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Cryogenic Refrigeration and
Liquid Hydrogen Storage

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17.1 Introduction

The use of cryogenics and access to low temperatures, once confined to the laboratories searching for the liquefaction of the permanent gases [1], is now almost worldwide. All low-temperature apparatus must be contained in a cryostat, a word derived from Greek meaning literally frost apparatus. Cryogenic storage and refrigeration are becoming common in our everyday lives. Liquid nitrogen is used for food and living tissue preservation, liquid oxygen for medical patient respiration, and liquid hydrogen for power generation, transportation, and propulsion. Large superconducting magnets are used for magnetic resonance imaging (MRI). All these applications use either vacuum-insulated containers (dewars) or foam-insulated vessels to contain the cryogens. This is because direct exposure to environmental radiation supplies more than enough heat to evaporate the cryogen in a short time. In the future, the use of cryogenic equipment will rapidly increase with new demands, for example, in computers and communication systems (cold and superconducting electronics), medicine (surgery and diagnostics), materials fabrication, transportation (motor vehicles, ships, and magnetically levitated trains), and space travel (propulsion, cooling, and water generation), particularly in the hydrogen economy. This last item is important because large amounts of hydrogen will be used, stored, and transported. There is no better way to store or transport hydrogen than as a liquid cryogen, which is more
safe, less expensive, and at higher density than any other form. Scientifically, cryogenics are used in virtually every area of research, with the widest uses in propulsion (combustion and fuel cells), condensed matter and particle physics, physical chemistry, geology, biology, and medical sciences.

In this short chapter, we offer an overview of the state of the art of cryogenic storage and small-scale refrigeration, with references that provide more detailed information. This chapter is divided into two major parts: Section 17.2 covers dewars and storage techniques, and refrigeration apparatus and techniques are discussed in Section 17.3.

17.2 Storage Vessels, Dewars, and Storage Techniques

17.2.1 Non-Vacuum-Insulated Containers

Cryogens, defined as gases that liquefy below 123 K, including nitrogen, oxygen, neon, hydrogen, and helium, are stored, transported, and used in double-walled, vacuum-insulated dewars (large, improved versions of the thermos bottle) or foam-insulated containers. The purpose of this special container is to protect the cryogen from the heat of its surroundings, thus preserving the cold liquid and reducing evaporation (boil-off). This heat leak cannot be reduced to zero, regardless of cleverness of design, unless an active refrigerator, using external power, is employed (see Sections 17.2.3 and 17.3.4). The damaging heat leak to the interior of the vessel, as usual, may have three components: conduction, convection, and radiation.

Conduction heat is minimized by suspending the vessel inside an outer housing, which is otherwise filled with powder, foam, or other porous media to inhibit gas convection heat leaks. The inner vessel is suspended by relatively thin supports made of poorly conducting metal (stainless steel) or polymer. Because the cryogen-containing vessel may be quite massive, care must be taken to balance forces in the suspension, accounting for thermal contractions in the vessel and suspension. Often, the vessel is hung by a neck tube, through which the cryogen is introduced and removed (see Figure 17.1). For larger vessels, a centering snub at the bottom or snubbing pieces on the sides keep the vessel from swinging during motion. These do not make contact between the inner vessel and outer container during normal use.

The insulation between the inner vessel and outer container must be maintained as a poor thermal conductor. In humid environments, therefore, the space it occupies must be sealed, which is often difficult and/or expensive to accomplish. Because this insulation may require frequent replacement, inexpensive materials such as vermiculite, perlite, glass bubbles, Styrofoam, or polyurethane foam are usually used. All these materials have thermal conductances about four orders of magnitude less than bulk copper. Besides being poor bulk conductors, like cork, their insulating property is enhanced by another order of magnitude since they consist of poorly contacting, small particles.

Under certain circumstances, for example, to save cost or weight, the outer shell of these containers may be eliminated. The most famous example of this is the external tank on the US space shuttle vehicle, which contains two cryogens, liquid hydrogen and liquid oxygen, in two separate vessels, surrounded by ridged insulating foam. Since this container is used in a very humid environment (Florida), there is a large amount of ice buildup on this foam during use (just prior to launch). This contributes to the launch weight, but, more important, it produces extreme loads on the foam insulation during the acceleration
It is known that pieces of this foam have caused damage to the shuttle vehicle, particularly its wings and heat shield tiles. This caused the catastrophic SS Columbia accident.

**17.2.2 Dewars**

If the space between the inner vessel and outer container is evacuated, the whole apparatus is called a dewar, after Sir James Dewar (see next section), and was originally constructed of blown glass. The inner surfaces of the vacuum spaces in this construction are silvered. The vacuum space minimizes conduction heating, and the silvering minimizes radiant heating, but this vacuum is sometimes inconvenient or impossible, requiring stronger container walls, more safety apparatus, and construction of higher integrity.

Vacuum-insulated dewars are the preponderance of cryogenic storage and research containers. Although dewars used in research are physically quite different in appearance from storage and transport dewars, they have similar requirements to reduce heat leaks into the cryogen. Special features of storage and transport dewars necessary for these uses, such as more robust construction, are included in standard designs of manufacturers. Here, we will also discuss research dewars, likely to be of more concern to experimenters who may have to design or write specifications for a dewar.

In most research at low temperatures, liquid cryogen is transferred from a storage dewar (Figure 17.2) to a research dewar (Figure 17.3), designed for specific uses. The dewar in Figure 17.3, constructed of aluminum with a fiberglass neck, is designed for a large
FIGURE 17.2
Cross-sectional view of standard transport (storage dewar), with cutaway drawing of the same. Cross-sectional view, courtesy of the author. (Courtesy of International Cryogenics, Inc., Indianapolis, IN.)

FIGURE 17.3
Research dewar with two inserts: Left is a 3 T magnet with a $^4$He evaporative cooling stage. Right is a transport measuring probe on a continuous $^3$He evaporative cooling stage. The dewar has an aluminum outer jacket and fiberglass G10 inner neck and aluminum bucket, with multilayer insulation in the vacuum space between. (Courtesy of Janis Research, Inc., Wilmington, MA.)
superconducting magnet. It has features to reduce helium consumption in common with most other dewars used in research and with storage and transport dewars.

Radiation from room temperature to the inner wall containing the cryogen is reduced dramatically by vapor-cooled heat shields and multilayer (super)insulation (usually aluminized Mylar film separated by thin, loose fiberglass layers) in the vacuum space. Heat transfer by conduction down the low-thermal-conductivity fiberglass neck is reduced further by these vapor-cooled shields attached to the neck at appropriate intervals, which are cooled by the enthalpy of the vapor boiling off the liquid cryogen. The large neck, necessary for inserting the superconducting magnet, also has baffles inside to reduce radiation from the top flange. A thin metal barrier is incorporated inside the fiberglass to prevent diffusion of helium and/or hydrogen into the vacuum space, which occurs if residual cryogen is left in the dewar on warming.

These features of the dewars shown in Figures 17.2 and 17.3 provide a quite low boil-off rate: about 1% of capacity for the storage dewar and less than 2 L/h for the research dewar, even in this relatively large dewar, which is about 3.7 m long with a neck diameter of 46 cm.

The absence of liquid-nitrogen shielding for these dewars has a number of advantages including simpler construction, lighter weight, with lower initial and operating costs, and also bothersome refilling of the nitrogen jacket is avoided. Furthermore, eliminating boiling nitrogen can reduce vibrations that may be critical in some uses.

Some small hand dewars and research dewars are constructed of Pyrex glass, in which case liquid-nitrogen shielding using a separate liquid-nitrogen dewar, surrounding the lower-temperature hydrogen or helium dewar, is common, since incorporation of superinsulation is impractical. In using Pyrex dewars, it is essential to avoid leaving helium and/or hydrogen gas in the dewar when it is warmed in order to prevent diffusion of gas into the vacuum space, which can create an insurmountable heat leak. The simplest way to achieve this is to terminate the vacuum space of the helium dewar with a single-wall neck at a point below the nitrogen level in the outer dewar. This construction also facilitates precooling of the lower dewar with liquid nitrogen.

Research dewars may also be of all-stainless-steel construction, with or without nitrogen shielding. Frequently, storage and transport dewars are also of all-stainless-steel construction in order to provide the necessary ruggedness. Additionally, the nonmagnetic stainless steel allows the dewar to be moved safely near a large magnet.

In cooling a dewar from room temperature, much less cryogen is used if the dewar is precooled with liquid nitrogen. In case a dewar has no nitrogen shielding, nitrogen is transferred directly into the cryogen space. After the equipment inside has been cooled to nitrogen temperature (and the shields, in the case of a vapor-shielded dewar), the nitrogen is back-transferred. This is accomplished by applying a small overpressure above the nitrogen surface to force it out through a tube extending through the top flange of the dewar to the inside bottom. Once liquid ceases to flow, the container space should be pumped, being careful to keep the pressure above the triple point of N\(_2\), until there is very little flow of gas. This assures no liquid nitrogen remains in the dewar at the time cryogen is transferred (which would require a large quantity of cryogen to cool the nitrogen to the boiling point of the cryogen).

If a separate nitrogen dewar is used, then cooling from room temperature to liquid-nitrogen temperature can be accomplished simply by filling the nitrogen dewar and waiting for the inner dewar and the apparatus inside it to be cooled to near 77 K. In this case, it is essential that there be an exchange gas of air or N\(_2\) at a pressure of a few mm Hg in the vacuum jacket of the inner dewar to provide heat transfer. Once the cryogen transfer begins, this exchange gas is frozen on the wall of the dewar, producing the high vacuum necessary for holding the cryogen.

The research dewar is usually closed at the top by a flange that constitutes the top of the cryostat insert used for the particular experiment. The insert has suitable tubulation
and electrical leads for the measurements to be made and for operation of the refrigeration. Cryogen is transferred from a storage dewar into the research dewar using a double-walled, vacuum-insulated transfer tube that extends to the bottom of the storage dewar. In the initial part of the transfer, it is important that the cryogen be introduced at the bottom of the research dewar in order to make full use of the enthalpy of the gas in cooling the dewar and equipment inside it. In subsequent topping-off of the cryogen, it is best that the liquid be introduced above the level of cryogen remaining in the dewar.

A port allows recovery of the cryogen’s gas, or it is vented into the atmosphere if not recovered (not recommended for hydrogen). In a situation where large amounts of cryogen are transferred causing moisture condensation, it is useful for the port to be through a collar below the top flange, thus avoiding freezing of the top flange. Also, one or more relief ports may be needed to allow gas to escape quickly in cases of rapid boil-off such as when a superconducting magnet quenches. Relief valves are required on transport dewars for safety, but full dewars of liquid helium may be flown on commercial aircraft.

### 17.2.3 Zero Boil-Off Storage

In some situations, it is desired to have no loss of cryogen from the storage container. These applications include such common installations as MRI machines or special situations as onboard spacecraft or satellites. Since, as mentioned previously, it is impossible to completely avoid heat leaks to the cryogenic storage vessel, this heat leak must be intercepted by some refrigeration technique to achieve zero boil-off (ZBO).

Terrestrial applications, such as MRI machines in hospitals and clinics, research magnets, or particle accelerators, are straightforward to achieve ZBO. Electrical power is readily available, and gravity ensures that the cryogen is well behaved, that is, remains in the bottom of the dewar. Typically, a cryocooler, such as that described in Section 17.3.4, is employed. The cryocooler is mounted on top of the dewar, and a thermal connection, such as a heat pipe, draws in evaporated cryogen and recondenses it. Such a system is shown diagrammatically in Figure 17.4, which uses the latest innovation in cryocoolers, the pulse tube refrigerator.

Space applications, particularly to liquid hydrogen storage, are more challenging. A test of such a ZBO system for nonterrestrial use is described in Ref. [2].

![Pulse tube cooler](image)

**FIGURE 17.4**

Dewar incorporating a pulse tube refrigerator (Courtesy of Janis Research, Inc., Wilmington, MA.), reducing the cryogen to ZBO. Detail of pulse tube refrigerator (Courtesy of CryoMech, Inc., New York.) shown to right.
17.3 Small-Scale Refrigeration

17.3.1 $^4\text{He}$ Evaporation Refrigeration

Temperatures from the normal boiling point of $^4\text{He}$, 4.2 K, to as low as about 1.2 K (limited by the pumping speed of the system) can be achieved by pumping the vapor above liquid helium [2–4]. The simplest means of doing this, in terms of the equipment inside the dewar, is to pump the entire bath of helium. However, this method has several disadvantages. A large fraction of the helium is used in cooling the remaining helium to the minimum temperature of about 1.2 K. If the temperature is lowered below the lambda point, 2.18 K, a film of the superfluid helium creeps up the wall of the dewar, contributing significantly to the boil-off rate, resulting in higher consumption of helium [4].

The disadvantages just described can be overcome by keeping the main helium bath at 4.2 K and placing the experiment and a small pot of helium to be pumped to a lower temperature inside a vacuum space immersed in the helium bath, as shown in Figure 17.5. The pumped pot of helium can be refilled periodically from the bath using a valve at the top of the vacuum space, operated from outside the cryostat. Instead of filling periodically, a small needle valve may be used, which can be adjusted so that the flow of liquid into the pot is just adequate for the heat load. The arrangement shown requires no valve and allows continuous filling of the pot by using an impedance of appropriate size between the bath and the pot [5]. Even under varying heat loads, the temperature remains almost constant up to a critical power that equals the cooling by the incoming liquid. As shown, the inlet may be below the top of the vacuum space to give longer times between helium transfers into the dewar. The impedance must be in the vacuum space, and a filter is necessary to prevent clogging of the small line.

In experiments using a pumped pot of $^4\text{He}$, care must be taken to ensure adequate thermal contact between the helium and the sample or equipment that must be cooled. This

FIGURE 17.5
Schematic diagram of a continuously operating $^4\text{He}$ evaporation refrigerator. See Ref. 3 for details.
can be done by immersing the sample in the helium within the pot, with access from the top through the pumping line. Another approach is to mount the sample on the outside of the pot using a screw contact if the sample can be electrically grounded, or for a sample that must be insulated, contact may be made with varnish, epoxy, or grease. Care must be taken to thermally ground leads to the sample and thermometers, otherwise there may be a heat leak into the sample that will keep it at an elevated temperature. These precautions become ever more important as the temperature of the sample is lowered, such as by the techniques discussed in the following [3].

In cases where the experimental parts to be cooled can be made small, miniature cryostats with a pumped inner pot of helium have been constructed that may be inserted directly into a storage dewar with a wide neck (up to 60 mm diameter) [6]. These have the advantages that no transfer of helium is required, helium consumption is low, and the time required to reach the desired temperature is short.

Another arrangement used frequently to lower the temperature of superconducting magnets below 4.2 K is the “lambda-plate” refrigerator (see Figure 17.11 and Section 17.3.3). The lambda plate, situated in the lower portion of the dewar but above the magnet, has a needle valve for admission of liquid 4He into a coil heat exchanger connected through a tube to the top of the cryostat where a pump is connected. The normal 4He above the lambda plate is a very poor thermal conductor and remains at 4.2 K, while the helium in the lower portion of the dewar, where the magnet is located, is pumped to a reduced temperature, allowing the magnet to operate at a higher field.

17.3.2 3He Evaporation Refrigeration

The vapor pressure of 3He is higher than that of 4He at the same temperature, a consequence of the higher zero-point motion of the lighter isotope [2]. Furthermore, 3He has no creeping film in the range of interest. Consequently, temperatures of 0.3 K or slightly lower can be obtained by pumping to lower the vapor pressure of 3He.

Most 3He is obtained from the decay of 3H; therefore, it is quite expensive. Consequently, 3He is used in relatively small quantities of a few liters of gas STP in a closed cycle, with sealed pumps (including the exhaust) to recover the helium. A 3He refrigerator is usually run in a continuous mode, with the helium gas from the pump returned to the evaporator as a liquid, after it has been brought into thermal contact with a 4He pot to remove the heat of vaporization. Also, the pressure of the returning 3He gas must be brought above its saturated vapor pressure at the temperature of the 4He pot by including sufficient impedance in the return line below the 4He pot. A 3He refrigerator with gas-handling system is shown in Figure 17.6. A typical 3He refrigerator, which may be directly inserted into a 4He transport dewar, is shown in Figure 17.7. The advantage of this design is the avoidance of transferring the liquid 4He for the bath, saving time and money.

Recently, heat exchangers have been developed for closed cycle refrigerators that allow operation of a 3He refrigerator or a dilution refrigerator (see Section 17.3.3) without using pumped 4He [7]. An example is shown in Figure 17.8.

One of the limiting factors in the temperature that may be reached, or the refrigeration available by pumping 3He, is the pumping speed of the system, including the pumping line and the external pumps. The pumping speed can be increased substantially by incorporating a small adsorption pump (usually with charcoal as the adsorbate) within the vacuum container. Shown in Figure 17.9 is such an adsorption pump
in a miniature dilution refrigerator (see Section 17.3.3) designed for insertion into a storage dewar [8].

A feature of these miniature cryostats worth pointing out is the compact cone seal with vacuum grease that works well at helium temperatures (see Figure 17.8). Earlier, similar seals were made with Wood’s metal, requiring undesirable heating to make the seal, or with bulkier bolted flanges using soft metal (e.g., indium or lead) O-rings.

Adsorption pumps may also be used to advantage in larger systems to increase the pumping speed and to reduce the expense, since large external pumps are not required. One disadvantage is that continuous operation would require a more complicated arrangement with two adsorbers and cold valves. However, this disadvantage can be partially overcome by including a larger quantity of $^3$He in the system. A system capable of holding a few cm$^3$ of liquid $^3$He can maintain the desired temperature for a few days if the heat input in the experiment is not great.

Because of the rapid increase of the thermal boundary resistance between materials as the temperature is decreased, the evaporator of a $^3$He refrigerator should have several cm$^2$ of surface area in contact with the $^3$He. This can easily be provided by some means such as milling slots in the body or by brazing a spiral sheet of copper to the bottom.
17.3.3 $^3$He–$^4$He Dilution Refrigeration

Refrigeration by pumping $^3$He is impractical below about 0.25 K because of the vanishingly small vapor pressure at lower temperatures. The most common means of reaching temperatures as low as a few millikelvin is by $^3$He–$^4$He dilution refrigeration [3]. The physical process itself is quite easy to understand: cooling is provided by the heat of mixing when the two isotopes are mixed. This is possible at ultralow temperatures because the two isotopes remain liquids all the way to absolute zero and a finite amount, up to 6.5%, of $^3$He will dissolve in $^4$He at the lowest temperature [2,9].

A schematic drawing, depicting the essential components of a dilution refrigerator, is shown in Figure 17.10. This consists of a mixing chamber in which two separated phases exist, a concentrated phase of almost pure $^3$He floating on top and a dilute phase of 6.5% $^3$He in $^4$He at the bottom; heat exchangers for transferring heat from the warm incoming stream of concentrated $^3$He to the outgoing cold dilute phase; and a still for extracting the $^3$He from the dilute phase, allowing the process to be continuous.

The refrigerator is immersed in a helium dewar to provide a 4.2 K environment. Typically, there is a heat shield (not shown) attached to the still to reduce the heat reaching the mixing chamber through 4.2 K radiation and thermal conduction through spacers. Also, a mixing-chamber heat shield may be used to reduce heat input to a sample or colder stage below the mixing chamber.
The very high vapor pressure of $^3$He relative to $^4$He provides a vapor phase in the still of almost pure $^3$He above the liquid, which is less than 6.5% $^3$He. Thus, almost pure $^3$He is extracted from the still for recirculation, with most of the $^4$He remaining in place to serve as a medium in which to dissolve the $^3$He. Maintaining sufficiently high vapor pressure to allow the desired circulation rate requires that the still be kept at about 0.7 K by supplying the heat of vaporization with an electric heater.

The returning $^3$He gas must be liquefied by removing the latent heat either with a pumped pot of $^4$He as described in Section 17.3.1 or with a heat exchanger between the outgoing and incoming streams [3]. Just as with the $^3$He refrigerator discussed in Section 17.3.2, the pressure of the incoming stream of gas must be brought above the saturated vapor pressure. Again, this requires a flow impedance below the $^4$He pot or heat exchanger.

Perhaps the most critical parts of a dilution refrigerator are the heat exchangers that are necessary to cool the incoming stream from the still temperature of about 0.7 K to near that of the mixing chamber, which is much colder. With a simple counterflow capillary heat exchanger, minimum mixing-chamber temperatures of about 50 mK can be achieved.
Typically, a refrigerator designed to achieve the lowest temperatures has a counterflow exchanger followed by several step exchangers. These are also counterflow exchangers that have a large inside surface area of very fine sintered metal powder (silver is commonly used) for heat transfer between the two streams and are bulkier in construction than capillary exchangers [10].

One of the main requirements for the mixing chamber is that it has adequate surface area, usually provided with sintered metal powder, to minimize the temperature difference between the chamber body and the cold dilute phase. Thermal contact to the material to be cooled can then be made using bolts screwed tightly to the mixing chamber. Another requirement is that the entrance tube for the dilute phase actually extends into this phase (see Figure 17.11).

An alternative to this “bottom-loading” refrigerator is to insert samples directly into the liquid in the mixing chamber, usually by loading them in through a vacuum port in the pumping line at the top of the cryostat. This “top-loading” refrigerator has the advantage that samples may be changed relatively quickly without warming the refrigerator to room temperature. However, care must be taken to insert the sample slowly and to adequately heat-sink the sample, ensuring it does not remain at a significantly higher temperature than the liquid in the mixing chamber.

FIGURE 17.9
Schematic diagram of a miniature charcoal-pumped $^3$He–$^4$He dilution refrigerator that may be used in a helium storage dewar. (Courtesy of Nanoway; From Uhlig, K., Cryogenics, 27, 454, 1987.)
With a very-well-designed refrigerator, minimum temperatures of about 2.5 mK have been achieved, although commercial refrigerators have typical minimum temperatures of 5–10 mK. The maximum cooling power of a dilution refrigerator, $Q(W)$, is given by

$$Q = 84\dot{n}T_m^2$$  \hspace{1cm} (17.1)

where

- $\dot{n}$ is the number of mol/s of $^3$He being circulated.
- $T_m$ is the mixing-chamber temperature (K).

The coefficient 84 is determined by the entropies of the dilute and concentrated phases [3,11].

Frequently, the cooling power of a dilution refrigerator is specified at 100 mK, which by Equation 17.1 is 840 $\mu$W/mmol/s of $^3$He in circulation. Near the minimum temperature of the dilution refrigerator, the cooling power drops significantly below the value given by Equation 17.1 [11].

Two examples of commercially available dilution refrigeration units are shown in Figure 17.12. These may be purchased with varying cooling capacities up to 1 mW at...
FIGURE 17.11
Schematic diagram of a $^3$He–$^4$He dilution refrigerator in an aluminum and fiberglass research dewar (as in Figure 17.2b) containing a lambda-plate refrigerator and two high field magnets. The lambda plate allows the helium below it to be pumped to about 2.1 K, allowing the 16 T magnet to achieve full field. Pumps and external gas-handling system are not shown. (Courtesy of J.S. Xia, Microkelvin Research Laboratory, University of Florida, Gainesville, FL.)

FIGURE 17.12
Two examples of the business end of dilution refrigeration, with still at the top, mixing chamber at the bottom, and continuous and block heat exchangers in between. (Courtesy of Janis Research Company LLC, Woburn, MA.)
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T = 0.1 K and then attached to the users’ pumped $^4$He cryostats. A sealed pumping system must be provided to continuously evaporate the $^3$He from the still. Also, some care must be taken to isolate the cryostat from electrical oscillations (from low to very high frequency) and mechanical vibration, both of which will overwhelm the cooling power of the dilution unit if not eliminated.

Miniature dilution refrigerators employing adsorption pumping, similar in design to the $^3$He refrigerator shown in Figure 17.8, for use in storage dewars, have been reported [8,12].

Dilution refrigerators provide the lowest temperature available for continuous cooling. The most common technique for achieving still lower temperatures is magnetic demagnetization using the nuclei of various metals such as copper. This technique, by which temperatures of nuclei of less than 1 nK have been reached, is quite specialized, and interested readers are referred to the literature [3].

17.3.4 Refrigeration above 4.2 K

There is more work done above the temperature of boiling liquid helium than below. Applications include almost anything also done at room temperature: light scattering, microscopy, x-ray Raman scattering, Mossbauer and Hall effect, nuclear magnetic and electron spin resonance (NMR and ESR), magnetization and susceptibility, matrix isolation, resistivity, and radio astronomy, to name a few. Cold traps and cryopumping are also broadly applied. Systems that cool from room temperature down to 4.2 K fall into two classes: open and closed systems. Open systems use cryogenic fluids that eventually boil and are released into the environment. Closed systems use pressurized gases, such as helium, nitrogen, neon, or hydrogen, in some type of expansion process.

Most open systems use helium or nitrogen because of the explosive nature of hydrogen/air mixtures or the high cost of neon. This method of cooling simply transfers the cryogen from a storage dewar, through a triaxial (vacuum-insulated) transfer tube to a cold head. Here, the cryogen evaporates, cooling the apparatus, with the evolved gas returning through heat exchangers, heat shields, and the transfer tube middle-annular space, maximizing efficient use of the cryogen. A heater at the cold head is used in an electric feedback circuit to hold the temperature at the desired value. If a Joule–Thomson expansion valve [13] is added to the cryogenic liquid exit port, temperatures as low as 2 K may be reached using helium.

Open systems are simple, have relatively high cooling capacity, and may be constructed to cool in confined spaces, such as in a magnet or with optical instrumentation. They may also be made quite vibration-free. Their obvious disadvantage is that cryogenic fluid must be continually supplied. Hence, expertise in handling the fluid and a source of the fluid must be maintained. In addition, as the system is adjusted to temperatures farther away from the boiling point, control becomes more and more difficult, with some intermediate temperatures becoming impossible to regulate. New types of microprocessor-based regulators (see Section 17.3.1) are reducing this problem.

Often, temperatures below 4 K and high cooling power are not necessary. In this case, closed cycle systems are often used. These systems require only electricity and a thermal bath (ambient air or cooling water) and run continuously for long periods of time. They may also be made very small and relatively vibration-free. There are three types of closed cycle refrigerators, all involving the expansion of a compressed gas: Joule–Thomson, Gifford–McMahon (GM) [14], pulse tube refrigerator [15], or a linear combination of these three types of expansion.
The Joule–Thomson expansion of a high-pressure gas extracts heat by doing work against the internal forces between the molecules of a nonideal gas. The expansion must begin in the region of the pressure–temperature plane where the isenthalps have positive slopes (the inversion region). For nitrogen, this includes room temperature, so that nitrogen expanded in this way from a gas cylinder can be made to reach 70 K with no moving parts (except the gas molecules). This process is used in microminiature refrigerators [16], which are centimeters in size, have essentially no electrical or mechanical vibrations, and require no maintenance. Larger versions can produce watts of cooling power below 100 K. The expanded cold gas must be used to precool the incoming pressurized gas for lowest temperatures to be achieved. As usual, efficient heat exchangers, often of counterflow construction, are necessary.

The GM process uses a displacer moving in a cylinder driven by pressurized gas. In addition, it uses a regenerator, which is essentially a single-chamber heat exchanger with the incoming and outgoing fluids sharing it at different times in the cycle. This regenerator must be extremely efficient (>98%). An advantage of the GM cycle is that stages may be easily put in series and driven on the same shaft to obtain lower temperatures and higher cooling capacities. Cooling powers of 2 W at 10 K and 100 W at 77 K have been achieved by commercial units [17]. A low temperature of less than 5 K may be reached if helium is the working medium.

Most units operate from a simple, small air-conditioning compressor using either helium or nitrogen gas. The compressor, ambient heat exchanger, and ancillary equipment are housed in a small (0.1 m$^3$) portable unit, connected to the cold head using standard flexible metal hoses. The cold head can be quite small and configured to meet almost any experimental need. It contains the moving displacer and valve disk/motor, which controls the gas cycle [18]. It may be operated in any orientation relative to gravity, or in zero gravity, since bulk cryogenic liquid is not part of the cycle. Experiments or samples may be thermally heat sunk to the cold head using mechanical or gas (heat pipe) contacts.

GM units are commonly used to cool the neck of a large cryostat, thus greatly reducing helium consumption. One dilution refrigerator (see Section 17.3.3) has been constructed using a GM machine to thermally shield the dilution unit and provide the cooling power to condense the circulating $^3$He. No liquid cryogens are required, allowing operation anywhere that electrical power is available.

By using a GM machine to precool pressurized helium gas, the inversion region of helium may be reached (<45 K). This is also a closed system, as the helium gas is reused and pressurized in the same compressor that runs the GM cycle. This adds very little to the size of the cold head while achieving a low temperature of 3.6 K with a cooling power of 1 W at 4.2 K.

A pulse tube refrigerator is very similar to a GM refrigerator (also developed by Gifford) but has the advantage of no moving cold parts (except the gas working medium). It has the disadvantage of being gravitation field dependent. This is because there is no displacer per se, such as the piston in the GM machine, so the moving gas is susceptible to convection. Therefore, buoyancy effects are important. However, the pulse tube refrigerator can function in very low or zero gravity.

Recently, the performance of pulse tube refrigerators has been greatly improved. They can reach almost 1 K, have useful capacity, are compact and simple to operate, and produce relatively low vibration levels. The working medium, often helium gas, is self-contained and therefore does not require circulating, cleaning, or replenishing. This device has ushered in the age of the cryogen-free refrigerator that can reach temperatures as low as 6 mK and the cryogen-free superconducting magnets.
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