JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 3, May–June 2002

Review of Spacecraft Cryogenic Coolers

Ravinder Singh Bhatia
California Institute of Technology, Pasadena, California 91125-3300

Nomenclature

A = surface area, m^2
B = external magnetic flux density, T
C_B = specific heat capacity for constant B, $J \cdot kg^{-1} \cdot K^{-1}$
I = current, A
L = magnet inductance, H
L_3 = latent heat of evaporation of ^{3}He, $J \cdot mol^{-1}$
M = magnetic moment, $J \cdot T^{-1}$
P_3 = vapor pressure above ^{3}He fluid
Q = cooling power, W
Q_{leak} = parasitic heat leak, W
R = gas constant, 8.31 $J \cdot K^{-1} \cdot mol^{-1}$
S = entropy, $J \cdot K^{-1}$
T = temperature, K
T_C = compression temperature, K
T_E = expansion temperature, K
X_3 = ^{3}He concentration
X_4 = ^{4}He concentration
ε = emissivity
σ = Stefan–Boltzmann constant, 5.7×10^{-8} $W \cdot m^{-2}$ K^{-4}

Introduction

CRYOGENIC cooling systems have found applications in a variety of spacecraft missions ranging from Earth remote sensing and surveillance missions to astronomical observatories. The achievement of high sensitivity in an infrared instrument requires cryogenic cooling to lower the background photon noise levels and also to lower any residual dark current or thermally induced noise in the detector itself. Similarly, cryogenic coolers are necessary to reduce the detector noise in gamma-ray spectrometers and shot noise in the detector amplifier systems. Superconducting technologies inherently need cryogenic cooling, whereas newer applications include in situ propellant liquefaction for a Mars sample return mission.

The cryogenic technologies that can be used for ground-based applications may be efficient and have high heatlift and high reliability but are in most cases totally unsuited for spacecraft use. Apart from the need to achieve the required heatlift at the various temperature stages specific to the instrument, there are further demanding requirements on the cooling system to make it suitable for use in space. Among these requirements are that the instrument should be capable of being fully tested on the ground; it should have low mass; it should have low volume; it should have a small mounting area; it should be able to survive the high gravitational acceleration levels during launch; there should ideally be several temperature stages available for cooling of baffles, optics, and detectors to their (differing) required temperatures; it should have excellent temperature stability characteristics; it should have (for a periodic system) good reproducibility of performance; it should have very high reliability levels for the several-year duration of a typical flight; the thermodynamic efficiency should be high; the power consumption should be low; and the system should be relatively immune to radiation damage. Most of these specifications also apply to electronic controllers that monitor and drive the cryocooler systems. The overall cryogenic design should be the best compromise between the payload requirements, the cooler performance, and the constraints imposed by the space environment. However, stringent requirements together with the very limited payload quantities being built each to a unique design do result in space cryogenic systems being very expensive.

There are a wide variety of cooling techniques, each of which have their advantages, disadvantages, and optimal temperature ranges. It is common practice to use a combination of these techniques to achieve the required performance, typically by precooling the outer shields of the system to the lowest temperature possible with a simpler system. The most straightforward technologies are passive systems, for example, radiators (temperatures down to ~80 K), solid cryogens (to ~7 K), and liquid cryogens (to ~1.2 K). Superfluid ^{4}He cryostats have flown on all of the far-infrared astronomy missions to date, but these cryostats have the disadvantages of high launch mass and limited lifetime [10 months for the Infrared Astronomical Satellite (IRAS) and 24 months for the Infrared Space Observatory (ISO)]. An alternative is to use small active mechanical systems, or so-called cryocoolers, to achieve temperatures down to ~2 K. The fundamentals of cryocooler technology have been reviewed by Walker.[1] Cryocoolers are generally in one of two categories: recuperative or regenerative. Regenerative systems use a high heat capacity matrix to extract heat alternately from and give up heat to the working fluid. In recuperative cryocoolers, this is done by using the return flow of the working fluid itself. Cryocoolers have the advantages of much lower launch mass than liquid or solid cryogen dewars and have a design life time of several years. Even lower temperatures below 0.3 K can now be achieved in flight using sorption cooling by reducing the vapor pressure above ^{3}He liquid, adiabatic demagnetization of a paramagnetic salt, or dilution refrigeration that makes use of the enthalpy difference between pure ^{3}He and a mixture of ^{3}He and ^{4}He. Such systems are currently in the process of undergoing space qualification or have recently flown. Pomeranchuk cooling and adiabatic nuclear demagnetization have not yet been developed for space applications because the temperature range over which they are useful is lower than that currently needed.

Ravinder S. Bhatia received his undergraduate degree in Aeronautics in 1991 from the Imperial College of Science, Technology, and Medicine (London). He was employed as a Cryogenics Engineer for Lucas Aerospace for three years and then pursued his doctoral studies at Queen Mary and Westfield College (London) in a joint program in Experimental Astrophysics and Aerospace Engineering. He graduated with a Ph.D. in 1998 and was a Postdoctoral Researcher with the California Institute of Technology's Observational Cosmology Group. His research interests include development of infrared and submillimeter cryogenic instruments for applications in astronomy and Earth observing. He is currently a Senior Thermal/Cryogenics Engineer with the ESA, Keplerlaan 1, P.O. Box 299, 2200 AG Noordwijk ZH, The Netherlands. He is a Member of AIAA.

Received 13 July 2001; revision received 16 November 2001; accepted for publication 2 December 2001.

Cryogenic technologies used for space missions have been previously reviewed in 1992 by Wanner[2] and in 1996 by Jewell.[3] Here we summarize the significant progress that has been achieved in development, space qualification, and flight experience of these and newer cryogenic technologies. We focus on civilian missions due to the classified nature of much of the defense-related research. A comprehensive and recent overview of cryogenic applications and of civilian space cryogenic missions is given in an excellent article by Collaudin and Rando,[4] and we, therefore, describe here only a selection of the missions that have flown. Sub-Kelvin temperatures are generally needed only by missions addressing fundamental scientific questions rather than with commercial aims, but sub-Kelvin coolers are nonetheless described here for the purpose of completeness and because significant advances have been made in these technologies over the past decade. It is not possible to list all references of interest; rather, pointers toward only the most important developments are given in conjunction with citations for important review papers. A survey of advances in ground-based cryocooler technology is given by Radebaugh.[5] For space cryocoolers, it is hoped that this review will be used together with the useful compendium of cryocoolers for temperatures ranging from 10 to 120 K that has recently been compiled by Curran et al.[6] and Glaister et al.[7] Each of the main cooling techniques will now be reviewed in terms of its theoretical basis of operation and its applicability for use with a cryogenic spaceborne instrument.

Radiative Coolers

The technique of passive radiative cooling is the easiest method of cooling available. Radiators are simple, reliable, and have a long lifetime and low mass. Radiators have been extensively used on spacecraft for heat rejection at ambient temperature and can be used at lower temperatures provided exposure to cold space is possible. However, the maximum level of heat radiation varies as

$$Q = A\varepsilon\sigma T^4 \quad (1)$$

At temperatures of 70 K, assuming a radiator area of 0.1 m^2 and a perfect emissivity, only 100 mW of cooling power is possible in the ideal case, from which the parasitic load from the support structure must be subtracted. For a low-Earth-orbit mission, the ability to achieve this cooling is further constrained by stringent pointing constraints that reduce the cold exposure time. Other potential problems include nonideal thermal conductivity (which creates temperature gradients across large radiators), difficulties with test and performance verification on-ground, and problems with surface finish contamination on-ground and in-orbit due to micrometeorites and/or outgassing.

The radiators are usually implemented in two stages, with the outer stage mechanically mounted to and thermally insulated from the spacecraft structure. This outer stage provides thermal shielding of the inner stage from the spacecraft, the sun, and the Earth. The cryogenic components are connected to this inner stage, which is mounted to and thermally insulated from the outer stage. A natural extension to this design is the multistage radiator, which does offer improved performance, but still has comparatively large conductive and radiative parasitic loads on the cold plate. The V-groove radiator uses several canted shields and allows multiple reflections of the radiation outward to reduce the radiative load. The radiator also has a structural support that partially disconnects postlaunch to reduce the conductive heatleak.[8–10] Cushman et al.[11] describe a design of radiator that has achieved a no-load base temperature of 34 K with rejection temperature of 91 K. Another type of passive radiator has been designed that uses a parabolic reflector arrangement. The shape and the location of the innermost focal point of the elliptical reflector is defined such that no (specular) reflection of radiation coming from the sunshield hits the second-stage radiator. This design will be implemented on the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) experiment[12] to be launched on ENVISAT in March 2002, and also on the Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument[13] for launch in mid-2002.

Much lower radiative base temperatures can be achieved if the spacecraft is in a thermally favorable orbit such as a solar orbit or a sun–Earth libration point. Orbits for radiatively cooled space telescopes have been discussed by Farrow.[14] The orbit is one of several parameters that must be traded at the system level,[15] but equilibrium temperatures of ~40 K can then be expected due to radiative cooling alone for spacecraft designs such as the Edison (see Ref. 16). As Wade[17] has noted, the predictions of radiative cooling to below 20 K for missions are based on studies assuming idealized beginning-of-life devices and, as such, are unrealistic of real missions. Nonetheless, low first-stage radiative temperatures of 40 K with ~10 mW of heatlift are feasible and can result in significantly improved performance for whatever cryogenic techniques may be used to achieve final instrument cooling, for example, the closed cryocoolers to be described.[18]

Open-Cycle Coolers

Open-cycle systems use stored fluid or solid cryogens. Cooling is produced by the latent heat of vaporization or sublimation, together with the residual enthalpy of the vapor as it warms toward ambient temperature. The cryogen is stored in a vessel that is insulated from the external environment and to which the cooled components are thermally connected. The major advantages of these systems are their high level of reliability, their ability to achieve excellent temperature stability, and their large amount of cooling power. The latter means that the required temperature can nearly always be maintained, even at the expense of reduced lifetime due to increased boiloff of cryogen. When interfaced with the detector system, there are no problems with microphonic vibrations and/or electromagnetic interference (EMI). The major problem is with the very high mass-to-lifetime ratio, which for a mission of several years means that a very large and heavy cryostat is necessary. This high mass increases launch costs and may further reduce the available instrument mass. The on-ground preparation procedures are also complex, especially with the limited access to the launch vehicle just before launch. The cryogen loss due to the parasitic heat load can be reduced by using the enthalpy of the vented vapor to cool the shields and the structural supports.[19] Other design concepts include the use of support struts for the cryostat that are rigid enough to withstand the launch and that are then partially or fully disconnected in-orbit to reduce the parasitic heatload on the cryogens.[20–22]

Table 1 lists the critical temperatures, normal boiling points, and triple-point temperatures of common cryogenic fluids, with boiloff temperatures ranging from 90 K for oxygen to 3 K for ^{3}He. Performance comparisons for spaceborne cryostats have recently been given by Holmes et al.[23] There are four methods of open-loop cryogen storage for spacecraft applications: single-phase fluid storage at supercritical pressure, two-phase fluid storage at subcritical pressure, high-pressure gas storage, and solid cryogen storage. We now briefly address each of these in turn.

Supercritical Storage

The critical pressure for the fluid is that pressure corresponding to the critical temperature, above which only a single-phase rather than a two-phase mixture can exist. In a supercritical storage system, the cryogen is kept at a pressure higher than the critical pressure of the fluid. The stored mass remains as a homogeneous single phase and has a tendency to expand out of the vessel because of the high pressure inside the vessel. This concept was used for oxygen and hydrogen storage on early flights [including Apollo (Fig. 1)] and remains in use on STS because there is no phase separation and consequently no problem of fluid confinement. Temperatures as low as 5 K can be produced by using helium as the working fluid. Because

Table 1 Critical temperatures, normal boiling points, and triple-point temperatures of common cryogenic fluids

Fluid	Critical temperature, K	Normal boiling point, K	Triple-point temperature, K
Oxygen	154.6	90.2	54.4
Argon	150.7	87.3	83.8
Nitrogen	126.1	77.3	63.2
Neon	44.4	27.1	24.5
Hydrogen	33.2	20.4	13.9
Helium-4	5.2	4.2	——
Helium-3	3.3	3.2	——

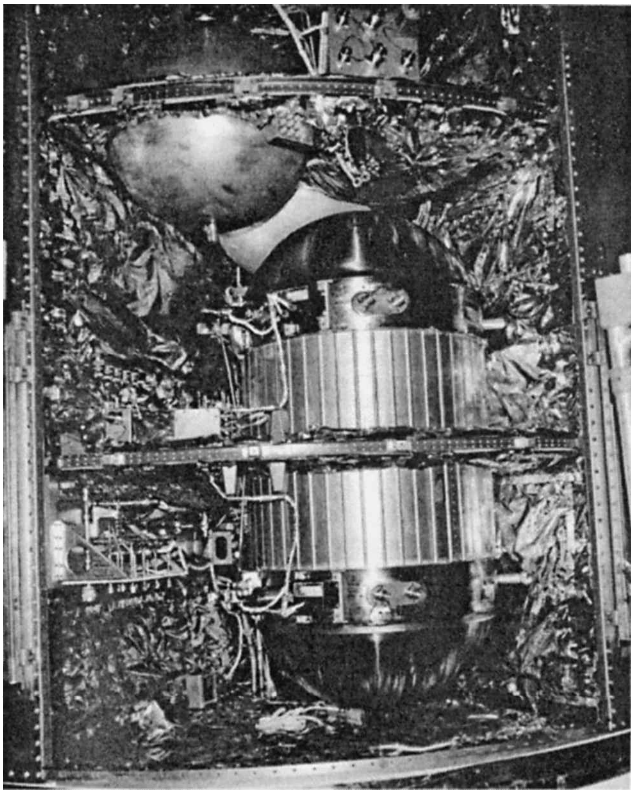


Fig. 1 Apollo 13 supercritical hydrogen and oxygen tanks.

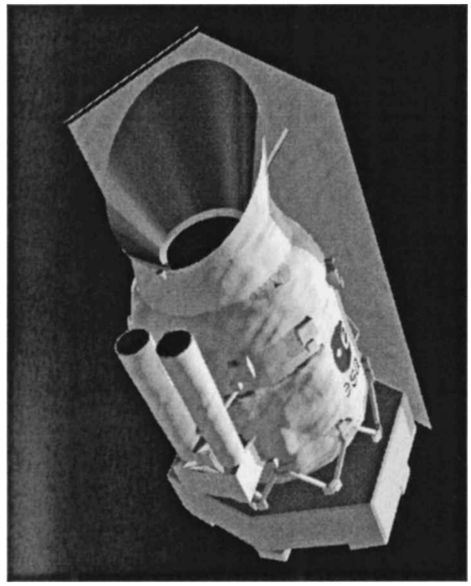


Fig. 2 ISO.

of the pressure decrease as the cryogen is vented, the temperature must be regulated by control of the fluid flow. This requirement increases the complexity of the system. Another disadvantage is the mass of the high-pressure storage vessel, so that this technology suits shorter missions.[24]

Subcritical Storage

In a subcritical storage system, the fluid is stored at a pressure lower than the critical pressure, and so exists in a liquid/vapor mixture. The main problem in a 0-g environment is that of keeping the vapor phase separate from the liquid: only the gas is to be vented, to retain the cooling power from liquid vaporization. For classical liquids, the preferred method of phase separation is the controlled expansion and vaporization of the liquid through a thermodynamic vent system (TVS). A TVS is a combined Joule–Thomson valve and heat exchanger. With superfluid helium, this is instead achieved using the thermomechanical (fountain) effect. A pressure drop is produced across a porous plug,[25,26] thereby producing an associated temperature drop. Most of the liquid returns to its superfluid state and is driven back into the tank by the higher pressure of the warmer He II that is evaporating and escaping. Considerations for operation of phase separators in 0-g have been described by Hendricks and Karr.[27] Other potential problems with this technique include mass movement of the cryogenic fluid,[28] flow choking and breakthrough,[29] and hysteresis effects.[25]

Temperatures as low as 1.2 K can be achieved using superfluid ^{4}He confined by a porous plug. The superfluid has the properties of high thermal conductivity and low viscosity, resulting in low thermal gradients between the helium bath and the tank walls. The behavior of superfluid ^{4}He in 0-g has been investigated by Mason et al.[30] Although the cryostat vents to a hard vacuum, the base temperature is limited by the pumping speed though the porous plug, or by the flow impedance necessary to exchange heat efficiently with the shields. Lower temperatures can be achieved using ^{3}He, but the high cost of this isotope precludes its use in open cycle systems. A system using surface tension to confine the liquid within the pores of a low-density sponge has been developed at NASA Goddard Space Flight Center (GSFC).[31] Surface tension keeps the liquid away from the cooler vent during 0-g operation. This technology is in current use for liquid–liquid (free interface) diffusion for the crystallization of proteins in 0-g (Ref. 32). The feasibility of transferring superfluid helium in space has been investigated as an option for extending mission duration.[33,34] The Superfluid Helium On-Orbit Transfer (SHOOT) experiment on the STS successfully demonstrated the feasibility of this by cooling down and refilling of a warm dewar with transfer rates of up to 720 l h^{-1}.

Cryostats with superfluid ^{4}He have flown on IRAS,[35] Spacelab,[36] Cosmic Background Explorer (COBE),[37] Infrared Telescope in Space (IRTS),[38] and ISO[39] (Fig. 2) as well as the ASTRO-E[40] spacecraft, which was lost due to launch vehicle malfunction. The technology of superfluid cryostats is now considered mature, and further missions to be flown in late 2002 include Gravity Probe-B (GP-B)[41] and Space Infrared Telescope Facility (SIRTF).[42] A warm telescope launch has been adopted for SIRTF,[43] and the primary and secondary mirrors will cool radiatively in-orbit to ~50 K before the helium vapor is used to cool them to base temperature. This mission strategy significantly reduces the cryogen boiloff rate. Parallel studies were undertaken to examine the relative merits of cooling the Herschel Space Observatory (HSO) by mechanical closed-cycle coolers,[44] or by a superfluid ^{4}He cryostat based on the ISO design.[45] For reasons of cost, prior experience with ISO, and technical maturity in 1997, the cryostat version of the HSO spacecraft was chosen. HSO will now use 2560 liters of superfluid ^{4}He for cooling to 1.7 K (Ref. 46). Infrared Imaging Satellite (IRIS),[47,48] a follow-on mission to IRTS, is being designed to perform an all sky point source survey and will use 150 liters of superfluid ^{4}He.

High-Pressure Gas Storage

This effect is used in the Joule–Thomson (J–T) expansion systems described subsequently. For an open-cycle system, a major problem is with the mass of the high-pressure gas tanks that must be used for extended missions, and so this technique is not in common use.

Solid Cryogen Storage

The difficulties of liquid/vapor surface control led originally to a preference to fly solid cryogens that have no liquid-/gas-phase separation problem. The cryogen has a higher effective latent heat (which comprises the heat of fusion) and has a marginally higher density of storage, and also there is no mass movement of the cryogen, particularly during the launch phase. Problems include the complex on-ground filling and launch preparation process, the lower thermal conductivity of the cryogen in its solid phase, and degradation of thermal conductance between the cryogen and the wall over the course of the mission. It is impractical to solidify helium, and solid hydrogen at 20 K can be somewhat hazardous, but neon at 27 K is a safe alternative.

Developments in the technology of early solid cryogen coolers have been reviewed by Nast.[49] The Cryogenic Limb Array Etalon

Spectrometer (CLAES) instrument[50] on the Upper Atmosphere Research Satellite (UARS) used solid neon and solid carbon dioxide[51] to cool the detectors to 16 K, the spectrometer to 30 K, and the telescope to 150 K. In-flight, the dewar exceeded the 15-month nominal mission lifetime by three months.[52] The Near-Infrared Camera Multi-Object Spectrometer (NICMOS) on the Hubble Space Telescope was cooled to 58 K using a solid nitrogen dewar.[53] The Wide Field Infrared Explorer (WIRE) spacecraft[54] was designed to study the evolution of starburst galaxies and search for distant ultraluminous galaxies. The design incorporated a primary solid hydrogen cooler[55] to cool its focal plane assembles to <7.5 K and a secondary solid hydrogen cooler to cool the optics to <18 K. The nominal mission lifetime was four months, but premature ejection of the telescope cover following orbital insertion meant that the cryogens vented within only two days.

Stirling Cryocoolers

The majority of space cryocoolers in development or in use are derived from the so-called Oxford heritage coolers. These are in turn based on the pressure modulators used on several spaceflights: the Pressure Modulator Radiometer (PMR) on Nimbus F,[56] the Stratospheric and Mesospheric Sounder (SAMS) radiometer on Nimbus 7,[57] the Infrared Radiometer on the Pioneer Venus Orbiter,[58] and the Improved Stratospheric and Mesospheric Sounder[59,60] on UARS. The primary design of these instruments was undertaken at the University of Oxford, and the development of Oxford heritage coolers has been reviewed by Davey.[61]

Stirling coolers are similar to Gifford–MacMahon coolers, which are commonly used for commercial low-temperature refrigeration but do not have valves. A simplified schematic of a Stirling cryocooler is shown in Fig. 3, following Walker (Ref. 1, p. 45). The compressor and displacer are separated by a regenerator matrix and a heat exchanger either side of the matrix. The molecules throughout the working fluid undergo different thermodynamic cycles depending on the physical motions they undergo, but here we assume that the fluid undergoes an ideal cycle. During compression, the pressure increases, but the heat of compression is rejected so that the process is isothermal at T_C (process 1–2). During the transfer process, both pistons move together with a constant volume between

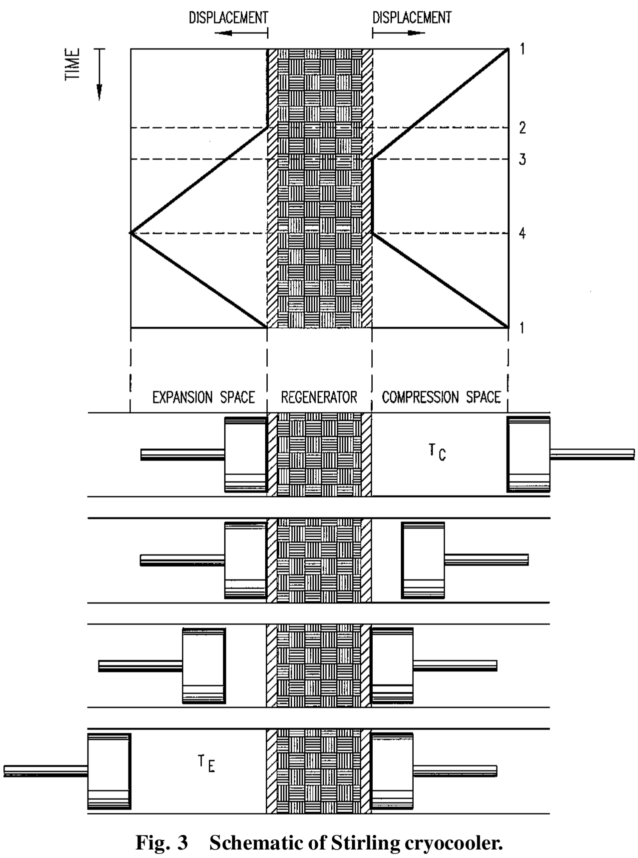


Fig. 3 Schematic of Stirling cryocooler.

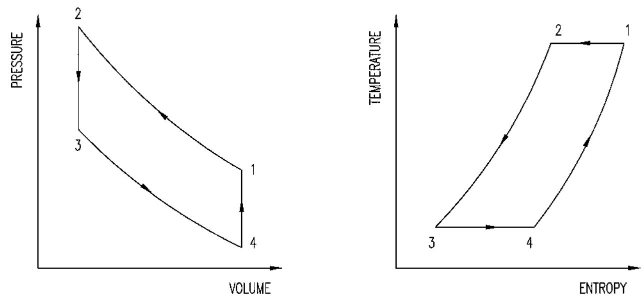


Fig. 4 Ideal Stirling cycle thermodynamic diagrams.

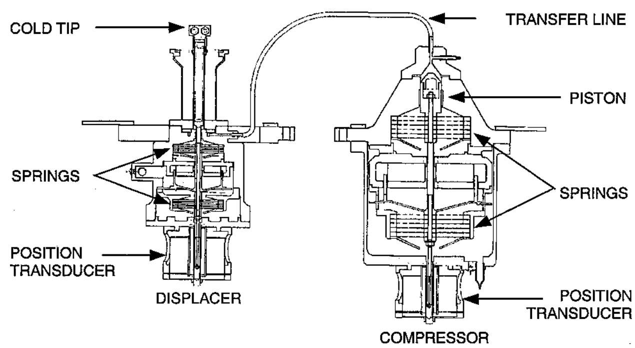


Fig. 5 Single-stage split Stirling cryocooler.

them. The fluid passes through the regenerator matrix which cools it from T_C to T_E (process 2–3). Next the expander piston moves away from the regenerator, but the compressor piston remains stationary (process 3–4), so that the volume increases and the pressure decreases. The temperature remains constant because heat is extracted from the surroundings; this is the useful refrigeration. Finally, the two pistons move back together to their original positions (process 4–1), and the fluid warms up as it passes through the regenerator. Ideal Stirling cycle thermodynamic diagrams are shown in Fig. 4.

Integral cryocoolers have the compressor and displacer colocated within the same unit. This has the advantage of smaller volume and lower pressure drops than for a split cryocooler where a transfer line separates the compressor (and, therefore, the majority of the vibration and EMI) from the displacer. A single-stage, split Stirling cryocooler developed for space use[62] is shown in Fig. 5. The compressor is driven by a linear motor coupled directly to the piston. The motor consists of a (stationary) permanent magnet and a soft iron flux path. This stator gives a large magnetic flux density in the gap that is occupied by a coil. The coil is rigidly connected to the piston via a shaft, and the whole system oscillates when an alternating current flows in the coil. To reduce power consumption, the compressor operates close to the mechanical resonance frequency of the gas spring provided by the helium gas. In addition, the piston is supported on two sets of diaphragm springs attached to the shaft, which have high radial stiffness to maintain precise linear motion of the piston. Each spring is of a flat disk, spiral arm design and is used in such a manner that life-limiting fatigue stress levels are not approached. This mechanical suspension system maintains a very small clearance at the seal, thus ensuring that there is no contact and no wear that is critical for long-life applications. An alternative but much less commonly used design is to use hydrodynamic gas bearings to align the piston.[63] The displacer unit contains an integral regenerator, which is mounted rigidly on a shaft. The displacer is pneumatically driven by the pressure wave from the compressor but has fine displacement control provided by a small internal linear motor of the same type as for the compressor. A clearance seal is maintained between the displacer and the thin-walled tube in which it oscillates. Both the compressor and the displacer are fitted with a position transducer that determines the displacement of the shaft away from the nominal zero point. A cryocooler control electronics system drives the compressor and displacer at the correct amplitude and oscillation frequency and at the correct phase angle between the compressor and the displacer.

These Stirling coolers have undergone space qualification[64,65] and are now considered to be a mature technology for space use. The results of the NASA spacecraft cryocooler characterization program have been published by the Jet Propulsion Laboratory[66] and GSFC,[67,68] and details of the U.S. Air Force cryocooler programs have been published by the Air Force Research Laboratory.[69] Examples of current instruments flying Stirling coolers include Measurements of Pollution in the Troposhere (MOPPITT)[70] (which uses Astrium 80-K coolers) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER),[71] both on the NASA Earth Observing System (EOS) Terra spacecraft, and the radiometer on the Odin spacecraft.[72] A single-stage Ball Aerospace Stirling cooler[73] will fly on High-Resolution Dynamic Limit Sounder (HIRDLS)[74] on the EOS Aura spacecraft. Single-stage Astrium Stirling coolers will be flown on the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) and Advanced Along-Track Scanning Radiometer (AATSR) instruments on ENVISAT.[64,75] Dual Stirling coolers use a pressure wave generated by each of two compressors into a common T-piece. The displacer has two regenerator matrices with an intermediate stage at a nominal temperature of ~150 K. Base temperatures down to below 20 K are possible using this system. The Rutherford–Appleton Laboratory (RAL)/Astrium 20-K cryocooler[76,77] achieves a heatlift of 120 mW at 20 K or 300 mW at 30 K and has been baselined for use on an absolute radiometer for measuring total solar irradiance, which is due to fly on the International Space Station.[78] The Ball two-stage Stirling cooler[79] achieves a heatlift of 400 mW at 30 K.

The option of using Stirling coolers to cool the outer shields of a cryogen-based instrument has been investigated to reduce the boiloff rate, and thereby to extend the nominal lifetime of the mission, and also to stabilize the temperature of vapor-cooled shields. The original design of the Chandra X-Ray Observatory (previously named the Advanced X-Ray Astrophysical Facility) baselined single-stage Stirling coolers to cool the dewar outer shield.[80,81] Similarly, the shields for the original design of the Spectroscopy of the Atmosphere Using Far-Infrared Emission (SAFIRE) instrument proposed for EOS were to be cooled by two single-stage Stirling cryocoolers plus a two-stage Stirling cryocooler.[82] These designs were subsequently rejected for reasons of cost and complexity, it being considered that the hybrid design incorporated the problems and failure modes of both types of cooling technique. However, partly because further experience has been gained with cryostats and Stirling cryocoolers, this type of hybrid system has recently been reintroduced and is the baseline for the design of IRIS[48] (ASTRO-F), which is scheduled for launch in 2003.

Potential problems with Stirling systems include the generation of microphonic vibrations and EMI from the reciprocating motion of the drive coils and pistons. Extensive work has been done on developing low-vibration drive electronics.[83–86] Integration of these systems with sensitive infrared detectors is also of concern.[87–89] The level of power consumption required for low-temperature operation is high, even for efficient Stirling coolers, so that high levels of waste heat must be rejected from the compressors and displacer. Great care must be taken to ensure that there is no damage to the fragile displacer cold finger during testing and during the launch phase. It may be necessary to incorporate a locking mechanism into the design of the motors to ensure that excessive forces are not generated by motion of the pistons during launch vibration. Concerns about reliability have been reduced by the use of clearance seals for the compressors and by careful choice of materials. The successful development of Stirling coolers resulting in their increased efficiency and reliability has led to them often being the preferred choice of cryocooler in the past, but these have now been superseded somewhat by pulse tube coolers.

Pulse Tubes

Pulse tubes are the most important type of space cryocooler under development and currently in use for temperatures from ~35 K up to 80 K. The development of pulse tubes has been reviewed by Radebaugh.[90–92] Basic pulse tubes were invented by Gifford and Longsworth who achieved a temperature of 173 K with their design.[93] A schematic of a pulse tube system is shown in Fig. 6.

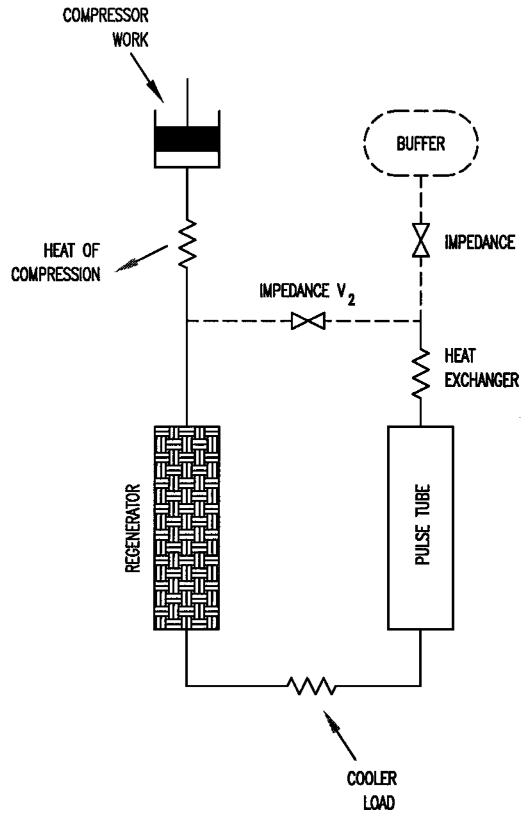


Fig. 6 Schematic of pulse tube cooler.

The pulse tube itself is a thin-walled cylinder with heat exchangers located at each end. It is supplied with pressure waves in the working fluid through the regenerator. The pressure waves are generated by a compressor, which for space coolers is of the ac gas-flow type. For basic pulse tubes, the cooling effect relies on a heat exchange mechanism between the gas and the wall, known as surface heat pumping,[94] which creates a small phase shift between the mass flow and the pressure oscillations. However, this becomes a loss for pulse tubes that achieve lower temperatures. The orifice pulse tube improves on the design of the basic pulse tube by adding a needle valve V_1 and a reservoir volume at the closed end. These make it possible to tune the flow for a larger total phase shift and, therefore, an even smaller phase difference between the pressure and the mass flow oscillations. This design considerably improves on the performance of previous pulse tubes, but a large volume of gas with no refrigerative effect still flows through the regenerator because of the pressure oscillation. The double inlet pulse tube has overcome this problem by adding a second valve V_2, which directly connects the hot end of the pulse tube to the compressor.[95]

The pulse tube is mechanically much simpler than other regenerative coolers because it has no cold moving parts. All of the moving elements are at ambient temperature in the compressor, which can be identical to that used in the standard Stirling cryocooler described earlier, and so can benefit from the development undertaken to make these reliable and efficient enough for spaceflight. Compared to a Stirling cooler, there is much less little vibration and no EMI originating from the cold head, which makes integration with the instrument more straightforward. What little vibration remains is caused by small elastic deformation of the pulse tube and the regenerator. Compared to J–T systems, there are no critical small orifices that may plug, and the simplicity of the cold end design makes it comparatively immune to working fluid contamination. The pressure oscillations are also relatively small. The pulse tube is therefore a preferred option over the J–T or Stirling cryocooler for space missions. The first pulse tubes were launched on the NASA John H. Glenn Research Center at Lewis Field Small Spacecraft Technology Initiative (SSTI) spacecraft.[96] The 55-K pulse tubes each with a heatlift of 1.75 W will cool the Atmospheric Infrared Sounder (AIRS) instrument focal plane[97,98] on

EOS Aqua and the Sounding of the Atmosphere Using Broadhand Emission Radiometry (SABER) instrument[99,100] on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft, both to be launched in mid-2002. A pair of 65-K pulse tube coolers[101,102] will cool four focal plane arrays on the tropospheric emission spectrometer[103] on EOS Aura, to be launched in 2004. Pulse tubes were baselined for use on INTEGRAL[104,105] (although this will now use Astrium Stirling 50–80 K coolers because of the delay in space qualification of the pulse tube). Building on the strength of the development and performance levels of pulse tubes, newer applications include propellant liquefaction for Mars sample return missions.[106] Although multistaging has enabled laboratory and commercial pulse tubes to achieve 4 K, these systems are not yet qualified for flight use.

Much of the effort in developing spacecraft cryogenic systems is currently aimed at achieving a better understanding of the underlying thermodynamics of pulse tubes. The absence of a cold moving regenerator leads to less EMI and microphonics, a more robust design, and simpler integration with the instrument compared to a Stirling cooler. The potential problems associated with the use of mechanical compressors must still be addressed, however.

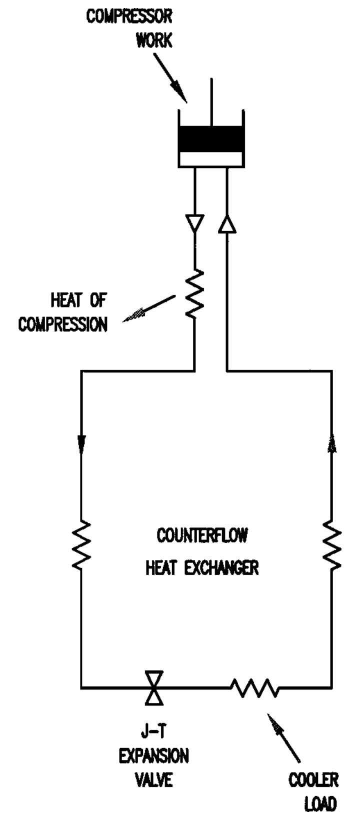


Fig. 8 Schematic of J–T cycle cooler.

J–T Coolers with Mechanical Compressors

Expansion of a nonideal working fluid from below its inversion temperature results in a cooling effect (Fig. 7). This effect is made use of in the J–T cycle, which is commonly used because of its simplicity, reliability, and efficiency. Different working fluids can be used to achieve a wide range of cooling temperatures. The basic J–T cycle is shown in Fig. 8. A compressor is used to compress the working fluid to a high pressure. The high-pressure gas passes through a counterflow heat exchanger, where it is precooled to below its inversion temperature by the returning low-pressure gas stream. The precooled gas is then expanded isenthalpically through an orifice. It is not necessary for the expansion to create a two-phase fluid: it may produce a single-phase gas. The expanded fluid absorbs the heat load at constant temperature, and the low-pressure gas returns to the compressor to complete the cycle.

Through the use of mixtures of gases as the working fluid, the enthalpy change is greater, and the efficiency of the cooler can be increased typically by an order of magnitude.[107] The characteristics of several types of binary mixtures can now be fairly accurately predicted.[108–110] There are several advantages to using J–T systems. The cold head inherently consists of small-diameter tubing, which takes up little volume, can be made to be flexible and can be engineered to have a low parasitic heat leak. In addition to improving the net efficiency of the system as a whole, this may obviate the need for separate heatswitches between multiple coolers and/or instrument components at differing temperatures. The absence of cold moving parts improves the reliability of the system and avoids the generation of EMI at the cold end, with little associated vibration. The lines connecting the compressor to the cold head are at ambient temperature, and in consequence, the compressor can be located away from the instrument. The compressor can be located near the spacecraft heat rejection system, which eliminates the need for a heat transfer system to remove heat generated by the compressor. However, there is also the possibility that the J–T orifice will plug. To prevent initial freeze out of contaminants in the cold stage, which would cause a partial or complete blockage in the J–T orifice, a contamination control system continuously removes residual contaminants from the working fluid. A partial or complete blockage is designated an outage rather than a failure because a heater at the orifice can disperse the contaminants, which are then removed using a hot reactive getter. The system can then cool down once more. Also, the J–T specific power (required input power per watt of refrigeration achieved) is high compared to other cryogenic cycles, particularly at higher pressure ratios.

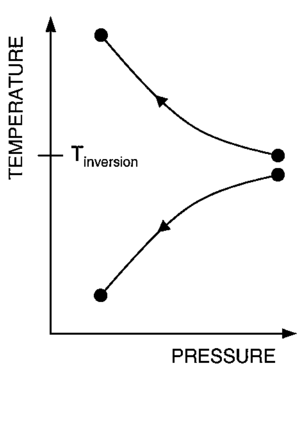


Fig. 7 Isenthalps for expansion of a working fluid from above (below) the inversion temperature to achieve warming (cooling).

A 65-K J–T system has been developed to operate in 0-g for space use.[111,112] This uses an oil-lubricated compressor, which passes the working fluid at 75 bars through a gas purifier. The oil scavenger and the coalescer remove the oil from the working fluid, a getter removes the gaseous contaminants, and a particle filter removes the particulate contamination. The fluid enters the cold head at ambient temperature and is cooled by counterflow heat exchange and a thermoelectric cooler.[113] On exit from the heat exchanger, the flow splits into two streams and is expanded to provide cooling at 122 and 65 K. Each stream then returns to the compressor to complete the cycle. This system has flown successfully on the STS in 1997 (Ref. 114).

Hybrid cryocooler systems consisting of a J–T expansion system precooled by a multistage Stirling system have been developed for use at 4 K (Refs. 115 and 116) and at 10 K (Ref. 117). At these low temperatures, the specific heat of the helium working fluid becomes comparable to that of the regenerator matrices, so that the regenerative heat exchangers become very inefficient and counterflow heat exchangers in conjunction with the J–T system are used instead. These J–T compressors are similar to the Stirling compressors described earlier, with the addition of one-way valves to provide a dc flow to the J–T expansion orifice at the cold stage. The RAL cryocooler heatlift capability is 11 mW at 4 K using ^{4}He and 3 mW at 2.5 K using ^{3}He. Theoretical inversion points for the ^{3}He curve have been compared to the experimentally available data by Maytal.[118] A schematic of the system is shown in Fig. 9 and a photograph of the cold end in Fig. 10. Space qualification of this 4-K cooler has been undertaken[119,120] and the J–T stage of the design is baselined for precooling of the Planck High Frequency Instrument.[121] A 6-K J–T system that uses a helium/hydrogen working fluid mixture is being developed for possible use on the Next Generation Space Telescope (NGST),[122] based on a 10-K U.S. Air Force cooler.

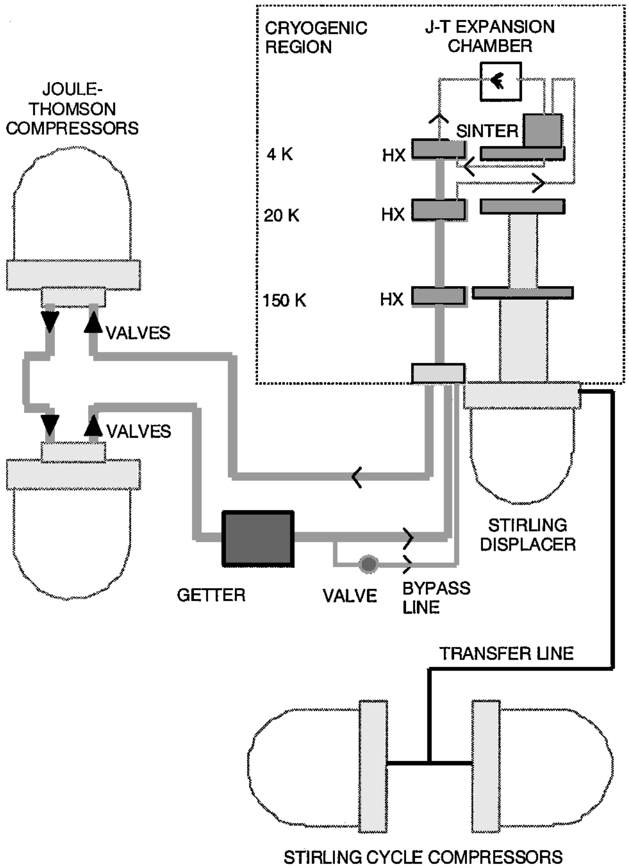


Fig. 9 Schematic of RAL 4-K cryocooler system.

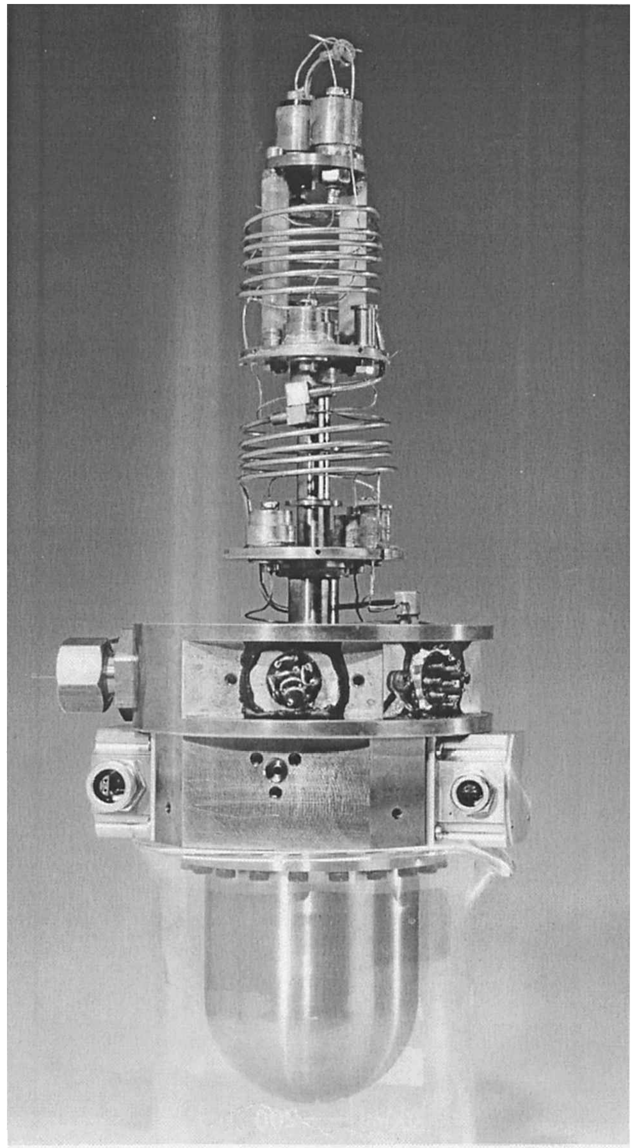


Fig. 10 Stirling displacer and J–T 4-K cold end.

Brayton Coolers

Brayton coolers are similar to J–T systems, but instead of expanding a working fluid using an orifice (which is irreversible and inefficient), they use an expansion engine to expand the fluid more efficiently. A schematic of a Brayton cooler is shown in Fig. 11. For expansion engines, these coolers typically use turbines that have gas bearings to achieve high reliability with low levels of induced vibration. These types of coolers achieve high heatlift at relatively high temperatures, but a challenge has been to miniaturize these coolers without introducing significant parasitic losses.[123,124] Recent advances include successful development of a small, permanent magnet-driven compressor that operates at speeds up to 10^4 revolutions s^{-1}, together with the demonstration of self-acting gas bearings. The NICMOS instrument on the Hubble Space Telescope (HST) was originally cooled using solid nitrogen, but a thermal short led to the cryogens being used up within two years. The instrument will be cooled again using the NICMOS Brayton cooler, which has a heatlift of 7 W at 77 K. This cooler flew on STS flight in 1998 and will be installed on the HST during the third servicing mission scheduled for March 2002 (Ref. 125).

Sorption Coolers

Two drivers behind the development of sorption refrigeration for space use were to eliminate the failure modes present in the mechanical compressors and to achieve a cooling system that was more compatible with the detector in terms of system integration and detector performance. Sorption refrigerators typically use a thermally driven compressor to supply high-pressure gas to the cold stage. For systems operating above $\sim$2 K, the cold stage has a separate expansion system. This is typically a J–T orifice, because the efficiency of both the sorption compressors and the J–T systems improves at high-pressure ratios and low flow rates. General developments in the techniques of sorption refrigeration[126,127] together with those applicable to cooling of astrophysics missions[128,129] have been reviewed.

There are two types of sorption process. Physical adsorption, or physisorption, relies on the relatively weak van der Waals forces between the refrigerant gas (sorbate) and the sorbent material. No covalent bonds occur, and the heats of physical adsorption are low. Activated charcoals, zeolites, and silica gels are some of the materials used in physisorption cooling. Chemical adsorption, or chemisorption, involves the formation of a chemical bond (usually covalent). Reaction occurs between the sorbent and sorbate, and so the heats of chemisorption are typically much higher. Chemisorption materials include metal hydrides and praseodymium cerium oxide (PCO).

Physisorption coolers have been developed over the past two decades, resulting in a steady improvement in performance attributable to the use of improved materials, higher preexpansion J–T pressures, improved J–T precooling, and also regeneration of the waste heat from cycling of each compressor. For example, thermal switches can be used to bring opposing compressors into thermal equilibrium. Alternatively, an active valved-regenerative system can substantially improve performance.[130] Considerable development has been undertaken toward a 10 K periodic chemisorption refrigerator that potentially has a 10-year lifetime.[131,132] This research includes further characterization of the sorbent material[133] and the sorbent bed design.[134] Stringent contamination control has been necessary to minimize the risk of J–T blockage and sorbent degradation. This technology has been flown as the Brilliant Eyes Ten-Kelvin Sorption Cooler Experiment (BETSCE)[135] on the *Endeavour* STS-77 mission.[136] The system achieved a base temperature

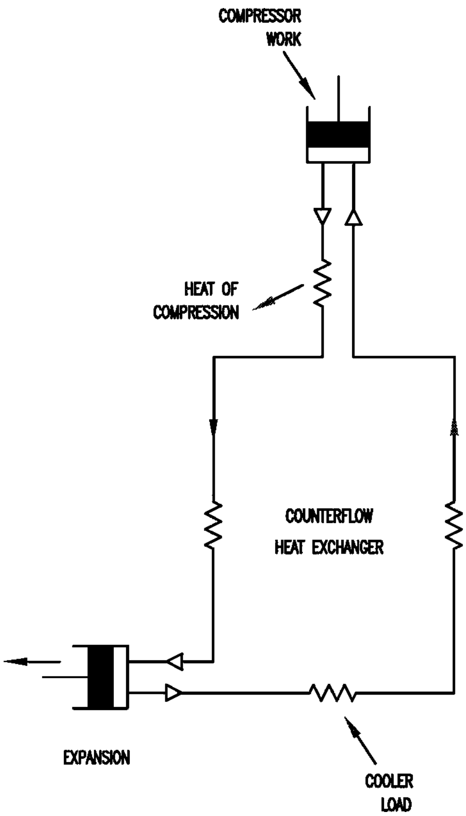


Fig. 11 Schematic of Brayton cycle cooler.

of 10 K on one cooldown. No in-orbit degradation was found, and so this flight has validated the use of hydride sorption coolers in space. Specifically, microgravity effects were negligible on the $LaNi_{4.8}Sn_{0.2}$ and ZrNi hydride powder conductivities, on the supercooling of the phase change material in the sorbent bed, and on the ability of the liquid reservoir to separate and retain both liquid and solid hydrogen.

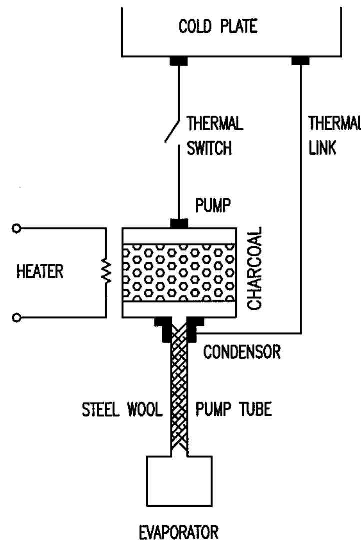
A prototype 20 K chemisorption system built for the Long-Duration Balloon Experiment[137] used four $LaNi_{4.8}Sn_{0.2}$ hydride sorption beds for continuous operation to pressurize a J–T system, with hydrogen as the working fluid. A derivative design will cool both instruments on the Planck spacecraft to measure the temperature anisotropy and polarization of the cosmic microwave background.[138] Sorption cooling is being considered as a potential option for cooling of the instruments on NGST.[139,140]

Sorption coolers to achieve temperatures of less than 2 K have been described by Duband et al.[141] and Kittel.[142] The difference between these coolers and those described earlier for use at higher temperatures is that these systems do not have a further expander system. The cooling to base temperature is accomplished, first, by achieving the saturated vapor pressure for the working fluid from thermal compression alone. Second, on cooling down, the sorbent material in the system adsorbs the vapor above the liquid, thus cooling the cold stage down further. These coolers use activated charcoal or zeolite as the sorbant and either ^3He or ^4He for the sorbate. The vapor pressure above the ^3He working fluid decreases exponentially with temperature as

$$P_3 \propto \exp[-L_3/RT] \tag{2}$$

L_3 tends to a constant at low temperatures, but the cooling power is the given by the product of the mass flow and L_3. The mass flow decreases because it is limited by the pressure drop in the pumping line, and this in turn is limited by the pressure difference between the vapor pressure and the pressure in the sorbent pump. The vapor pressure decreases rapidly with decreasing temperature, and the pump pressure raises as the sorbent saturates. As a result, the cooling power decreases as the temperature decreases, and a practical limit to this type of cooler is a base temperature of ~0.25 K. A schematic of a simple ^3He system for ground-based use is shown (following Duband et al.[141]) in Fig. 12. This design only works in the presence of gravity. All components are first cooled down to ~2 K, typically by pumping on the ^4He bath to which the cold plate is thermally heat sunk. At this temperature the ^3He is all adsorbed by the sorbent in the pump. The sorption cycle is started by heating the pump to ~30 K to desorb the ^3He gas from the sorbent. When the ^3He gas pressure exceeds the saturated vapor pressure of ^3He at the cold plate temperature, liquid condenses in the condenser and falls into the evaporator. After condensation is complete, the pump allowed to cool. The adsorptivity of the charcoal increases, which reduces the vapor pressure of the ^3He gas. In turn this reduces the temperature of the ^3He liquid. Typically, the temperature will fall to ~0.3 K. The purpose of the steel wool is to prevent Taconis oscillations from occurring and does not affect the pumping speed. Adsorption isotherms of helium on activated charcoal at the higher pressures of interest for sorption coolers have been measured at the Centre de Recherches sur les Très Basses Températures (CRTBT)[143] and NASA Ames Research Center.[144] The adsorption isotherms for ^3He have been shown by Duband et al.[141] to be the same as those of ^4He, as shown in Fig. 13. Figure 13 also shows the temperature of the sorption pump during the cycle procedure. From process 1 to process 2, the pump and, therefore, the gas is heated. Eventually the sorbate will be hot enough to be desorbed from the charcoal, and the reduced specific heat of the fluid alone results in a rapid increase in temperature (process 2–3) with the gas eventually reaching saturated vapor pressure. If the condensation point is colder than the critical temperature of the fluid, the gas will condense and liquefy. The pump is then allowed to cool and pumps on the liquid, which in turn reduces the vapor pressure of the liquid and decreases its temperature (process 3–4). During process 4–1, the still has reached

Fig. 12 Basic ^3He sorption system.



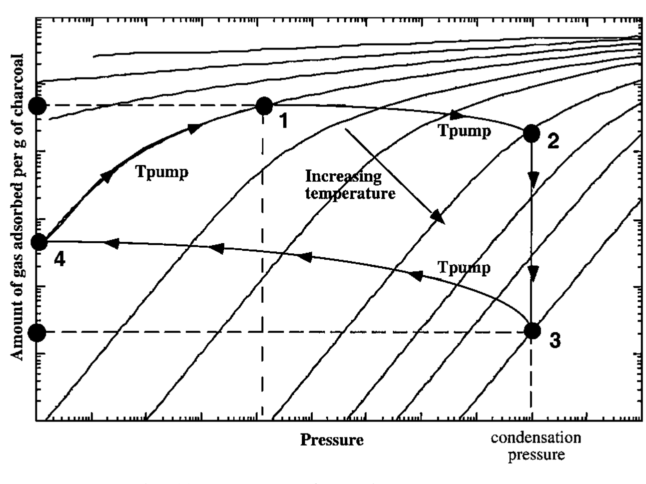


Fig. 13 Isotherms for helium on charcoal.

base temperature and the pump absorbs the vapor boiled off by the incident heatload.

Helium sorption systems have been used for many years in ground-based instruments. One problem with the single-stage ^{3}He system is that the critical temperature for ^{3}He at 3.3 K is below the temperature of a ^{4}He bath at 1 bar (standard atmospheric) pressure. To achieve condensation of liquid ^{3}He, it is necessary to have a bath temperature lower than 33 K. For balloon-based systems, the reduction in the ambient pressure with increasing altitude ensures that this requirement is met, although the systems are in fact usually cycled at sea level. The cryogenic instrument designed by Torre and Chanin achieved 0.32 K in its first flight.[145,146] The Argo balloon-borne cosmology experiment uses a 0.28 K ^{3}He refrigerator with a hold time of 50 h (Ref. 147). Three flights of the Far Infrared Survey (FIRS) and three flights of Medium-Scale Anisotropy Measurement 1 (MSAM1) used a 0.23 K refrigerator,[148] looking at the temperature anisotropy of the cosmic microwave background. This system uses zeolite and has a hold time of more than seven days with an ~100-μW heatload. A 0.3 K system was flown both on the North American test flight and the 10-day Antarctic flight of the Balloon Observations of Microwave Extragalatic Radiation and Geomagnetics (BOOMERanG) payload, again to measure the temperature anisotropy of the cosmic microwave background.[149] For ground-based observations and aircraft flights, it is inconvenient to have to pump on the ^{4}He bath each time the system is cycled, and so two-stage systems have been developed that operate from a liquid 4.2 K bath.[150,151] These two-stage systems use a separate precooler stage, similar to the ^{3}He sorption system but with ^{4}He as the working fluid. The critical temperature of ^{4}He is 5.2 K. By the pumping on this independent ^{4}He volume, which is thermally connected to the ^{3}He condensation point, the ^{3}He can then be liquefied. These multistage refrigerators are currently being produced by Duband[152] and by Chase as described in Bhatia et al.[153]

Considerations for using a ^{3}He refrigerator in space have been outlined by Kittel and Rodriguez.[154] In the 0-g environment, it is necessary to confine and separate the two phases of the working fluid. This separation can be done by first using the necessary temperature gradients to condense the liquid directly into the evaporator and then to use a matrix to hold the liquid by capillary attraction.[155] Pore sizes typically below 10 μm are needed. The effects of bubble nucleation and growth during the evaporation phase must be considered. Also, it is important to ensure that the thermal conductivity of the porous matrix does not degrade the thermodynamic efficiency of the system. Tests using porous matrices to hold ^{3}He and ^{4}He have been carried out at NASA Ames Research Center[156] and at CRTBT. A single-stage system designed for a rocketborne experiment[157] achieved 372 mK in flight.[158] Figure 14 shows a schematic for a further system developed for space use[159,160] that achieved 302 mK between three weekly cycles over the course of the IRTS mission. The evaporator used a silica sponge to contain the liquid ^{3}He. This sponge has low thermal conductivity, but low density and high porosity. During pump cooldown, there is a large heatload on the evaporator due to conduction down the pump tube. The purpose of the thermal link on the tube is to shunt this heat load directly to the heatsink. This prevents a large quantity of liquid from being boiled away and also leads to a higher condensation efficiency, which in turn leads to a longer hold time. This type of sorption refrigerator will be used on the Spectral and Photometric Imaging Receiver (SPIRE) instrument on the HSO.[161]

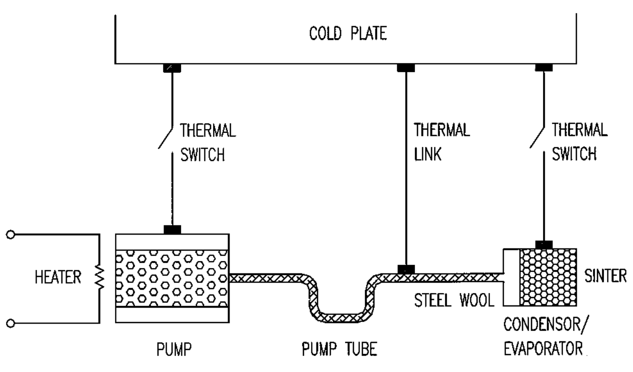


Fig. 14 Space-based ^{3}He sorption refrigerator.

To achieve temperatures below 1 K, ^{3}He is used because it has a higher saturated vapor pressure than ^{4}He at these temperatures. Liquid ^{3}He also has a larger heat capacity than liquid ^{4}He, resulting in a larger heat reservoir at the base temperature. Finally, ^{3}He is not superfluid over this range of temperatures. If, however, a temperature of only 1 K is needed, then ^{4}He is used instead. The major concern in building an ^{4}He cooler is the presence of a film of superfluid ^{4}He, which can creep along the wall of the pump tube. This fluid creep not only reduces the residual liquid left for evaporation, but also substantially increases the parasitic heatload on the evaporator because the thermal conductivity of the superfluid is high. This effect can be eliminated through the use of a small diaphragm or orifice at the pumping line–evaporator interface. A ^{4}He refrigerator has been successfully flown on a sounding rocket.[162] The problems of liquid confinement are also encountered in developing a ^{3}He/^{4}He dilution refrigerator for space use. Metal sinters and sorption pumps have been used to alleviate these problems by Roach and Helvensteijn.[163,164] One problem with the ^{3}He and ^{4}He sorption coolers previously flown in space is that they were dependent on a superfluid ^{4}He cryostat for precooling. For IRTS, this limited the mission lifetime, as is usually the case for a system flying liquid cryogens. Several groups are developing a design with precooling of the sorption system from a mechanical cryocooler. In summary, sorption coolers are reliable, have no moving parts (unless flow check valves are used), generate little EMI and vibration, and have been qualified for use in space for temperatures as low as 0.3 K.

Adiabatic Demagnetization Refrigerators

The operating principle of adiabatic demagnetization refrigerators (ADRs) is the magnetocaloric effect, where the entropy changes as a function of temperature and magnetic field according to[165]

$$dS = \frac{C_B}{T}\,dT + \left(\frac{\partial M}{\partial T}\right)_B dB \tag{3}$$

This effect can be used to achieve temperatures from ~20 K down to the milli-Kelvin region, and early applications of adiabatic demagnetization refrigeration have been reviewed by Barclay.[166] Magnetic refrigerators can be incorporated into Stirling cryocoolers, using the same working fluid as these regenerative cycles. These hybrid systems can then improve on the reduced efficiency of regenerators at low temperatures.[167,168] For space-based applications at sub-Kelvin temperatures, however, the main technology of interest remains that of adiabatic demagnetization of paramagnetic salts.

The thermodynamic principles underlying this cooling technique have been described by several authors (for example, Refs. 169 and 170). The thermodynamic cycle for an ADR is given in Fig. 15. This diagram shows the variation with temperature of theoretically determined values of entropy (normalized to the gas constant R) for various levels of magnetic field applied to the salt. The ideal cycle for states 1 to 2 to 3 is considered first. During isothermal magnetization from state 1 to state 2, the field changes from its zero level to (in this case) 6 T. The heat content Q of the salt changes by

$$\Delta Q_{T1} = \int_{S1}^{S2} T_1\,dS \tag{4}$$

During the adiabatic demagnetization process from state 2 to state 3, the entropy stays constant. Finally, the system warms up along the zero field curve from state 3 to state 1 (Fig. 15).

Temperature control is important for the stability of infrared detectors. If the salt pill is completely demagnetized, then the base temperature T_3 is achieved, but the system has zero hold time at this temperature. Control about a set point above the minimum temperature T_3 can be achieved using a resistive heater. This technique is simple and reliable but is inefficient. Through partial demagnetization initially to state 5, it is possible to periodically reduce this residual field to compensate for the heatleak into the cold stage (Fig. 15). The salt pill warms up from state 5 to state 6 from the

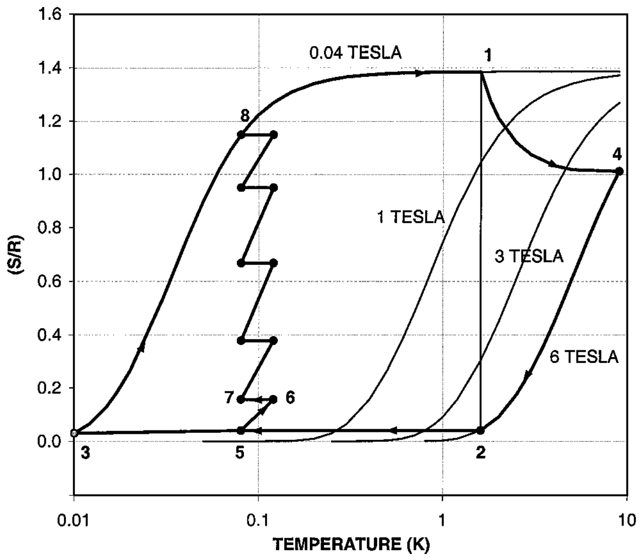


Fig. 15 ADR cycle.

parasitic heatleak and the optical/thermal dissipation. However, by decreasing the residual field further, the pill cools from state 6 to state 7, and so temperature control about (in this case) 100 mK is achieved (Fig. 15). The process is repeated until no residual field remains, after which the salt pill warms from state 8 to state 1, and the cycle is repeated. Proportional integral derivative temperature control has been used successfully for temperature control on many cryogenic systems.[171] Temperature control using field regulation in this manner has been described by Kittel[172–174] and Bernstein et al.[175]

The salt pill material should ideally have a number of characteristics that make it appropriate for use in a space-based ADR. It should have a high magnetic moment density and low enough magnetic interactions that it remains in the paramagnetic state down to the lowest temperature of interest; have low density to keep the support structure small and minimize parasitic heatloads; be capable of repeated thermal cycling between the heat rejection temperature (typically 1.6 K) and the base temperature; be chemically and physically stable over the mission lifetime; be able to withstand the residual level of incident radiation that passes through the shielding provided by the spacecraft and the ADR; be able to survive room temperature storage for the duration of the spacecraft assembly and prelaunch phase; not be adversely affected by a preflight bake-out temperature of ~60°C, which is necessary to outgas many of the volatile components in the spacecraft; and have a high thermal conductivity. Salt pill development and testing has improved the cycle efficiency while retaining the longevity of the pill for long flight durations.[176,177] The paramagnetic salts commonly used for the sub-Kelvin temperature range are hydrated salts, which contain elements from the iron group. Ferric ammonium alum (FAA) and chromic potassium alum (CPA) are two common such materials. The dipole–dipole and exchange interactions in these compounds are small, due to the relatively large spacing between magnetic ions. This degree of ordering is necessary to achieve a low ordering temperature because the dipoles then interact with the externally applied field rather than with each other. The large spacing between the ions arises from the presence of the water molecules, but this can also cause a problem because they are loosely bound and chemically active. This can lead to a variation over time of the properties of the salt pill at low temperature. FAA and CPA are mildly corrosive and dehydrate when exposed to air or vacuum. They decompose at moderate temperatures (40°C for FAA and 89°C for CPA). The effect is reduced by compressing the salt into the shape of a pill and sealing it with a fiber-glass tube. The salt pill subassembly must be able to achieve good thermal contact from the salt pill to the detector stage. One way of achieving this is to grow the salt pill directly onto gold-plated copper wires. The wires are silver-soldered or welded to a copper post, which is thermally connected to the detector stage. The electrical and thermal dissipation at the bolometer stage is usually small compared to the parasitic heat load from the suspension of the salt pill, and so the design of the salt pill suspension is critical.

The magnet functions correctly only if all parts of the windings remain superconducting. If any part of the windings becomes normal, the Joule heating of the current passing through it will increase the size of the normal zone. If the heating effect is large then it is possible that the normal zone may propagate through the whole of the magnet. The energy Q stored in the magnet is

$$Q = \tfrac{1}{2} L I^2 \tag{5}$$

If all of this energy is released, then a large amount of helium liquid may be evaporated away and the stage warm to significantly above base temperature. This process is referred to as a quench. A diode is included in parallel with the magnet to limit the possible voltage drop across the leads in the event of a quench, thereby protecting the magnet.

ADRs have been successfully used in astronomical instruments for ground-based telescopes, for example, at the Hale telescope[178] and the South Pole at 100 mK (Ref. 179) and at 50 mK when used with a ^{3}He precooler stage.[180] An ADR has been built at the University of Wisconsin for cooling an array of microcalorimeters to 60 mK and has now flown three times on a sounding rocket.[181] A prototype ADR for cooling superconducting tunnel junction detectors has been developed for space use.[182] Practical considerations for space use of ADRs have been outlined by Kittel.[183] NASA GSFC developed a prototype ADR[184] followed by a flight model[185,186] for use on the x-ray spectrometer on Chandra. This mission originally proposed the use of Stirling mechanical cryocoolers to help cool the outer vapor-cooled shield of the cryostat.[80,81,187] After rescoping and the splitting of the mission into two flights,[188] the spectrometer was launched on the ASTRO-E mission with the ADR precooled by solid neon and liquid helium cryogens,[189] but this payload was lost because of a problem during launch and is now scheduled to be flown again in 2005. A similar cryogenic design to that for Chandra was baselined for cooling the bolometers on SIRTF.[190] A demonstrator ADR was built at the University of California, Berkeley,[191] and served as a prototype for the original SIRTF ADR.[192–194] Although the SIRTF mission was descoped and the bolometers removed from this flight, the ADR has since been successfully flown on the fourth and fifth flights of the balloon-borne Millimeter Wave Anisotropy Experiment (MAX)[195,196] and on the upgrade instrument Millimeter Anisotrophy Experiment Imaging Array (MAXIMA) for measurement of the temperature anisotropy of the cosmic microwave background.[149] A similar balloon-borne experiment using an ADR was developed at Brown University.[197]

ADR development is now focusing on multistaging and integrating with mechanical cryocoolers. A two-stage ADR using two salt pills magnetized using a single solenoid has also been developed at Berkeley.[198] These types of thermal guards have been used in the past for laboratory ADRs.[199,200] ADRs have been developed in Europe for potential use on spaceflights requiring temperatures on the order of 100 mK (Refs. 201 and 202). Modeling performed at the Mullard Space Science Laboratory (MSSL) of an ADR precooled by mechanical cryocooler has shown that good performance is still achievable even with precooler temperatures as high as 4 K (Refs. 203 and 204). This higher temperature is important because the cooling power of a closed-cycle cryocooler increases rapidly with increasing temperature. In contrast to the Berkeley two-stage ADR, MSSL has developed a double ADR with an individual magnet for each of two salt pills.[205,206] The double ADR has the advantages of lower individual magnet currents and field levels, thereby reducing the peak power dissipation on the cryocoolers. A double ADR precooled to 6 K by a pulse tube cryocooler will be flown on a sounding rocket in 2003 to precool superconducting tunnel junction detectors. GSFC has built a three-stage ADR, has designed a four-stage ADR for continuous operation[207] and is investigating the operation of ADRs from mechanical coolers.[208]

ADRs have high reliability and are insensitive to gravity orientation, with the obvious advantages of these for space flight. The magnetic fields can be of potential concern and need to be shielded.

Magnetic shielding has been developed for returning the magnetic flux from the solenoid and so mitigating the influence of EMI on sensitive electronics.[209,210] To improve the cycling efficiency of the ADR, it is important to consider the effect of losses due to eddy current heating.[211] The size and power consumption of the refrigerators has been considerably reduced, while maintaining the required performance and reliability. Some concerns with the generated magnetic fields and the possibility of a quench occurring still remain, and ADRs do have a duty cycle, but these systems nonetheless now present an attractive option for achieving temperatures below 0.3 K in space. In summary, much of the basic development of ADRs is now complete and work in progress is aimed at space qualification of these systems, particularly integration with cryocoolers.

Dilution Refrigeration

Dilution refrigeration is a widely used cooling technique to temperatures below 0.3 K in ground-based low-temperature applications. Dilution refrigeration has been reviewed by Radebaugh[212] and will be considered here in some detail because this technology has not yet been flown in space but is the baseline 0.1 K cooling technique for the Planck spacecraft. We first describe the principle of cooling, then discuss the modifications that are necessary for such a system to operate in 0-*g*.

The phase diagram of liquid $^3He/^4He$ mixtures is shown[213] in Fig. 16. Above 0.87 K, the mixture is in a single-phase state for all concentrations of ^3He, and so separation is never observed. For mixtures with a concentration of ^3He greater than 0.064 that are below 0.87 K, the mixture separates into two phases, one of which is rich in ^4He and the other of which is rich in ^3He. The ^3He rich phase is less dense than the ^4He phase and in the presence of gravity will float on top of it. As the temperature is reduced, the concentration of ^4He atoms in the ^3He rich phase decreases exponentially, but the concentration of ^3He on the diluted side tends to a constant value[214] of 0.064 so that even at the lowest temperatures we have ^3He dissolved in superfluid ^4He.

The simplest design of dilution refrigerator (DR) for laboratory use is shown in Fig. 17. The coldest part of this DR is termed the mixing chamber and contains a phase-separated mixture of ^3He and ^4He at a temperature typically of a few tens of milli-Kelvin. The upper phase is almost pure ^3He, and the lower phase contains a concentration of ^3He of 0.064. If we can pump ^3He out of the lower phase, we create a net flow of ^3He across the interface and achieve cooling through the latent heat of mixing: the mixture has a different enthalpy from the total enthalpy of the individual phases. However, the vapor pressure at these low temperatures is very low, and it is not possible to achieve this pumping with standard vacuum pumps. As the temperature increases, the partial pressure of ^3He increases. Therefore, pumping is achieved using a separate distillation pot (or still), which is maintained at a higher temperature than the mixing chamber, typically 0.7 K. The fluid is precooled typically to ~1.3 K via liquefaction in the condenser.

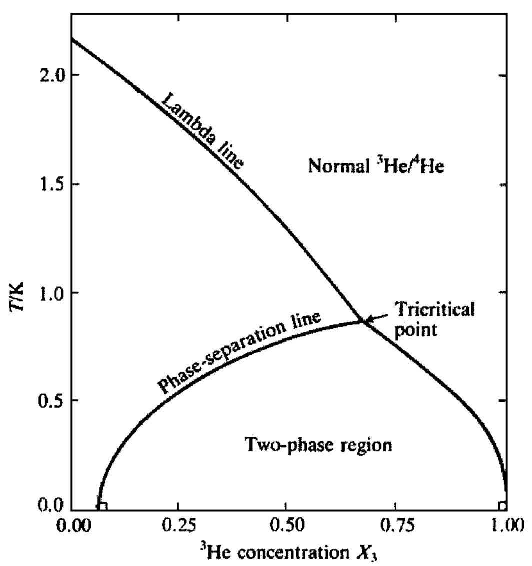


Fig. 16 Phase diagram of liquid $^3He/^4He$ mixtures.

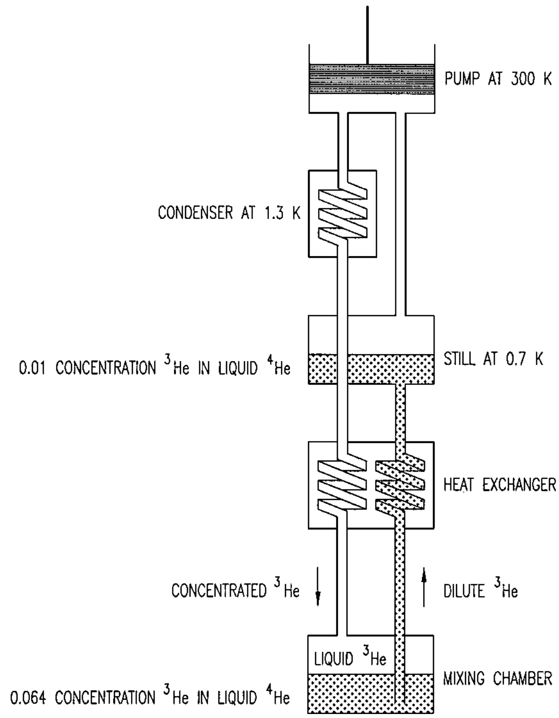


Fig. 17 Simplified schematic of DR.

Problems arise with adaptation of the classical dilution system for use in space because gravity is used to maintain the phase separation in the still, the mixing chamber, and (for some systems) in the condenser. Additional demands are imposed by the complex pumping installation needed to cycle the ^3He. The classical ^3He circulation DR has three phase boundaries: the vapor/liquid interface in the ^3He condenser, the dilute solution/concentrated solution interface in the mixing chamber, and the vapor/liquid interface in the still.

The vapor/liquid thermal interface in the condenser is set by the condenser thermal gradient. The wall temperature falls rapidly at the condenser, and the fluid changes state over a short distance from single-phase vapor to single-phase liquid. Also, the tube is of small diameter so that the fluid is roughly isothermal, and free convection will not occur. Under these conditions, gravity is not an important factor.

In Fig. 17, the ^3He is shown entering the concentrated phase and diffusing across the interface. In practice, the ^3He is introduced into the dilute solution directly to increase mixing and to maintain the concentration equilibrium in the mixing chamber. If droplets of pure ^3He do leave the mixing chamber and flow toward the still, then that quantity of ^3He is not available for cooling and will flow around the loop, adding a parasitic heatload on the mixing chamber as it is recooled. Furthermore, that ^3He will evaporate on its way to the still, interrupting the flow of ^3He and, therefore, the dilution in the mixing chamber and the refrigeration. The position of the phase interface in the mixing chamber is set by the amount of ^4He in the system. To first order, the ^4He acts as a mechanical vacuum. If the still ^4He phase boundary is fixed, then the position of the phase interface will be fixed. The still and connecting lines remain full of dilute solution, and the phase interface remains in the mixing chamber without breaking up even if part of the phase interface leaves the mixing chamber.

The final phase boundary is in the still. Here, the dilute solution is a superfluid so that the walls are coated with a superfluid film, which can creep into the pumping lines and contribute a large parasitic load. In 0-*g*, the film creep can reach through the cold section of the pump lines, and the ^4He level will be much higher than in 1-*g* operation. Therefore, the phase boundary in the still must be controlled for successful 0-*g* operation.

A DR for use in a 0-g environment has been developed by Roach and Helvensteijn.[163,164] This refrigerator uses gas desorption from charcoal pumps for all pumping operations, with a porous metal sinter to confine and control the liquid phases at low temperatures. The sinter pore size is coarser than that usually used to confine ^{3}He because it was found that a very fine pore size impeded the flow of dilute ^{3}He from the mixing chamber to the still. This system is most suitable for single-cycle operation, but can be modified relatively easily for continuous operation. An ^{4}He circulation DR for possible 0-g use has been investigated by Hendricks.[215] It circulates ^{4}He, but there is only one phase boundary, in the mixing chamber. Only the mixing chamber operating point is on the phase separation line in Fig. 17. The rest of the dilute solution has subcritical ^{3}He concentration. The demixing chamber can then operate at temperatures above the phase separation point, and it is feasible that a ^{3}He vapor precooler may not be needed. Tests of a porous metal phase separator for this system have shown that trapping of a ^{3}He/^{4}He mixture against gravity can be achieved. Another attempted method for 0-g operation using electrostiction to separate and hold the two phases in the mixing chamber has been investigated by Jackson,[216] but this requires high electric field intensities and is yet to be demonstrated.

Instead of using osmotic pressure to extract ^{3}He from the dilute phase in the mixing chamber, it is possible to use the mutual friction between dissolved ^{3}He and ^{4}He to drive ^{3}He out of the mixture,[217] provided the velocity of the ^{4}He is high enough. This is the principle of operation of the Benoît DR. The two pure liquid isotopes are precooled in a heat exchanger, then mixed together to produce the cooling due to the enthalpy difference between the pure isotopes and the dilute mixture.[218] The viscosity of the ^{3}He–^{4}He dilute phase has been measured by Bradley and Oswald.[219] To keep viscous heating to a minimum, the inlet gases flow through cylindrical tubes of very small diameter. The gases are at a pressure higher than the critical pressure, and there is only a small pressure drop due to viscous losses. The mix return line is of slightly larger diameter, and the three tubes are soldered together forming a recuperative heat exchanger. In thermodynamic equilibrium, the ^{3}He concentration decreases with increasing temperature. To extract the ^{3}He at the warmer end of the heat exchanger, it is necessary to avoid the counterflow diffusion of ^{3}He in the tube by maintaining the ^{3}He injection rate at a level higher than the solubility limit. In these narrow tubes, the surface tension maintains a sequence of concentrated and dilute drops to avoid ^{3}He diffusion in the dilute phase.[220] As the temperature increases, the bubbles dissolve, and in the warmest part of the heat exchanger, it is the mutual friction between ^{3}He and ^{4}He that prevents ^{3}He counterflow. To run such a system, it is not necessary to use a mechanical pump or circulator, but only to store the pure isotopes at high pressure (and ambient temperature) and allow the gases to flow at the correct rates and in the correct ratios into the cryostat using mass flowmeters. The development of this DR is described by Paragina et al.[221] This system precooled using the 4 K hybrid J–T/Stirling cryocooler described earlier has been adapted for potential use on astronomical missions.[222,223] Figure 18 shows a schematic of the Planck spacecraft's High Frequency Instrument that multistages many of the cryogenic technologies discussed here. The 60 K heatsink is provided by three V-groove radiators viewing the anti-sun direction from the L_2 Lagrange point of the sun–Earth system. The 18 K stage and the 20 K stages for the instruments are provided by hydrogen sorption coolers with J–T expansion at 18 K. The 4 K stage is provided by this hybrid J–T/Stirling cooler and the final 0.1 K stage by the Benoît DR. The J–T cooling effect at 1.6 K of the returning diluted mixture is essential for thermal shielding of the 0.1 K stage. The nominal cooling power of the system is 100 nW at 100 mK. Systems-level testing of microvibrations on a bolometer cooled using this dilution system[224] have shown that it is possible to achieve a fair degree of immunity to the effects of microphonics.

In summary, DRs have a long history of use in ground-based experiments, but it is only very recently that the potential problems associated with operation in a 0-g environment have been successfully addressed. Contamination remains a concern, and adequate precautions must be taken to ensure that the working fluid remains sufficiently pure to prevent blockage in the capillaries.

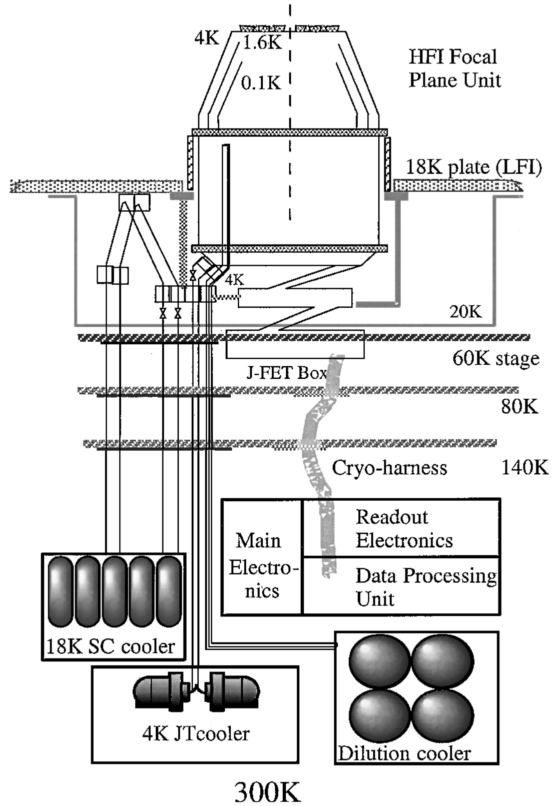


Fig. 18 Planck High Frequency Instrument.

Systems-Level Issues

Particular attention must be paid to systems-level issues involved in the use of cryocoolers. These include generated vibration and EMI, voltage ripples, thermal stability, and cold interfaces and warm interfaces for heat rejection. Along with the cryocoolers, several technologies are, therefore, being developed to facilitate the integration of cryocoolers with payloads. Cryogenic heat switches have been developed to reduce the parasitic heatload on cold stages, or to connect to a heat bath at specific points in the operational cycle. Gas gap heat switches have been developed for missions including IRTS, ASTRO-E, and Planck. The heat switches have a high on-state conduction, have a low off-state conduction, can withstand the launch vibration, and do not themselves generate any vibration or EMI when in use.[225–227] A mechanical switch using differential thermal contraction is described by Marland et al.[228] Thermal storage units have been developed to potentially allow periodic switch off of cryocooler systems and also to reduce thermal variations associated with the point source cryocoolers.[229,230] Systems engineering of cryogenic instruments is discussed further by Collaudin and Rando.[4]

Conclusions

Several cryogenic technologies have now been successfully developed for use on space missions. Radiators and open-cycle cryogen systems were initially popular choices, and it is only within the past decade that cryocoolers have become attractive alternatives and indeed feasible for multiyear missions requiring temperatures below 80 K. The latest technologies for sub-Kelvin temperatures are presently undergoing space qualification. There is no ready answer to the question of determining which is the optimal cryogenic system to fly on a particular mission; a number of tradeoffs must be made in, for example, the available heatlift, the reliability and failure modes, the lifetime, the cost, and the ease of integration with the instrument complement. The advantages of using cryocoolers over cryogens are partly offset by the introduction of new problems such as microphonic vibrations and electromagnetic interference, and these integration issues are critical. Nonetheless, confidence in the use of cryocooler systems for space has increased markedly within the past decade.

Acknowledgments

We acknowledge financial support from NASA Grant NAG5-6573 for United States Involvement in Planck. We thank several colleagues for useful discussions, in particular Alain Benoît, Thomas Bradshaw, Bernard Collaudin, Lionel Duband, Ian Hepburn, Peter Kittel, Christopher Paine, Ray Radebaugh, and Lawrence Wade. We also thank Kathy Deniston for administrative support and an anonymous referee for detailed comments on the manuscript.

References

[1]Walker, G., *Cryocoolers, Vol. 1 Fundamentals*, 1st ed., Plenum, New York, 1983, pp. 1–353.

[2]Wanner, M., "Future Development in Cryogenic Techniques for Space," *Proceedings of a European Space Agency Symposium on Photon Detectors for Space Instrumentation*, edited by T. D. Guyenne and J. J. Hunt, SP-356, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1992, pp. 115–122.

[3]Jewell, C. I., "Cryogenic Cooling Systems in Space," *Submillimetre and Far-Infrared Space Instrumentation*, edited by E. J. Rolfe, SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 267–276.

[4]Collaudin, B., and Rando, N., "Cryogenics in Space: A Review of the Missions and of the Technologies," *Cryogenics*, Vol. 40, No. 12, 2000, pp. 797–819.

[5]Radebaugh, R., "Advances in Cryocoolers," *Proceedings of the Sixteenth International Cryogenic Engineering Conference and International Cryogenic Material Conference*, edited by K. Yamafuji, T. Haruyama, and T. Mitsui, 1st ed., Elsevier Science, Oxford, 1997, pp. 33–44.

[6]Curran, D. G. T., Donabedian, M., Glaister, D. S., and Davis, T., "Cryocooler State of the Art for Space-Borne Applications," *Advances in Cryogenic Engineering*, edited by Q.-S. Shu, 1st ed., Vol. 45, Kluwer Academic/Plenum, New York, 2000, pp. 585–594.

[7]Glaister, D. S., Donabedian, M., Curran, D. G. T., and Davis, T., "An Overview of the Performance and Maturity of Long Life Cryocoolers for Space Applications," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1999, pp. 1–20.

[8]Bard, S., "Advanced Passive Radiator for Spaceborne Cryogenic Cooling," *Journal of Spacecraft and Rockets*, Vol. 21, No. 2, 1984, pp. 150–155.

[9]Bard, S., "Development of a High-Performance Cryogenic Radiator with V-Groove Radiation Shields," *Journal of Spacecraft and Rockets*, Vol. 24, No. 3, 1987, pp. 193–197.

[10]Kittel, P., "Is the V-Groove Radiative Cooler Optimized?," *Proceedings of the 6th International Cryocooolers Conference*, edited by G. Green and M. Knox, 1st ed., Vol. 2, 1991, pp. 145–151; also David Taylor Research Center, Rept. DTRC-01/001-002, Bethesda, MD, Oct. 1990.

[11]Cushman, G. M., Mather, J. C., and Fixsen, D. J., "Demonstration of Low Temperature Radiative Cooler for Future Space Missions," *Review of Scientific Instruments*, Vol. 68, No. 12, 1997, pp. 4596–4599.

[12]Mager, R., Fricke, W., Burrows, J. P., Frerick. J., and Bovensmann, H., "SCIAMACHY–A New Generation of Hyperspectral Remote Sensing Instrument," *Proceedings of the SPIE*, Vol. 3106, edited by K. Schaefer, *Spectroscopic Atmospheric Monitoring Techniques*, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1997, pp. 84–94.

[13]Petersen, H., Teunissen, F. J. H. M., and Vázquez, H. B., "Passive Cryogenic Cooler for MSG SEVIRI, Design and Performance," *Proceedings of the 6th European Symposium on Space Environmental Control Systems*, edited by T. D. Guyenne, ESA SP-400, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1997, pp. 523–531.

[14]Farrow, J. B., "Orbits for Radiatively Cooled Space Telescopes," *Space Science Reviews,* Vol. 61, No. 1–2, 1992, pp. 187–210.

[15]Thronson, H. A., Jr., Rapp, D., Bailey, B., and Hawarden, T. G., "Ecological Niches in Infrared and Submillimeter Space Astronomy: Expected Sensitivity as a Function of Observatory Parameters," *Publications of the Astronomical Society of the Pacific*, Vol. 107, No. 717, 1995, pp. 1099–1118.

[16]Thronson, H. A., Hawarden, T. G., Penny, A. J., Vigroux, L., and Sholomitskii, G., "The Edison Infrared Space Observatory," *Space Science Reviews,* Vol. 74, No. 1–2, 1995, pp. 139–144.

[17]Wade, L. A., "Active Refrigeration for Space Astrophysics Missions," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 845–854.

[18]Hawarden, T. G., Crane, R., Thronson, H. A., Jr., Penny, A. J., Orlowska, A. H., and Bradshaw, T. W., "Radiative and Hybrid Cooling of Infrared Space Telescopes," *Space Science Reviews*, Vol. 74, No. 1–2, 1995, pp. 45–56.

[19]Cunnington, C. R., "Thermodynamic Optimization of a Cryogenic Storage System for Minimum Boiloff," AIAA Paper 82-0075, Jan. 1982.

[20]Kittel, P., "Comparison of Dewar Supports for Space Applications," *Cryogenics,* Vol. 33, No. 4, 1993, pp. 429–434.

[21]Spradley, I. E., and Parmley, R. T., "Design and Test of Modified Passive Orbital Disconnect Strut (PODS-IV)," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 33, Plenum, New York, 1988, pp. 935–942.

[22]Seidel, A., Schwabbauer, P., Hilmer, K. H., Pulkert, G., Schällig, R., and Jewell, C., "Novel Orbital Disconnect Support for Cryogenic Tanks," *Cryogenics*, Vol. 34, No. 5, 1994, pp. 389–392.

[23]Holmes, W., Cho, H., Hahn, I., Larson, M., Schweickart, R., and Volz, S., "Performance Comparisons for Space Cryostats," *Cryogenics*, Vol. 41, Nos. 11–12, 2001, pp. 865–870.

[24]Forney, P., "Supercritical Helium Dewar Space Flight Results," *Proceedings of the 6th International Cryocooolers Conference*, edited by G. Green and M. Knox, 1st ed., Vol. 2, 1991, pp. 251–262; also David Taylor Research Center, Rept. DTRC-01/001-002, Bethesda, MD, Oct. 1990.

[25]Nakano, A., Petrac, D., and Paine, C., "He II Liquid/Vapour Phase Separator for Large Dynamic Range Operation," *Cryogenics*, Vol. 36, No. 10, 1996, pp. 823–828.

[26]Petrac, D., and Mason, P. V., "Evaluation of Porous-Plug Liquid Separators for Space Superfluid Helium Systems," *Proceedings of the 7th International Cryogenic Engineering Conference*, IPC Science and Technology Press, Guildford, England, U.K., 1980, pp. 120–125.

[27]Hendricks, J. B., and Karr, G. R., "Operation of Phase Separators in Zero Gravity," *Cryogenics*, Vol. 27, No. 1, 1987, pp. 49–53.

[28]Hung, R. J., Long, Y. T., and Zu, G. J., "Sloshing of Cryogenic Helium Driven by Lateral Impulse/Gravity Gradient Dominated/or *g*-Jitter-Dominated Accelerations and Orbital Dynamics," *Cryogenics*, Vol. 36, No. 10, 1996, pp. 829–841.

[29]Yuan, S. W. K., Frank, D. J., and Lages, C., "The Dependence of Choked Flow and Breakthrough on Pore Size Distribution in Vapour–Liquid Phase Separation of He II Using Porous Media," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 41B, Plenum, New York, 1996, pp. 1577–1584.

[30]Mason, P., Collins, D., Petrac. D., Yang, L., Edeskuty, F., Schuch, A., and Williamson, K., "The Behaviour of Superfluid Helium in Zero Gravity," *Proceedings of the 7th International Cryogenic Engineering Conference*, 1st ed., IPC Science and Technology Press, Guildford, England, U.K., 1979, pp. 99–112.

[31]Castles, S. H., and Schein, M. E., "Development of a Space Qualified Surface Tension Confined Liquid Cryogen Cooler (STCLCC)," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 33, Plenum, New York, 1988, pp. 819–826.

[32]Koszelak, S., Leja, C., and McPherson, A., "Crystallization of Biological Macromolecules from Flash Frozen Samples on the Russian Space Station Mir," *Biotechnology and Bioengineering*, Vol. 52, No. 4, 1996, pp. 449–458.

[33]Kittel, P., "Transferring Superfluid Helium in Space," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 31, Plenum, New York, 1986, pp. 897–904.

[34]DiPirro, M., Shirron, P., and Tuttle, J., "On-Orbit Superfluid Transfer—Preliminary Results from the Shoot Flight Demonstration," *Cryogenics*, Vol. 34, No. 5, 1994, pp. 349–356.

[35]Urbach, A. R., and Mason, P. V., "IRAS Cryogenic System Flight Performance Report," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 29, Plenum, New York, 1983, pp. 651–659.

[36]Urban, E. W., and Katz, L., "A Cryogenic Helium II System for Spacelab," *Proceedings of the 7th International Cryogenic Engineering Conference*, 1st ed., IPC Science and Technology Press, Guildford, England, U.K., 1979, pp. 113–119.

[37]Mather, J. C., "The Cosmic Background Explorer (COBE)," *Optical Engineering*, Vol. 21, No. 4, 1982, pp. 769–774.

[38]Murakami, M., Okuda, H., Matsumoto, T., Fuji, G., and Kyoya, M., "Design of the Cryogenic System for IRTS," *Cryogenics*, Vol. 29, No. 5, 1989, pp. 553–558.

[39]Collaudin, B., and De Sa, L., "Thermal and Cryogenic Aspects of the ISO Optical Subsystem," *Proceedings of the 3rd European Symposium on Space Thermal Control & Life Support Systems*, edited by T. D. Guyenne and J. J. Hunt, ESA SP-288, 1st ed., Noordwijk, The Netherlands, 1988, pp. 399–405.

[40]Breon, S. R., Gibbon, J. A., Boyle, R. F., DiPirro, M. J., Warner, B. A., and Tuttle, J. G., "Thermal Design of the XRS Helium Cryostat," *Cryogenics*, Vol. 36, No. 10, 1996, pp. 773–780.

[41]Parmley, R., "Progress Report on the Relativity Mission Superfluid Helium Flight Dewar," *Cryogenics*, Vol. 36, No. 10, 1996, pp. 753–761.

[42]Werner, M. W., and Simmons, L. L., "SIRTF—The Moderate Mission," *Space Science Reviews*, Vol. 74, No. 1–2, 1995, pp. 125–138.

[43]Lysek, M. J., Israelsson, U. E., Garcia, R. D., and Lucik, T. S., "Cryogenic and Thermal Aspects of the SIRTF Launch Concept," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 41B, Plenum, New York, 1996, pp. 1143–1150.

[44]Higgins, J., Villefranche, P., and Scull, S., "The FIRST Spacecraft with Mechanical Cryogenic Coolers," *The Far Infrared and Submillimetre Universe*, edited by A. Wilson, ESA SP-401, 1st ed., Institut de Radio-Astronomie Millimétrique, Grenoble, France, 1997, pp. 377–380.

[45]Juillet, J. J., Trogus, W., Schupp, J., and Cornelisse, J. W., "FIRST: A Satellite Concept Based on the ISO Cryostat," *The Far Infrared and Submillimetre Universe*, edited by A. Wilson, ESA SP-401, 1st ed., Institut de Radio-Astronomie Millimétrique, Grenoble, France, 1997, pp. 385, 386.

[46]Schupp, J., Seidel, A., Moßbacher, B., Birkl, R., Sander, M., and Jochimsen, G., "A He II—Cryostat for the Far-Infrared and Submillimetre Space Telescope (FIRST)," *The Far Infrared and Submillimetre Universe*, edited by A. Wilson, ESA SP-401, 1st ed., Institut de Radio-Astronomie Millimétrique, Grenoble, France, 1997, pp. 429–432.

[47]Shibai, H., and Murakami, H., "The InfraRed Imaging Surveyor (IRIS) Project," *Proceedings of SPIE*, Vol. 2744, *Infrared Technology and Applications XXII*, edited by B. F. Andresen and M. S. Scholl, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 75–83.

[48]Shibai, H., Okuda, H., and Nakagawa, T., "Far-Infrared Survey of the IRIS Project," *The Far Infrared and Submillimetre Universe*, edited by A. Wilson, ESP SP-401, 1st ed., Institut de Radio-Astronomie Millimétrique, Grenoble, France, 1997, pp. 333–335.

[49]Nast, T. C., "Status of Solid Cryogen Coolers," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 31, Plenum, New York, 1986, pp. 835–849.

[50]Roche, A. E., Kumer, J. B., Mergenthaler, J. L., Ely, G. A., Uplinger, W. G., Potter, J. F., James, T. C., and Sterritt, L. W., "The Cryogenic Limb Array Etalon Spectrometer (CLAES) on UARS: Experiment Description and Performance," *Journal of Geophysical Research*, Vol. 98, No. D6, 1993, pp. 10,763–10,775.

[51]Naes, L. G., "Design and Performance Analysis of the CLAES Ne/CO_2 Cryostat," *Proceedings of SPIE*, Vol. 973, *Cryogenic Optical Systems and Instruments III*, edited by R. K. Melugin and W. G. Pierce, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1988, pp. 369–377.

[52]Bell, G. A., Burriesci, L. G., and Naes, L. G., Jr., "CLAES Cryostat On-Orbit Performance Versus Ground Test Predictions," *Proceedings of SPIE*, Vol. 1765, *Cryogenic Optical Systems and Instruments V*, edited by R. K. Melugin, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1992, pp. 217–226.

[53]Oonk, R., "Design of the Solid Cryogen Dewar for the Near-Infrared Camera and Multi-Object Spectrometer," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1385–1391.

[54]Schember, H. R., Kemp, J., Ames, H., Hacking, P., Herter, T., Fafaul, B., Everett, D., and Sparr, L., "Wide-Field Infrared Explorer (WIRE)," *Proceedings of SPIE*, Vol. 2744, *Infrared Technology and Applications XXII*, edited by B. F. Andresen and M. S. Scholl, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 751–760.

[55]Costanzo, B., Menteur, P., Schick, S., and Foster, W., "Design and Performance Analysis of the Wide-Field Infrared Explorer H_2/H_2 Cryostat," *Proceedings of SPIE*, Vol. 2814, *Cryogenic Optical Systems and Instruments VII*, edited by L. G. Burriesci and J. D. Heaney, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 147–153.

[56]Curtis, P. D., Houghton, J. T., Peskett, G. D., and Rodgers, C. D., "Remote Sounding of Atmospheric Temperature from Satellites V. The Pressure Modulator Radiometer for Nimbus F," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. A337, No. 1608, 1974, pp. 135–150.

[57]Drummond, J. R., Houghton, J. T., Peskett, G. D., Rodgers, C. D., Wale, M. J., Witney, J., and Williamson, E. J., "The Stratospheric and Mesospheric Sounder on Nimbus 7," *Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. A296, No. 1418, 1980, pp. 219–241.

[58]Taylor, F. W., Vescelus, F. E., Locke, J. R., Foster, G. T., Forney, P. B., Beer, R., Houghton, J. T., Dederfield, J., and Schofield, J. T., "Infrared Radiometer for the Pioneer Venus Orbiter. 1: Instrument Description," *Applied Optics,* Vol. 18, No. 23, 1979, pp. 3893–3900.

[59]Taylor, F. W., Rodgers, C. D., Whitney, J. G., Werrett, S. T., Barnett, J. T., Peskett, G. D., Venters, P., Ballard, J., Palmer, C. W. P., Knight, R. J., Morris, P., Nightingale, T., and Dudhia, A., "Remote Sensing of Atmospheric Structure and Composition by Pressure Modulator Radiometry from Space: The ISAMS Experiment on UARS," *Journal of Geophysical Research—Atmospheres*, Vol. 98, No. D6, 1993, pp. 10,799–10,814.

[60]Werrett, S. T., and Peskett, G. D., "The Pressure Modulators, Closed Cycle Coolers and Detector Cooling System in ISAMS," *Proceedings of SPIE*, Vol. 589, *Instrumentation for Optical Remote Sensing from Space*, edited by J. W. Lear, A. Monfils, S. L. Russak, and J. S. Seeley, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1985, pp. 96–103.

[61]Davey, G., "Review of the Oxford Cryocooler," *Advances in Cryogenic Engineering*, edited by R. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1423–1430.

[62]Werrett, S. T., Peskett, G. D., Davey, G., Bradshaw, T. W., and Delderfield, J., "Development of a Small Stirling Cycle Cooler for Spaceflight Applications," Rutherford Appleton Lab., Internal Rept. RAL-85-087, Chilton, England, U.K., Aug. 1985.

[63]Duband, L., Ravex, A., and Rolland, P., "Development of a Stirling Cryocooler Using Hydrodynamic Gas Bearings," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 47–53.

[64]Jones, B. G., Scull, S. R., and Jewell, C. I.,"The Batch Manufacturing of Stirling Cycle Coolers for Space Applications Including Test Qualification and Integration Issues," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 59–68.

[65]Berry, D., Carrington, H., Gully, W. J., Luebbert, M., and Hubbard, M., "System Test Performance Data for the Ball Two Stage Stirling Cycle Cooler," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 69–77.

[66]Mon, G. R., Smedley, G. T., Johnson, D. L., and Ross, R. G., Jr., "Vibration Characteristics of Stirling Cycle Cryocoolers for Space Application," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 13–22.

[67]Sparr, L., Boyle, R., Cory, R., Connors, F., James, E., Fink, R., Arillo, V., and Marketon, J., "NASA/GSFC Cryocooler Test Program Results," *Proceedings of the 7th International Cryocooler Conference*, 1st ed., 1993, pp. 699–727; also U.S. Air Force Phillips Lab., Rept. PL-CP-93-1001, Kirtland AFB, NM, Nov. 1992.

[68]Sparr, L., Banks, S., James, E., and Castles, S., "NASA/GSFC Cryocooler Test Program Results for Ball and Lockheed Space Flight Cryocoolers," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 41B, Plenum, New York, 1996, pp. 1577–1584.

[69]Crawford, L. D., Kalivoda, C. M., and Glaister, D. S., "An Overview of Air Force Phillips Laboratory Cryocooler Programs," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 1–9.

[70]Mand, G., Drummond, J. R., Hackett, J., and Henry, D., "MOPPITT On-Orbit Stirling Cycle Cooler Performance," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 759–768.

[71]Kawada, M., and Fujisada, H., "Long-Life Cooler Development Program for ASTER," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 35–46.

[72]Hjalmarson, A., "ODIN: A Swedish Submillimeter Wave Spectroscopy Satellite for Astronomy and Aeronomy," *Twenty-Five Years of Millimeter Wave Spectroscopy*, International Astronomical Union Symposium 170, National Radio Astronomy Observatory, Tucson, AZ, 1997, pp. 227–229.

[73]Kiehl, W., Richards, J., and Stack, R., "HIRDLS Instrument Flight Cryocooler Subsystem Integration and Acceptance Testing," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 131–138.

[74]Dials, M. A., Gille, J. C., Barnett, J. J., and Whitney, J. G., "A Description of the High Resolution Dynamic Limb Sounder (HIRDLS) Instrument," *Proceedings of SPIE*, Vol. 3437, *Infrared Spaceborne Remote Sensing VI*, edited by M. S. Scholl and B. F. Andresen, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1998, pp. 84–91.

[75]Jones, B. G., Scull, S. R., and Jewell, C. I., "The Batch Manufacture of Single Stage Stirling Cycle Coolers for Space Applications," *Submillimetre and Far-Infrared Space Instrumentation*, edited by E. J. Rolfe, ESA SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 297–300.

[76]Orlowska, A. H., and Bradshaw, T. W., "Closed Cycle Cryocoolers for Space Applications," *Space Science Reviews*, Vol. 61, No. 1–2, 1992, pp. 233–240.

[77]Bradshaw, T. W., and Orlowska, A. H., "Mechanical Cooling Systems for Use in Space," *Journal of Aerospace Engineering*, Vol. 207, No. 1, 1993, pp. 21–25.

[78]Martin, J. E., and Thwaite, C., "Absolute Radiometry in Space Using a Cryogenic Mechanical Cryocooler," *Proceedings of SPIE*, Vol. 2814, *Cryogenic Optical Systems and Instruments VII*, edited by L. G. Burriesci and J. D. Heaney, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 18–27.

[79]Carrington, H., Arter, P., Gully, W. J., Hubbard, M., and Varner, C., "Multi-Stage Cryocooler for Space Applications," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 93–102.

[80]Hopkins, R. A., Nieczkoski, S. J., Payne, D. A., Siebert, J. F., and Breon, S. R., "Mechanical Cooler-to-Dewar Interfacing in a Long-Lifetime, Hybrid Stored Cryogen System," *Cryogenics*, Vol. 32, No. 2, 1992, pp. 111–116.

[81]Hopkins, R. A., Nieczkoski, S. J., and Breon, S. R., "Update on the Design and Performance of the Cryogenic Subsystem for the AXAF X-ray Spectrometer," *Cryogenics*, Vol. 34, No. 5, 1994, pp. 443–450.

[82]Lee, J. H., Payne, D. A., and Averill, R. D., "Design of the Cryogenic System for the SAFIRE Instrument," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1211–1219.

[83]Aubrun, J.-N., Clappier, R. R., Lorell, K. R., Nast, T. C., and Reshatoff, P. J., Jr., "A High-Performance Force-Cancellation Control System for Linear-Drive Split-Cycle Stirling Cryocoolers," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1029–1036.

[84]Ross, R. G., Jr., Johnson, D. L., and Kotsubo, V., "Vibration Characterisation and Control of Miniature Stirling-Cycle Cryocoolers for Space Application," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1019–1027.

[85]Boyle, R., Connors, F., Marketon, J., Arillo, V., James, E., and Fink, R., "Non-Real Time, Feed Forward Vibration Control System Development & Test Results," *Proceedings of the 7th International Cryocooler Conference*, 1st ed., 1993, pp. 809–819; also U.S. Air Force Phillips Lab., Rept. PL-CP-93-1001, Kirtland AFB, NM, Nov. 1992.

[86]Collins, S. A., von Flotow, A. H., and Paduano, J. D., "Analogue Adaptive Vibration Cancellation for Stirling Cryocoolers," *Cryogenics,* Vol. 34, No. 5, 1994, pp. 399–406.

[87]Bhatia, R. S., Bock, J. J., Ade, P. A. R., Benoît, A., Bradshaw, T. W., Crill, B. P., Griffin, M. J., Hepburn, I. D., Hristov, V. V., Lange, A. E., Mason, P. V., Murray, A. G., Orlowska, A. H., and Turner, A. D., "The Susceptibility of Incoherent Detector Systems to Cryocooler Microphonics," *Cryogenics*, Vol. 39, No. 8, 1999, pp. 701–715.

[88]Bhatia, R. S., Ade, P. A. R., Bradshaw, T. W., Griffin, M. J., and Orlowska, A. H., "The Effects of Cryocooler Microphonics, EMI and Temperature Variations on Bolometric Detectors," *Cryogenics*, Vol. 41, Nos. 11–12, 2001, pp. 851–863.

[89]Bhatia, R. S., Ade, P. A. R., Bradshaw, T. W., Griffin, M. J., Murray, A. G., and Orlowska, A. H., "Integration of a Photoconductive Detector with a 4 K Cryocooler," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 949–958.

[90]Radebaugh, R., "A Review of Pulse Tube Refrigeration," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1191–1205.

[91]Radebaugh, R., "Pulse Tube Cryocoolers for Cooling Infrared Sensors," *Proceedings of SPIE*, Vol. 4130, *Infrared Technology and Applications XXVI*, edited by B. F. Andresen, G. F. Fulop, and M. Strojnik, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 2000, pp. 363–379.

[92]Radebaugh, R., "Development of the Pulse Tube Refrigerator as an Efficient and Reliable Cryocooler," *Australian Refrigeration, Air Conditioning and Heating (AIRAH) Journal*, Pt. 1, Vol. 55, No. 2, 2001, pp. 22–29; Pt. 2, Vol. 55, No. 3, 2001, pp. 21–27.

[93]Gifford, W. E., and Longsworth, R. C., "Pulse Tube Refrigeration," *Journal of Engineering for Industry*, Vol. 86, No. 3, 1964, pp. 264–268.

[94]Richardson, R. N., "Pulse Tube Refrigerator—An Alternative Cryocooler?," *Cryogenics,* Vol. 26, No. 6, 1986, pp. 331–340.

[95]Zhu, S. W., Wu, P. Y., and Chen, Z. Q., "Double Inlet Pulse Tube Refrigerators: An Important Improvement," *Cryogenics,* Vol. 30, No. 6, 1990, pp. 514–520.

[96]Tward, E., Chan, C. K., Jaco, C., Godden, J., Chapsky, J., and Clancy, P., "Miniature Space Pulse Tube Cryocoolers," *Cryogenics*, Vol. 39, No. 8, 1999, pp. 717–720.

[97]Chan, C. K., Carlson, C., Colbert, R., Nguyen, T., Raab, J., and Waterman, M., "Performance of the AIRS Pulse Tube Engineering Model Cryocooler," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 195–202.

[98]Ross, R. G., Jr., and Green, K. E., "AIRS Cryocooler System Design and Development," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 885–894.

[99]Esplin, R., Zollinger, L., Batty, C., Folkman, S., Roosta, M., Tansock, J., Jensen, M., Strauder, J., Miller, J., Vanek, M., and Robinson, D., "SABER Instrument Design Update," *Proceedings of SPIE*, Vol. 2553, *Infrared Spaceborne Remote Sensing III*, edited by M. S. Scholl and B. F. Andresen, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1995, pp. 253–263.

[100]Jensen, S., Batty, J. C., and Roettker, W. A., "SABER Thermal Management Update," *Proceedings of SPIE*, Vol. 2814, *Cryogenic Optical Systems and Instruments VII*, edited by L. G. Burriesci and J. D. Heaney, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 8–17.

[101]Collins, S. A., and Rodriguez, J. I., "TES Cryocooler System Design and Development," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 131–138.

[102]Rabe, J., Abedzadeh, S., Coilbert, R., Godden, J., Harvey, D., and Jaco, C., "TES FPC Flight Pulse Tube Cooler System," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 131–138.

[103]Beer, R., Glavich, T. A., and Rider, D. M., "Tropospheric Emission Spectrometer for the Earth Observing System's Aura Satellite," *Applied Optics-LP*, Vol. 40, No. 15, 2001, pp. 2356–2367.

[104]Winkler, C., "The INTEGRAL Mission," *Experimental Astronomy*, Vol. 6, No. 4, 1995, pp. 71–76.

[105]Briet, R., "INTEGRAL Spectrometer Cryostat Design and STM Performances," *Advances in Cryogenic Engineering*, edited by Q.-S. Shu, 1st ed., Vol. 45, Kluwer Academic/Plenum, New York, 2000, pp. 489–498.

[106]Marquadt, E. D., and Radebaugh, R., "Pulse Tube Oxygen Liquefier," *Advances in Cryogenic Engineering*, edited by Q.-S. Shu, Vol. 45, Kluwer Academic/Plenum, New York, 2000, pp. 457–464.

[107]Alfeev, V. N., Brodyansky, V. M., Yagodin, V. M., Nikolsky, V. A., and Ivantsov, A. V., "Refrigerant for a Cryogenic Throttling Unit," U.K. Patent GB 1336892, 14 Nov. 1973.

[108]Xu, M., He, Y., and Chen, Z., "Analysis of Using Binary Cryogenic Mixtures Containing Nitrogen and Alkanes or Alkenes in Cryocoolers," *Cryogenics*, Vol. 36, No. 2, 1996, pp. 69–73.

[109]Gustafsson, O., "On the Joule–Thomson Effect for Gas Mixtures," *Physica Scripta,* Vol. 2, No. 1–2, 1970, pp. 7–15.

[110]Robinson, L. B., "Phase Equilibria in Cryogenic Mixtures: Part II," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 559–567.

[111]Levenduski, R., and Scarlotti, R., "Joule–Thomson Cryocooler for Space Applications," *Cryogenics,* Vol. 36, No. 10, 1996, pp. 859–866.

[112]Levenduski, R., and Scarlotti, R., "Joule–Thomson Cryocooler Development at Ball Aerospace," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 543–558.

[113]Lester, J., "Closed Cycle Hybrid Cryocooler Combining the Joule–Thomson Cycle with Thermoelectric Coolers," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1335–1340.

[114]Fernandez, R., and Levenduski, R., "Flight Demonstration of the Ball Joule–Thomson Cryocooler," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1999, pp. 449–456.

[115]Orlowska, A. H., Bradshaw, T. W., and Hieatt, J., "Development Status of a 2.5 K–4 K Closed-Cycle Cooler Suitable for Space Use," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 517–524.

[116]Bradshaw, T. W., and Orlowska, A. H., "Cryogenic Cooling Apparatus," U.K. Patent 2241565, 4 Sept. 1991.

[117]Levenduski, R., Gully, W., and Lester, J., "Hybrid 10 K Cryocooler for Space Applications," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 505–511.

[118]Maytal, B.-Z., "^{3}He Joule-Thomson Inversion Curve," *Cryogenics,* Vol. 36, No. 4, 1996, pp. 271–274.

[119]Jones, B. J., and Ramsay, D. W., "Qualification of a 4 K Mechanical Cooler for Space Applications," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 525–535.

[120]Scull, S. R., Jones, B. G., Bradshaw, T. W., Orlowska, A. H., and Jewell, C. I., "Design and Development of a 4 K Mechanical Cooler for FIRST," *Submillimetre and Far-Infrared Space Instrumentation*, edited by E. J. Rolfe, ESA SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 293–296.

[121]Lamarre, J. M., Ade, P. A. R., Benoît, A., de Bernardis, P., Bock, J., Bouchet, F., Bradshaw, T., Charra, J., Church, S., Couchot, F., Delabrouille, J., Efstathiou, G., Giard, M., Giraud-Héraud, Y., Gispert, R., Griffin, M., Lange, A., Murphy, A., Pajot, F., Puget, J. L., and Ristorcelli, I., "The High Frequency Instrument of Planck: Design and Performances," *Astronomy Letters and Communications*, Vol. 37, No. 3–6, 2000, pp. 161–170.

[122]Oonk, R. L., Glaister, D. S., Gully, W. J., and Lieber, M. D., "Low Temperature, Low Vibration Cryocooler for Next Generation Space Telescope Instruments," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 775–782.

[123]McCormick, J. A., Gibbon, J. A., Izenson, M. G., Nellis, G. F., Sixsmith, H., Swift, W. L., and Zagarola, M. V., "Advanced Developments for Low Temperature Turbo-Brayton Cryocoolers," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 481–488.

[124]Breedlove, J. J., Dolan, F. X., Gibbon, J. A., Nellis, G. F., Swift, W. L., and Zagarola, M. V., "Life and Reliability Characteristics of Turbo-Brayton Coolers," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 489–498.

[125]Nellis, G., Dolan, F., McCormick, J., Swift, W., Sixsmith, H., Gibbon, J., and Castles, S., "Reverse Brayton Cooler for NICMOS," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 431–438.

[126]Wade, L. A., "Advances in Cryogenic Sorption Cooling," *Recent Advances in Cryogenic Engineering-1993,* edited by J. P. Kelley and J. Goodman, HTD-Vol. 267, American Society of Mechanical Engineers, New York, 1993, pp. 57–63.

[127]Wade, L. A., "An Overview of the Development of Sorption Refrigeration," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37, Plenum, New York, 1991, pp. 1095–1105.

[128]Wade, L. A., and Levy, A. R., "Sorption Cooling of Astrophysics Science Instruments," *Submillimetre and Far-Infrared Space Instrumentation*, edited by E. J. Rolfe, ESA SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 285–288.

[129]Wade, L. A., Levy, A. R., and Bard, S., "Continuous and Periodic Sorption Cryocooler for 10 K and Below," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 577–586.

[130]Wade, L., and Sywulka, P., "High Efficiency Sorption Refrigerator Design," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1375–1382.

[131]Wu, J. J., Bard, S., Boulter, W., Rodriguez, J., and Longsworth, R., "Experimental Demonstration of a 10 K Sorption Cryocooler Stage," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 39, Plenum, New York, 1994, pp. 1507–1514.

[132]Karlmann, P., Bard, S., and Wu, J. J., "Development of a Periodic 10 K Hydrogen Sorption Cryoooler," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 41, Plenum, New York, 1996, pp. 1305–1312.

[133]Wade, L. A., Wu, J. J., Bard, S., Flanagan, T. B., Clewley, J. D., and Lou, S., "Perfromance, Reliability and Life of Hydride Compressor Components for 10 to 30 K Sorption Cryocoolers," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 39, Plenum, New York, 1994, pp. 1483–1490.

[134]Wade, L. A., Bowman, R. C., Jr., Gilkinson, D. R., and Sywulka, P. H., "Development of Sorbent Bed Assembly for a Periodic 10 K Solid Hydrogen Cryocooler," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 39, Plenum, New York, 1994, pp. 1491–1498.

[135]Bard, S., Cowgill, P., Rodriguez, J., Wade, L., Wu, J. J., Gehrlein, M., and Von der Ohe, W., "10 K Sorption Cryocooler Flight Experiment (BETSCE)," *Proceedings of the 7th International Cryocooler Conference*, 1st ed., 1993, pp. 1107–1119. U.S. Air Force Phillips Lab., Rept. PL-CP-93-1001, Kirtland AFB, NM, Nov. 1992.

[136]Bard, S., Karlmann, P., Rodriguez, J., Wu, J., Wade, L., Cowgill, P., and Russ, K. M., "Flight Demonstration of a 10 K Sorption Cryocooler," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 567–576.

[137]Wade, L. A., and Levy, A. R., "Preliminary Test Results for a 25 K Sorption Cryocooler Designed for the UCSB Long Duration Balloon Cosmic Microwave Background Radiation Experiment," *Proceedings of the 9th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1997, pp. 587–596.

[138]Bhandari, P., Bowman, R. C., Chave, R. G., Lindensmith, C. A., Morgante, G., Paine, C., Prina, M., and Wade, L. A., "Sorption Cryocooler Development for the Planck Surveyor Mission," *Astrophysical Letters and Communications*, Vol. 37, No. 3–6, 2000, pp. 227–237.

[139]Mather, J. C., Seery, B. D., and Bely, P. Y., "The Next Generation Space Telescope," *Proceedings of SPIE*, Vol. 2807, *Space Telescopes and Instruments IV*, edited by P. Y. Bely and J. B. Breckinridge, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 98–105.

[140]Mather, J. C., Seery, B. D., Stockman, H. S., and Bely, P. Y., "The Next Generation Space Telescope (NGST)—Science and Technology," *The Far Infrared and Submillimetre Universe*, edited by A. Wilson, ESA SP-401, 1st ed., Institut de Radio-Astronomie Millimétrique, Grenoble, France, 1997, pp. 213–218.

[141]Duband, L., Lange, A., and Bock, J., "Helium Adsorption Coolers for Space," edited by E. J. Rolfe, *Submillimetre and Far-Infrared Space Instrumentation*, ESA SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 289–292.

[142]Kittel, P., "^{3}He Cooling Systems for Space—Status Report," NASA TM 85985, July 1984.

[143]Duband, L., Ravex, A., and Chaussy, J., "Adsorption Isotherms of Helium on Activated Charcoal," *Cryogenics*, Vol. 27, No. 7, 1987, pp. 397–400.

[144]Helvensteijn, B. P. M., Kashani, A., and Wilcox, R. A., "Adsorption of Helium in Commercially Available Activated Carbons," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1129–1135.

[145]Torre, J. P., and Chanin, G., "Miniature Liquid-^{3}He Refrigerator," *Review of Scientific Instruments*, Vol. 56, No. 2, 1985, pp. 318–320.

[146]Torre, J. P., and Chanin, G., "Test Flight Results of a Balloon-Borne ^{3}He Cryostat," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 23, Plenum, New York, 1977, pp. 640–643.

[147]Palumbo, P., Aquilini, E., Cardoni, P., de Bernadis, P., De Ninno, A., Martinis, L., Masi, S., and Scaramuzzi, F., "Balloon-Borne ^{3}He Cryostat for Millimetre Bolometric Photometry," *Cryogenics*, Vol. 34, No. 12, 1994, pp. 1001–1005.

[148]Cheng, E. S., Meyer, S. S., and Page, L. A., "A High Capacity 0.23 K ^{3}He Refrigerator for Balloon-Borne Payloads," *Review of Scientific Instruments,* Vol. 67, No. 11, 1996, pp. 4008–4016.

[149]Jaffe, A. H., Ade, P. A. R., Balbi, A., Bock, J. J., Bond, J. R., Borrill, J., Boscaleri, A., Coble, K., Crill, B. P., de Bernardis, P., Farese, P., Ferreira, P. G., Ganga, K., Giacometti, M., Hanany, S., Hivon, E., Hristov, V. V., Iacoangeli, A., Lange, A. E., Lee, A. T., Martinis, L., Masi, S., Mauskopf, P. D., Melchiorri, A., Montroy, T., Netterfield, C. B., Oh, S., Pascale, E., Piacentini, F., Pogosyan, D., Prunet, S., Rabii, B., Rao, S., Richards, P. L., Romeo, G., Ruhl, J. E., Scaramuzzi, F., Sforna, D., Smoot, G. F., Stompor, R., Winant, C. D., and Wu, J. H. P., "Cosmology from MAXIMA-1, BOOMERANG, and COBE DMR Cosmic Microwave Background Observations," *Physical Review Letters*, Vol. 86, No. 16, 2001, pp. 3475–3479.

[150]Dall'Oglio, G., Pizzo, L., Piccirillo, L., and Martinis, L., "New ^{3}He/^{4}He Refrigerator," *Cryogenics*, Vol. 31, No. 1, 1991, pp. 61–63.

[151]Dall'Oglio, G., Fischer, W., Martinis, L., and Pizzo, L., "Improved ^{3}He/^{4}He Refrigerator," *Cryogenics,* Vol. 33, No. 2, 1993, pp. 213, 214.

[152]Duband, L., "Double Stage Helium Sorption Coolers," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 561–566.

[153]Bhatia, R. S., Chase, S. T., Edgington, S. F., Glenn, J., Jones, W. C., Lange, A. E., Maffei, B., Mainzer, A. K., Mauskopf, P. D., Philhour, B. J., and Rownd, B. K., "A Three-Stage Helium Sorption Refrigerator for Cooling of Infrared Detectors to 280 mK," *Cryogenics*, Vol. 40, No. 11, 2000, pp. 685–691.

[154]Kittel, P., and Rodriguez, A. F., "Design Considerations for a ^{3}He Refrigerator for Space Applications," NASA TM 85973, 1984.

[155]Ostermeier, R. M., Nolt, I. G., and Radostitz, J. V., "Capillary Confinement of Cryogens for Refrigeration and Liquid Control in Space," *Cryogenics,* Vol. 18, No. 2, 1978, pp. 83–86.

[156]Ennis, D. J., Kittel, P., Brooks, W., Miller, A., and Spivak, A. L., "A Helium-3 Refrigerator Employing Capillary Confinement of Liquid Cryogen," *Refrigeration for Cryogenic Sensors*, edited by M. Gasser, 1st ed., NASA CP-2287, 1983, pp. 405–417.

[157]Duband, L., Alsop, D., and Lange, A., "A Rocket-Borne ^{3}He Refrigerator," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1447–1456.

[158]Duband, L., Alsop, D., Lange, A., Hayata, S., Matsumoto, T., and Sato, S., "Flight Performance of a Rocket-Borne ^{3}He Refrigerator," *Cryogenics,* Vol. 31, No. 5, 1991, pp. 338–340.

[159]Duband, L., Hui, L., and Lange, A., "Space-Borne ^{3}He Refrigerator," *Cryogenics,* Vol. 30, No. 3, 1990, pp. 263–270.

[160]Freund, M. M., Duband, L., Lange, A. E., Matsumoto, T., Murakami, H., Hirao, T., and Sato, S., "Design and Flight Performance of a Space Borne ^{3}He Refrigerator for the Infrared Telescope in Space," *Cryogenics*, Vol. 38, No. 4, 1998, pp. 435–443.

[161]Griffin, M., Swinyard, B., and Vigroux, L., "The SPIRE Instrument for FIRST," *Proceedings of SPIE*, Vol. 4013, *UV, Optical and IR Space Telescopes and Instruments*, edited by J. B. Breckinridge and P. Jakobsen, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 2000, pp. 184–195.

[162]Bock, J. J., Duband, L., Kawada, M., Matsuhara, H., Matsumoto, T., and Lange, A. E., "^{4}He Refrigerator for Space," *Cryogenics,* Vol. 34, No. 8, 1994, pp. 635–640.

[163]Roach, P. R., and Helvensteijn, B. P. M., "Development of a Dilution Refrigerator for Low-Temperature Microgravity Experiments," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 647–653.

[164]Roach, P. R., and Helvensteijn, B. P. M., "Progress on a Microgravity Dilution Refrigerator," *Cryogenics,* Vol. 39, No. 12, 1999, pp. 1015–1019.

[165]Kral, S. F., and Barclay, J. A., "Magnetic Refrigeration: A Large Cooling Power Cryogenic Refrigeration Technology," *Applications of Cryogenic Technology*, edited by J. P. Kelley, Vol. 10, Plenum, New York, 1991, pp. 27–41.

[166]Barclay, J. A., "Magnetic Refrigeration, a Review of a Developing Technology," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 33, Plenum, New York, 1988, pp. 719–731.

[167]Barclay, J. A., "The Theory of Active Magnetic Regenerative Refrigerator," edited by M. Gasser, *Refrigeration for Cryogenic Sensors*, 1st ed., NASA CP-2287, 1983, pp. 375–387.

[168]Jeong, S., and Smith, J. L., Jr., "Magnetically Augmented Regeneration in Stirling Cryocooler," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 39, Plenum, New York, 1994, pp. 1399–1405.

[169]Hudson, R. P., *Principles and Application of Magnetic Cooling*, 1st ed., North-Holland, London, 1972.

[170]Lounasmaa, O. V., *Experimental Principles and Methods Below 1 K*, 1st ed., Academic Press, London, 1974, pp. 82–102.

[171]Forgan, E. M., "On the Use of Temperature Controllers in Cryogenics," *Cryogenics*, Vol. 4, No. 4, 1974, pp. 207–214.

[172]Kittel, P., "Temperature Stabilized Adiabatic Demagnetization for Space Applications," *Cryogenics,* Vol. 10, No. 10, 1980, pp. 599–601.

[173]Kittel, P., "Temperature Stability Limits for an Isothermal Demagnetization Refrigerator," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 29, Plenum, New York, 1984, pp. 613–620.

[174]Kittel, P., "Ultimate Temperature Stability of a Magnetic Refrigerator," *Cryogenics*, Vol. 13, No. 9, 1983, pp. 477–478.

[175]Bernstein, G., Labov, S., Landis, D., Madden, N., Millet, I., Silver, E., and Richards, P., "Automated Temperature Regulation System for Adiabatic Demagnetization Refrigerators," *Cryogenics*, Vol. 31, No. 2, 1991, pp. 99–101.

[176]Savage, M. L., Kittel, P., and Roellig, V, "Salt Materials Testing for a Spacecraft Adiabatic Demagnetization Refrigerator," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1439–1446.

[177]Hagmann, C., Benford, D. J., and Richards, P. L., "Paramagnetic Salt Pill Design for Magnetic Refrigerators Used in Space Applications," *Cryogenics*, Vol. 34, No. 3, 1994, pp. 213–219.

[178]Lesyna, L., Roellig, T. P. L., and Kittel, P., "Bolometers Operated at 0.1 K and 0.2 K Cooled by Adiabatic Demagnetization," *International Journal of Infrared and Millimeter Waves*, Vol. 5, No. 6, 1984, pp. 755–760.

[179]Tucker, G. S., Peterson, J. B., Netterfield, C. B., Griffith, E. L., and Griffith, G. S., "Cryogenic Bolometric Radiometer and Telescope," *Review of Scientific Instruments*, Vol. 65, No. 2, 1994, pp. 301–308.

[180]Ruhl, J., and Dragovan, M., "A Portable 0.050 K Refrigerator for Astrophysical Observations," *Proceedings of the IVth International Workshop on Low Temperature Detectors for Neutrinos and Dark Matter*, edited by N. E. Booth and G. L. Salmon, 1st ed., Editions Frontières, Gif sur Yvette, France, 1992, pp. 461–464.

[181]Porter, F. S., Almy, R., Apodaca, E., Figueroa-Feliciano, E., Galeazzi, M., Kelley, R., McCammon, D., Stahle, C. K., Szymkowiak, A. E., and Sanders, W. T., "Observations of the Soft X-ray Background with the XQC Microcalorimeter Sounding Rocket," *Nuclear Instruments and Methods In Physics Research Section A—Accelerators Spectrometers Detectors and Associated Equipment*, Vol. 444, No. 1–2, 2000, pp. 175–179.

[182]Labov, S., Silver, E., Le Gros, M., Bland, R. W., Dickson, S. C., Dignan, T. G., Laws, K., Johnson, R. T., Simon, M. W., Stricker, D. A., Watson, R. M., Madden, N., and Landis, D., "Aluminum Tunnel Junction Detector Operation in an Adiabatic Demagnetization Refrigerator," *Proceedings of the IVth International Workshop on Low Temperature Detectors for Neutrinos and Dark Matter*, edited by N. E. Booth and G. L. Salmon, 1st ed., Editions Frontières, Gif sur Yvette, France, 1992, pp. 285–290.

[183]Kittel, P., "Magnetic Refrigeration in Space—Practical Considerations," *Journal of Energy*, Vol. 4, No. 6, 1980, pp. 266–272.

[184]Castles, S., "Design of an Adiabatic Demagnetization Refrigerator for Studies in Astrophysics," *Refrigeration for Cryogenic Sensors*, edited by M. Gasser, 1st ed., NASA CP-2287, 1983, pp. 389–404.

[185]Serlemitsos, A. T., Warner, B. A., Castles, S., Breon, S. R., San Sebastian, M., and Hait, T., "Adiabatic Demagnetization Refrigerator for Space Use," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1431–1437.

[186]Serlemitsos, A. T., SanSebastian, M., and Kunes, E., "Design of a Spaceworthy Adiabatic Demagnetization Refrigerator," *Cryogenics*, Vol. 32, No. 2, 1992, pp. 117–121.

[187]Breon, S., Hopkins, R. A., and Nieczkoski, S. J., "The X-ray Spectrometer—a Cryogenic Instrument on the Advanced X-ray Astrophysics Facility," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 1193–1200.

[188]Breon, S., and Hopkins, R. A., "The New X-ray Spectrometer (XRS)—a Revamped Cryogenic Instrument for the Restructured AXAF-S Mission," *Advances in Cryogenic Engineering*, edited by P. Kittel, 1st ed., Vol. 39, Plenum, New York, 1994, pp. 187–192.

[189]Volz, S. M., Mitsuda, K., Inoue, H., Ogawara, Y., Hirabayashi, M., and Kyoya, M., "The X-ray Spectrometer (XRS): a Multi-Stage Cryogenic Instrument for the ASTRO-E X-Ray Astrophysics Mission," *Cryogenics,* Vol. 36, No. 10, 1996, pp. 763–771.

[190]Mason, P. V., Petrac, D., Petrick, S. W., and Strayer, D. M., "Space Infrared Telescope Facility Mission and Cryogenic Design," *Cryogenics*, Vol. 32, No. 2, 1992, pp. 107–110.

[191]Britt, R. D., and Richards, P. L., "An Adiabatic Demagnetization Refrigerator for Infrared Bolometers," *International Journal of Infrared and Millimeter Waves*, Vol. 2, No. 6, 1981, pp. 1083–1096.

[192]Clapp, A., Hagmann, C., Benford, D., Holmes, W., and Richards, P. L., "100 mK Magnetic Refrigerators for Low Background Bolometric Receivers," *Proceedings of SPIE*, Vol. 1946, *Infrared Detectors and Instrumentation*, edited by A. M. Fowler, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1993, pp. 126–133.

[193]Timbie, P. T., Bernstein, G. M., and Richards, P. L., "An Adiabatic Demagnetization Refrigerator for SIRTF," *IEEE Transactions on Nuclear Science*, Vol. 36, No. 1, 1989, pp. 898–902.

[194]Bernstein, G. M., Timbie, P. T., and Richards, P. L., "A 100 mK Bolometer System for SIRTF," *Proceedings of the Third Infrared Detector Technology Workshop*, NASA TM 102209, Oct. 1989, pp. 35–44.

[195]Hagmann, C., and Richards, P. L., "Adiabatic Demagnetization Refrigerators for Small Laboratory Experiments and Space Astronomy," *Cryogenics*, Vol. 35, No. 5, 1995, pp. 303–309.

[196]Tanaka, S., Alsop, D., Cheng, E., Clapp, A., Cottingham, D., Devlin, M., Fischer, M., Gundersen, J., Hagmann, C., Holmes, W., Hristov, V., Koch, T., Kreysa, E., Lange, A., Lim, M., Lubin, P., Mauskopf, P., Meinhold, P., Richards, P., Smoot, G., and Timbie, P., "The Millimeter Wave Anisotropy Experiment (MAX)," *Astrophysical Letters and Communications*, Vol. 32, No. 1–6, 1995, pp. 223–228.

[197]Timbie, P. T., "Far-Infrared Detectors for Observational Cosmology," *Remote Sensing Reviews*, Vol. 8, 1993, pp. 235–244.

[198]Hagmann, C., and Richards, P. L., "Two-Stage Magnetic Refrigerator for Astronomical Applications with Reservoir Temperatures Above 4 K," *Cryogenics*, Vol. 34, No. 3, 1994, pp. 221–226.

[199]Vilches, O. E., and Wheatley, J. C., "Techniques for Using Liquid Helium in Very Low Temperature Apparatus," *Review of Scientific Instruments*, Vol. 37, No. 7, 1966, pp. 819–831.

[200]Mess, K. W., Lubbers, J., Nielsen, L., and Huiskamp, W. J., "Thermal and Magnetic Properties of Cerium Magnesium Nitrate Below 1 K," *Physica*, Vol. 41, No. 2, 1969, pp. 260–288.

[201]Hepburn, I. D., Ade, P. A. R., Davenport, I., Smith, A., and Sumner, T. J., "In Orbit Adiabatic Demagnetization Refrigeration for Bolometric and Microcalorimetric Detectors," *Proceedings of a European Symposium on Photon Detectors for Space Instrumentation*, edited by T. D. Guyenne and J. J. Hunt, ESA SP-356, 1st ed., Noordwijk, The Netherlands, 1992, pp. 317–320.

[202]Hepburn, I. D., Davenport, I., and Smith, A., "Adiabatic Demagnetisation Refrigerators for Future Sub-Millimetre Space Missions," *Space Science Reviews,* Vol. 74, No. 1–2, 1995, pp. 215–223.

[203]Davenport, I. J., Smith, A., Hepburn, I., Ade, P. A. R., and Sumner, T. J., "An Adiabatic Demagnetisation Refrigerator with a Mechanical Precooler for Space Applications," *Proceedings of a European Symposium on Photon Detectors for Space Instrumentation*, edited by T. D. Guyenne and J. J. Hunt, ESA SP-356, 1st ed., Noordwijk, The Netherlands, 1992, pp. 275–279.

[204]Hepburn, I. D., Smith, A., Duncan, W., and Kerley, N., "High Cooling Power, Low Magnetic Field ADR for Space," *Proceedings of a Workshop on Bolometers for Millimetre and Submillimetre Space Projects*, edited by J. M. Lamarre, J. P. Torre, and V. Demuyt, 1st ed., 1995, pp. 161–164; also Inst. d'Astrophysique Spatiale, Rept. RS 95-02, Paris, June 1995.

[205]Hepburn, I. D., Smith, A., Duncan, W., and Kerley, N., "A Possible Cryogen Free Adiabatic Demagnetization Refrigerator for Space," *Submillimetre and Far-Infrared Space Instrumentation*, edited by E. J. Rolfe, ESA SP-388, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1996, pp. 311–314.

[206]Bromiley, P. A., Hepburn, I. D., and Smith, A., "Ultra Low Temperature Cryogen Free Refrigerator," *Proceedings of the 6th European Symposium on Space Environmental Control Systems*, edited by T. D. Guyenne, ESA SP-400, 1st ed., European Space Research and Technology Centre, Noordwijk, The Netherlands, 1997, pp. 507–513.

[207]Shirron, P. J., Canavan, E. R., DiPirro, M. J., Jackson, M., King, T., Panek, J., and Tuttle, J. G., "A Compact, High-Performance Continuous Magnetic Refrigerator for Space Missions," *Cryogenics*, Vol. 41, Nos. 11–12, 2001, pp. 789–795.

[208]Shirron, P., Abbondante, N., Canavan, E., DiPirro, M., Grabowski, M., Hirsch, M., Jackson, M., Panek, J., and Tuttle, J., "A Continuous Adiabatic Demagnetization Refrigerator for Use with Mechanical Coolers," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 587–596.

[209]Warner, B. A., Shirron, P. J., Castles, S. H., and Serlemitsos, A. T., "Magnetic Shielding for a Spaceborne Adiabatic Demagnetization Refrigerator (ADR)," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 37B, Plenum, New York, 1992, pp. 907–914.

[210]Kamiya, K., Warner, B. A., and DiPirro, M. J., "Magnetic Shielding for Sensitive Detectors," *Cryogenics*, Vol. 41, No. 5–6, 2001, pp. 401–405.

[211]Kittel, P., "Eddy Current Heating in Magnetic Refrigerators," *Advances in Cryogenic Engineering*, edited by R. W. Fast, 1st ed., Vol. 35, Plenum, New York, 1990, pp. 1141–1148.

[212]Radebaugh, R., "Very-Low-Temperature Cooling Systems," *Cryocoolers, Vol. 2: Applications*, 1st ed., Plenum, New York, 1983, pp. 187–210.

[213]Wilks, J., and Betts, D. S., *An Introduction to Liquid Helium*, 2nd ed., Clarendon Press, Oxford, England, U.K., 1987, p. 106.

[214]Edwards, D. O., Ifft, E. M., and Sarwinski, R., "Number Density and Phase Diagram of Dilute ^{3}He–^{4}He Mixtures at Low Temperatures," *Physical Review*, Vol. 177, No. 1, 1969, pp. 380–391.

[215]Hendricks, J. B., "^{3}Helium/^{4}Helium Dilution Cryocooler for Space," Final Report, NASA Contract NAS8-37437, 1991.

[216]Jackson, H. W., "Can ^{3}He–^{4}He Dilution Refrigerators Operate Aboard Spacecraft?," *Cryogenics*, Vol. 22, No. 2, 1982, pp. 59–62.

[217]Kuerten, J. G. M., Castelijns, C. A. M., de Waele, A. T. A. M., and Gijsman, H. M., "Comprehensive Theory of Flow Properties of ^{3}He Moving Through Superfluid ^{4}He in Capillaries," *Physics Review Letters*, Vol. 56, No. 21, 1986, pp. 2288–2290.

[218]Benoît, A., and Pujol, S., "A Dilution Refrigerator Insensitive to Gravity," *Physica B*, Vol. 169, No. 1–4, 1991, pp. 457, 458.

[219]Bradley, D. I., and Oswald, R., "Viscosity of ^{3}He–^{4}He Dilute Phase in the Mixing Chamber of a Dilution Refrigerator," *Journal of Low Temperature Physics*, Vol. 80, Nos. 1/2, 1990, pp. 89–97.

[220]de Bruyn Ouboter, R., van den Brandt, B., and Tierolf, J. W., "Visual Observations of the Counterflow of the Two Liquid Phases in the ^{4}He-Cycling ^{3}He–^{4}He Dilution Refrigerator," *Physica* $B + C$, Vol. 107, No. 1–3, 1981, pp. 557, 558.

[221]Paragina, A., Pouilloux, B., Benoit, A., and Lamarre, J.-M., "Influence of the Astrophysical Requirements on Dilution Refrigerator Design," *Cryogenics*, Vol. 39, No. 8, 1999, pp. 665–669.

[222]Benoît, A., Bradshaw, T., Jewell, C., Maciaszek, T., Orlowska, A., and Pujol, S., "A Future Potential Long Life Refrigerator for 0.1 K Cooling in Space," *Proceedings of the 24th International Conference on Environmental Systems and 5th European Symposium on Space Environmental Control Systems*, 1st ed., SAE International, the Engineering Society for Advancing Mobility in Land, Sea, Air, and Space, Warrendale, PA, 1994; also Society of Automotive Engineers, SAE TP Series 941276, 1994.

[223]Benoît, A., and Pujol, S., "Dilution Refrigerator for Space Applications with a Cryocooler," *Cryogenics,* Vol. 34, No. 5, 1994, pp. 421–423.

[224]Bhatia, R. S., Benoît, A., Bock, J. J., Griffin, M. J., and Mason, P. V., "Testing of Infrared Detectors Using a Zero-Gravity Dilution Refrigerator," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 795–804.

[225]Duband, L., "A Thermal Switch for Use at Liquid Helium Temperature in Space-Borne Cryogenic Systems," *Proceedings of the 8th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1995, pp. 731–741.

[226]Canavan, E. R., Tuttle, J. G., Shirron, P. J., and DiPirro, M. J., "Performance of the XRS ADR Heatswitch," *Advances in Cryogenic Engineering*, edited by Q.-S. Shu, 1st ed., Vol. 45, Kluwer Academic/Plenum, New York, 2000, pp. 545–552.

[227]Prina, M., Bhandari, P., Bowman, R. C., Jr., Paine, C. G., and Wade, L. A., "Development of Gas Gap Heat Switch Actuator for the Planck Sorption Cooler," *Advances in Cryogenic Engineering*, edited by Q.-S. Shu, 1st ed., Vol. 45, Kluwer Academic/Plenum, New York, 2000, pp. 553–560.

[228]Marland, B., Bugby, D., Davis, T., Stouffer, C., and Tomlinson, B., "Development and Testing of a High Performance Cryogenic Thermal Switch," *Proceedings of the 11th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 2001, pp. 689–698.

[229]Arkhipov, V. T., Getmanets, V. F., Levin, A. Y., Mikhalchenko, R. S., and Stears, H., "Cold Accumulators as a Way to Increase Lifetime and Cryosystem Temperature Range," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 689–696.

[230]Wiliams, B. G., and Spradley, L. E., "Test Results of a Nitrogen Triple-Point Thermal Storage Unit," *Proceedings of the 10th International Cryocooler Conference*, edited by R. G. Ross Jr., 1st ed., Plenum, New York, 1998, pp. 697–706.

I. E. Vas
Associate Editor