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Cryogenics, Key to Advanced Science and Technology

by

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More than a complete overview of cryogenics today, this brief article aims at presenting its continuing relation with advanced science and technology, not only as ancillary, but also in many instances as a central technique driving the development of ideas as much as the practical achievements. Its intellectually demanding and technically challenging nature in a variety of disciplines also make it an excellent training ground for technicians, engineers and applied physicists.

INTRODUCTION

Cryogenics, the science and technology of temperatures below 120 K[1] has entered its second century of existence. It is the result of a historical conjunction of progress in science – the gradual construction of thermodynamics throughout the 19th century, from the macroscopic theory of energy of J. Joule and S. Carnot, to the statistical mechanics of systems composed of microscopic particles by L. Boltzmann and J.W. Gibbs – and development in technology - the quest for liquefying the so-called "non-condensable" gases of the atmosphere, calling for the ingenuity of engineers and applied physicists in properties of pure chemical substances and their mixtures, compressor machinery, fluid flow and heat exchange, as well as thermal insulation techniques. The first liquefaction of air [L. Cailletet and R. Pictet, 1877] and separation of oxygen and nitrogen [K. Olszewski and S. Wroblewski, 1883] were soon followed by that of hydrogen, made possible by the invention of the vacuum-insulated, radiation-shielded container [J. Dewar, 1898]. It was however the first liquefaction of helium [H. Kamerlingh Onnes, 1908] which paved the way to the study of condensed matter at low temperatures, still a major line of research today, and the discovery of novel, unexpected phenomena such as superconductivity [H. Kamerlingh Onnes, 1911] and superfluidity [W.H. Keesom, 1928], which only the emerging quantum mechanics could eventually explain in the second half of the 20th century. It must be noted that, at a time when most experimental work in physics was performed by isolated scientists using table-top devices, H. Kamerlingh Onnes's laboratory in Leiden showed what is probably the first example of "big science", involving multidisciplinary team work, structured effort, quasi-industrial methods and international collaboration. Since then, cryogenics has shown a sustained development towards ever lower temperatures (*Figure 1*), attaining values down to about 0.1 nK today in specialized laboratories through a combination of helium dilution and adiabatic demagnetization techniques.

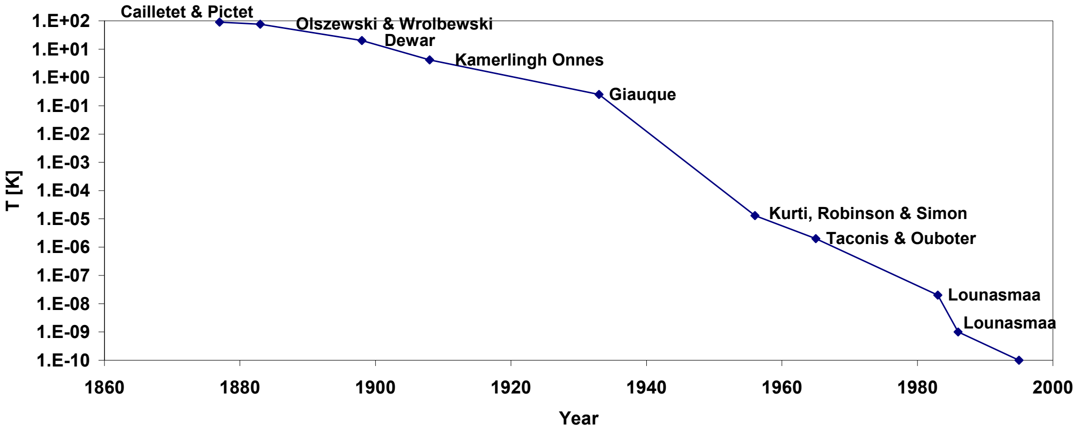

Figure 1. History of low temperatures, a sustained development over 120 years

This brief historical account only serves as an attempt to demonstrate how cryogenics was, from the onset and throughout the 20th century, associated with advanced science and technology. It still is today, thanks to a number of unique characteristics reviewed in the following.

I. LOW-ENERGY PHENOMENA AT WORK

The low absolute temperatures encountered in cryogenics can be used to reveal and study physical phenomena with low characteristic energy (1 K corresponds to 10^{-4} eV or 10^{-23} J), normally occulted at room temperature by thermal excitations — e.g. the intrinsic transport properties of metals and alloys – and to create new forms of condensed matter dominated by the quantum “zero-point” energy rather than the interactions between particles and atoms — superconductors, superfluids and even true Bose-Einstein condensates (*Table 1*). Although the application potential of these phenomena was identified very early, it took an unusually long time span to bring them out from the laboratory into practical devices (*Figure 2*). It is only with the development of practical type II superconductors in the early 1960s and the progress in power refrigeration technology down to helium II temperature, that superconductivity and superfluidity have become industrial techniques, applied on a grand scale (*Figures 3, 4, 5*) in nuclear magnetic resonance (NMR) systems,[2] magnetic-confinement fusion devices[3] and high-energy particle accelerators.[4,5] With some 15 000 units operating worldwide and a continuously growing demand, magnetic resonance imaging (MRI) devices constitute the first market application of superconductivity.

Table 1. Characteristic temperatures of low-energy phenomena encountered in cryogenics

“High-temperature” superconductors	~ 100 K
“Low-temperature” superconductors	~ 10 K
Intrinsic transport properties of metals	< 10 K
Cryopumping	few K
Cosmic microwave background	2.7 K
Superfluid Helium 4	2.2 K
Bolometers for cosmic radiation	< 1 K
Low-density atomic Bose-Einstein condensates	~ μK

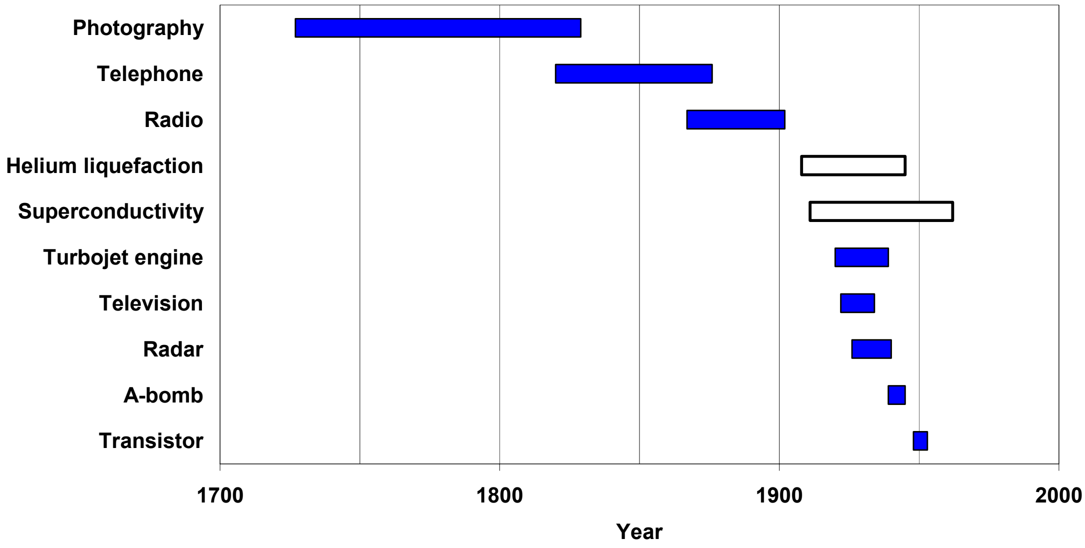

Figure 2. Time from discovery of principle to emergence of technology

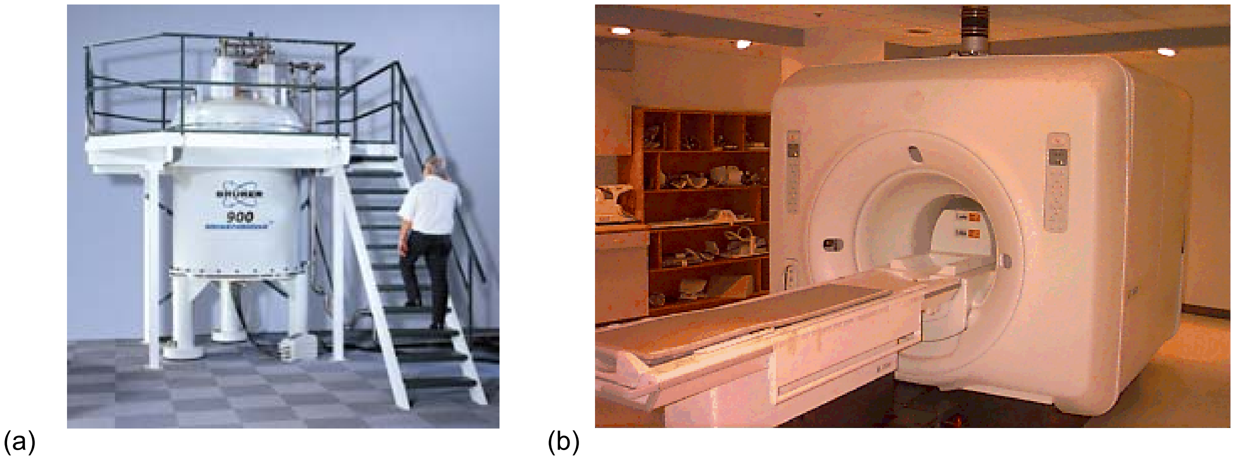
(a) (b)

Figure 3. Magnets for (a) NMR 900 MHz, superfluid helium cooled and (b) full-body MRI, liquid helium bath cooled with active shield refrigeration (Bruker)

Figure 4. View of the Large Hadron Collider (LHC), a high-energy particle accelerator with superfluid-helium cooled superconducting magnets in construction at CERN

Practical “high-temperature” superconductors (HTS) — a class of young materials still in the development phase — will eventually supersede conventional technology in specific niches of the electro-technical machine and power line markets.[6] Although the main benefit of HTS would be to greatly simplify cryogenics by operating at liquid nitrogen temperature (down to the vicinity of the triple point at 63 K), the potential of the presently available materials still requires low-temperature cryogenics (typically 20 K or down to liquid helium) for several applications (*Figure 6*).

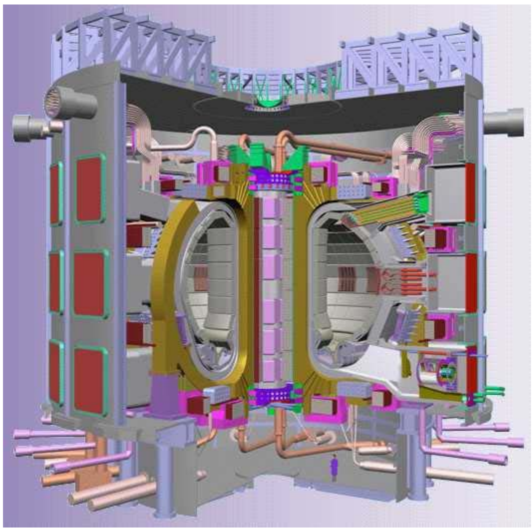

Figure 5. View of ITER, a large magnetic-confinement fusion tokamak in project

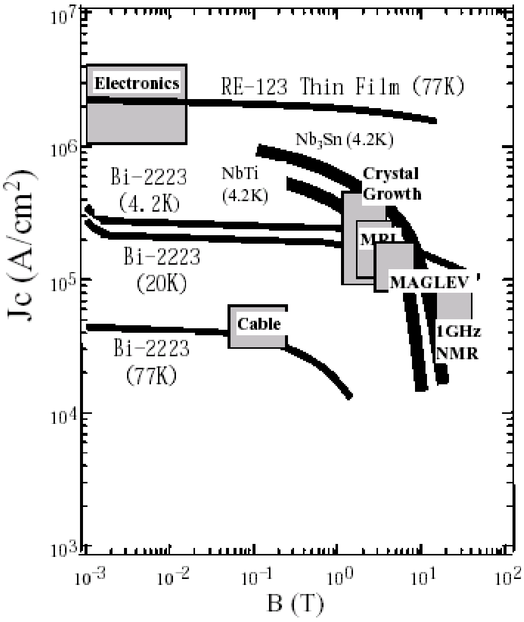

Figure 6. Performance of industrial HTS (BSCCO 2223) and range of applications[7]

Some electro-technical applications of superconductivity, however have no conventional equivalent. The absence of electrical resistance has permitted to plan and build superconducting magnetic energy storage (SMES) devices, used for peak shaving of demand, network stabilization or uninterrupted power supply. The particular property of superconductors to switch rapidly from the superconductive to the resistive state when their critical current is exceeded, has already been applied to fault current limiters protecting networks from destructive over-intensities.[8]

Figure 7. Field test of 114 MVA three-phase HTS cable system, cooled by forced flow of pressurized liquid nitrogen (TEPCO, CRIEPI, SEI)

The small value of the magnetic flux quantum in superconductors is used for precision measurement standards and sensitive detection of magnetic fields: superconducting quantum interference device (SQUID) detectors have become irreplaceable tools in geophysical surveying, underwater detection, and magneto-encephalography.[9] In many instances, the full benefit of precision and sensitivity may only be reaped by simultaneous reduction of thermal noise, thus compelling large-bandwidth devices to operate at cryogenic temperature, even though they may use novel "high-temperature" superconductors. With the operation of sensitive detectors and reduction of thermal noise, cryogenics has found its place to cool embarked semiconductor detectors looking at the cosmic microwave background of the universe or at astronomical objects in different ranges of the electromagnetic spectrum, from space probes in Earth orbit or beyond.[10]

Thanks to the exponential factor in Arrhenius' equation, the kinetics of chemical reactions can be effectively blocked when the absolute temperature becomes lower than their activation energy. The cryogenic preservation of biological cells and semen is standard practice today, while its extension to blood components and organs is being considered. Adsorption or condensation cryopumps also make use of temperatures below 20 K to trap residual gas molecules and attain clean high vacuum with large pumping speeds.

II. HIGH-DENSITY, LOW-VISCOSITY FLUIDS

In line with its historical development, cryogenics remains largely used today for densification, liquefaction and separation by distillation of gases and gas mixtures. Although competing with other, non-cryogenic separation processes, gas liquefaction is second to none when purification is critical or difficult, e.g. tritium separation and recovery, or when the final product must be kept at maximum density, either for compact transport - liquid rocket propellants and liquid natural gas tankers – or particle beam interactions – liquid hydrogen targets, noble liquid ionization chambers and calorimeters, and cold neutron sources.[11]

In liquid-hydrogen fuelled rockets, which have developed to very powerful launch vehicles operating with industrial reliability (*Figure 8*), subcooled liquid[12] and even solid-liquid mixtures ("slush") could further increase the mass of propellant per unit volume of tank, while reducing loss of propellant ("zero boil-off") for long missions.[13]

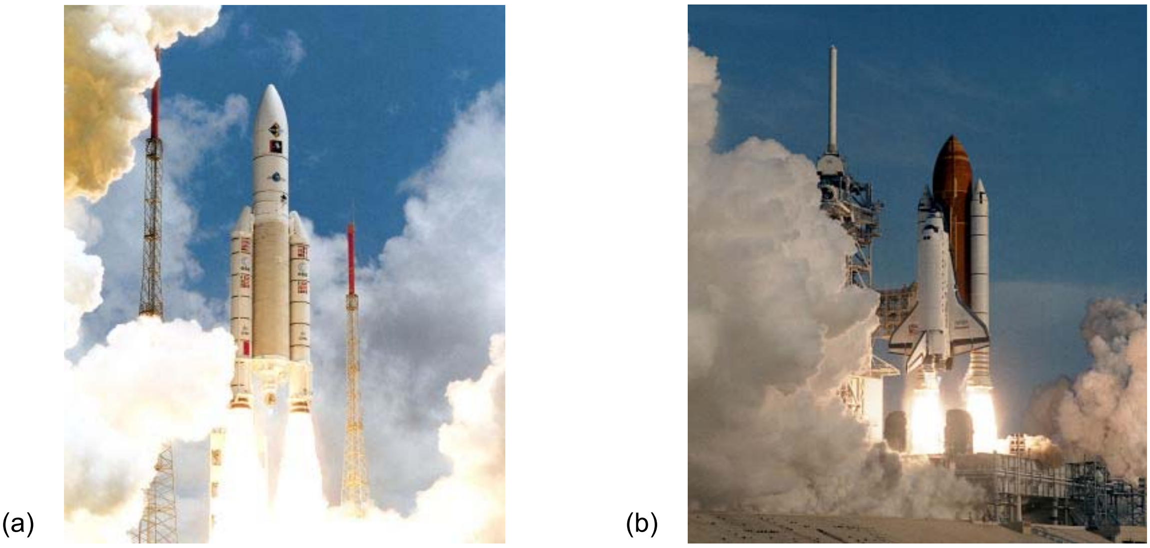

Figure 8. Cryogenic liquid rocket propulsion (a) Ariane 5 (25 t H_2, 130 t O_2)
(b) Space Shuttle (100 t H_2, 600 t O_2)

If hydrogen, in spite of its low molecular mass, is to become a widespread energy vector – the “hydrogen economy” is repeatedly announced as a possible solution to the issues of growing energy consumption and environmental protection in industrialized countries – there is no doubt that its cryogenic liquid form will play an important role, as it already does today in the fuel tanks of prototype cars and commercial vehicles, in conjunction with internal-combustion engines or fuel cells.[14]

Cryogenic liquids show particular characteristics, requiring special attention or opening new possibilities for their use. In view of their low critical temperatures and moderate critical pressures, cryogens are often used in the supercritical domain, with continuous transition from the liquid to the gaseous phase and divergence of some thermodynamic properties at the critical point. Several extended superconducting devices – strings of magnets in particle accelerators or single large magnets - are cooled by forced flow of single-phase supercritical helium, thus avoiding the risk of two-phase instabilities.[15] The combination of high heat capacity and low viscosity exhibited by liquid and superfluid helium make them irreplaceable as stabilizing medium against thermal disturbances in superconducting devices.[16]

As viscosity decreases at low temperature, liquid or vapour flows become highly turbulent, with the prospect of reaching very high Reynolds numbers in laboratory experiments of limited size, a tool of choice to investigate scaling laws of fluid turbulence. Moreover, the simultaneous variation of density and viscosity with temperature enables to preserve both the Reynolds and the Mach similarity conditions in scale model flows: this is the rationale for cryogenic wind tunnels, essential tools for the wing design of transonic aircraft where compressibility effects can no longer be neglected. Finally, the large volume expansion ratio at low temperature yields high Rayleigh numbers and strong natural convection. Pioneering experiments have recently been conducted on controlled flows at very high Reynolds and Rayleigh numbers using cryogenic helium.[17]

III. EFFICIENT AND RELIABLE REFRIGERATION

The second-law thermodynamic penalty of operating at low temperature can be much worsened by the presence of internal irreversibilities impacting on the overall efficiency of the refrigerator, and hence on its capacity and energy consumption. For cryogenic plants producing several kW of cooling power, the main factor driving the optimization of refrigeration cycles and the choice of machinery — compressors, heat exchangers, expanders, valves — is therefore second-law efficiency, achieved by limiting irreversibilities in heat transfer and fluid flow. In this fashion, the large cryogenic helium refrigerators (*Figure 9*) which all operate today on variants of the Claude cycle, have seen their efficiency improve significantly over the past decades to reach some 30 % of the reversible Carnot cycle, an excellent performance for thermodynamic machines operating between 4.5 K and 300 K.[18] Moreover, in case of strongly varying load, this performance can be preserved over a wide dynamic range thanks to elaborate control techniques implemented on programmable logic controllers and computers. These machines operate continuously for more than 6000 hours per year, showing availability in excess of 99% and requiring only one yearly scheduled maintenance period. It is the advent of such efficient and reliable industrial helium refrigerators which opened the way to the large-scale applications of superconductivity mentioned in the first section.

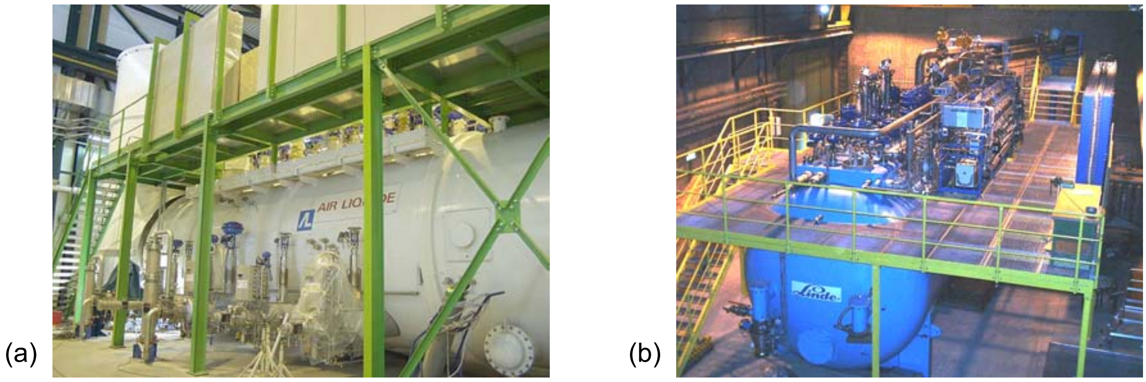

Figure 9. 18 kW at 4.5 K helium cryogenic plants for the LHC by (a) Air Liquide and (b) Linde

At the other end of the capacity range, cryocoolers are small machines ranging from a few mW to a few tens of W cooling power, requiring no manipulation of cryogens and often integrated in the piece of equipment they serve.[19] The issue of efficiency is usually less critical here, but that of reliability becomes essential, particularly for embarked aerospace applications requiring long MTBF and no possibility of servicing or repair. An important element of reliability is design simplicity, exemplified by the sorption compressors[20] and non-contact pressure oscillators of space cryocoolers,[21] as well as the absence of cold moving parts in pulse tube[22] refrigerators (*Figure 10*). Noteworthy developments in this domain concern the use of selected refrigerant mixtures in Joule-Thomson[23] or pulse-tube coolers, as well as of regenerator materials showing magnetic phase transition to beat the decrease in specific heat of solids at low temperature and permit operation of pulse-tube coolers down to below 4 K.[24] While the domain of large-scale cryogenic refrigeration is in the hands of a few companies world wide, the large variety of specific applications and the ingenuity of the researchers and developers render the field of cryocoolers very lively and industrially attractive for small and medium-size industry.

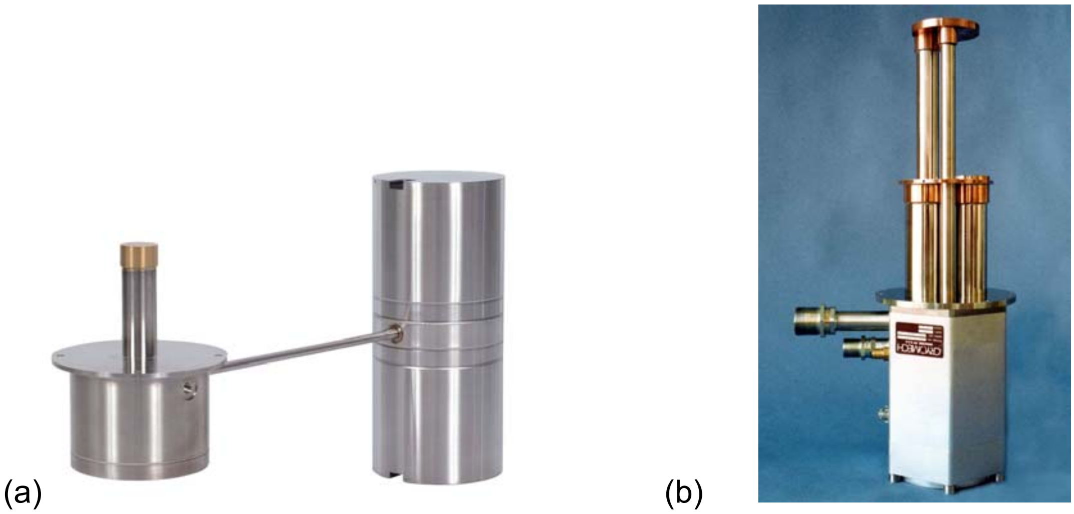

Figure 10. (a) Single-stage linear Stirling cooler for space applications with MTBF of 20 000 hours (Thales); (b) Two-stage pulse tube cooler operating down to 4 K (Cryomech)

IV. A MULTIDISCIPLINARY ENGINEERING EDUCATION

Cryogenics is seldom appearing as an academic subject in the syllabus of universities and engineering schools. It is rather a combination of scientific and technical disciplines, applied to the realm of low temperatures which make process analysis, equipment design and machine construction less forgiving, thus demanding knowledge, rigour and ingenuity from the cryogenic engineer, but also providing him with particular insights in many aspects of these diverse disciplines. As an example of this, consider the rather abstract concept of entropy: in a low-temperature process, the loss of exergy – “useable energy”, an entity much more accessible to intuition – is largely dominated by entropy generation, thus rendering the latter more amenable to the cryogenic student’s understanding. In a similar fashion, the study and practice of cryogenics make its students fully conversant with phase transitions, supercritical fluids, two-phase flows, non-linear heat transfer regimes, flow instabilities and other such oddities frequently appearing, though not necessarily at low temperature, in the field of advanced science and technology. On a more technical level, cryogenic construction requires the mastering of structural materials, assembly and joining techniques, leak testing and quality assurance procedures, thus constituting a school of excellence for the engineering student as for the technical trainee.

CONCLUSION

This rapid survey of cryogenics in advanced science and technology shows that after a century of parallel progress and synergetic growth, it is clearly here to stay and equally clearly will further develop along with the variety of fields it serves today. To keep abreast of these developments, the interested reader is invited to attend the ICEC and CEC/ICMC international conferences, held in alternance every two years, as well as the specialized IIR or IIR-co-sponsored conferences, focal points to the scientific and technical community.

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