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AN INTRODUCTION TO CRYOGENICS

This paper aims at introducing cryogenics to non-specialists. It is not a cryogenics course, for which there exists several excellent textbooks mentioned in the bibliography. Rather, it tries to convey in a synthetic form the essential features of cryogenic engineering and to raise awareness on key design and construction issues of cryogenic devices and systems.

The presentation of basic processes, implementation techniques and typical values for physical and engineering parameters is illustrated by applications to helium cryogenics.

1. LOW TEMPERATURES IN SCIENCE AND TECHNOLOGY

Cryogenics 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 (Table 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, liquid natural gas (LNG) represents one of the largest – and fast-growing – industrial domains of application of cryogenic.

(Figure 1), together with the liquefaction and separation of air gases (Figure 2). The densification by condensation, and separation by distillation of gases was historically – and remains today - the main driving force for the cryogenic industry, exemplified not only by liquid oxygen and nitrogen used in chemical and metallurgical processes, but also by the cryogenic liquid propellants of rocket engines.

(Figure 3) and the proposed use of hydrogen as a “clean” energy vector in transportation.

Figure 4).



Table 1
Characteristic temperatures of cryogenic fluids [K]

Cryogen	Triple point	Normal boiling point	Critical point
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2*	4.2	5.2



Figure 1 130 000 m³ LNG carrier with integrated LPG→ tanks



Figure 2 Cryogenic air separation plant with heat exchanger and distillation column towers



a) Ariane 5
(25 t liquid hydrogen, 130 t liquid oxygen)



b) Space Shuttle
(100 t liquid hydrogen, 600 t liquid oxygen)

Figure 3 Rockets using cryogenic liquid propellants.



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.

It is however with the advent of Boltzmann's statistical thermodynamics in the late nineteenth century that temperature – until then a phenomenological quantity - could be explained in terms of microscopic structure and dynamics.

Consider a thermodynamic system in a microstate which can be obtained by a multiplicity W of microstates. The entropy S of the system was postulated by Boltzmann as :

$$S = kB \ln W$$



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

$$ST Qd= d (2)$$

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

$$E \sim kB T (3)$$

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 $kB T$ is small compared to the characteristic energy of the process considered. Cryogenic temperatures thus reveal phenomena with low characteristic energy (Table 2), and enable their application when significantly lower than the characteristic energy of the phenomenon of interest.

From Tables 1 and 2, it is clear that “low temperature” superconductivity requires helium cryogenics: several examples of helium-cooled superconducting devices are shown in Figure 6. Considering vapour pressures of gases at low temperature (Figure 7), it is also clear that helium must be the working cryogen for achieving “clean” vacuum with cry pumps.

Table 2
Characteristic temperatures 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	~ 10^{-6}



2. CRYOGENIC FLUIDS

2.1 Thermo physical 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.

As a consequence, 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 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.

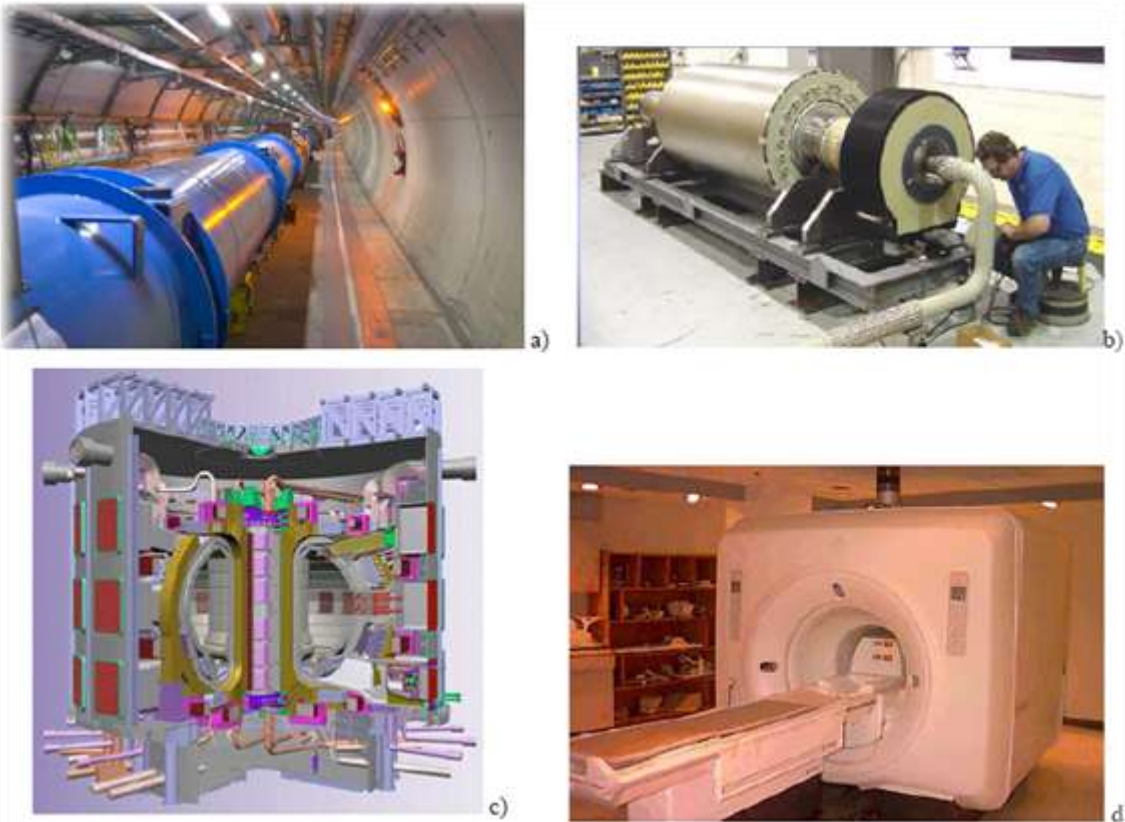


Figure 6 Helium-cooled superconducting devices a) Large Hadron Collider at CERN, b) 5 MW HTS ship propulsion motor (AMS), c) ITER experimental fusion reactor, d) whole-body MRI system (Bruker)

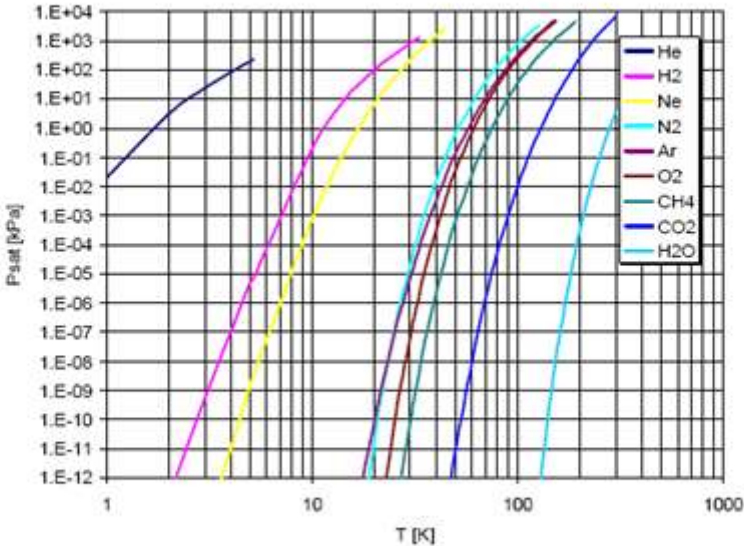


Figure 7 Vapour pressure of common gases at cryogenic temperature



Table 3
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/vapor density ratio*	7.4	175	1600
Heat of vaporization* [kJ/kg]	20.4	199	2260
Liquid viscosity* [μPl]	3.3	152	278

* at normal boiling point

2.2 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 4).

This illustrates the need for implementing much better insulation techniques in liquid helium vessels to achieve comparable holding times.

Table 4
Vaporization of liquid helium and liquid nitrogen at normal boiling point under 1 W applied heat load

Cryogen	[mg/s]	[l/h liquid]	[l/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 m_{vap} precisely equals the vapour flow m_{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 vapour 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 vapour is taken at saturation in equilibrium with the liquid.

$$\dot{m}_{out} = \dot{m}_{vap} \left(1 - \frac{\rho_v}{\rho_l} \right) < \dot{m}_{vap}$$



The escaping gas flow measured must therefore be corrected upwards to obtain the true boil-off. From values of saturated liquid to vapour density ratios in Table 3, 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 Cryogen usage for equipment cool down

For both fluids, the sensible heat of the vapour 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 dm of cryogenic liquid at saturation temperature T_v , latent heat of vaporization L_v and vapour specific heat C (taken as constant), is assuming perfect heat exchange with the liquid and the vapour $m_{Fe} C_{Fe}(T) dT = [L_v + C (T - T_v)] dm$ (5)

Hence the specific liquid cryogen requirement for cool-down from temperature $T/0$. 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 vapour.

$$m_{Fe} C_{Fe}(T) dT = [L_v + C (T - T_v)] dm$$

Calculated values of specific liquid cryogen requirements for iron are given in Table 5, clearly demonstrating the interest of recovering the sensible heat of helium vapour, as well as that of precooling equipment with liquid nitrogen.

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

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Table 5
Volume [l] of liquid cryogens required to cool down 1 kg of iron

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

2.4 Phase domains

Typical operating domains with cryogenic helium are shown in Figure 8, superimposed on the – peculiar – phase diagram of the substance: the solid phase only exists under pressure and the normal liquid He I undergoes below 2.2 K a transition to another liquid phase, He II 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 II exhibits super fluidity, a macroscopic quantum behaviour 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 mono-phase supercritical helium in forced-flow systems avoids the problems of two-phase flow. However, the strongly varying properties of the fluid in the vicinity of 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 re-cooling in extended systems. At lower temperature, He II demonstrates excellent transport properties which make it a coolant of choice for advanced superconducting devices [3].

Besides the thermodynamic penalty of 8 lower temperature, the use of He II imposes that at least part of the cryogenic circuits operate at sub atmospheric pressure, thus requiring efficient compression of low-pressure vapour and creating risks of dielectric breakdown and contamination by air in-leaks.

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

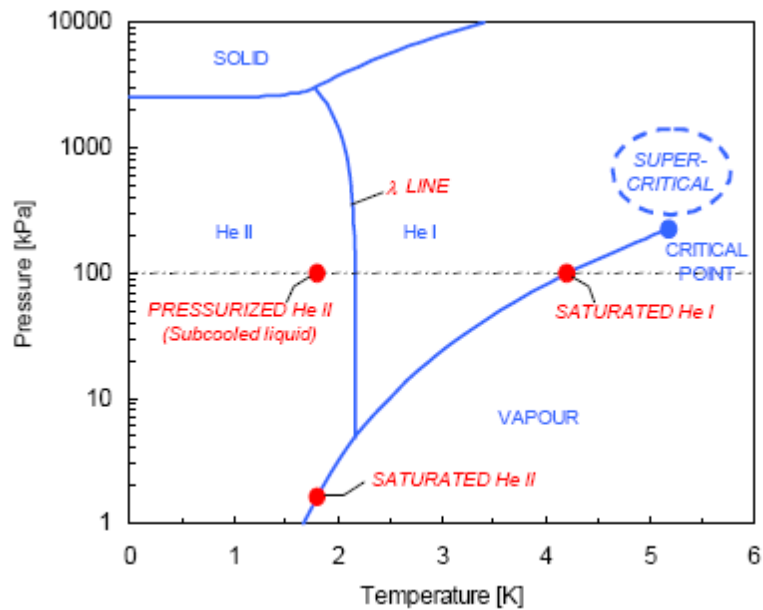


Figure 8 Phase diagram of helium, showing typical operating domains.

3. HEAT TRANSFER AND THERMAL DESIGN

With the exception of superfluids 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 non-linear, thus requiring numerical integration.

Cryogenic thermal 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 (cool-down & warm-up, thermal stabilization, thermometry) [4].

3.1 Solid conduction

Heat conduction in solids is represented by Fourier's law, expressing proportionality of heat flux with thermal gradient.

In one dimension, this reads:

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



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:

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

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 6, 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 non-metallic composites, combined with their good mechanical properties, makes them materials of choice for low heat-in leak structural supports (Figure 9).

Table 6
Thermal conductivity integrals of selected materials [W/m]

From vanishingly low temperature up to	20 K	80 K	290 K
OFHC copper	11000	60600	152000
DHP copper	395	5890	46100
Aluminum 1100	2740	23300	72100
2024 aluminum alloy	160	2420	22900
AISI 304 stainless steel	16.3	349	3060
G-10 glass-epoxy composite	2	18	153



Figure 9 Non-metallic composite support post with heat intercepts for LHC superconducting magnets



3.2 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,

$$\lambda_{max} T = 2898 [\mu\text{m K}]$$

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

$$Q = \sigma A T^4$$

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 vapour.

Conversely, it makes it very difficult to cool equipment down 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 make use of passive radiators to release heat only down to about 100 K, and embarked active refrigerators are required to reach lower temperatures.

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

$$Q = \epsilon \sigma A T^4$$

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 literature [5], a subset of which is given in Table 7. As a general rule, emissivity decreases at low temperature, for good electrical conductors and for polished surfaces.

As Table 7 shows, a simple way to obtain this combination of properties is to wrap cold equipment with aluminium foil. Conversely, radioactive 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 aluminium.

Table 7 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, mech. polished	0.12	0.07
Stainless steel, electro-polished	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, mech. polished	0.10	0.06
Aluminum, electro-polished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mech. polished	0.06	0.02

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

$$Q = E \sigma A (T_1^4 - T_2^4)$$

geometrical configuration and of the type of reflection (secular 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

$$Q_s = E \sigma A (T_1^4 - T_s^4) = E \sigma A (T_s^4 - T_2^4)$$

3.3 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 [6], 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 Nusselt number Nu 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

$$Nu = f(Pr, Re)$$

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 Nusselt number is an increasing function of the Prandtl and Grashof Gr numbers, with the latter representing the ratio of buoyancy to viscous forces

$$Nu = f(Pr, Gr)$$

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.

As a consequence, 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.

3.4 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 ℓ relative to the typical distance d between the cold and warm surfaces.

The mean free path of gas molecules, as predicted by kinetic theory, scales with the square root of temperature and inversely with pressure and the square root of molar mass. It therefore becomes large at low pressure, high temperature and for light gas species. 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 high (viscous regime), and heat diffuses as in any continuous medium

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

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

$$Q = A \alpha(T) \Omega P (T_2 - T_1)$$

where Ω is a parameter depending upon the gas species, an α is the "accommodation coefficient" representing the thermalisation 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 8.

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Table 8
Typical values of heat flux to vanishingly low temperature between flat plates [W/m²]

Black-body radiation from 290 K	401
Black-body 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	1-1.5
MLI (10 layers) from 80 K, pressure < 1 mPa	0.05
MLI (10 layers) from 80 K, pressure 100 mPa	1-2