a fraction of its thermal energy as mechanical work. If the expanded gas is made to cool the high-pressure gas arriving at the engine, by interposing a heat exchanger, the operating temperatures are reduced to the required level.

Very compact refrigerators of this type are made by combining a reciprocating compressor and expansion engine with a regenerative heat exchanger, for example a block of porous metal. Such machines are restricted to temperatures above about 15 K because the rapidly falling specific heat of solids limits the capacity of the regenerator at lower temperatures. They are, however, widely used for condensing hydrogen and providing refrigeration up to a few hundred watts at 20 K.

A much larger hydrogen refrigerator is shown in Fig. 13. This is to cool the 2 m hydrogen bubble chamber (2 m HBC) at CERN, and uses counter-current recuperative heat exchangers and high-speed turbines as expansion machines. The cold hydrogen exhausting from the turbines is used to condense hydrogen at 8 atm for circulation in the cooling loops of the bubble chamber. The plant provides more than 7 kW of refrigeration at 21 K. It has run some 50,000 hours in the last 10 years with a high degree of reliability.

In general, low-temperature refrigeration systems require high-efficiency heat exchangers since any thermal losses must be made up by extra cold production in the expansion machines. Turbines also pose some special problems. The volumetric flow through the turbines is usually small, partly because of the low temperature, and so, in consequence, is the diameter of the rotor. But for optimum efficiency the peripheral speed of the rotor must be something like 60% of the sonic velocity, so the rotational speed must be high. In certain applications, speeds as high as half a million rpm are used, and some manufacturers have developed turbines mounted on gas-lubricated bearings to solve this problem.

The refrigerator for the Big European Bubble Chamber (BEBC) (Fig. 14) is required to provide 25 kW of refrigeration at 28 K for the bubble chamber itself, and 1.8 kW at 4.4 K for the superconducting magnet. In this case, all the precooling is supplied by expansion

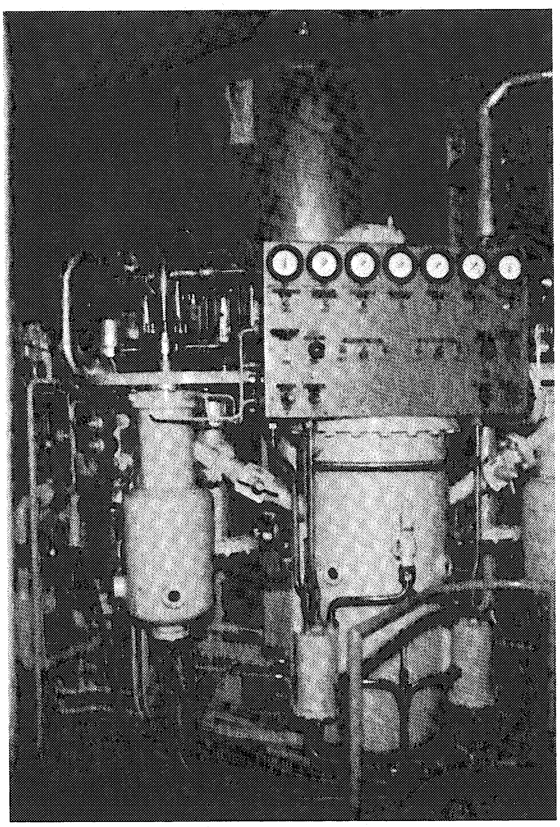

Fig. 13 Refrigerator cold box for the CERN 2 m HBC (Sulzer)

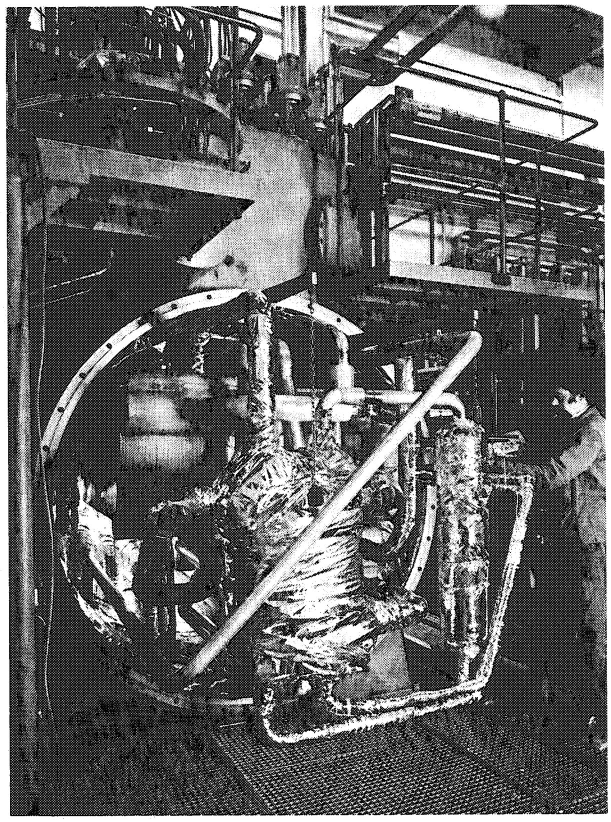

Fig. 14 Refrigerator for BEBC (Sulzer)

turbines in the helium circuit, which precool a side-stream of hydrogen. They also cool some of the high-pressure helium to a temperature which allows it to be expanded to the liquid state. This plant is by far the largest refrigerator in Europe in this temperature range.

Figure 15 shows a rather smaller refrigerator used for cooling the superconducting magnet of the Omega spectrometer and circulating supercritical helium in the windings. The plant gives about 800 W at 4.5 K.

The refrigeration at less than 2 K needed to cool large-scale high-frequency superconducting devices is produced in a somewhat similar way, with the important difference that the helium must be evaporated at very low pressure. For example, at 1.8 K the vapour pressure is less than 13 Torr, and a considerable pumping capacity must be installed in the circuit. Heat exchangers which introduce pressure drops of only a few Torr must also be provided.

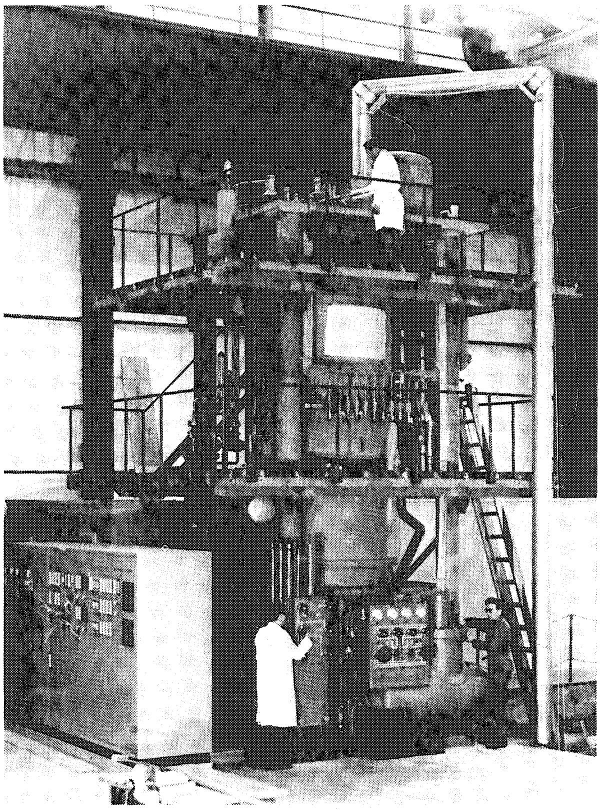

Fig. 15
Refrigerator for the Omega magnet (Sulzer)

Three large systems of this type exist, and a fourth is due to be installed at CERN. They produce about 300 W of refrigeration at 1.8 K. Figures 16 and 17 show one of them.

At lower temperatures the use of ordinary helium ^{4}He is limited, even in very small installations, to temperatures above 0.9 K, mainly because the vapour pressure falls so rapidly with temperature. Temperatures down to about 0.3 K can be reached on a small scale by evaporating the rare isotope ^{3}He under very low pressure, but for still lower temperatures a different approach is needed -- the dilution refrigerator.

In this device, instead of evaporating the ^{3}He directly, it is first dissolved in ^{4}He and then evaporated from the solution at higher temperature. Owing to the peculiar properties

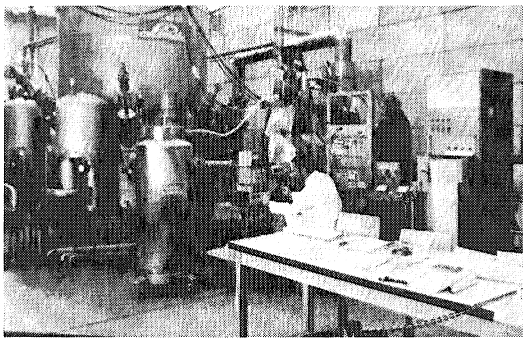

Fig. 16 Cold box of a refrigerator for 300 W at 1.8 K (Linde) (Courtesy Gesellschaft für Kernforschung, Karlsruhe)

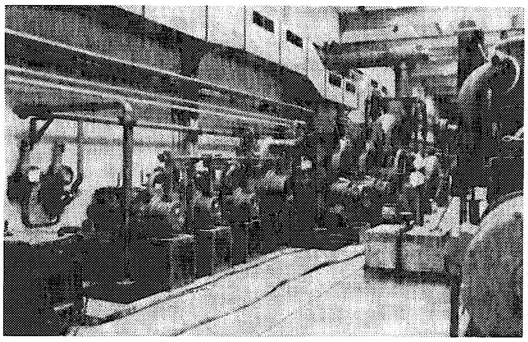

Fig. 17 Helium vacuum pumps in a refrigerator for 300 W at 1.8 K (Pfeiffer) (Courtesy Gesellschaft für Kernforschung, Karlsruhe)

of ^4He at very low temperature, this process has an effect roughly equivalent to imposing a lower limit on the vapour pressure of ^3He.

Dilution refrigerators were first demonstrated in 1966 by Hall et al. in England and Neganov et al. in the USSR following a suggestion of London et al. some years earlier. They can produce useful amounts of continuous refrigeration down to temperatures some two orders of magnitude lower than those available from evaporation systems.

8. CONCLUSION

Some of the low-temperature techniques which have been described here are beginning to find commercial applications, especially in the field of technical superconductivity. If European industry is in a relatively strong position to cater for these applications, this is due in no small degree to the stimulus provided by the use of cryogenic techniques in experimental elementary particle physics.