# Chapter 2
# Cryogenic Technologies

Cryogenics is the science that addresses the production and effects of very low temperatures. The word originates from the Greek words "kryos" meaning "frost" and "genic" meaning "to produce." Under such a definition, it could be used to include all temperatures below the freezing point of water (0 °C). However, Prof. Kamerlingh Onnes of the University of Leiden in the Netherlands first used the word in 1894 to describe the art and science of producing much lower temperatures. He used the word in reference to the liquefaction of permanent gases such as oxygen, nitrogen, hydrogen, and helium. Oxygen had been liquefied at −183 °C a few years earlier in 1887, and a race was in progress to liquefy the remaining permanent gases at even lower temperatures. The techniques employed in producing such low temperatures were quite different from those used somewhat earlier in the production of artificial ice. In particular, efficient heat exchangers are required to reach very low temperatures. Over the years the term cryogenics has generally been used to refer to temperatures below approximately −150 °C (123.15 K, −238.00 °F).

## 2.1 Introduction

According to the laws of thermodynamics, there exists a limit to the lowest temperature that can be, achieved, which is known as absolute zero. Molecules are in their lowest, but finite, energy state at absolute zero. Such a temperature is impossible to reach because the input power required approaches infinity. However, temperatures within a few billionths of a degree above absolute zero have been achieved. Absolute zero is the zero of the absolute or thermodynamic temperature scale. It is equal to −273.15 °C or −459.67 F. The metric or SI (International System) absolute scale is known as the Kelvin scale whose unit is the kelvin (not Kelvin) which has the same magnitude as the degree Celsius. The symbol for the Kelvin scale is K, as adopted by the 13th General Council on Weights and Measures (CGPM) in 1968, and not K. Thus, 0 °C equals 273.15 K. The English absolute scale, known



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**Table 2.1** Normal boiling and triple and critical points

| Cryogen | (K) | (°C) | (°R) | (°F) | Triple point | Critical point |
|---|---|---|---|---|---|---|
| Methane | 111.7 | −161.5 | 201.1 | −258.6 | 90.7 | 190.5 |
| Oxygen | 90.2 | −183.0 | 162.4 | −297.3 | 54.4 | 154.6 |
| Nitrogen | 77.4 | −195.8 | 139.3 | −320.4 | 63.1 | 126.2 |
| Hydrogen | 20.3 | −252.9 | 36.5 | −423.2 | 13.8 | 33.2 |
| Helium | 4.2 | −269.0 | 7.6 | −452.1 | 2.2 | 5.2 |
| Absolute zero | 0.0 | −273.15 | 0.0 | −459.67 | – | – |

as the Rankine scale, uses the symbol R and has an increment the same as that of the Fahrenheit scale. In terms of the Kelvin scale, the cryogenic region is often considered to be that below approximately 120 K (−153 °C). The common permanent gases referred to earlier change from gas to liquid at atmospheric pressure at the temperatures shown in Table 2.1, called the normal boiling point (NBP). In this table, we have included the triple point and critical point, which we will explain them in the next chapter. Such liquids are known as cryogenic liquids or cryogens. When liquid helium is cooled further to 2.17 K or below, it becomes a superfluid with very unusual properties associated with being in the quantum mechanical ground state. For example, it has zero viscosity and produces a film that can creep up and over the walls of an open container, such as a beaker, and drip off the bottom as long as the temperature of the container remains below 2.17 K.

The measurement of cryogenic temperatures requires methods that may not be so familiar to the public in general. Normal mercury or alcohol thermometers freeze at such low temperatures and become useless. One of the metal elements that have a well-defined behavior of electrical resistance versus temperature is platinum resistance thermometer. It is commonly used to measure accurately, including cryogenic temperatures down to about 20 K. Certain semiconducting materials, such as doped germanium, are also useful as electrical resistance thermometers for temperatures down to 1 K and below, as long as they are calibrated over the range they are to be used. Such secondary thermometers are calibrated against primary thermometers that utilize fundamental laws of physics in which a physical variable changes in a well-known theoretical way with temperature.

The production of cryogenic temperatures usually utilizes the compression and expansion of gases. In typical air liquefaction process, the air is compressed, causing it to heat, and allowed to cool back to room temperature while still pressurized. The compressed air is further cooled in a heat exchanger before it is allowed to expand back to atmospheric pressure. The expansion causes the air to cool and a portion of it to liquefy. The remaining cooled gaseous portion is returned through the other side of the heat exchanger where it precools the incoming high-pressure air before returning to the compressor. The liquid portion is usually distilled to produce liquid oxygen, liquid nitrogen, and liquid argon. Other gases, such as helium, are used in a similar process to produce even lower temperatures, but several stages of expansion are necessary.

Cryogenics has many applications. Cryogenic liquids, such as oxygen, nitrogen, and argon, are often used in industrial and medical applications. The electrical resistance of most metals decreases as temperature decreases. Certain metals lose all electrical resistance below some transition temperature and become superconductors. An electromagnet wound with a wire of such a metal can produce extremely high magnetic fields with no generation of heat and no consumption of electric power once the field is established and the metal remains cold. These metals, typically niobium alloys cooled to 4.2 K, are used for the magnets of magnetic resonance imaging (MRI) systems in most hospitals. Superconductivity in some metals was first discovered in 1911 by Onnes, but since 1986, another class of materials, known as high-temperature superconductors, has been found to be superconducting at much higher temperatures, currently up to about 145 K. They are a type of ceramic, and because of their brittle nature, they are more difficult to fabricate into wires for magnets.

Other applications of cryogenics include fast freezing of some foods and the preservation of some biological materials such as livestock semen as well as human blood, tissue, and embryos. The practice of freezing an entire human body after death in the hope of later restoring life is known as cryonics, but it is not an accepted scientific application of cryogenics. The freezing of portions of the body to destroy unwanted or malfunctioning tissue is known as cryosurgery. It is used to treat cancers and abnormalities of the skin, cervix, uterus, prostate gland, and liver.

## 2.2 Low Temperature in Science and Technology

Cryogenics as it was described in the previous section is defined as *that branch of physics, which deals with the production of very low temperatures and their effect on matter* [1], a formulation which addresses both aspects of attaining low temperatures which do not naturally occur on Earth and of using them for the study of nature or the human industry. In a more operational way [2], it is also defined as *the science and technology of temperatures below* 120 K. The reason for this latter definition can be understood by examining characteristic temperatures of cryogenic fluids as it is shown in Table 2.1.

The limit temperature of 120 K comprehensively includes the normal boiling points of the main atmospheric gases, as well as of methane, which constitutes the principal component of natural gas. Today, liquefied natural gas (LNG) represents one of the largest—and fast-growing—industrial domains of application of cryogenics (see Fig. 2.1), together with the liquefaction and separation of air gases (see Fig. 2.2). The densification by condensation and separation by distillation of gases were historically—and remain today—the main driving force for the cryogenic industry. Exemplified not only by liquid oxygen and by nitrogen used in chemical as well as metallurgical processes but also by the cryogenic liquid propellants of rocket engines (see Fig. 2.3) where the proposed use of hydrogen as a “clean” energy vector in transportation (see Fig. 2.4).

As we have stated, the cryogenic technology has the need for smaller cryocoolers because of the advances in the miniaturization of electrical and optical devices and the need for cooling and conducting efficiency. Cryogenic technology deals with materials at low temperatures and the physics of their behavior at these temperatures.


**Fig. 2.1** 130,000 $m^3$ LNG carrier with integrated Invar tank


**Fig. 2.2** Cryogenic air separation plant with heat exchanger and distillation column towers

In this book, we try to demonstrate the ongoing new applications are being discovered for cryocooled electrical and optical sensors and devices, with particular emphasis on high-end commercial applications in medical and scientific fields as well as in the aerospace and military industries.

Refrigerators, cryocoolers, and micro-coolers are needed by various commercial, industrial, space, and military systems. Cryogenic cooling plays an important role in unmanned aerial vehicle systems, infrared search and track sensors, missile warning receivers, satellite tracking systems, and a host of other commercial and military systems.

(a) Ariane 5
(25 t Liquid Hydrogen, 130 t Liquid Oxygen)

(b) Space Shuttle
(100 t Liquid Hydrogen, 600 t Liquid Oxygen)

**Fig. 2.3** Rockets using cryogenic liquid propellants

**Fig. 2.4** Automotive liquid hydrogen fuel tank

Now with new generation of nuclear power plants that are known as GEN-IV, a lot of attention is focused toward making them more efficient and cost-effective [3] as well as using cryogenic techniques to implement energy storage in nuclear plants [4]. Energy storage in nuclear power plants resides on a novel method of integration of nuclear power generation with cryogenic energy storage (CES) to achieve an effective time shift of the electrical power output. CES stores excess electricity in the form of cryogen (liquid air/nitrogen) through an air liquefaction process at off-peak hours and recover the stored power by expanding the cryogen at peak hours [5].

The quest for low temperatures however finds its origin in early thermodynamics, with Amontons's gas pressure thermometer (1703) opening the way for the concept of absolute zero inferred a century later by Charles and Gay-Lussac and eventually formulated by Kelvin. However, with the advent of Boltzmann's statistical


**Fig. 2.5** Ludwig Boltzmann's grave in the Zentralfriedhof Vienna, bearing the entropy formula

thermodynamics in the late nineteenth century, temperature—a phenomenological quantity—could be explained in terms of microscopic structure and dynamics. Consider a thermodynamic system in a macrostate, which can be obtained by a multiplicity $W$ of microstates. The entropy S of the system was postulated by Boltzmann as

$$S = k_B \log W \tag{2.1}$$

with $k_B \simeq 1.38 \times 10^{-23}$J/K. This formula, which founded statistical thermodynamics, is displayed on Boltzmann's grave in Vienna (see Fig. 2.5).

Adding reversibly heat $dQ$ to the system produces a change of its entropy $dS$, with a proportionality factor $T$ which is precisely temperature

$$T = \frac{dQ}{dS} \tag{2.2}$$

Thus, a low-temperature system can be defined as one to which a minute addition of heat produces a large change in entropy, i.e., a large change in its range of possible microscopic configurations. Boltzmann also found that the average thermal energy of a particle in a system in equilibrium at temperature $T$ is

$$E \sim k_B T \tag{2.3}$$

Consequently, a temperature of 1 K is equivalent to a thermal energy of $10^{-4}$ eV or $10^{-23}$ J per particle.

A temperature is therefore low for a given physical process when $k_B T$ is small compared to the characteristic energy of the process that is considered.

**Table 2.2** Characteristic temperature of low-energy phenomena

| Phenomenon | Temperature (K) |
|---|---|
| Debye temperature of metals | Few 100 |
| High-temperature superconductors | ~100 |
| Low-temperature superconductors | ~10 |
| Intrinsic transport properties of metals | <10 |
| Cryopumping | Few |
| Cosmic microwave background | 2.7 |
| Superfluid helium-4 | 2.2 |
| Bolometers for cosmic radiation | <1 |
| Low-density atomic Bose-Einstein condensates | $\sim 10^{-6}$ |

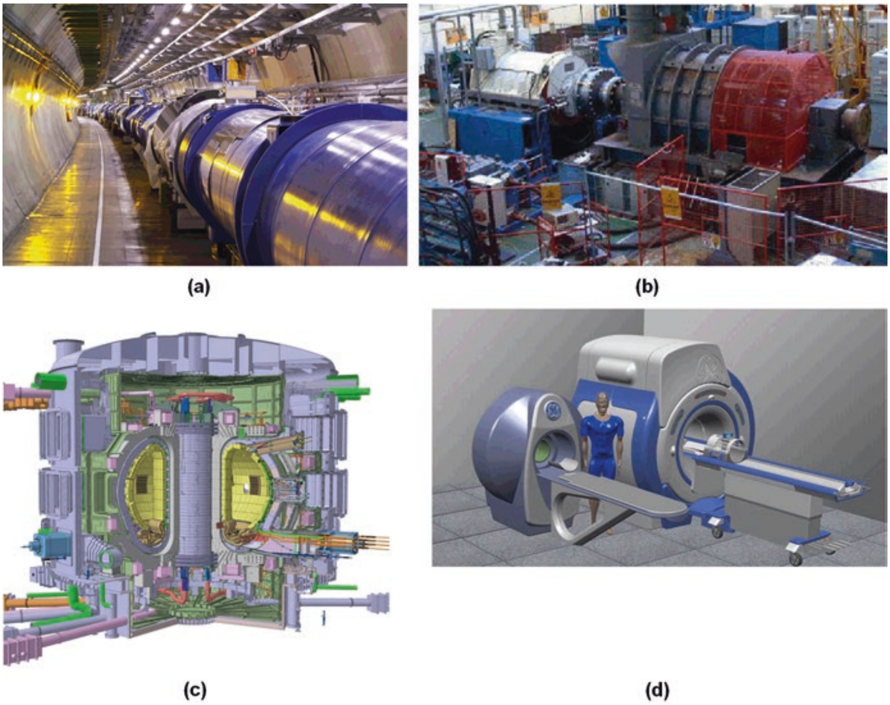
(a) (b) (c) (d)

**Fig. 2.6** Helium-cooled superconducting devices. (**a**) Large Hadron Collider at CERN. (**b**) 5 MW HTS ship propulsion motor (AMS). (**c**) ITER experimental fusion reactor. (**d**) Whole-body MRI system (Bruker)

Cryogenic temperatures thus reveal phenomena with low characteristic energy (Table 2.2) and enable their application when significantly lower than the characteristic energy of the phenomenon of interest. From Tables 2.1 and 2.2, it is clear that "low-temperature" superconductivity requires helium cryogenics: several examples of helium-cooled superconducting devices are shown in Fig. 2.6. Considering vapor pressures of gases at low temperature (see Fig. 2.7), it is also clear that helium must be the working cryogen for achieving "clean" vacuum with cryopumps.

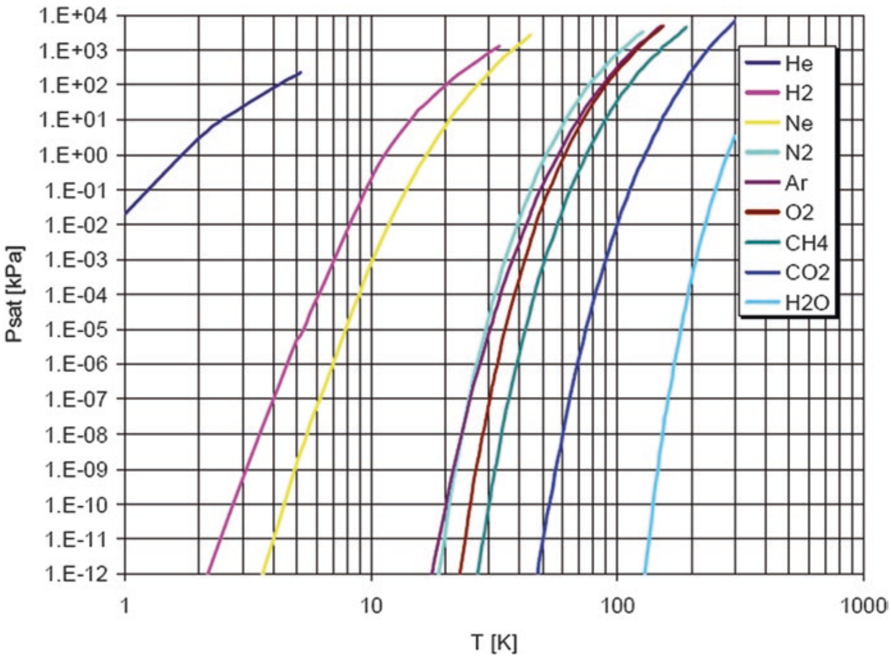


**Fig. 2.7** Vapor pressure of common gases at cryogenic temperature

## 2.3 Defining Cryogenic Fluids or Liquids

Cryogenic liquids, also known as cryogens, are gases at normal temperatures and pressures. However, at low temperatures, they are in their liquid state. These liquids are extremely cold and have boiling points less than −150 °C (−238 °F). Even the vapors and gases released from cryogenic liquids are very cold. They often condense the moisture in air, creating a highly visible fog. Different cryogens become liquids under different conditions of temperature and pressure, but all have two properties in common; extremely cold and small amounts of liquid can expand into very large volumes of gas. Everyone who works with cryogenic liquids must be aware of their hazards and know how to work safely with them. Figure 2.8 is a presentation of liquid nitrogen (LN).

The discovery of superconducting materials with critical temperatures significantly above the boiling point of liquid nitrogen has provided new interest in reliable, low-cost methods of producing high-temperature cryogenic refrigeration.

**Fig. 2.8** Liquid nitrogen

The term "high-temperature cryogenic" describes temperatures ranging from above the boiling point of liquid nitrogen, −195.79 °C (77.36 K; −320.42 °F), up to −50 °C (223.15 K; −58.00 °F), the generally defined upper limit of study referred to as cryogenics [6]. Cryogenicists use the Kelvin or Rankine temperature scales present in nature.

### *2.3.1 Defining Cryogenic Fluids or Liquids*

Each cryogenic liquid has its own specific properties, but most cryogenic liquids can be placed into one of the three groups:

- *Inert gases*: Inert gases largely to any extent do not react chemically. They do not burn or support combustion. Examples of this group are nitrogen, helium, neon, argon, and krypton.
- *Flammable gases*: Some cryogenic liquids produce a gas that can burn in air. The most common examples are hydrogen, methane, carbon monoxide, and liquefied natural gas.
- *Oxygen*: Many materials considered as noncombustible can burn in the presence of liquid oxygen. Organic materials can react explosively with liquid oxygen. The hazards and handling precautions of liquid oxygen must therefore be considered separately from other cryogenic liquids.

It is generally agreed that cryogenic fluids are those whose boiling points (bp) at atmospheric pressure are about 120 K or lower, although liquid ethylene with its boiling point of 170 K is often included. A list of the cryogenic fluids, together with some selected properties, is given in Table 2.3. Detailed properties are available commercially on computer disk.

Perhaps the most important and widely used fluids are liquefied natural gas or LNG (bp = boiling point about 120 K), *liquid oxygen* (bp 90.2 K), and liquid nitrogen (bp 77.3 K).

The availability of cryogenic fluids forms an essential part of the infrastructure of a modem industrialized and civilized society. One of the major reasons for using liquid cryogens is to allow transport and storage as liquid at atmospheric pressure, rather than as high-pressure gas in thick-walled vessels, although there is an energy penalty involved in *refrigeration*. However, the distillation of liquid air (air separation) enables the production of very high-purity oxygen and nitrogen. Plants producing up to several hundred tons per day and more of oxygen are commonplace, sometimes connected permanently to a chemical plant or steel works. Liquid nitrogen—formerly a by-product of the process—is now a product in its own right, being used principally as a convenient source of refrigeration, especially in the frozen food industry.

The other important by-product of air separation is liquid argon, which again can be produced at a very high purity. For welding, it is increasingly being stored as liquid at the factory rather than being delivered in high-pressure cylinders.

All cryogenic fluids except *helium* and *hydrogen* behave as "normal" fluids, their common distinguishing features in general being a low specific heat and enthalpy of vaporization. All gaseous cryogens are odorless, and all liquid cryogens are colorless apart from *oxygen*, which is pale blue, and fluorine, which is pale yellow. They are all diamagnetic except oxygen, which is quite strongly paramagnetic.

With the exception of oxygen, all the gases are asphyxiants, and even oxygen will not support human life in concentrations greater than about 60%. Fluorine and oxygen are powerful oxidizers even in liquid form. Some cryogens are flammable; hydrogen is especially delicate to handle.

Hydrogen is an unusual fluid in that the molecule exists in two forms known as ortho and para, with somewhat different properties. The ratio of ortho to para is determined by conventional thermodynamics and is dependent on temperature. There are also different forms of isotopes (deuterium and tritium), and these two isotopes are used in driving fusion energy production via either magnetic confinement fusion (MCF) [7] or inertial confinement fusion (ICF) [8].

An explanation of the behavior of the hydrogen molecule requires knowledge of quantum mechanics and will not be discussed here. At low temperatures, equilibrium hydrogen (e-$H^2$) is entirely para. At room temperature, the ortho-para ratio is 3. The equilibrium state at room temperature is often known as normal hydrogen or n-hydrogen. The transition from the ortho to the para state involves a heat of conversion—which can be greater than the enthalpy of vaporization—so that the vaporization rates of hydrogen are often much larger than expected. It is for this reason that a catalyst is often included in a hydrogen liquefier to ensure that only para hydrogen is present in the liquid [9].

**Table 2.3** Some properties of cryogens at their normal boiling points

| | $He^4$ | n-$H_2$ | $d_2$ | Ne | $N_2$ | CO | $F_2$ | Ar | $O_2$ | $CH_4$ | Kr | Xe | $C_2H_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Normal boiling point (K) | 4.22 | 20.4 | 23.7 | 21.1 | 77.3 | 81.7 | 85.0 | 87.3 | 90.2 | 111.6 | 120.0 | 165.0 | 169.4 |
| Liquid density (kg/$m^3$) | 125 | 71.0 | 163 | 1205 | 809 | 792 | 1502 | 1393 | 1141 | 423 | 2400 | 3040 | 568 |
| Liquid density-vapour density | 7.4 | 53 | 71 | 126 | 175 | 181 | 267 | 241 | 255 | 236 | 270 | 297 | 272 |
| Enthalpy of vaporisation (kJ/kg) | 20.42 | 446 | 301 | 86 | 199 | 216 | 175 | 161 | 213 | 512 | 108 | 96 | 482 |
| Enthalpy of vaporisation (kJ/kg-mole) | 80.6 | 899 | 1211 | 2333 | 5565 | 6040 | 6659 | 6441 | 6798 | 8206 | 9042 | 12,604 | 13,534 |
| Volume of liquid vaporised by energy input of 1 W-hr. ($cm^3$) | 1410 | 114 | 74 | 35 | 22 | 21 | 14 | 16 | 15 | 17 | 14 | 13 | 13 |
| Dynamic viacosity of liquid (μNsec/$m^2$) | 3.3 | 13.3 | 28.3 | 124 | 152 | – | 240 | 260 | 195 | 119 | 404 | 506 | 170 |
| Surface tension (mN/m) | 0.10 | 1.9 | ~3 | 4.8 | 8.9 | 9.6 | 14.8 | 12.5 | 13.2 | 13.2 | 5.5 | 18.3 | 16.5 |
| Thermal conductivity of liquid (mW $m^{-1}$ $K^{-1}$) | 18.7 | 100 | ~100 | 113 | 135 | – | – | 128 | 152 | 187 | 94 | 74 | 192 |
| Volume of gas at 15 °C released from 1 volume of liquid | 739 | 830 | 830 | 1412 | 681 | 806 | 905 | 824 | 842 | 613 | 689 | 520 | 475 |

Source: Hands [9]

[a]Pressure of 1.01325 bar

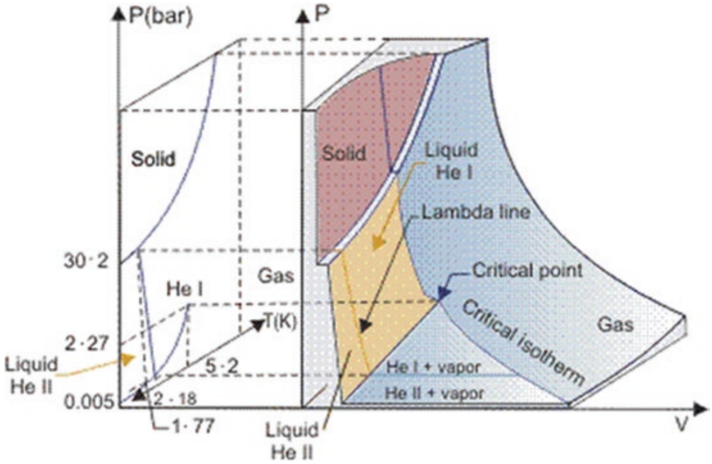


**Fig. 2.9** From cryogenic engineering by hand [9]

Helium is the one cryogenic fluid, which can be claimed to be unique. Because of its low molecular weight and chemical inertness, quantum mechanical effects are important. There are two isotopic forms: the natural form He-4, which has a nucleus consisting of two protons and two neutrons, and the comparatively rare manufactured form He-3, with only one neutron. The two isotopes have markedly different properties due to their different nuclear spins. He-3 is not considered here.

Below 2.2 K, He-4 becomes "superfluid" and is often known as He-2, the "normal" liquid being known as "He-1." The locus of the He-1/He-2 transition is known as the *Lambda line or λ line* from the shape of the curve of specific heat as a function of temperature. The phase diagram of He-4 is shown in Fig. 2.9, in which features of particular interest are the absence of a triple point and the fact that the liquid can only be solidified under pressure (greater than about 26 bars).

The temperature of the normal-superfluid transition depends somewhat on pressure. One end of this boundary forms with solid He-1 and He-2 as the "upper lambda point" (at 1.77 K and 30.2 bars). The other end of the line (at 2.18 K, 0.005 bar) where vapor, He-1, and He-2 coexist is known as the "lower lambda point."

He-1 behaves as a conventional liquid (except when near the λ line) but requires much more care in handling than other cryogenic fluids, principally because of its extremely low latent heat of vaporization. He-2 is quite different, having a variety of properties quite different from those of any other liquid. It will, for instance, climb up over the edge of a container and drip off the bottom; it has a small or zero viscosity and a very large thermal conductivity. Flow velocity through fine capillaries is independent of the pressure head and is greater in tubes of smaller diameter. Flow may be induced by a temperature gradient in the absence of any pressure gradient. A consequence of the very high thermal conductivity is that below the λ point, boiling ceases and the liquid becomes "quiescent," although the rate of heat transfer remains very high. Vinen has published a brief but useful review of the properties of superfluid helium.

**Table 2.4** Properties of helium and nitrogen compared to water

| Property | Helium | Nitrogen | Water |
|---|---|---|---|
| Normal boiling point (K) | 4.2 | 77 | 373 |
| Critical temperature (K) | 5.2 | 126 | 647 |
| Critical pressure (bar) | 2.3 | 34 | 221 |
| Liquid density (kg/m$^3$) | 125 | 808 | 960 |
| Liquid density ratio[a] | 7.4 | 175 | 1600 |
| Heat of vaporization[a] (kJ/kg) | 20.4 | 199 | 2260 |
| Liquid viscosity[a] (μP1) | 3.3 | 152 | 278 |

[a]At normal boiling point

### 2.3.2 Thermophysical Properties

The simplest way of cooling equipment with a cryogenic fluid is to make use of its latent heat of vaporization, e.g., by immersion in a bath of boiling liquid. Consequently, the useful temperature range of cryogenic fluids is that in which there exists latent heat of vaporization, i.e., between the triple point and the critical point, with a particular interest in the normal boiling point, i.e., the saturation temperature at atmospheric pressure. This data is given in Table 2.1. In this introduction to cryogenics, we will concentrate on two cryogens: helium, which is the only liquid at very low temperature, and nitrogen for its wide availability and ease of use for pre-cooling equipment and for thermal shielding.

To develop a feeling about properties of these cryogenic fluids, it is instructive to compare them with those of water (see Table 2.4). In both cases, but particularly with helium, applications operate much closer to the critical point, i.e., in a domain where the difference between the liquid and vapor phases is much less marked: the ratio of liquid to vapor densities and the latent heat associated with the change of phase are much smaller. Due to the low values of its critical pressure and temperature, helium can be used as a cryogenic coolant beyond the critical point, in the supercritical state. It is also interesting to note that, while liquid nitrogen resembles water as concerns density and viscosity, liquid helium is much lighter and less viscous.

This latter property makes it a medium of choice for permeating small channels inside superconducting magnet windings and thus stabilizing the superconductor.

### 2.3.3 Liquid Boil-off

The factor of ten in latent heat of vaporization between helium and nitrogen, combined with the lower density of the former, induces a large difference in vaporization rates under the same applied heat load (Table 2.5). This illustrates the need for implementing much better insulation techniques in liquid helium vessels to achieve comparable holding times.

**Table 2.5** Vaporization of liquid helium and liquid nitrogen at normal boiling point under 1 W applied heat load

| Cryogen | mg/s | 1/h Liquid | 1/min gas NTP |
|---|---|---|---|
| Helium | 48 | 1.38 | 16.4 |
| Nitrogen | 5 | 0.02 | 0.24 |

Boil-off measurements constitute a practical method for measuring the heat load of a cryostat holding a saturated cryogen bath. In steady conditions, i.e., provided the liquid level in the bath is maintained constant, the boil-off $\dot{m}_{\text{vap}}$ precisely equals the vapor flow $\dot{m}_{\text{out}}$ escaping the cryostat, which can be warmed up to room temperature and measured in a conventional gas flow meter. At decreasing liquid level though, part of the vapor will take the volume in the cryostat previously occupied by the liquid, which has vaporized, and the escaping flow will be lower than the boil-off. More precisely, if the boil-off vapor is taken at saturation in equilibrium with the liquid

$$\dot{m}_{\text{out}} = m_{\text{vap}}\left(1-\frac{\rho_v}{\rho_\ell}\right) < \dot{m}_{\text{vap}} \tag{2.4}$$

The escaping gas flow measured must therefore be corrected upward to obtain the true boil-off. From values of saturated liquid to vapor density ratios in Table 2.4, this correction factor is only 1.006 for nitrogen and can therefore be neglected. For helium though, it amounts to 1.16 and must clearly be taken into account.

### 2.3.4 Cryogen Usage for Equipment Cooldown

For both fluids, the sensible heat of the vapor over the temperature range from liquid saturation to ambient is comparable to or larger than the latent heat of vaporization. This provides a valuable cooling potential at intermediate temperature, which can be used for thermal shielding or for precooling of equipment from room temperature. The heat balance equation for cooling a mass of, say, iron $m_{Fe}$ of specific heat $C_{Fe}(T)$ at temperature $T$ by vaporizing a mass d$m$ of cryogenic liquid at saturation temperature $T_v$, latent heat of vaporization $L_v$, and vapor specific heat $C$ taken as constant, assumes perfect heat exchange with the liquid and the vapor.

$$m_{Fe}C_{Fe}(T)\,dT = \left[L_v + C(T-T_v)\right]dm \tag{2.5}$$

Hence, the specific liquid cryogen requirement for cooldown from temperature $T_0$

$$\frac{m}{m_{Fe}} = \int_{T_0}^{T} \frac{C_{Fe}(T)\,dT}{L_v + C(T-T_v)} \tag{2.6}$$

**Table 2.6** Volume of liquid cryogens required to cool down 1 kg of iron [1]

| Using | Latent heat only | Latent heat and enthalpy of vapor |
|---|---|---|
| Liquid helium from 290 to 4.2 K | 29.5 | 0.75 |
| Liquid helium from 77 to 4.2 K | 1.46 | 0.12 |
| Liquid nitrogen from 290 to 77 K | 0.45 | 0.29 |

The term $C(T-T_v)$ adding to $L_v$ in the denominator brings a strong attenuation to the specific liquid requirement, provided there is good heat exchange between the solid and the escaping vapor. Calculated values of specific liquid cryogen requirements for iron are given in Table 2.6, clearly demonstrating the interest of recovering the sensible heat of helium vapor, as well as that of precooling equipment with liquid nitrogen.

### *2.3.5 Phase Domains*

Typical operating domains with cryogenic helium are, as shown in Fig. 2.10, superimposed on the peculiar phase diagram of the substance: the solid phase only exists under pressure, and the normal liquid, He-1, transitions to another liquid phase, He-2, below 2.2 K instead of solidifying. There is no latent heat associated with this phase transition, but a peak in the specific heat, the shape of which gave the name "λ-line" to the phase boundary. He-2 exhibits superfluidity, a macroscopic quantum behavior entailing very high thermal conductivity and very low viscosity. While operating in saturated He I provides fixed (saturation) temperature and high boiling heat transfer at moderate heat flux, it may develop instabilities in two-phase flow and is prone to boiling crisis above the peak nucleate boiling flux (about 1 W/cm2). The use of monophase supercritical helium in forced-flow systems avoids the problems of two-phase flow. However, the strongly varying properties of the fluid near the critical point may create other issues, such as density wave oscillations. More fundamentally, supercritical helium exhibits no latent heat, so that applied heat loads result in temperature increases, which must be contained by high flow rate or periodic recooling in extended systems. At lower temperature, He-2 demonstrates excellent transport properties, which make it a coolant of choice for advanced superconducting devices [10]. Besides the thermodynamic penalty of lower temperature, the use of He-2 imposes that at least part of the cryogenic circuits operate at subatmospheric pressure, thus requiring efficient compression of low-pressure vapor and creating risks of dielectric breakdown and contamination by air in-leaks. See Fig. 2.10.

Thermophysical properties of cryogenic fluids are available from tables, graphs, and software running on personal computers, a selection of which is listed in the bibliography.

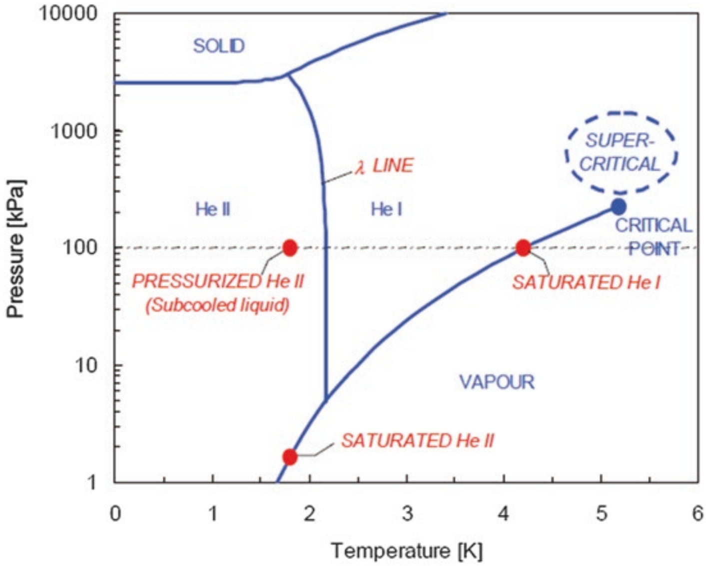


**Fig. 2.10** Phase diagram of helium, showing typical operating domains

## *2.3.6 Personal Protective Equipment to Be Worn*

As part of safety requirement in order to handle any cryogenic liquids, we need to consider the following personal protective equipments (PPEs) and wear them during handling of such liquids, in order to protect our skin and eyes:

- Be sure to work in a well-ventilated area to prevent oxygen-deficient atmospheres under 19.5% oxygen.
- Wear safety shoes when handling containers along with long sleeve shirts and trousers without cuffs.
- *Always* wear a full-face shield and splash resistant safety goggles. Contact lenses should not be worn.
- Wear a lab coat and an apron when dispensing liquid nitrogen.
- Wear insulated or leather gloves when handling liquid nitrogen or large, cold objects.

## *2.3.7 Handling Cryogenic Liquids*

Handling the cryogenic liquids requires the following precautions as part of standard operating procedures, and they are listed here as:

- Never allow any unprotected part of the body to touch noninsulated pipes or vessels, which contain cryogenic fluids. Tissue damage that results is similar to frostbite or thermal burns.

- The extremely cold metal will cause flesh to stick fast and tear when one attempts to withdraw from it.
- Use a suitable hand truck for container movement.
- Do not drop, tip, or roll containers on their sides. Do not remove or interchange connections. If user experiences any difficulty operating container valve or with container connections, discontinue use and contact supplier. Use the proper connection. *Do not use adapters*.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

### 2.3.8 Storing Cryogenic Liquids

In order to store the cryogenic liquids, we should consider the following steps as pointed out here:

- Store and use with adequate ventilation.
- Do not store in a confined space.
- Cryogenic containers are equipped with pressure relief devices to control internal pressure. Under normal conditions, these containers will periodically vent product. Do not plug, remove, or tamper with pressure relief device for this could cause an explosion.
- Containers shall be handled and stored in an upright position.
- Small quantities of liquid nitrogen can be stored in Dewar bottles. Dewar bottles are hollow-walled glass-lined containers, which provide excellent insulation.

### 2.3.9 Hazards of Cryogenic Liquids

Hazards of cryogenic liquids are also listed here as follows:

- *Extreme Cold Hazard*: Cryogenic liquids and their associated cold vapors and gases can produce effects on the skin similar to a thermal burn. Brief exposures that would not affect skin on the face or hands can damage delicate tissues such as the eyes. Prolonged exposure of the skin or contact with cold surfaces can cause frostbite. The skin appears waxy yellow. There is no initial pain, but there is intense pain when frozen tissue thaws. Unprotected skin can stick to metal that is cooled by cryogenic liquids. The skin can then tear when pulled away. Even nonmetallic materials are dangerous to touch at low temperatures. Prolonged breathing of extremely cold air may damage the lungs.
- *Asphyxiation Hazard*: When cryogenic liquids form a gas, the gas is very cold and usually heavier than air. This cold, heavy gas does not disperse very well and can accumulate near the floor. Even if the gas is nontoxic, it displaces air. When there is not enough air or oxygen, asphyxiation and death can occur. Oxygen deficiency

is a serious hazard in enclosed or confined spaces. Small amounts of liquid can evaporate into very large volumes of gas.
- *Toxic Hazards*: Each gas can cause specific health effects. Refer to the MSDS for information about the toxic hazards of a particular cryogen.

### 2.3.10 General Hazards of Cryogenic Liquids

The following points are important to bear in mind, when it comes to general hazards of cryogenic liquids, and they are listed as:

- *Fire Hazard*: Flammable gases such as hydrogen, methane, carbon monoxide, and liquefied natural gas can burn or explode. Hydrogen is particularly hazardous. It forms flammable mixtures with air over a wide range of concentration. It is also very easily ignited.
- *Oxygen-Enriched Air*: When transferring liquid nitrogen through uninsulated metal pipes, the air surrounding a cryogen containment system can condense. Nitrogen, which has a lower boiling point than oxygen, will evaporate first. This evaporation can leave an oxygen-enriched condensate on the surface that can increase the flammability or combustibility of materials near the system, creating potentially explosive conditions. Equipment containing cryogenic fluids must be kept clear of combustible materials in order to minimize the fire hazard potential.
- *Liquid Oxygen Hazard*: Liquid oxygen contains 4000 times more oxygen by volume than normal air. Materials that are usually considered noncombustible (carbon and stainless steels, cast iron, aluminum, zinc, Teflon (PTFE), etc.) may burn in the presence of liquid oxygen. Many organic materials can react explosively, especially if a flammable mixture is produced. Clothing splashed or soaked with liquid oxygen can remain highly flammable for hours.
- *Embrittlement*: Rubber, plastic, and carbon steel are some examples of materials that can be can become brittle and break with very little stress applied to them. Try to avoid using these materials when working with cryogenic. If these materials are used, perform an inspection before use.

## 2.4 Heat Transfer and Thermal Design

With the exception of superfluid helium, the heat transfer processes at work in cryogenics are basically the same as for any engineering temperature range. The strong variation of thermal properties of materials and fluids at low temperature however has two consequences: the relative and absolute magnitudes of the processes may be very different from those at room temperature, and the equations become nonlinear, thus requiring numerical integration. Cryogenic thermal

**Table 2.7** Thermal conductivity integrals of selected materials (W/m)

| From vanishing low temperature up to | 20 K | 30 K | 290 K |
|---|---|---|---|
| OFHC copper | 11,000 | 60,600 | 152,000 |
| DHP copper | 395 | 5890 | 46,100 |
| Aluminum 1100 | 2740 | 23,300 | 72,100 |
| 2024 aluminum alloy | 160 | 2420 | 22,900 |
| AISI 304 stainless steel | 16.3 | 349 | 3060 |
| G-10 glass-epoxy composite | 2 | 18 | 153 |

design is the art of using these processes adequately, either for achieving thermal insulation (cryostats, transfer lines) or for improving thermal coupling between equipment and coolant (cooldown and warm-up, thermal stabilization, thermometry) [11].

### *2.4.1 Solid Conduction*

Heat conduction in solids is represented by Fourier's law as it can be seen in Eq. 2.7 and expressing proportionality of heat flux with thermal gradient. In one dimension, this reads

$$Q = k(T) A \frac{dT}{dx} \tag{2.7}$$

This equation also defines the thermal conductivity $k(T)$ of the material, which varies with temperature. Conduction along a solid rod of length $L$, cross section $A$ spanning a temperature range $[T_1, T_2]$, e.g., the support strut of a cryogenic vessel, is then given by the integral form as

$$Q = \frac{A}{L} \int_{T_1}^{T_2} k(T) \, dT \tag{2.8}$$

Thermal conductivity integrals $\int_{T_1}^{T_2} k(T) \, dT$ of standard materials are tabulated in the literature. A few examples are given in Table 2.7, showing the large differences between good and bad thermal conducting materials; the strong decrease of conductivity at low temperatures, particularly for pure metals; and the interest of thermal interception to reduce conductive heat in-leak in supports. As an example, the thermal conductivity integral of austenitic stainless steel from 80 K to vanishingly low temperature is nine times smaller than from 290 K, hence the benefit of providing a liquid nitrogen-cooled heat sink on the supports of a liquid helium vessel. The lower thermal conductivity values of nonmetallic composites, combined with their good mechanical properties, make them materials of choice for low heat in-leak structural supports (Fig. 2.11).

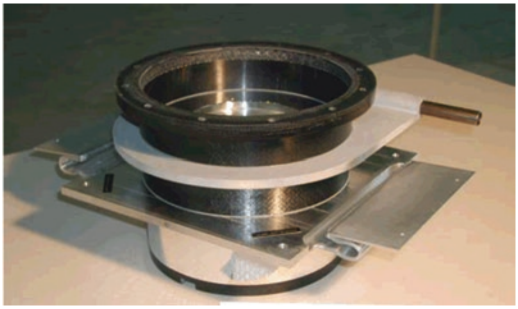

**Fig. 2.11** Nonmetallic composite support post with heat intercepts for LHC superconducting magnets at CERN

### *2.4.2 Radiation*

Blackbody radiation strongly and only depends on the temperature of the emitting body, with the maximum of the power spectrum given by Wien's law

$$\lambda_{max} T = 2898 [\mu m \mathrm{K}] \tag{2.9}$$

and the total power radiated given by Stefan-Boltzmann's law as

$$Q = \sigma A T^4 \tag{2.10}$$

with Stefan-Boltzmann's constant $\sigma \simeq 5.67 \times 10^{-8} \mathrm{W m^{-2} K^{-4}}$. The dependence of the radiative heat flux on the fourth power of temperature makes a strong plea for radiation shielding of low-temperature vessels with one or several shields cooled by liquid nitrogen or cold helium vapor. Conversely, it makes it very difficult to cool down equipment to low temperature by radiation only: in spite of the 2.7 K background temperature of outer space and notwithstanding the sun's radiation and the Earth's albedo, which can be avoided by proper attitude control, satellites or interplanetary probes can use passive radiators to release heat down to about 100 K and embarked active refrigerators are required to reach lower temperatures.

Technical radiating surfaces are usually described as "gray" bodies and characterized by an emissivity $\varepsilon < 1$

$$Q = \varepsilon \sigma A T^4 \tag{2.11}$$

The emissivity ε strictly depends on the material, surface finish, radiation wavelength, and angle of incidence. For materials of technical interest, measured average values are found in the literatures, a subset of which is given in Table 2.8. As a general rule, emissivity decreases at low temperature, for good electrical conductors and for polished surfaces. As Table 2.7 shows, a simple way to obtain this combination of properties is to wrap cold equipment with aluminum foil. Conversely, radiative thermal coupling requires emissivity as close as possible to that of a blackbody, which can be achieved in practice by special paint or adequate surface treatment, e.g., anodizing of aluminum.

**Table 2.8** Emissivity of some technical materials at low temperature

| | Radiation from 290 K surface at 77 K | Radiation from 77 K surface at 4.2 K |
|---|---|---|
| Stainless steel, as found | 0.34 | 0.12 |
| Stainless steel, mesh polished | 01.2 | 0.07 |
| Stainless, electropolished | 0.10 | 0.07 |
| Stainless steel + aluminum foil | 0.05 | 0.01 |
| Aluminum, black anodized | 0.95 | 0.75 |
| Aluminum, as found | 0.12 | 0.07 |
| Aluminum, mesh polished | 0.10 | 0.06 |
| Aluminum, electropolished | 0.08 | 0.04 |
| Copper, as found | 0.12 | 0.06 |
| Copper, mesh polished | 0.06 | 0.02 |

The net heat flux between two "gray" surfaces at temperature $T_1$ and $T_2$ is similarly given by

$$Q = E\sigma A\left(T_1^4 - T_2^4\right) \tag{2.12}$$

with the emissivity factor $E$ being a function of the emissivities $\varepsilon_1$ and $\varepsilon_2$ of the surfaces, of the geometrical configuration, and of the type of reflection (specular or diffuse) between the surfaces. Its precise determination can be quite tedious, apart from the few simple geometrical cases of flat plates, nested cylinders, and nested spheres.

If an uncooled shield with the same emissivity factor $E$ is inserted between the two surfaces, it will "float" at temperature $T_s$ given by the energy balance equation.

$$Q = E\sigma A\left(T_1^4 - T_s^4\right) = E\sigma A\left(T_s^4 - T_2^4\right) \tag{2.13}$$

Solving for $T_s$ yields the value of $Q_s = Q/2$: the heat flux is halved in presence of the floating shield. More generally, if $n$ floating shields of equal emissivity factor are inserted between the two surfaces, the radiative heat flux is divided by $n+1$.

### *2.4.3 Convection*

The diversity and complexity of convection processes cannot be treated here. Fortunately, in the majority of cases, the correlations established for fluids at higher temperature are fully applicable to the cryogenic domain [12], and reference is made to the abundant technical literature on the subject.

In the case of forced convection, one should keep in mind that the high density and low viscosity of cryogenic fluids often result in flows with high Reynolds number Re and hence strong convection. The Nüsselt number *Ni* which characterizes the efficiency of convective heat transfer relative to conduction in the fluid is an increasing function of the Prandtl Pr and Reynolds numbers, respectively, representing the ratio of mass to heat transport and the ratio of inertial to viscous forces.

$$Ni = f\left(\mathrm{Pr}, \mathrm{Re}\right) \tag{2.14}$$

The case of natural convection at low temperature however deserves particular mention, as this mechanism, usually weak at room temperature except on very large scales, becomes dominant in cryogenic equipment. In this case, the Nüsselt number is an increasing function of the Prandtl and Grashof number $Gr$, with the latter representing the ratio of buoyancy to viscous forces.

$$Ni = f\left(\mathrm{Pr}, Gr\right) \tag{2.15}$$

For gases, while Pr is about constant and independent of temperature, $Gr$ is proportional to the heated volume, temperature difference, and coefficient of volume thermal expansion which scales as $1/T$ in the ideal case. Consequently, there may exist in helium cryostats strong natural convection processes with Grashof numbers up to the $10^{12}$ range, i.e., higher than those encountered in the general circulation of the Earth's atmosphere. This has been used by hydrodynamics specialists to study turbulent convection in extreme conditions. The cryogenic engineer sees it as a powerful mechanism for cooling equipment and homogenizing its temperature.

### *2.4.4 Gas Conduction*

Since J. Dewar's invention (1898) of the cryogenic vessel, which bears his name, evacuated envelopes provide the best insulation against heat transport in gaseous media. At low pressure, convection becomes negligible and only residual gas conduction is at work. This process operates in two distinct regimes, depending upon the value of the mean free path of gas molecules $\ell$ relative to the typical distance $d$ between the cold and warm surfaces.

When $\ell \ll d$ corresponding to higher residual pressure, the probability of interaction of a given molecule with others before it travels distance $d$ is a highly viscous regime, and heat diffuses as in any continuous medium, then we can write

$$Q = k\left(T\right) A \frac{dT}{dx} \tag{2.16}$$

Note that the thermal conductivity $k(T)$ of the gas is independent of pressure.

When $\ell \gg d$ at low residual pressure, the molecular regime prevails and the heat transfer between two surfaces at temperatures $T_1$ and $T_2$ is given by Kennard's law

**Table 2.9** Typical values of heat flux to vanishingly low temperature between flat plates (W/m$^2$)

| | |
|---|---|
| Blackbody radiation from 290 K | 401 |
| Blackbody radiation from 80 K | 2.3 |
| Gas conduction (100 mPa helium) from 290 K | 19 |
| Gas conduction (1 mPa helium) from 290 K | 0.19 |
| Gas conduction (100 mPa helium) from 80 K | 6.8 |
| Gas conduction (1 mPa helium) from 80 K | 0.07 |
| MLI (30 layers) from 290 K, pressure < 1 mPa | 1–15 |
| MLI (10 layers) from 80 K, pressure < 1 mPa | 0.05 |
| MLI (10 layers) from 80 K, pressure 100 mPa | 1–2 |

$$Q = A\alpha(T)\Omega P(T_2 - T_1) \tag{2.17}$$

where $\Omega$ is a parameter depending upon the gas species and $\alpha$ is the "accommodation coefficient" representing the thermalization of molecules on the surfaces; its value depends on $T_1$, $T_2$, the gas species, and the geometry of the facing surfaces. Note that the conductive heat flux in molecular regime is proportional to pressure $P$ and independent of the spacing between the surfaces (and therefore not amenable to the concept of thermal conductivity). Typical values of heat flux by gas conduction at cryogenic temperature are given in Table 2.9.

### 2.4.5 Multilayer Insulation

Multilayer insulation (MLI) is based on multiple reflecting shields wrapped around the cryogenic piece of equipment to be insulated, with the aim of benefiting from the $n+1$ reduction factor in radiative heat in-leak. In practice, this is implemented in the form of aluminum or aluminized polymer films, with low packing density achieved by crinkling or by insertion of a net-type spacer between layers. The wrapping can be made by winding the layers and spacer in situ or by prefabricated blankets installed and held in place by insulating fasteners (Fig. 2.12). In all cases, MLI is a complex thermal system, involving the combination of radiation, solid contact conduction, and residual gas conduction between layers. As a result, increasing the number of layers, while beneficial for cutting radiation, usually results in increased packing with more contacts and

**Fig. 2.12** Prefabricated MLI blankets are being installed around an accelerator superconducting magnet

trapped residual gas between layers, two effects which increase heat transfer. In view of the nonlinearity of these elementary processes, thermal optimization requires layer-to-layer modeling and efficient control of the critical parameters. In practice, performance is measured on test samples, and measured data is available from an abundant literature. Typical values for some practical MLI systems are given in Table 2.9.

Of particular interest is the case of operation in degraded vacuum, where the heat in-leak by molecular conduction is directly proportional to the residual pressure. The presence of a multilayer system, which segments the insulation space into many cells thermally in series significantly, contains the increase in heat in-leak to the low-temperature surface (Table 2.8). In this respect, the multilayer system is no longer used for its radiative properties but for the reduction of molecular gas conduction.

In the extreme case of complete loss of vacuum in a liquid helium vessel, MLI also efficiently limits the heat flux, which would otherwise be very high due to condensation of air on the cold wall, thus alleviating the requirements for emergency discharge systems.

### 2.4.6 *Vapor Cooling of Necks and Supports*

The enthalpy of cryogen vapor escaping from a liquid bath can be used to continuously intercept conduction heat along solid supports and necks connecting the cryogenic bath with the room temperature environment (Fig. 2.13).

Assuming steady state and perfect heat exchange between the escaping vapor and the solid, the energy balance equation reads

$$k(T)A\frac{dT}{dx} = Q_v + \dot{m}C(T - T_v) \tag{2.18}$$

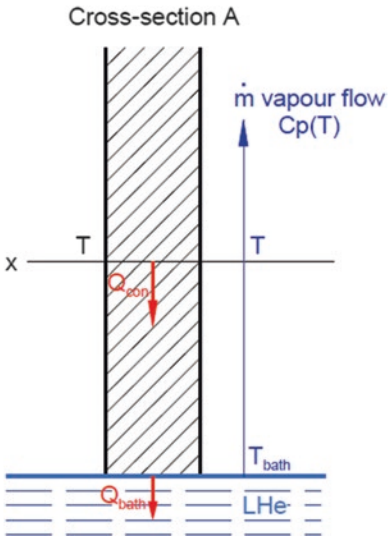


**Fig. 2.13** Vapor cooling of necks and supports with perfect heat exchange

**Table 2.10** Attenuation of heat conduction between 290 K and 4 K by self-sustained helium vapor cooling (W/cm)

| Material | Purely conductive regime | Self-sustained vapor cooling |
|---|---|---|
| ETP copper | 1620 | 128 |
| OFHC copper | 1520 | 110 |
| Aluminum 1100 | 728 | 39.9 |
| Nickel 99% pure | 213 | 8.65 |
| Constantan | 51.6 | 1.94 |
| AISI 300 stainless steel | 30.6 | 0.92 |

where $Q_v$ is the heat reaching the liquid bath and $\dot{m}$ is the vapor mass flow rate. In the particular case of self-sustained vapor cooling, i.e., when the vapor mass flow rate $\dot{m}$ precisely equals the boil-off from the liquid bath

$$Q_v = L_v \dot{m} \tag{2.19}$$

Combining Eqs. 2.18 and 2.19 and integrating yields the value of $Q_v$

$$Q_v = \frac{A}{L} \int_{T_v}^{T_0} \frac{k(T)}{1 + (T - T_v)\frac{C}{L_v}} dT \tag{2.20}$$

The denominator of the integrand clearly acts as an attenuation term for the conduction integral. Numerical results for helium and a few materials of technical interest appear in Table 2.10. If properly used, the cooling power of the vapor brings an attenuation of one to two orders of magnitude in the conductive heat in-leak.

Vapor cooling can also be used for continuous interception of other heat loads than solid conduction. In cryogenic storage and transport vessels with vapor-cooled shields, it lowers shield temperature and thus reduces radiative heat in-leak to the liquid bath. In vapor-cooled current leads, a large fraction of the resistive power dissipation by Joule heating is taken by the vapor flow, in order to minimize the residual heat reaching the liquid bath [13].

A worked-out example of how these diverse thermal insulation techniques are implemented in a real design is given in reference [14].

## 2.5 Refrigeration and Liquefaction

Refrigeration and liquefaction of gases are historically at the root of cryogenics, as they constitute the enabling technology, which gave access to the low-temperature domain. They have developed over the years along several lines to become a specialized subject, which would deserve a thorough presentation. In the following, we shall briefly describe the basic thermodynamics, the cooling processes at work, and the corresponding equipment in the case of helium refrigerators/liquefiers based on the Claude cycle. For a more complete review, see reference [15].

### *2.5.1 Thermodynamics of Refrigeration*

A refrigerator is a machine raising heat $Q_i$ from a low-temperature source $T_i$ to a higher-temperature sink (usually room temperature) $T_0$, by absorbing mechanical work $W_i$; doing so, it rejects heat $Q_0$ (see Fig. 2.14). These quantities are related through the application of the first (Joule) and second (Clausius) principles of thermodynamics.

$$Q_0 = Q_i + W_i \tag{2.21}$$

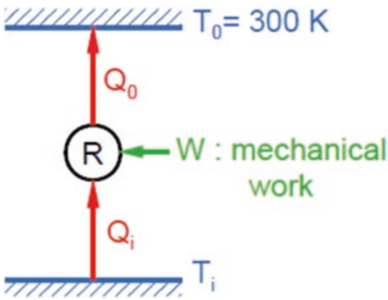


**Fig. 2.14** Thermodynamic scheme of a refrigerator

$$\frac{Q_0}{T_0} \geq \frac{Q_i}{T_i} \tag{2.22}$$

In Eq. 2.22, the equality applies to the case of reversible process. From the above

$$W_i \geq T_0 \frac{Q_i}{T_i} - Q_i \tag{2.23}$$

This expression can be written in three different ways. Introducing the reversible entropy variation as $\Delta S_i = Q_i/T_i$, then we have

$$W_i \geq T_0 \Delta S_i - Q_i \tag{2.24a}$$

Another form isolates the group $[(T_0/T_i) - 1]$ as the proportionality factor between $Q_i$ and $W_i$, i.e., the minimum specific refrigeration work as

$$W_i \geq Q_i \left( \frac{T_0}{T_i} - 1 \right) \tag{2.24b}$$

As Carnot has shown in 1824, this minimum work can only be achieved through a cycle constituted of two isothermal and two adiabatic transforms (Carnot cycle). All other thermodynamic cycles entail higher refrigeration work for the same refrigeration duty.

A third form of Eq. 2.23 is

$$W_i \geq \Delta E_i \tag{2.24c}$$

This introduces the variation of exergy $\Delta E_i = (T_0/T_i) - 1$, a thermodynamic function representing the maximum mechanical work content (Gouy's "energy utilizable") of a heat quantity $Q_i$ at temperature $T_i$, given an environment at temperature $T_0$.

Equation 2.24b enables to calculate the minimum mechanical power needed to extract 1 W at 4.5 K (saturated liquid helium temperature at 1.3 bar pressure, i.e., slightly above atmospheric) and reject it at 300 K (room temperature), yielding a value of 65.7 W. This is the power that would be absorbed by a refrigerator operating on a Carnot cycle between 4.5 K and 300 K. In practice, the best practical cryogenic helium refrigerators have an efficiency of about 30% with respect to a Carnot refrigerator, hence a specific refrigeration work of about 220.

Cryogenic refrigerators are often required to provide cooling duties at several temperatures or in several temperature ranges, e.g., for thermal shields or continuous heat interception (see paragraph 3.6 above). Eq. 2.24b can then be applied to the cooling duty at every temperature and every elementary mechanical power $W_i$ summed or integrated in the case of continuous cooling. This also allows comparison of different cooling duties in terms of required mechanical work.

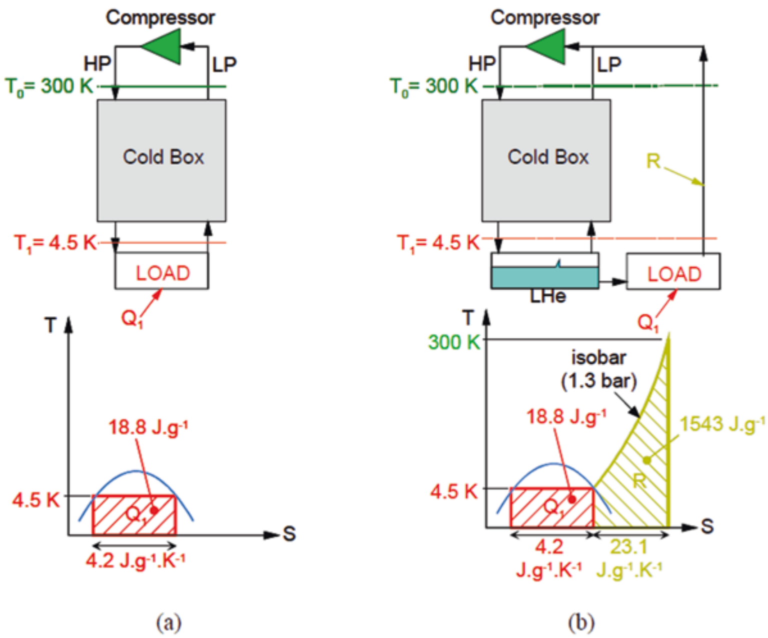


**Fig. 2.15** Helium refrigerator (**a**) vs. liquefier (**b**)

## *2.5.2 Helium Refrigerators Versus Liquefiers*

A 4.5 K helium refrigerator absorbs heat isothermally at this temperature, usually by recondensing cold helium vapor at saturation (the saturation pressure is 1.3 bar). By contrast, a liquefier also eventually condenses cold helium vapor at saturation, but starting from gaseous helium at 300 K which it must first precool to 4.5 K (Fig. 2.15). From Eq. 2.24a, the minimum mechanical power for helium liquefaction is

$$W_{\text{liq}} = W_{\text{condens}} + W_{\text{precool}} \tag{2.25}$$

$$W_{\text{liq}} = T_0 \Delta S_{\text{condens}} - Q_{\text{condens}} + T_0 \Delta S_{\text{precool}} - Q_{\text{precool}} \tag{2.26}$$

The heat quantities $Q_{\text{condens}}$ and $Q_{\text{precool}}$ exchanged at constant pressure are given by the enthalpy variations $\Delta H_{\text{condens}}$ and $\Delta H_{\text{precool}}$. With $T_0 = 300$ K and the entropy and enthalpy differences taken from thermodynamic tables, one finds $W_{\text{liq}} = 6628$ W per g/s of helium liquefied. Given the minimum specific mechanical work of 65.7 at 4.5 K, this yields an approximate equivalence of about 100 W at 4.5 K for 1 g/s liquefaction. More precisely, a liquefier producing 1 g/s liquid helium at 4.5 K will absorb the same power (and thus have similar size) as a refrigerator extracting about 100 W at 4.5 K, provided they both have the same efficiency with respect to the Carnot cycle. For machines with mixed refrigeration and liquefaction duties, this equivalence can be approximately verified by trading some liquefaction against refrigeration around the design point and vice versa.

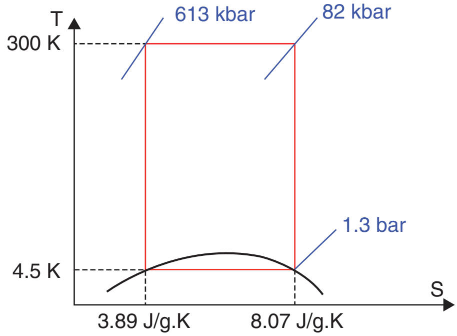


**Fig. 2.16** A hypothetical Carnot cycle for helium liquefaction

## *2.5.3 Real Cycles and Refrigeration Equipment*

Thus far, we have only addressed cryogenic refrigeration and liquefaction through thermodynamics, i.e., through the exchanges of mass, heat, and work at the boundaries of machines seen as "black boxes." We will now consider cycles, cooling methods, and equipment of real refrigerators.

In order to minimize the specific mechanical work requirement (and hence the size and power consumption), an efficient refrigerator should try and approximate the Carnot cycle, which is represented by a rectangle on the temperature-entropy diagram: the two isotherms are horizontal lines, while the two isentropic transforms are vertical lines. To liquefy helium, the base of the rectangle should intercept the liquid-vapor dome (Fig. 2.16).

However, superimposing this cycle on the temperature-entropy diagram of helium shows that one should operate at a high pressure of about 613 kbar, with a first isentropic compression from 1.3 bar to 82 kbar, followed by an isothermal compression. This is clearly impractical, and real helium cycles are elongated along isobar (or isochoric) lines, thus involving transforms, which require heat exchange between the high- and low-pressure streams. This heat exchange can be performed in recuperative or regenerative heat exchangers, respectively, for continuous or alternating flows. In the following, we focus on the continuous flow cycles using recuperative heat exchangers, which constitute the operating principles of large-capacity helium refrigerators and liquefiers.

Practical elementary cooling processes are shown on the temperature-entropy diagram, which is depicted in Fig. 2.17. The gas stream can first undergo quasi-isobar cooling in a counterflow heat exchanger (segment $AB_1$): modern refrigerators make use of brazed aluminum plate heat exchangers (Fig. 2.18). Refrigeration can be produced by adiabatic (quasi-isentropic) expansion with extraction of mechanical work (segment $AB'_2$): the expansion engine is a gas turbine, with the extracted power transmitted to a compressor wheel sharing a common shaft and later dissipated in a brake circuit (Fig. 2.19). A third process is isenthalpic Joule-Thomson expansion, i.e., without extraction of mechanical work, in a valve or restriction (segment $AB_3$).

Unfortunately, this latter process does not does work for ideal gases, the enthalpy of which is a sole function of temperature. For real gases, however, enthalpy depends both on temperature and pressure, so that isenthalpic expansion can produce warm-

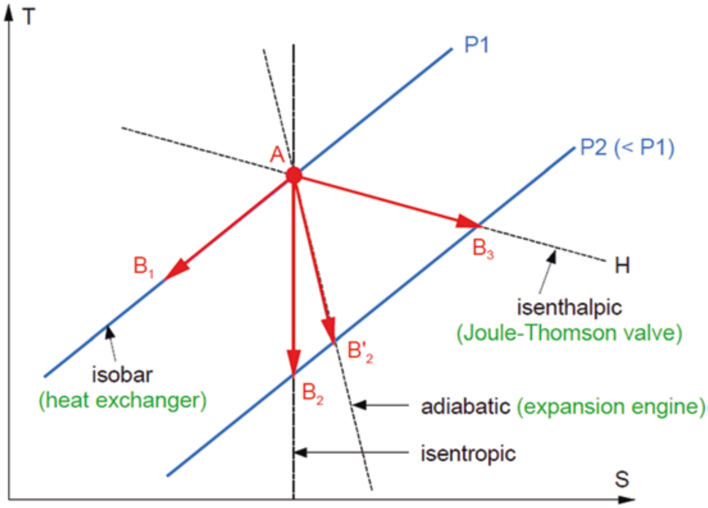


**Fig. 2.17** Elementary cooling processes shown on temperature-entropy diagram

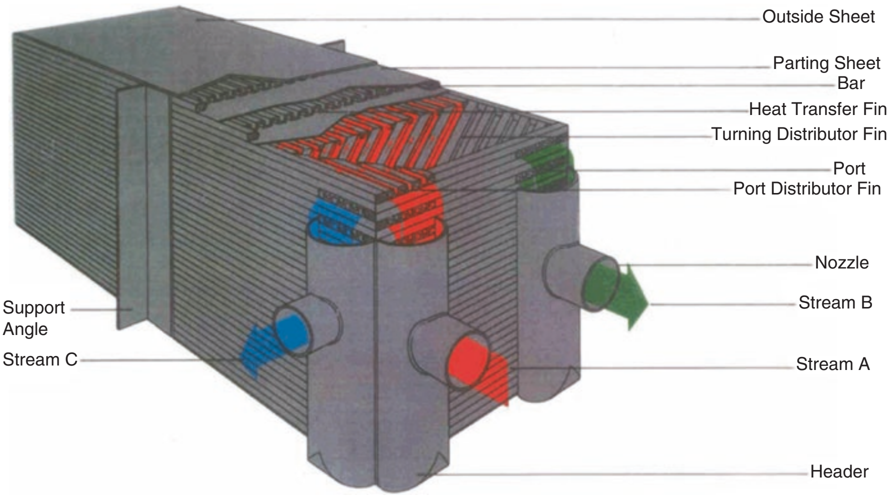


**Fig. 2.18** Schematic view of a brazed aluminum plate heat exchanger

ing or cooling, depending upon the slope of the isenthalps on the diagram. In order to cool the gas stream, Joule-Thomson expansion must start below a limit called the inversion temperature. The values of inversion temperature for cryogenic fluids (Table 2.11) show that while air can be cooled from room temperature by Joule-Thomson expansion (the risk of freezing the pressure reducer on the air bottle is well known to scuba divers), helium must first be precooled down to below its inversion temperature of 43 K. The moderate downward slope of isenthalps on the temperature-entropy diagram indicates that in any case, Joule-Thomson expansion

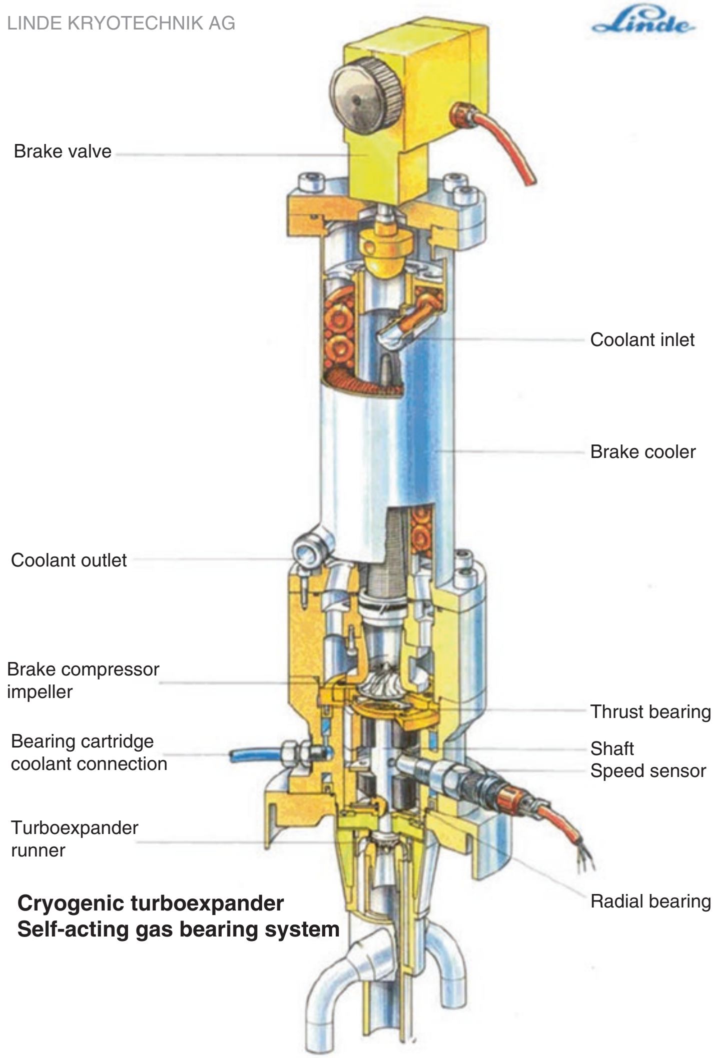


**Fig. 2.19** Cryogenic turbo-expander

**Table 2.11** Maximum values of Joule-Thomson inversion temperature

| Cryogen | Maximum inversion temperature (K) |
|---|---|
| Helium | 43 |
| Hydrogen | 202 |
| Neo | 260 |
| Air | 603 |
| Nitrogen | 623 |
| Oxygen | 761 |

generates substantial entropy. Its relative inefficiency with respect to adiabatic expansion is, however, accepted in view of the simplicity of its implementation, particularly when it results in partial condensation of the stream entailing two-phase flow conditions, which would be difficult to handle in an expansion turbine. In Chapter 14 of this book by Zohuri [16], we have defined the inversion temperature.

For better understanding of heat exchanger and compact heat exchanger, readers can refer to famous book by Kay and London 25 and their application of such heat exchanger in the two books by Zohuri [17–19].

These elementary cooling processes are combined in practical cycles; a common example for helium refrigeration is provided by the Claude cycle and its refinements. A schematic two-pressure, two-stage Claude cycle is shown in Fig. 2.20: gaseous helium, compressed to HP in a lubricated screw compressor, is recooled to room temperature in water coolers, dried and purified from oil aerosols down to the ppm level, before being sent to the HP side of the heat exchange line where it is refrigerated by heat exchange. This process takes place with the counterflow of cold gas returning on the low-pressure (LP) side. Part of the flow is tapped from the HP line and expanded in the turbines before escaping to the LP line. At the bottom of the heat exchange line, the remaining HP flow is expanded in a Joule-Thomson valve and partially liquefied.

Large-capacity helium refrigerators and liquefiers operate under this principle, however, with many refinements aiming at meeting specific cooling duties and improving efficiency and flexibility of operation, such as three- and sometimes four-pressure cycle process. In this case, liquid nitrogen precooling of the helium stream requires numerous heat exchangers, many turbines in series or parallel arrangements, Joule-Thomson expansion replaced by adiabatic expansion in a “wet” turbine, and cold compressors to lower the refrigeration temperature below 4.5 K. A view of such a large plant appears in Figs. 2.21, 2.22 and 2.23.

The capital cost of these complex machines is high, but scales less than linearly with refrigeration power, which favors large units. Operating costs are dominated by that of electrical energy, typically amounting to about 10% of the capital cost per year in case of quasi-continuous operation. For overall economy, it is therefore very important to seek high efficiency, which is also easier to achieve on large units. For a review of these aspects, see reference [20].

## 2.6 Industrial Applications

Liquefied gases, such as liquid nitrogen and liquid helium, are used in many cryogenic applications. Liquid nitrogen is the most commonly used element in cryogenics and is legally purchasable around the world. Liquid helium is also commonly used and allows the lowest attainable temperatures to be reached.

These liquids may be stored in Dewar flasks, which are double-walled containers with a high vacuum between the walls to reduce heat transfer into the liquid.

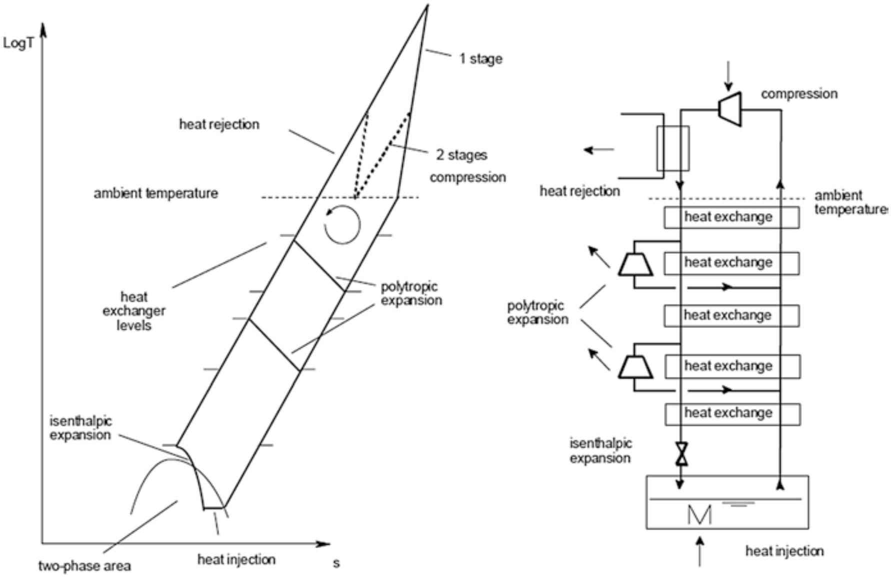


**Fig. 2.20** Schematic example of two-pressure, two-stage Claude cycle: T-S diagram (left) and flow scheme (right)

**Fig. 2.21** Image of compressor station at CERN

**Fig. 2.22** Image of a 4.5 K cold box for the LHC (Linde) at CERN


**Fig. 2.23** Front view of 4.5 K cold box for the LHC (Linde) at CERN

Typical laboratory Dewar flasks are spherical, made of glass, and protected in a metal outer container. Dewar flasks for extremely cold liquids such as liquid helium have another double-walled container filled with liquid nitrogen. Dewar flasks are named after their inventor, James Dewar, the man who first liquefied hydrogen. Thermos bottles are smaller vacuum flasks fitted in a protective casing.

Cryogenic bar code labels are used to mark Dewar flasks containing these liquids and will not frost over down to −195 °C.

Cryogenic transfer pumps are the pumps used on LNG piers to transfer liquefied natural gas from LNG carriers to LNG storage tanks, as are cryogenic valves.

### *2.6.1 Cryogenic Processing for Alloy Hardening*

The field of cryogenics advanced during World War II when scientists found that metals frozen to low temperatures showed more resistance to wear. Based on this theory of cryogenic hardening, the commercial cryogenic processing industry was founded in 1966 by Ed Busch. With a background in the heat-treating industry, Busch founded a company in Detroit called CryoTech in 1966, which merged with 300 Below in 1999 to become the world's largest and oldest commercial cryogenic processing company. Busch originally experimented with the possibility of increasing the life of metal tools to anywhere between 200% and 400% of the original life expectancy using cryogenic tempering instead of heat-treating. This evolved in the late 1990s into the treatment of other parts.

Cryogens, such as liquid nitrogen, are further used for specialty chilling and freezing applications. Some chemical reactions, like those used to produce the active ingredients for the popular statin drugs, which reduce cardiovascular disease (CVD), must occur at low temperatures of approximately −100 °C (−148 °F). Special cryogenic chemical reactors are used to remove reaction heat and provide a low-temperature environment. The freezing of foods and biotechnology products, like vaccines, requires nitrogen in blast freezing or immersion freezing systems. Certain soft or elastic materials become hard and brittle at very low temperatures, which make cryogenic milling (cryomilling) an option for some materials that cannot easily be milled at higher temperatures.

Cryogenic processing is not a substitute for heat treatment, but rather an extension of the heating-quenching-tempering cycle. Normally, when an item is quenched, the final temperature is ambient. The only reason for this is that most heat-treaters do not have cooling equipment. There is nothing metallurgically significant about ambient temperature. The cryogenic process continues this action from ambient temperature down to −320 °F (140 °R; 78 K; −196 °C). In most instances, the cryogenic cycle is followed by a heat tempering procedure. As all alloys do not have the same chemical constituents, the tempering procedure varies according to the material's chemical composition, thermal history, and/or a tool's particular service application.

The entire process takes 3–4 days.

### 2.6.2 Cryogenic Fuels

Another use of cryogenics is cryogenic fuels for rockets with liquid hydrogen as the most widely used example. Liquid oxygen (LOX) is even more widely used but as an oxidizer, not a fuel. NASA's workhorse space shuttle used cryogenic hydrogen/oxygen propellant as its primary means of getting into orbit. LOX is also widely used with RP-1 kerosene, a non-cryogenic hydrocarbon, such as in the rockets built for the Soviet space program by Sergei Korolev.

Russian aircraft manufacturer Tupolev developed a version of its popular design Tu-154 and later on was known as Tu-155 with a cryogenic fuel system, known as the Tu-155. The plane uses a fuel referred to as liquefied natural gas or LNG and made its first flight in 1989.

### 2.6.3 Cryogenic Application in Nuclear Magnetic Resonance Spectroscopy (NMR)

Nuclear magnetic resonance (NMR) is one of the most common methods to determine the physical and chemical properties of atoms by detecting the radio frequency absorbed and subsequent relaxation of nuclei in a magnetic field. This is one of the most commonly used characterization techniques and has applications in numerous fields. Primarily, the strong magnetic fields are generated by supercooling electromagnets, although there are spectrometers that do not require cryogens. In traditional superconducting solenoids, liquid helium is used to cool the inner coils because it has a boiling point of around 4 K at ambient pressure. Cheap metallic superconductors can be used for the coil wiring. So-called high-temperature superconducting compounds can be made to superconduct with the use of liquid nitrogen (LN), which boils at around 77 K.

### 2.6.4 Cryogenic Application in Magnetic Resonance Image (MRI)

Cryogenics is the study and use of materials at extremely low temperatures. Such low temperatures cause changes in the physical properties of materials that allow them to be used in unusual engineering, industrial, and medical applications. For example, in the cryogenic temperature range, air becomes a liquid—or even a solid—and living tissue freezes instantly. Matter behaves strangely at the lowest temperatures of the cryogenic range. Electric currents never stop flowing, liquids run uphill, and rubber becomes as brittle as glass. In medicine, cryogenic cooling is used in some diagnostic techniques, such as magnetic resonance imaging (MRI). Cryosurgery uses liquid nitrogen to kill unhealthy tissue by freezing


**Fig. 2.24** Cryogenic gases delivery truck at a supermarket

it. Cryogenics is expected to play an important role in the development of better procedures for preserving human organs for transplant.

MRI is a complex application of NMR where the geometry of the resonances is deconvoluted and used to image objects by detecting the relaxation of protons, which have been perturbed by a radio-frequency pulse in the strong magnetic field. This is mostly commonly used in health applications.

### *2.6.5 Cryogenic Application in Frozen Food Transport*

Cryogenic gases are used in transportation of large masses of frozen food. When very large quantities of food must be transported to regions like war zones, earthquake-hit regions, etc., they must be stored for a long time, so cryogenic food freezing is used. Cryogenic food freezing is also helpful for large-scale food processing industries. See Fig. 2.24 for transportation of cryogenic gases.

Cryogenic technology gives low-temperature applications in the food sector. There is a tremendous scope for application of cryogenic technology in food processing and preservation. Cryopreservation is the only viable method available for long-term preservation of the both plant and animal origin species, such as dairy products. Cryogenic preservation of food offers great promise for the country, both for export and for domestic consumptions due to assurance of the food quality and safety, also. Most industries employ evaporative air chilling systems; preservation by cryogenic technology is less familiar in this sector. Product shrinkage, toughening and loss of tenderness, products' shelf life, microbial products, drip loss, and dehydration losses are the major quality considerations in freezing of the food products, e.g., meat products [21].

The preservation by cryogenic technology will improve the situation. Proper economic considerations including payback period and life of the system, etc. should be taken into account while selecting the cryogenic applications. The availability of indigenous cryogenic technology for food processing would ensure production of better quality products within the country and export the processed products to different countries.

In food processing, cryogenics implies use of very low-temperature materials for chilling and freezing. This type of refrigeration differs from other procedure because it does not depend on the external low-temperature production systems.

The freezing of foods and biotechnology products, like vaccines, requires nitrogen in blast freezing or immersion freezing systems. Cryogenic freezing with nitrogen is carried out by first passing the food through nitrogen vapor at about −50 °C and then freezing the food by spraying the refrigerant directly onto the food.

Fish, meat, poultry, fruit, vegetables, and bakery products can all be frozen in this way.

The extremely low-temperature characteristics of cryogenic food provide the ultimate in chilling and freezing rates.

The physical properties of the cryogenic gases provided an important tool to help the food industry to improve the plant automation, versatility, efficiency, and manufacturing cost.

### *2.6.6 Cryogenic Application in Forward Looking Infrared (FLIR)*

Many infrared cameras require their detectors to be cryogenically cooled as it can be seen in Figs. 2.25 and 2.26.

Miniaturized versions of cryocoolers are known as micro-coolers, which have potential applications to space sensors and military airborne systems such as IR line scanners, IR search and track sensors, high-resolution thermal imaging systems, and forward looking infrared (FLIR) sensors. Micro-cooler design based on the Stirling-cycle operating principle can achieve a cooling temperature of 77 K within 3 min.

The micro-cooler configuration normally incorporates a generator to produce a compression and expansion refrigerator cycle with no valves. It is important to mention that the regenerator has a large heat capacity and acts like an efficient heat exchanger.

A micro-cooler designed for NASA thermal imaging applications consumes electrical power less than 3 W, weighs less than 15 oz., has a life expectancy of 5 years, and has demonstrated continuous operation exceeding 8000 h with no degradation in performance. High reliability of a micro-cooler requires improved materials with self-lubrication capability, elimination of gaseous contamination, clearance seals with very low friction, and a linear drive mechanism. For cryogenic temperature measurement down to 30 K, PT-100 sensor (resistance temperature detectors (RTDs)) is used. Additionally, for lower than 30 K, it is required to use silicon diode for accuracy, and there are also other cryogenic detectors which are used to detect cryogenic particles.

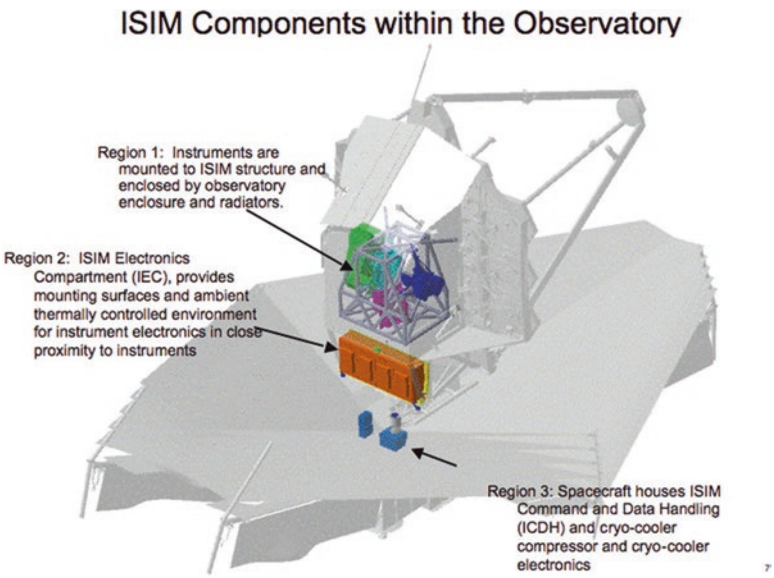


**Fig. 2.25** Diagram of an infrared space telescope

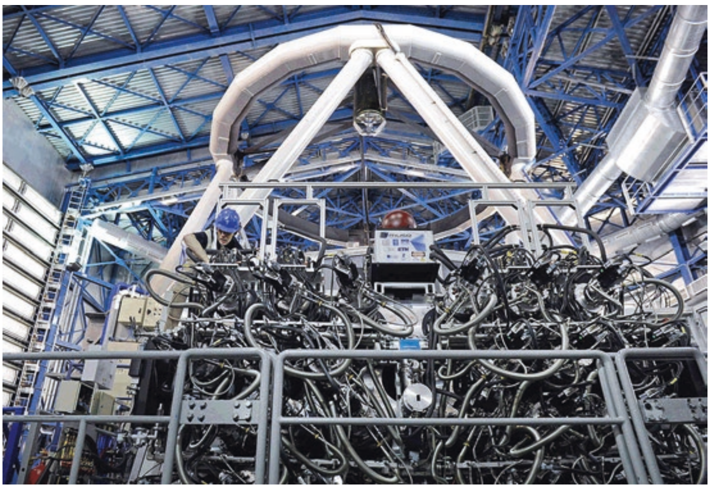

**Fig. 2.26** Astronomical instruments on the very large telescope are equipped with continuous flow cooling systems

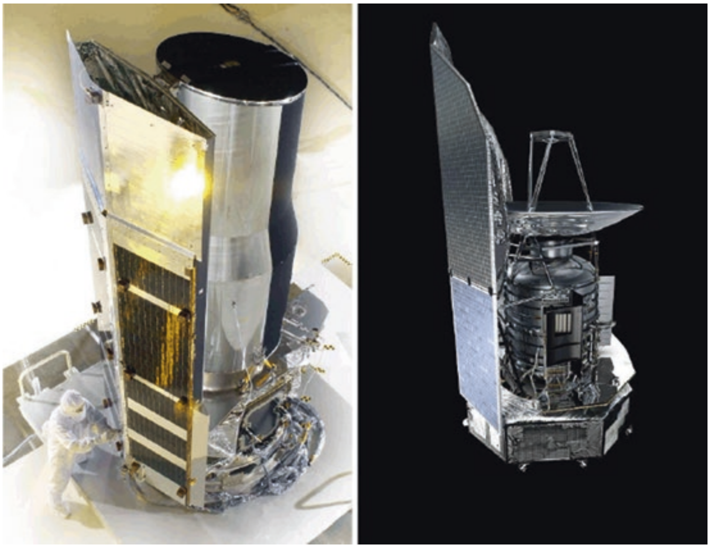

**Fig. 2.27** Left is Spitzer spacecraft during final testing (NASA) and right is Herschel spacecraft (ESA)

### *2.6.7 Cryogenic Application in Space*

Einstein and IRAS are the first "cryogenic missions," which flew, respectively, in 1978 and 1983. *Einstein (HEAO-2)* was the second of NASA's three High Energy Astrophysical Observatories and the first X-ray telescope put into space in 1978. Among other instrument, Einstein carried a solid-state spectrometer using a Si(Li) crystal detector (range 0.5–4.5 keV) cooled at about 100 K via a solid ammonia/methane cryostat [22, 23].

IRAS (Infrared Astronomical Satellite, launched in 1983) was the first cryogenic scientific satellite. Its mission was to map the entire sky from 8 μm to 120 μm, and it was equipped with a 0.6 m telescope cooled with liquid He to about 4 K. The focal plane assembly operated 62 photoconductive elements at 3 K.

Cosmic Background Explorer (COBE) was developed by NASA to measure the cosmic background radiation. The satellite was launched in November 1989. It carried three instruments, operating at wavelengths between 1.25 μm and 240 μm with focal planes at 1.6 K, cooled by 650 l, superfluid helium cryostat.

As we stated, the first cryogenic missions, such as IRAS, launched in 1983, COBE (COBE 1992), launched in 1989, and ISO, launched in 1995, were based on liquid He cryostats, with the bath temperature regulated by adjusting the vapor pressure. Lifetime was correspondingly limited by the amount of cryogen, typically to about 12–18 months. More recently, the same approach has been used by Spitzer (Fig. 2.27, left). Spitzer, thanks to an optimized cryogenic system (passive radiation, use of helium gas enthalpy, orbit choice), was designed to provide a minimum lifetime of 2.5 years, using only 360 l of superfluid He.

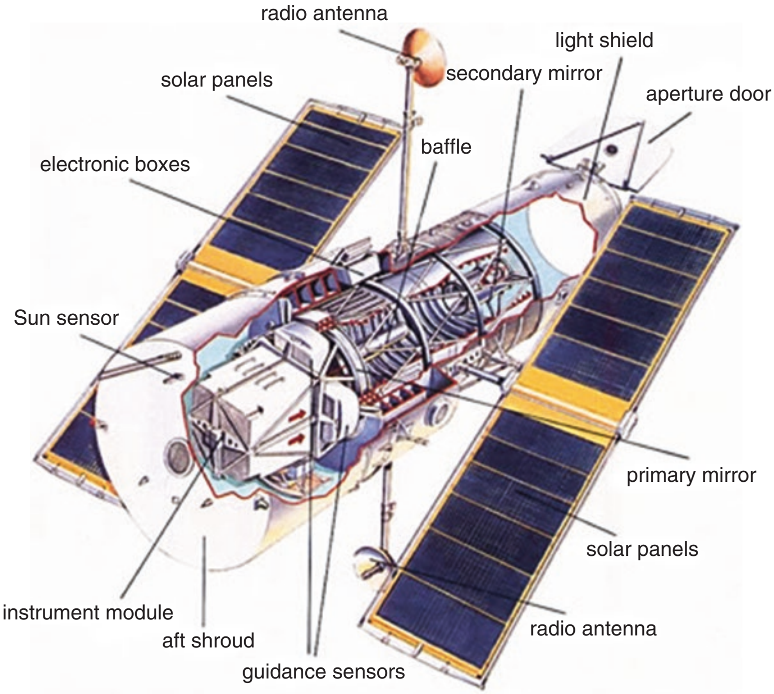


**Fig. 2.28** Hubble space telescope image

The European Space Agency (ESA) is presently developing (phase C/D, 2003) two important cryogenic astronomical missions: *Planck* and *Herschel* [24]. *Planck's* main objective is to map the temperature anisotropies of the cosmic microwave background (CMB) over the whole sky, with a sensitivity $\Delta T/T = 2.10^{-6}$ and an angular resolution of 10 arc min. Such goals require bolometers operating at 0.1 K, HEMT at 20 K, and a cooled telescope (60 K). Planck's cryogenic system uses precooling to 60 K by passive radiators, cooling to 20 K with a H2 Joule-Thomson cooler (adsorption compressors), cooling to 4 K with a He Joule-Thomson cooler (mechanical compressors), and final cooling to 0.1 K with an open-loop dilution refrigerator.

ESA's Infrared Space Observatory (ISO) operated at wavelengths from 2.5 μm to 240 μm between November 1995 and May 1998 in a highly elliptical orbit. The satellite is based on a cryostat containing about 2200 liters of superfluid helium and on a 0.6 m diameter telescope. The instruments made use of different photoconductors based on InSb, Si, and Ge and operated between 1.8 K and 10 K [25].

Near Infrared Camera and Multi-Object Spectrometer (NICMOS) is a Hubble Space Telescope (HST) instrument based on three cameras designed for simultaneous operations, operating between 0.8 μm and 2.5 μm and using HgCdTe photoconductive detectors, cooled down to 50–60 K via 120 kg of solid nitrogen. See Fig. 2.28.

**Fig. 2.29** Doctors prepare a patient for cryogenic surgery

### *2.6.8 Cryogenic in Blood Banking, Medicine, and Surgery*

Certain rare blood groups are stored at low temperatures, such as −165 °C. Liquid nitrogen is one of the safest cooling agents available. In medicine, it is, used to kill unhealthy tissues by freezing them. Cryogenic processes are also used to supply "banks" storing eye corneas, blood, and sperm for future surgical procedures. Some embryos have also been frozen and stored for later implantation (surgical placement) in women.

In 1961 American surgeon, Irving S. Cooper, introduced a freezing technique called cryosurgery. Cryosurgery is relatively bloodless because the low temperatures used constrict the blood vessels, stemming the flow. Special instruments are used that have freezing tips to kill the damaged tissue and shields to protect surrounding tissue. Cooper used cryosurgery to freeze and destroy damaged tissue in the brains of patients with Parkinson's disease (a degenerative illness). Since then, cryosurgery has found many applications. It is used to repair detached retinas and to remove cataracts. It is also used to treat liver cancer and prostate cancer.

In medicine and surgery, the low-temperature and cryogenic application goes a long way. The application of ultralow temperature and cryogenics to clinical situation and underlying principles in the absence of ice have under study fall back to ancient history of humankind, which goes back to ancient Egypt 2500 years ago. In the fifth century B. C., the Greek physician Hippocrates advocated the clinical utility of cold for relieving pain in trauma and in certain diseases affecting the bones and joints. James Arnott is often described as the father of modern cryosurgery. In 1851, he achieved temperature of −24 °C by using a solution of ice and saline for the treatment of various surface conditions (see Fig. 2.29). The effects of low temperature on mammalian systems can be explained together with the effect of hypothermia by the researcher in this field of medicine [26].

Low-temperature storage of tissues and organs for transplantation in the liquid state is playing a role of life and death in today's emergency room (ER) around the world, and we can see the application of cryogenic state that is associated with the formation of ice and subsequent freezing of cells and tissues as well as organ cryopreservation.

There are two categories of the processes, which occur within living cells:

1. One is the biochemical processes, which are the distinguishing feature of living materials by using metabolic energy often involving enzymatic catalysts.
2. The second one or the others are the physical processes, which are also common in nonliving systems.

One example is the diffusion of a solute due to a concentration gradient. Both categories can be affected by temperature gradient and changes. It is observed that the biochemical processes are usually slowed to great extent upon exposure to cooling environment and vice versa. This observation can be described by some mathematical relationship, by putting it into some conceptual perspective. In other words, the starting point of cryobiology, including cryopreservation, cryosurgery, and cryogenic medicine, is the Van't Hoff's rule, which states that the change in the rate of a process such as metabolism produced by 10 °C changes the system temperature. It is called $Q_{10}$, which can be expressed in form of the following equation:

$$Q_{10} = \frac{\text{Reaction Rate at T} + 10}{\text{Reaction Rate at T}} \tag{2.27}$$

Usually, $Q_{10}$ has a value of about 2 in biological systems, 2.3 in most thermochemical reactions, and 1–3 for reactions in organism up to 50 °C. For example, a reduction in human body temperature from its basal state of 37 °C results in a decline in the metabolic rate by one-half.

Another important law basic to cryobiology is the Arrhenius relationship, which can be expressed in the logarithmic form as

$$\log \nu = -\left(\frac{\Delta H_a}{2.303R}\right) / T \tag{2.28}$$

where $\nu$ denotes the specific rate of change such as degradation in the biomaterial, $R$ is presenting universal gas constant, and $\Delta H_a$ is heat of activation, while $T$ stand for absolute temperature in this relationship. Or in the exponential form, Eq. 2.28 takes a new form as

$$\nu = C \exp\left(\frac{\Delta H_a}{2.303RT}\right) \tag{2.29}$$

where C is a constant.

When a tissue is cooled, the rate of heat transfer depends mainly on water content, blood supply, thermal conductivity of the tissue, rate of freeze, and the temperature of the refrigerant. Table 2.12 lists the extent of surface temperature reductions attainable with various refrigerants [26].

The contour of cryolesion by an open spray is rounded down to the depths of about 6 mm, but below this, it becomes more triangular shape. The method gives a more rapid drop in temperature and will freeze to a greater depth than a closed probe.

However, the shape of the cryolesion is similar for the two methods.

**Table 2.12** Surface tissue temperature reductions attainable with various refrigerants [26]

| Refrigerant | Temperature attainable, °C |
|---|---|
| Ice | 0 |
| Salt-ice | −20 |
| $CO^2$ snow | −79 |
| Nitrogen oxide | −75 |
| Liquid nitrogen | −196 (spray or probe) |

**Fig. 2.30** Cryogenic valve

Cryosurgery is also widely used in the fields of dermatology, gynecology, plastic surgery, orthopedics, and podiatry. Cryosurgery has also been used successfully for more than 30 years in veterinary medicine.

Cryogens, like liquid nitrogen, are further used for specialty chilling and freezing applications. Some chemical reactions, like those used to produce the active ingredients for the popular statin drugs, must occur at low temperatures of approximately −100 °C. Special cryogenic chemical reactors are used to remove reaction heat and provide a low-temperature environment.

### *2.6.9 Cryogenic in Manufacturing Process*

The introduction of cryogenic gases in the early 1960s as an alternative to improve freezing processes in the frozen industry was a major product quality and process improvement.

Cryogenic cooling is used to cool the tool tip at the time of machining. It increases the tool life. Oxygen is used to perform several important functions in the steel manufacturing process. See Fig. 2.30.

### *2.6.10 Cryogenic in Recycling of Materials*

By freezing the automobile or truck tire in liquid nitrogen, the rubber is made brittle and can be crushed into small particles. These particles can be used again for other items. The theory was based on how heat-treating metal works. A heat-treated metal is cooled from a very high temperature down to room temperature causing certain strength increases in the molecular structure to occur. They theorized that continuing the temperature descent would allow for further strength increases. Using liquid nitrogen, CryoTech formulated the first early version of the cryogenic processor. Unfortunately, for the newly born industry, the results were unstable, as components sometimes experienced thermal shock when they were cooled too fast. Some components in early tests even shattered because of the ultralow temperatures. In the late twentieth century, the field improved significantly with the rise of applied research, which used new controls and technology to create more stable results.

## 2.7 Cryogenic Application in Research

Experimental research on certain physics phenomena, such as spintronics and magneto-transport properties, requires cryogenic temperatures for the effects to be observed. Cryogenic cooling of devices and material is usually achieved via the use of liquid nitrogen, liquid helium, or a mechanical cryocooler (which uses high-pressure helium lines). Gifford-McMahon cryocoolers, pulse tube cryocoolers, and Stirling cryocoolers are in wide use with selection based on required base temperature and cooling capacity. The most recent development in cryogenics is the use of magnets as regenerators as well as refrigerators. These devices work on the principle known as the magnetocaloric effect.

### *2.7.1 Research Overview*

Cryocoolers are the key component of ZBO propellant storage systems. New developments are required to significantly improve the performance of coolers for the ZBO storage of liquid hydrogen. For ZBO liquid hydrogen systems, cooling powers of 1–20 W are required at 20 K. These systems require extensive development to achieve the same levels of efficiency that are reached for the higher-temperature

**Fig. 2.31** High efficiency cryocooler

liquid oxygen (LOX) and methane ZBO coolers. At present, no long-lived 30 K or colder closed-cycle coolers have flown in space. Current commercial, non-flight pulse tube cryocoolers are available for temperatures down to 3 K; however, these machines are not space qualified and are inefficient.

The final development frontier for LH2 coolers is to achieve high efficiency and reliability at lower operating temperatures. Pulse tube and Stirling coolers offer the best opportunity for achieving high efficiency at these temperatures and power levels. The key to such improvements is the design of the regenerator and the selection and formation of the regenerator material. The ARC Cryogenics Group and its partners have been developing high heat capacity rare earth alloys for just this purpose.

### *2.7.2 Right: Lightweight, High Efficiency Cryocooler*

Along with advancing the SOA of cryocoolers, system studies are also being conducted with GRC, JPL, and MSFC. One of the major advances in this area is the development of an analytical tool for sizing the ZBO system, including tankage, passive insulation, cryocooler, radiator, and power system mass. This model optimizes cryogenic thermal storage system performance. Tank sizes and configurations for selected mission scenarios can be easily and quickly evaluated. Topologies can be compared and trade-offs performed to arrive at a concept optimized for specific mission parameters. See Fig. 2.31.

Once the system is adequately modeled, the insulation system can be designed appropriately. New materials and integration techniques can be quantitatively analyzed with our SOA transport phenomena test facilities. Our thermal conductivity apparatus features a sample chamber within a vacuum chamber (isothermal). A hot plate is embedded in the sample to minimize alternate heat paths. In this manner, the thermal conductivity can be determined within an accuracy of a few percent. What makes the apparatus truly unique is that the thermal conductivity measurements can be made in the presence of a gas, including planetary analogues.

### *2.7.3 Background*

Since 1976, Ames Research Center's (ARC) Cryogenics Group has provided cryogenic support for the agency's missions. For the Infrared Astronomical Satellite (IRAS) mission, ARC performed focal plane testing, thermal design, and development of a backup cryogenic valve. For the Superfluid Helium On-Orbit Transfer (SHOOT) mission, ARC developed the flight flow meters and the flight and ground operation software.

The Cryogenics Group has also established a database for cryogenic thermal contact conductance down to superfluid helium temperatures, characterized swirl in liquid helium in a rotating Dewar, measured thermal conductivity of cryogenic insulation in the presence of gases, and developed a cryogenic mirror test facility for IR astronomy.

### *2.7.4 Right Liquefier Demo and Cryogenic Insulation Test Facility*

The Cryogenics Group has developed coolers down to 50 mK, including dilution coolers, helium-3 refrigerators, and adiabatic demagnetization coolers. Recently, ARC developed a flight-qualified pulse tube cryocooler, in collaboration with the Department of Defense (DOD). This program is for demonstration of zero boil-off (ZBO) storage, which is working with Atlas Scientific. This is also in collaboration with the Department of Energy (DOE), to develop high-performance regenerator materials to improve cryocooler efficiency. In addition, ARC has several unique capabilities for measuring the thermal conductivity of insulation materials and moisture absorption in the presence of gases, including planetary analogues within an accuracy of a few percent. See Fig. 2.32.

## 2.8 Cryogenic Fluid Management

Cryogenic Fluid Management (CFM) technology is an integral part of exploration systems for Earth-to-Orbit Transportation, manned missions to the Moon and Mars, planetary exploration, and In Situ Resource Utilization (ISRU). CFM also plays a key role in infrared and X-ray astronomy, biological sciences, and fundamental investigations into the origins of our universe.

**Fig. 2.32** Liquid demo and cryogenic insulation test facility

### *2.8.1 Benefits*

The challenges of NASA's exploration vision require advanced Cryogenic Fluid Management technology. The exploration vision requires high-performance propulsion systems (high specific impulse) for both human and robotic missions. The vision includes in-space cryo-propulsion stages and In Situ Resource Utilization (ISRU) for cryo-propellant production and liquefaction of breathable gases. Cryogenic propellants such as oxygen, methane, and hydrogen can satisfy this requirement. The current state of the art (SOA) for cryo-propellant storage is a loss rate of 3%/month in low Earth orbit (LEO) using passive technology. Advances in passive thermal control technology might reduce losses to 1%/month, still an unacceptable rate for a 2 + year mission to Mars. By using cryocoolers to balance the entire parasitic and internally generated heat loads in the cryo-tank, no propellant will be lost, resulting in a zero boil-off (ZBO) system and eliminating the need for oversized tanks and extra propellant. Each pound of propellant tank mass saved is directly tradable for payload mass.

## 2.9 Conclusion

The brief introductory in this chapter has presented the basic ideas and principles of the most important aspects of cryogenics, i.e., cryogenic fluids, heat transfer, thermal design, and refrigeration. It has also provided the reader with typical numerical values of the relevant parameters, enabling him or her to perform orders of magnitude estimates and apply his or her engineering judgment. There is of course much more to say on each of these topics, some of which have significantly developed over the years and still constitute areas of technical progress. Many other subjects not addressed here also pertain to cryogenic engineering, such as materials at low temperature, storage, handling and transfer of fluids, two-phase flow and discharge, vacuum and leak-tightness technology, instrumentation (in particular thermometry), process control, impurity control, and safety. In all cases, the interested reader is referred to the selected bibliography for detailed information and to the proceedings of the cryogenic engineering conferences for recent developments.

To cool down the Large Hadron Collider (LHC) superconducting magnets at CERN, eight refrigerators of 18 kW at 4.5 K have been built (four by Air Liquide and four by Linde). The compressor station is composed of five oil-lubricated screw compressors able to compress a total mass flow of 1.6 kg/s of helium between 1 bar and 19 bar. The cold box is composed of ten heat exchangers and ten turbines. Each refrigerator cools at 1/8 of the LHC that constitute a cold mass of 4595 t over 3.3 km. A refrigerator can provide up to 240 g/s of supercritical helium at 4.5 K and 3 bar to the LHC and 250 g/s between 50 K and 75 K to cool down thermal screens.

## References


1. *Oxford English Dictionary*, 2nd edn. (Oxford University Press, 1989)
2. J. Wilks, D.S. Betts, *An Introduction to Liquid Helium*, 2nd edn. (Oxford Science Publications/ Clarendon Press, Oxford, 1987)
3. B. Zohuri, *Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants: An Innovative Design Approach*, 1st edn. (Springer, Cham, 2015)
4. B. Zohuri, *Nuclear Energy for Hydrogen Generation through Intermediate Heat Exchangers: A Renewable Source of Energy*, 1st edn. (Springer, Cham, 2016)
5. A Kanni Raj, *Cryogenics: Energy Storage in Nuclear Plants* (Create Space Independent Publishing Platform, 20 Nov 2015)
6. J.M. Nash, Vortex expansion devices for high temperature cryogenics. Proc. Intersoc. Energy Convers. Eng. Conf. **4**, 521–525 (1991)
7. B. Zohuri, *Magnetic Confinement Fusion Driven Thermonuclear Energy*, 1st edn. (Springer, Cham, 2017)
8. B. Zohuri, *Inertial Confinement Fusion Driven Thermonuclear Energy*, 1st edn. (Springer, Cham, 2017)
9. B.A. Hands, *Cryogenic Engineering* (Academic Press, 1986)
10. W. Obert et al., Emissivity measurements of metallic surfaces used in cryogenic applications. Adv. Cryo. Eng. **27**, 293 (1982)
11. Ph. Lebrun, Cryogenics, key to advanced science and technology. Bull IIR, **LXXXIII**(2003–6), 4 (2003). http://www.iifiir.org/2enarticles_bull03_6.pdf
12. M.C. Jones, V. Arp, Review of hydrodynamics and heat transfer for large helium cooling systems, in *Advances in Refrigeration at the Lowest Temperatures*, IIR-IIF Commission A1-2, (Zürich, 1978) p. 41
13. Y.L. Buyanov, Current leads for use in cryogenic devices, principle of design and formulae for design calculations. Cryogenics **25**, 94 (1985)
14. Ph. Lebrun, Design of a cryostat for superconducting accelerator magnets: The LHC main dipole case, CERN-2004-008, (Geneva, 2004) p. 348
15. U. Wagner, Refrigeration, CERN-2004-008, (Geneva, 2004) p. 295
16. B. Zohuri, *Compact Heat Exchangers: Selection, Application, Design and Evaluation*, 1st edn. (Springer, Cham, 2017)

17. B. Zohuri, *Application of Compact Heat Exchangers For Combined Cycle Driven Efficiency In Next Generation Nuclear Power Plants: A Novel Approach* (Springer, Cham, 2017)
18. B. Zohuri, *Nuclear Energy for Hydrogen Generation through Intermediate Heat Exchangers: A Renewable Source of Energy* (Springer, Cham, 2016)
19. B. Zohuri, *Physics of Cryogenic An Ultra-Low Temperature Phenomena* (Elsevier, 2017)
20. S. Claudet et al., Economics of large helium cryogenic systems: Experience from recent projects at CERN. Adv. Cryo. Eng. **45B**, 1301 (2000)
21. P. Barnwal, K.K. Singh, Application of Cryogenic Technology in Food Processing and Preservation. Indian Dairy Engineers Association (IDEA) ICAR—National Dairy Research Institute (NDRI), Karnal, Haryana, India
22. B. Collaudin, N. Rando, Cryogenics **40**, 797–819 (2001)
23. R. Giacconi, et al., Astrophys. J. Part 1, **230**, 540–550 (1 June 1979)
24. B. Collaudin, T. Passvogel, Proc. SPIE, **3358** (1998)
25. M.F. Kessler et al., Astron. Astrophys. **315**, L27–L31 (1996)
26. W.J. Yang, S. Mochizuki, Low temperature and cryogenic application in medicine and surgery, in *Low Temperature and Cryogenic Refrigeration*, NATO Science Series, vol. 99 (Springer), pp. 295–308
27. R. G. Scurlock (ed.), *History and Origins of Cryogenics* (Clarendon Press, Oxford, 1992)
28. W.M. Kay, A.L. London, *Compact Heat Exchangers,* 3 Sub edn. (Krieger Publishing, Malabar, Jan 1998)

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