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Cryocoolers: The Underlying Requirement of Superconductors

Presently, superconductivity only exists at temperatures below 138 K. For practical applications of superconductors cryogenic temperatures (T < 120 K or T < -153°C) are required. The practical temperature ranges vary from about 50 K to 80 K for the high temperature superconductors (HTS), about 15 K to 25 K for magnesium diboride and about 4 K to 9 K for low temperature superconductors (LTS). Although such temperatures are often achieved with liquid cryogens (liquid nitrogen or liquid helium) in the laboratory, closed-cycle cryocoolers are required for nearly all practical applications of superconductors. In addition to superconductivity, cryogenic temperatures bring about dramatic property changes in many materials, which can provide a variety of benefits. Table 1 lists these benefits.

The superconductor applications are the main focus of this article, although cryocoolers developed for some of the other applications can be used for cooling superconductors. The significant advantages offered by superconductors compared with normal materials can be successfully marketed only if the cooling requirement is made an insignificant disadvantage. Any feature of the cryocooler that brings attention to it would be considered a problem or disadvantage. Potential problems associated with cryocoolers are listed in Table 2. The goal of most research and development on cryocoolers is to reduce or eliminate these potential problems so that the user is not aware of the presence of a cryocooler, hence the term "invisible" cryocooler is often used in the cryocooler community. Considerable progress has been made in the last twenty years or so in developing invisible cryocoolers.

Table 1. Benefits of Cryogenic Temperatures

- **Preservation of biological material and food**
- **Densification (liquefaction and separation)**
- **Quantum effects (superfluids and superconductivity)**
- **Low thermal noise**
- **Low vapor pressures (cryopumping)**
- **Property changes (permanent and temporary)**
- **Tissue ablation (cryosurgery)**

Table 2. Potential Cryocooler Problems

- **Reliability**
- **Size and weight**
- **Cooldown time**
- **Electromagnetic Interference**
- **Efficiency**
- **Vibration**
- **Heat rejection**
- **Cost**

Superconductor Applications

The potential problems listed in Table 2 have varying importance, depending on the application. For example, space applications require extreme reliability, typically 10 year lifetimes with no maintenance and high efficiency. Space cyocoolers may cost upwards of $1 million but still remain invisible to the user when the total mission cost may be close to $1 billion. When the mission requires cryogenic temperatures for success, the cryocooler can remain invisible only when something else in the system limits the duration of the mission. For commercial applications, the potential problem areas are quite different from those of space applications. Though reliability is still very important, lifetimes of two to five years is often adequate, but cost of a few thousand dollars per cryocooler may be needed to keep its cost a small fraction of the total product cost.

Noise from a cryocooler, either audible or electromagnetic, could reveal its presence in some systems. The potential problems associated with cryocoolers can be minimized by selecting the best cryocooler type for that particular application.

There are four broad categories of superconductor applications, described by a matrix of LTS, HTS, electronic applications and power applications. The intermediate temperatures required for magnesium diboride may soon add a third temperature range to the matrix when that material begins to compete in the marketplace. Figure 1 provides a current map of many cryocooler applications in terms of refrigeration power versus temperature. The superconductor applications are shown in various shades of blue. Other applications are also shown in the figure, and when their regions are near that of superconducting applications, the same type of cryocooler may potentially be used.

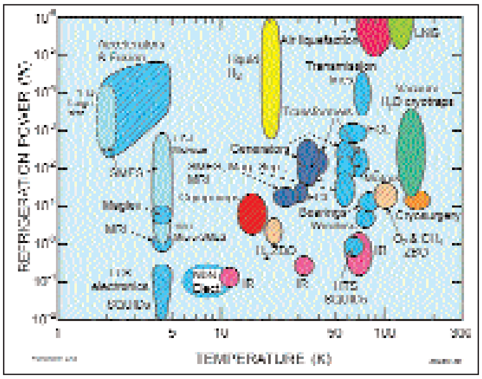

Figure 1. Map of net refrigeration power versus temperature for various cryocooler applications. Superconducting applications are shown in various shades of blue.

The largest superconducting application in terms of number of units and dollar amount is that of MRI magnets, which are found in most major hospitals. MRI magnets typically provide magnetic fields of about 1.5 T, but some newer models have fields of 3 T to provide improved image resolution. Normal copper electromagnets are limited to fields of about 0.15 T, which makes them impossible to compete with superconductors. Over 22,000 LTS MRI magnets are now in use since their first introduction in about 1980.

Early models were cooled to 4.2 K with liquid helium trucked in every few months. Since 1995 over 7,000 systems have cryocoolers operating at 4 K to reliquefy the helium boiloff or to cool the magnets directly without the use of any liquid helium. The largest superconducting project in terms of size is that of the Large Hadron Collider (LHC) at CERN, which has 1,232 superconducting dipole magnets each 14.2 m long cooled to 1.9 K around the 27 km circumference of the accelerator. The magnetic field produced by each magnet is 8.36 T. The equivalent 4.5 K refrigeration capacity for the complete ring is

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144 kW, which makes the LHC the world's most powerful helium refrigeration plant.

Electric power applications using HTS wires are being actively pursued. They include transmission lines, fault current limiters (FCL), transformers, motors and generators. The transmission lines require fairly large liquid nitrogen plants, but the other applications make use of intermediate sized cryocoolers that deliver about 100 W of refrigeration power and require only a few kilowatts of input power. Electronic applications of superconductors need only miniature cryocoolers, primarily to absorb the small amount of heat being conducted through electrical leads from room temperature. For HTS electronic applications, power inputs to drive the cryocooler may be in the range of a few watts to a hundred watts, but some new research is currently underway with microcryocoolers using MEMS fabrication techniques where power inputs can be less than one watt, which is easily provided with small batteries. HTS microwave filters for cellular phone base stations require about 6 W of cooling at 77 K and are currently employed in about 4,000 base stations, which is about 2 percent of the total number of US base stations. LTS electronics offer performance advantages over their HTS counterparts, but power inputs of about a kilowatt are required for the cryocoolers even for 0.1 W of cooling. Current research on improved cryocoolers for temperatures around 4 K may lead to input powers being reduced to about 200 W within the next few years.

Cryocooler Types

Figure 2 shows the five types of cryocoolers in common use today. These are known as gas cycles, and they are able in principle to operate at temperatures from about 2 K up to 300 K. The Joule-Thomson (JT) and the Brayton cryocoolers are recuperative types in which the working fluid flows steadily in one direction, with steady low- and high-pressure lines, analogous to DC electrical systems. The compressor may have inlet and outlet valves to maintain the steady flow, but for larger systems the compressor may use a scroll or screw mechanism to provide for steady flow and compression. The recuperative heat exchangers transfer heat from one flow stream to the other over some distance. Recuperative heat exchangers with the high effectiveness needed for cryocoolers can be expensive to fabricate. Though not shown in Fig. 2, the Claude cycle is a combination of the Brayton cycle with the addition of a final JT expansion stage for the liquefaction of the working fluid. It is commonly used in large helium liquefaction systems for cooling superconducting magnets and RF cavities in accelerators.

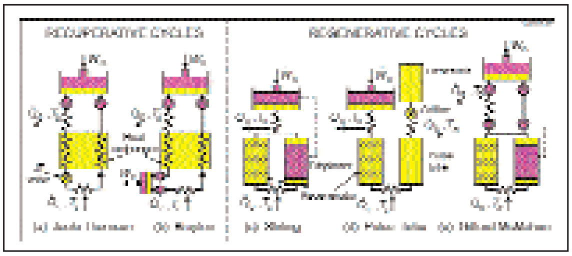

Figure 2. Schematics of five common types of cryocoolers. Moving parts are shown in red. The recuperative cycles operate with steady pressures and flow. The regenerative cycles operate with oscillating pressures and flow.

Small JT cryocoolers have been developed in the last few years to provide a few watts of refrigeration power at temperatures down to about 80 K. They use gas mixtures instead of a pure fluid in order to increase the overall efficiency and to allow operation at pressures that can be provided by commercial refrigeration compressors. As a result of using commercial oil-lubricated refrigeration compressors, the price for this type of cryocooler is only a few thousand dollars, which makes it attractive for commercial applications. They are also called Kleemenko cryocoolers after the name of the original inventor. The use of a phase separator at some intermediate temperature allows enough of the lubricant to be separated from the refrigerant before it passes on to the cold end to prevent any freezing. At least one of these cryocoolers has been able to demonstrate 10 years of continuous operation with no maintenance. Others are undergoing similar tests.

Currently the Brayton cycle is primarily used for cooling large systems where refrigeration powers of at least 100 W are needed. The expansion engines are often turbines with gas bearings for long life and low vibration. Some small systems providing a few watts of cooling in the range of 30 K to 80 K have been developed for space applications of infrared telescopes, such as the Hubble Space Telescope. Research on even smaller systems is ongoing.

The three regenerative cycles shown in Figure 2 operate with oscillating flows and oscillating pressures, analogous to AC electrical systems and almost always use high-pressure helium as the working fluid. Frequencies vary from about 1 Hz for the Gifford-McMahon (GM) and some pulse tube cryocoolers to about 60 Hz for Stirling and some pulse tube cryocoolers. Heating occurs as the pressure increases and cooling occurs as the pressure decreases. The use of a displacer in the Stirling and GM cryocoolers moves most of the gas to either the hot or cold end at the proper time in the cycle to separate the heating and cooling effects. Oscillating flow through the orifice (or inertance tube) in the pulse tube cryocooler carries out a similar function. The regenerative heat exchanger (regenerator) used for these cycles has only one flow channel that is filled with a porous matrix with high surface area and heat capacity (packed screens or spheres). Heat is transferred from the 'hot blow' to the 'cold blow' via the matrix, where the heat is stored for a half cycle in the heat capacity of the matrix. Such heat exchangers are simple to make and are less expensive than recuperative heat exchangers.

Stirling cryocoolers, named after the inventor of the heat engine using the same cycle, but operating in the opposite direction, were developed originally in the 1950s and have been manufactured in very large quantities (>150,000) mostly for military applications of infrared detectors in night vision equipment. They are designed for cooling to 70 K to 80 K with net refrigeration powers ranging from 0.15 W to 1.75 W. Input powers range from about 5 W to 100 W. In the last 20 years most of these Stirling cryocoolers use dual-opposed pistons on the compressor that are driven with linear motors to reduce the vibration, although the single oscillating displacer produces significant vibration at the cold end. Figure 3 shows several sizes of these linear-drive Stirling cryocoolers. Typical lifetimes of these

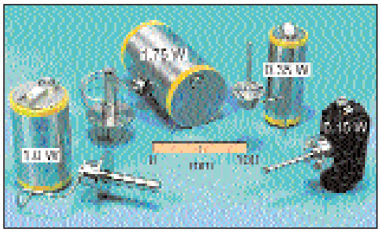

Figure 3. Four sizes of Stirling cryocoolers with dual-opposed linear compressors. Photo courtesy of Texas Instruments/DRS Infrared Technologies

oilless cryocoolers are now about one year of continuous operation. Lifetimes of about ten years have been achieved in Stirling cryocoolers for space applications when flexure bearings are used to support the oscillating piston and displacer in the cylinder with no rubbing contact. Flexure-bearing and gas-bearing Stirling cryocoolers are now being produced for long-life commercial applications. Superconducting microwave filters in some cellular phone base stations are cooled with Stirling cryocoolers using gas bearings.

Gifford-McMahon (GM) cryocoolers, developed in 1960, are the most common commercial cryocooler and are made by several different manufactures. Their use in cryopumps for the semiconductor industry has led to production rates up to about 20,000 per year in some years. They use an oil lubricated air conditioning compressor with a replaceable adsorber cartridge to remove the last remaining traces of oil from the helium working fluid before it enters the cold head through a rotary or poppet valve that provides an oscillating pressure at a frequency of about 1 Hz.

The use of valves to produce the oscillating pressure significantly reduces the efficiency of the system compared with the Stirling or pulse tube cryocoolers that use no valves. The valves and displacer seals may require maintenance about every one to three years. Single-stage systems for temperatures in the range of 30 K to 80 K and two-stage systems for temperatures in the range of 3°K to 30 K are readily available. Refrigeration powers range from about 0.1 W to 1.5 W at 4.2 K and 10 W to 600 W at 80 K. Input powers may range from 1 kW to 14 kW. These rather large compressors are fairly noisy, but they can be placed a considerable distance (adjacent room) away from the cold head. The oscillating displacer results in vibration, audible noise, and magnetic noise at the cold end, which can disturb some electronic systems but not most power systems.

The pulse tube cryocooler, first developed for cryogenic use in the early 1980s, has no displacer, thereby eliminating the wear, vibration and noise problems associated with the displacer. The oscillating flow is controlled by a passive orifice or with a long tube called an inertance tube on systems operating at higher frequencies (>30 Hz). The pressure oscillation can be provided with either a Stirling-type compressor that uses no valves or with a GM-type compressor and a rotary valve.

The Stirling-type pulse tube typically operates at frequencies around 60 Hz and has about the same high efficiency as the Stirling cryocooler (about 10 to 15 percent of Carnot at 80 K), but without any of the disadvantages associated with the oscillating displacer. The use of a flexure-bearing compressor can provide it with a life time of ten years or more. About 20 such systems are onboard satellites and many others are being developed for commercial applications. Refrigeration powers of commercial pulse tubes at 80 K vary from about 1 W to 1,000 W. The GM-type pulse tubes are used primarily for 4 K operation where the 1 Hz frequency allows the regenerator to operate more efficiently at these very low temperatures.

Recent Advances

The use of flexure bearings or gas bearings in Stirling and pulse tube cryocoolers in the past five or ten years has increased typical lifetimes of these cryocoolers from about 1 year to at least five years or more. The push for high efficiency for space applications has resulted in efficiencies at 80 K for small Stirling and pulse tube cryocoolers increasing from about 2 to 3 percent of Carnot up to about 15 percent of Carnot. Most research on crycoolers in the last few years has been on the pulse tube cryocooler because of its potential for long life, high efficiency, low vibration and low cost. Within the last year or so, much research is also being focused on increasing frequencies from about 60 Hz up to several hundred hertz in order to reduce the size and mass of Stirling or pulse tube cryocoolers and reduce their cooldown time. Improving the efficiency and reducing the size of 4 K pulse tube cryocoolers is also under active investigation for electronic applications of LTS. Many of the potential problems of cryocoolers listed in Table 2 have been significantly reduced in the last few years. As a result, more applications of superconductors may soon find their way into the marketplace.

Dr. Radebaugh has been the Group Leader of the Cryogenic Technologies Group for the National Institute of Standards and Technology in Boulder, Colorado, since 1995 and a physicist there since 1966. From 1966 to 1968 he was a NRC-NIST Postdoctoral Associate. He has conducted and supervised research on measurements and models for cryogenic properties and processes, such as refrigeration and heat transfer, at temperatures ranging from about 10 mK to room temperature. He can be reached at radebaugh@boulder.nist.gov.

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