Chapter 4
Cryocooler Applications at Neutron Scattering Facilities

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Abstract A global shortage of helium gas can seriously jeopardise the scientific programmes of neutron scattering laboratories due to the use of cryogenic sample environment in the majority of the neutron scattering experiments. Recently developed cryogen-free technology allows a significant reduction or even a complete elimination of liquid helium consumption. Here we review the impact of the cryogen-free revolution on cryogenic equipment used at large neutron facilities, such as cryostats, dilution refrigerators, superconducting magnets and other cryogenic systems.

4.1 Introduction

In the last decade, neutron scattering facilities have experienced a booming popularity. Two major neutron sources, SNS in the United States and J-PARC in Japan, have already started operating, and other major facilities such as ESS (European Spallation Source) and CSNS (China Spallation Neutron Source) are at advanced stages of construction. Leading players in the neutron scattering field such as ILL in France, ISIS in the UK or FRM II in Germany have significantly upgraded their capabilities and continue to carry out further facility development programmes. This, rapidly growing interest in neutron scattering, can be explained by astonishing new opportunities offered to users of neutron scattering facilities, due to considerable progress in a number of areas such as neutron optics, neutron detection, large and complex dataset analysis, neutron scattering instrumentation and sample environment.

Today, two thirds of all neutron scattering experiments are performed under cryogenic conditions [1, 2]. There are fundamental reasons for that. Firstly, the thermal motion of atoms is reduced at low temperature, significantly improving

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the precision of structural characterisation of materials. Secondly, a cryogenic temperature range allows the study of low temperature phase transitions.

A cryogenic environment is also required to provide the high magnetic field sample environment generated by superconducting magnets [3], or for operating of neutron moderators (where the energies of neutrons get reduced to usable level) [4] and some components of neutron beamline instruments, such as cryogenic beryllium filters [5] or cryopumps [6].

Traditionally at neutron scattering facilities, the cryogenic environment is used to be provided by liquid cryogen-based systems; however, extensive use of this kind of equipment requires significant resources, including the considerable cost of the required cryogens and a number of logistic issues, and poses health and safety problems.

In the middle of the 2000s, neutron scattering facilities have been exposed to another serious threat—global helium shortage. In the period from 2008 until 2012, some of the commercial helium traders occasionally suspended the liquid helium supply to research organisations. For neutron facilities, this problem is of special importance, because during the last two decades, they are permanently in the top-ten list of liquid helium users in the scientific world, somewhere after large accelerators, fusion reactors and MRI and NMR laboratories. Large-scale neutron facilities like ILL, SNS or ISIS used to consume tens of thousands litres of liquid helium annually. This situation posed one of the major risks on sustainability of a neutron facility's operation. Another negative consequence of helium supply shortage is the decade-long rise in helium prices. During the period from 2005 to 2015, the cost of liquid helium in the UK has quadrupled. That increase created a significant additional burden on facilities budgets. There is also very serious environmental aspect of this problem. According to William Halperin: "Helium gas is a natural resource which is not replaceable and when released it will rise through, and escape from our atmosphere and be gone forever" [7].

Luckily the new ground-breaking cryogen-free approach emerged at the beginning of the twenty-first century, offering an effective solution. So, what is the essence of this approach?

In the case of a conventional cryostat, the cooling power required to maintain the cryogenic conditions is provided by evaporating liquid cryogens: helium and nitrogen. In the case of cryogen-free systems, the cooling power is provided by a closed cycle refrigerator (CCR), also known as a cryocooler. There are two options available in order to reduce or, in the ultimate case, eliminate the usage of cryogens. The first option is comprised of the so-called dry systems, which do not contain liquid cryogens at all, and are built around a CCR, utilising the cooling power produced by the cold head [8–11]. The second option is based on the idea of recondensing the evaporating helium back to the cryostat by a CCR [12].

The breakthrough became possible due to a new generation of CCRs developed in late 1990s and early 2000s. Initially cryogen-free systems were based on conventional Gifford-McMahon (GM) cryocoolers [13]. However, despite obvious advantages, such as operational simplicity, the use of these systems was limited by the high level of mechanical vibrations produced by GM cryocoolers, and the necessity of expensive and regular service inspections. A new generation of CCRs based on the pulse tube refrigerator (PTR) technology offers an effective solution to both problems [14, 15]. A unique feature of the PTR is the absence of cold moving parts. This considerably reduces the noise and vibrations generated by CCR, a critical issue for a number of scientific instruments. Furthermore, the PTR offers lower maintenance costs and less disruption, as expensive high-precision seals are not required, and the cold head can be operated without a service inspection.

Out of all the large-scale scientific facilities, cryogen-free technology produced most of its impact on neutron facilities. This is because the approach based on CCRs is only efficient for small cryogenic devises, like cryostats, but not for bigger cryogenic systems, such as large superconducting magnets or cavities of accelerators. For the latter, industrial scale liquefiers are much more effective.

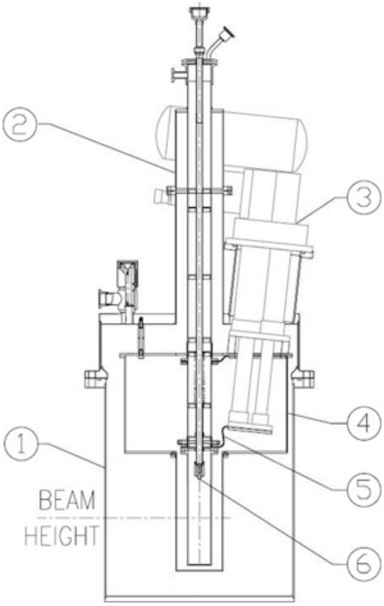
In the last couple of years, the helium shortage situation has noticeably eased and helium prices have stabilised; however, the CCR technology continues to expand, mostly due to its operational simplicity and reliability. At ISIS facility, between 60 and 70% of all user experiments that require cryogenic sample environment use CCR-based systems. Currently there are 57 operational cold-heads at ISIS facility, and this number continues to grow.

In this chapter, we briefly review the impact of CCR technology on the major cryogenic systems in a neutron facility experimental hall: cryostats, dilution refrigerators, superconducting magnets and neutron beamline instrument components. Naturally all cryogenic systems described in this chapter fall into two major groups: mobile cryogenic devises and stationary systems. Each of them utilises different advantages of CCR technology. Mobile cryogenic devises benefit from the compactness of CCR-based systems and a relatively quick turnover, while stationary systems exploit low maintenance and low resource requirements, which are characteristic for this technology.

4.2 Cryogen-Free Cryostats

A cryostat is a device that allows to maintain the cryogenic environment of a sample, for as long as required. In modern cryogenics, there is a great variety of different types of cryostats, each with its own advantages and disadvantages relative to others. Since the late 1970s, the Orange cryostat designed at the ILL [16] has been the workhorse of all neutron scattering facilities. This is a top-loading, liquid helium bath cryostat, with a liquid nitrogen-cooled infrared radiation shield, and a base temperature of ~1.5 K. However, at the beginning of the twenty-first century, new cryostats based on cryogen-free technology have emerged. Even though all these cryostats, developed at different facilities, have the same basic principles of operation, the concept has generated many individual designs [8–11, 17]. Photos of an example of a top-loader system (based on PTR) developed by ISIS, and manufactured by AS Scientific, are presented in Fig. 4.1 [10, 11]. The system consists of (1) the outer vacuum vessel; (2) the top-loading insert with an internal

Fig. 4.1 Diagram of the pulse tube top-loading system



diameter of 50, 75 or 100 mm; (3) the CCR; (4) the infrared radiation shield attached to the first stage of CCR and (5) the thermal link between the second stage and the insert base flange. A sample is loaded into the insert on the end of a sample stick. The infrared radiation shield is made of highly conductive copper and is covered with high emissivity aluminium foil. The neutron beam access to the sample is provided through the thin aluminium or vanadium foil windows in the cryostat tails. In order to enable laser alignment of samples, sapphire windows might be fitted on the reflectometer instruments.

For all designs of CCR-based top-loading cryostat, those based on PTR systematically reach lower base temperatures (3.0–3.5 K) than those based on GM (4.3–6 K).

The system cooling time of under 3 h, for PTR based systems, is also shorter than the approximate 4 h for the GM-based systems. The vibration level measured in the PTR cryostat is an order of magnitude less than that in a similar system based on a standard GM cryocooler [10].

For a rough estimation of the CCR-based top-loading cryostat efficiency, we can compare the cost of liquid helium required to run a standard Orange cryostat at ~60/day (based on liquid helium price in 2016) with the cost of the electric energy consumed by a CCR ~10/day [17]. This difference can only rise in the foreseeable future.

Currently ISIS has 11 PTR-based and 8 GM-based top-loading cryostats and 21 Orange cryostats. Most neutron facilities, including ISIS, also have a number of bottom-loading CCR cryostats which can be used as a cryo-furnace with temperature range 2.8–700 K [9]. The capacity of the fleet of cryogen-free cryostats allows running more than half of all the low-temperature sample environment experiments at ISIS.

However, experiments which need temperatures lower than 2 K still use Orange or similar cryostats. At ILL, a third-stage Joule–Thomson refrigerator added to the GM 10 K cryocooler reduced the temperature down to 1.8 K [1]. Addition of a similar Joule–Thomson stage to the CCR-based top-loading cryostat, for reaching 1.5 K, was later suggested in [11]. This idea has been realised in a prototype of the 1.5 K cryogen-free, 50 mm diameter, top-loading cryostat based on a PTR, which has been developed and successfully tested at ISIS [11–19]. The sample temperature range of this system is 1.4–300 K in the continuous flow regime. A sustainable high cooling power of 0.23 W at 1.9 K and temperature stability of 0.1 K across the temperature range 1.4–200 K has been achieved. This top-loading cryogen-free cryostat may also be used with ultra-low temperature inserts. Thanks to the high cooling power of the cryostat's VTI heat exchanger, the cryostat temperature range can be extended to the millikelvin area by inserting a standard dilution refrigerator insert in the VTI. In our tests using the Kelvinox dilution insert, a base temperature of 55 mK has been achieved in the continues circulation regime [19]. All the parameters of the new system are very close to the ones of conventional cryogen-based cryostats, such as the Orange cryostat. Furthermore, the new system does not require cryogenic liquid top-ups, which are challenging from the logistical, economical, operational and safety points of view.

High interest in cryogen-free cryostats in the neutron scattering community has stimulated industrial companies to develop commercial products for neutron scattering sample environments based on the technology. Currently Oxford Instruments, Ice Oxford, AS Scientific, Cryogenics, Janis and other companies are offering variety of cryostats based on cryocoolers.

4.3 Powerful Cryogen-Free Dilution Refrigerators Used in Neutron Scattering Experiments

A significant number of experiments at advanced neutron scattering facilities require sample temperatures below 1 K. Such sample environments are usually provided by dilution and/or 3He evaporation refrigerators. Many dilution refrigerators available at neutron facilities are based on the design incorporating sintered silver heat exchangers [20–22]. For many years, this used to be the standard of conventional dilution refrigerators. Usually this kind of dilution refrigerators are built in a liquid helium bath cryostat, with all the consequences typical for liquid cryogen-based cryogenics.

The development of the cryogen-free dilution refrigerator started at the very beginning of the twenty-first century, alongside the development of cryogen-free technology in general [23–25]. In most case, the design of modern, powerful, cryogen-free dilution refrigerators is based on the prototype developed by Kurt Uhlig [26], where the PTR is used to precool the dilution unit. These powerful dilution refrigerators are usually used in experiments with heavy and large sample

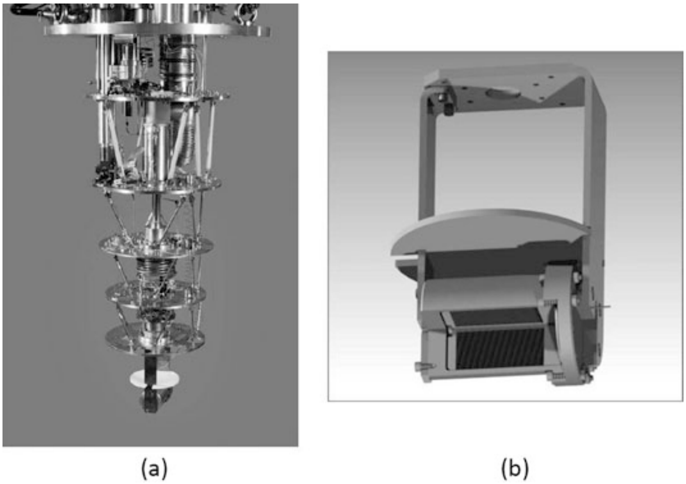


Fig. 4.2 (**a**) Powerful cryogen-free dilution refrigerator E-18; (**b**) 110 cm^3 solid 4He sample cell (also shown attached to the mixing chamber in (**a**))

cells, like those used for high-pressure measurements. The photo of a similar powerful cryogen-free dilution refrigerator (E-18) developed by Oxford Instruments in collaboration with ISIS [2] is presented in Fig. 4.2a. The fridge is capable of cooling large (diameter 200 mm; height 250 mm) and heavy (up to 20 kg) samples and provides access for the neutron beam through a set of thin aluminium alloy windows. The base temperature of the refrigerator is 15 mK and the cooling power is 370 W at 100 mK. In experiments where E-18 has been used to cool down 110 cc solid and liquid 4He sample cells (Fig. 4.2b; also attached to the mixing chamber in Fig. 4.2a), the base temperatures of 35 mK for the solid sample and 50 mK for the liquid sample (up to 25 bar) have been held for weeks [27–29]. To our knowledge, the paper published in [27] became the first publication where a powerful cryogen-free dilution refrigerator has been used in a neutron scattering experiment.

Today dilution refrigerators of this type are commercially available from a number of companies such as Leiden Cryogenics [30], Air Liquide [31], Oxford Instruments [32], LTLab [33], Cryoconcept, Janis and BlueFors.

4.4 Cryogen-Free Advanced Superconducting Magnets for Neutron Scattering Experiments

Neutron scattering is an invaluable tool for solid state magnetism. In many experiments, a sample needs to be exposed to a high magnetic field, low temperature and a neutron beam simultaneously [34]. Nowadays, these conditions can be satisfied only in superconducting magnets. First generation of superconducting magnets for neutron scattering has been developed in late 1980s, and by the middle of 1990s, the design had settled down and magnets became a part of the standard sample environment (SE) kit [35]. Most of them are split-pair magnets made of NbTi and Nb3Sn filamentary superconducting wires. The magnet is usually built in a conventional liquid helium bath cryostat, with a thermal shield cooled by liquid nitrogen. A set of windows made of neutron transparent materials provide a neutron beam access to the sample.

However, in the last decade, the rapid development in superconducting magnet technology and cryogenics has made it possible to build the new generation of advanced magnets for neutron scattering SE [3, 36–40]. The new magnets are usually designed to satisfy specific requirements of a particular advanced neutron scattering instrument, such as magnet aperture/opening tailored to instrument detectors coverage or compatibility with special collimating systems. This allows to create an optimal combination of instrument and magnet, which can achieve much faster experiments with much higher resolution.

Here we discuss two superconducting magnets, cryogenics of those is based on helium recondensing by a PTR cryocooler: the 14 T magnet for neutron diffraction and the 9 T wide-angle chopper magnet for neutron spectroscopy developed by Oxford Instruments in collaboration with ISIS neutron source [3, 38, 40, 41].

The 14 T magnet for diffraction measurements is a high field, split pair magnet which consists of NbTi and Nb3Sn superconducting coils. Today the maximum magnetic field for a state-of-the-art split pair magnet is 15 T with an opening angle 3°, but by limiting the maximum field to 14 T, it is possible to increase the detector viewing angle to 7.5°. In order to optimise the magnet design for use on the WISH long-wavelength diffractometer, we have chosen an asymmetric split $-5°$ to $+10°$, which for a single crystal studies allows access to at least one extra scattering plane, apart from the main horizontal plane. The magnet split is supported by aluminium rings. The diffraction data demonstrate a very good angular coverage and data quality (low noise) thanks to the collimator and the cadmium shielding.

Similar to 14 T diffraction magnet, the 9 T wide-angle chopper magnet for spectrometry is a split pair magnet consisting of NbTi and Nb3Sn superconducting coils. As presented in Fig. 4.3, in this case the magnet split is supported by nonmagnetic stainless still wedges, rather than aluminium rings. This design allows to minimise the amount of the material in the beam. The chopper instruments derive their power from being able to survey large volumes of reciprocal space in a single measurement, and so it is vital to build a magnet that can exploit this advantage. This would necessitate a trade-off between maximum field and a wide aperture. Detailed modelling allowed us to design and manufacture 9 T magnet with 15 opening in vertical plane and 45 (two openings separated by 180) opening in horizontal plane. This magnet has been designed and built specifically for use on neutron spectrometers, such as MERLIN and LET (with the unprecedented continuous angular coverage of their detectors).

The 14 T and 9 T magnets share similar top parts of the recondensing cryostat with variable temperature inserts (VTI) but have different bottom parts accommodating split pair magnets and sample space. The design of recondensing magnet

Fig. 4.3 Wide-angle chopper instrument 9 T superconducting magnet in the cryostat with helium recondensed by PTR

cryostats is usually based on the design of similar bath cryostats [12]. The superconducting magnet is immersed in the liquid helium. The radiation shield is cooled by the cooler's first stage, and the second stage recondenses helium directly in the helium vessel. Thus, the recondensing system does not consume any liquid helium during normal operations. The main advantage of this system is that all the magnet operating modes, for example cooling, running up to field and quenching, remain the same as for a standard magnet in a bath cryostat. This method also provides a homogeneous temperature distribution which is crucial for optimum magnet performance. Another significant advantage is the ability of the magnet to stay at field in the event of a power failure.

The cooling power for helium recondensing is provided by CryoMech pulse tube refrigerator PT410. This type of cryocoolers has no cold moving parts and, therefore, has low level of mechanical vibrations [12]. Additionally the pulse tube refrigerator requires little maintenance.

In a regime without VTI helium circulation and no ramping of filed pulse tubes on both magnets performs so efficiently that it recondenses all the helium in the cryostat and has an excess of cooling power between 600 and 650 mW [3]. This extra cooling power allows us to recondense the helium flow passing through a VTI during the operation of a dilution refrigerator insert [41].

4.5 Specialised Cryogen-Free Sample Environment Systems

In the last decade, cryogen-free technology has spread far beyond traditional low temperature/high magnetic field sample environment and has allowed conceptually new systems to be created. In this section I present a few examples of unconventional sample environments based on the cryogen-free approach.

There has been growing demand for investigations of the mechanical behaviour of materials at cryogenic temperatures, due to the recent progress in cryogenic technologies. Applications include cryogenic texture processing of alloys, strain sensitivity of superconducting magnet wires, cryogenic structural steels and low temperature shape memory alloys for space applications. ISIS has developed a cryogen-free cryogenic testing chamber for neutron scattering measurements of internal stress in engineering materials under loads up to 50 kN and at temperatures from 30 to 300 K [42]. Two CCRs provide the cooling power for keeping the sample at cryogenic temperatures. A similar approach has been used in the design of cryogenic load frames developed at the LANSCE [43] and JAEA [44] facilities. A distinctive characteristic of the JAEA device is the lower base temperature ~4.8 K, which allows the study of stress–strain effects in type 2 superconducting materials simultaneously with critical current measurements.

Recently, ISIS facility designed, manufactured and commissioned a new cryogenic testing chamber, for neutron scattering measurements of internal stresses in engineering materials under the load of up to 100 kN, in the temperature range from 6.5 to 300 K [45]. Complete cooling of the system from room to base temperature takes around 90 min. A photo of the experimental set-up is presented in Fig. 4.4. The cryostat design is similar to the one described in [42]. The main difference is the use of two-stage cryocoolers, instead of the single stage ones used in the previous design. The first stages of each of the two cryocoolers are thermally connected to the infrared radiation shield. They are also connected through copper braids to 100 K thermal anchoring points on the left and right grips. The sample holder grip is thermally linked to the second stage of the cryocooler. The design of left and right sides of the grips assembly is completely symmetric.

Excessive cooling power at first stages of cryocoolers allowed the ISIS team to incorporate a couple of high-temperature superconductor current leads into the system. This allows to supply a high current of up to 200 A to the sample, under

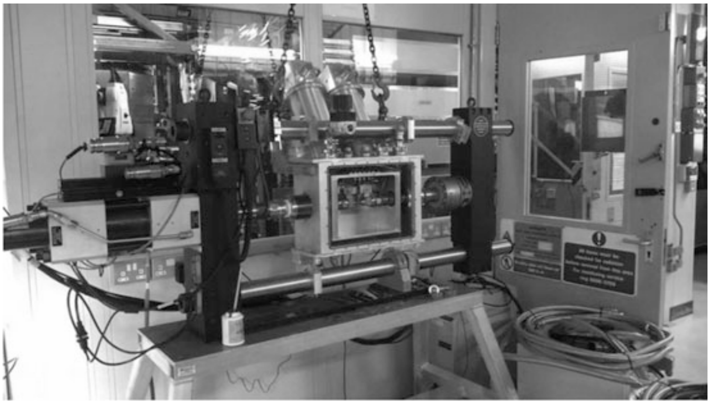


Fig. 4.4 Experimental set-up for the measurement of internal stress in engineering materials under loads. The uniaxial load up to 100 kN is provided by hydraulic loading rigs

load, simultaneously measuring stresses in the sample. In the system commissioning experiment, a dependence of the second-generation HTS tape sample, critical current has been successfully measured as a function of the sample's internal strain [46].

Another example of cryogenic sample environment is the cryogen-free cryostat, for cooling a 10 GPa Paris Edinburgh (PE) cell down to 3 K built by the ILL [9].

The 18 kg cell is attached to the second stage of the CCR and is enclosed in a tight chamber filled with exchange gas. It takes only 4 h to reach 3 K from room temperature. A cryogen-free cell based on a different design developed by FRMII allows high-pressure (up to 0.2 GPa) sample environment to operate in the temperature range of 20–600 K [47]. The cooling down time of this cell is similar to the ILL one.

Another version of cryogenic PE cell has been designed and developed at ISIS (please see photo in Fig. 4.5) [46]. This cryo-system is capable of varying the sample temperature over 17.5–300 K range in a little less than 3 h, cooling from room temperature to base temperature. The highest pressure achievable in the sample area is 30 GPa (300 kbar). The insert utilises two powerful 1.5 W at 4.2 K Sumitomo GM cryocoolers to cool just the sample and the standard profile tungsten carbide anvils. The variable temperature insert assembly is thermally insulated from the PE press. The temperature of the PE press cylinder housing is maintained close to ambient by means of a separate constant-temperature circuit. The system is designed to operate in completely automated regime, ran by a program script from the instrument computer.

Significant reductions in the neutron beam-time required for measurements with the new generation of neutron scattering instruments create the need for remote and fast sample handling to enable a high throughput of samples in a controlled

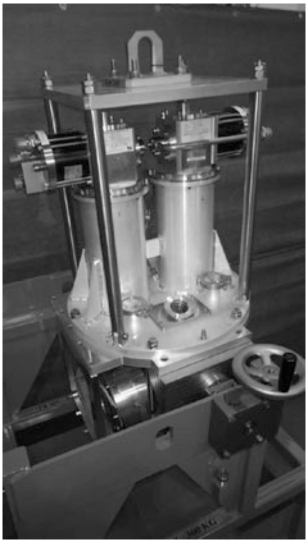


Fig. 4.5 Cryogenic PE cell based on two 1.5 W at 4.2 K Sumitomo GM cryocoolers

environment. A cryogen-free automated sample changer has been developed at SNS to serve this purpose [48]. The samples are contained in hermetically sealed vanadium cans attached to the sample handler. The system uses a CCR for cooling. The time to cool the sample from ambient temperature to ∼10 K is approximately 7 min. A resistive heating coil can be used to extend the temperature range from 10 to ∼350 K.

4.6 Cryogen-Free Technology in Neutron Scattering Instruments

The compactness and reliability of CCRs allowed them to occupy a new niche as coolers for components of neutron scattering instruments. Here we present a few examples of this approach.

The most widespread application of this kind is the CCR-based cryogenic beryllium filter. Polycrystalline beryllium Bragg cut-off occurs at an energy of 5.2 meV [46]. A block of beryllium transmits low energy neutrons up to this value, but scatters neutrons of higher energy. The beryllium filter based on this beryllium property is getting more and more popular in the design of neutron spectrometers. The transmission of the filter for neutrons of wavelengths beyond the cut-off depends mainly on phonon scattering. This can be largely removed by cooling the filter below 100 K and so removing the energy gain scattering from thermally excited phonons. Keeping beryllium filters at cryogenic temperature in the Tosca (ISIS) [5] and Vision (SNS) [49] instruments requires five CCRs, whereas in the case of the Lagrange (ILL) [50] and the recently upgraded Macs (NIST) [51] spectrometers, one or two CCRs provide enough cooling power.

Some instruments might require a cryogenic sample environment for the majority of experiments. In this case a cryogenic sample chamber can be incorporated in the design of the instrument. For the cryogenic chamber embedded in the Tosca instrument (ISIS), the necessary cooling power is provided by three CCRs, which allows measurements in the range between 3.7 K and room temperature [52].

A cryopump is a vacuum pump that traps gases and vapours by condensing them on a cold surface. In neutron instruments, cryopumps based on CCRs are used to improve the level of vacuum and accelerate pumping out of large vacuum chambers. For example, after venting the sample chamber of an SNS instrument Arcs, a combination of a large mechanical pump with a roots blower and a cryopump restores the vacuum to the 10-6 mbar range in under 15 min [53]. CCR-based cryopumps have also been used for the ISIS instruments Maps [54] and Merlin [6].

An elegant exploitation of superconductivity has been realised in the cryogen-free compact cryogenic polarisation analysis device (Cryopad) developed at the ILL [55]. This device takes advantage of Meissner shields made of niobium, to properly define the magnetic field and zero-field regions crossed by the incident and scattered neutron beams. Using the Cryopad, all the components of the complicated expression of the final polarisation vector of a neutron beam can be measured, which provides unique information on magnetic structures and nuclear/magnetic interferences occurring in the scattering process.

4.7 Conclusions

The cryogen-free revolution, driven by advances in cryocooler technology, started in the early 2000s and is not over yet. Every year, CCR-based technology conquers new areas traditionally occupied by conventional cryogenics. However, more than two decades of using cryocooler technology has allowed the accumulation of vast operational experience. Evaluation of the experience gained by ISIS, and other large neutron facilities, which are arguably the most intense users of CCR-based equipment, give us an opportunity to determine the advantages and disadvantages of these systems.

Advantages common for all CCR-based systems:

- Operational simplicity. Most of the cryogen-free systems only need maintenance services for the CCR cold-head (not required for PTRs) and the compressor after installation.
- Reduction or, in some cases, complete elimination of liquid cryogen top-ups, which is logistically demanding and expensive. CCR-based technology also reduces system downtime caused by top-ups.
- Significant reduction in technical resources. No need for specially trained personnel to prepare conventional cryostats for an experiment and perform top-ups.
- CCR technology is safer. The involvement of technical personnel regularly handling cryogens raises quite serious safety issues. The highest risk is associated with asphyxiation due to the lack of oxygen replaced by rapidly evaporating nitrogen or helium. This is a potentially lethal hazard. CCR technology significantly reduces, and in some cases completely eliminates all cryogenic hazards involved.
- Thermodynamic efficiency. Despite the fact that a cryocooler is less thermodynamically efficient than any industrial liquefier, the total efficiency of CCR-based systems is comparable with conventional cryogenic systems. This can be explained by the significant losses which conventional cryogenics experience due to transporting and storing cryogens and transferring them to cryostats. CCR technology eliminates these losses because cooling power is directly supplied from a cryocooler to the cooling apparatus.
- CCR technology significantly reduces the system size. The systems do not have a nitrogen vessel and do not require extra volume for holding liquid helium, which is necessary for providing sufficient hold time in the case of conventional cryostats.

- CCR technology is much more environmentally friendly than conventional cryogenics. Helium losses are minimised (and in some cases are completely eradicated) and the strategic gas can be saved for future generations. Evaluation of our operational experience also reveals some disadvantages of CCR-based systems.
- The most serious disadvantage of cryogen-free systems is the limited cooling power of the CCR. The most powerful GM cryocoolers and PTRs achieve no more than 1.5 W cooling power at 4.2 K. In conventional liquid helium-based systems, one can easily achieve more than an order of magnitude higher cooling power just by opening a needle-valve, but increasing helium consumption as a result. In comparison with conventional cryostat based on liquid cryogens, this means longer sample change time. However, in the case of recondensing systems, one can accelerate sample cooling by allowing helium boil-off.
- CCR-based equipment significantly increases demand for electricity and cooling water supplies, which in the case of massive scale operations can be a major issue.
- The cost of the cryocooler (tens of thousands dollars) can be a significant addition to the total cost of a cryogen-free cryostat.
- CCR operations generate significant noise, mechanical vibrations and magnetic field disturbances. This difficulty has been drastically alleviated by the absence of cold moving parts in the PTR design. However, in the cases of measurements extremely sensitive to such disturbances, special additional arrangements might be required.
- Some of the PTRs experience deterioration of cooling power (from 10% to 20% after ~5 years in operation), although the fast development in CCR technology promises significant improvement of PTR reliability in the near future.

CCR-based systems already make up a significant part of neutron facility cryogenic equipment, and the situation continues to change rapidly. The benefits of CCR technology lie not only in reducing helium consumption and eliminating the risks associated with global helium availability but also in the operational simplicity of cryogen-free systems, reduction in required technical resources and significantly improved safety. All these aspects are crucial for efficient exploitation of any large-scale neutron facility. A combination of CCR technology with advanced neutron optics, neutron scattering instrumentation and more powerful neutron sources opens up extraordinary new opportunities across broad areas of science.

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