Aerospace Coolers: a 50-Year Quest for Long-life Cryogenic Cooling in Space

R.G. Ross, Jr.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Cryogenic temperatures are critical to allow infrared, gamma-ray and x-ray detectors to operate with low background noise and high sensitivity. As a result, the world's aerospace industry has long dreamed of having the means for multi-year cryogenic cooling in space to enable long-life sensors of various forms for scientific, missile defense, and reconnaissance observations. Not long after the first Sputnik was launched into space in October 1957, engineers and scientists were actively seeking means of providing cryogenic cooling for ever more sophisticated and sensitive detectors in a variety of spectral regions. Although both passive cryoradiators, as well as stored cryogens, have provided a source of cryogenic cooling for many missions, the consistent dream of scientists and mission planners was always for a mechanical refrigerator that could achieve the temperatures of the coldest cryogens—vastly colder than possible with passive radiators—and have multi-year life without the finite-life limitations of stored cryogens. The first cryocoolers in space were short-life J-T and Stirling cryocoolers flown on both US and USSR missions around 1970. Since that time, extensive research and development of ever more sophisticated cryocoolers — Stirling, Vuilleumier, Brayton, magnetic, sorption, and pulse tube — has taken place in the world's aerospace industry. This paper examines the enormous progress made by the aerospace industry over the past 50 years in developing both cryostats and cryocoolers to enable the widespread use of cryogenic temperatures in space.

INTRODUCTION

The quest for cryogenics in space has long been a worldwide endeavor by two main communities—the civilian space and Earth science communities and the military defense communities. The overlap between the community's needs has been fortuitous, for this has allowed the combined funding of many of the cryogenic technology developments over the years. And, although many of the military reconnaissance missions are themselves classified, the military contributions to the cooler developments by themselves have generally not been. This provides relatively good visibility into the total scope of accomplishment.

In contrast to other cryogenic communities, the civilian and defense space communities share a fairly common set of constraints—the most common ones being the huge expense of

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getting a payload into orbit, the strong leverage that cryogenics has in terms of enabling improved science and reconnaissance measurements, and the small number of cooling units of a particular type that are ever needed. The result is a demand for high efficiency, very high reliability and long life, the ability to justify large levels of funding to achieve the desired performance, and the typical purchase of only one or two units of a particular design. Thus, space coolers (radiators, cryostats or cryocoolers) are distinct from typical commercial or tactical (ground-based military) products by their high level of sophistication, hand-built nature with few if any mass-produced components, and correspondingly high price—generally in the millions of dollars per unit.

In the bigger picture, the world's space community can be almost thought of as two communities, the Western world, which includes the US, Canada, Europe and most of Asia (Japan, China, Korea and India), and the Russian countries (Russia, Ukraine, etc). Since the days of the Cold War and the beginning of the Space Race, there has been only minimal interchange between these two politically-separated communities, and each has developed more or less separately using its own set of cryogenic technologies, nomenclature, and jargon. As a result, Western conferences and journals contain only periodic references to the Russian accomplishments, which have been extensive. As a result, this review is mostly a record of the space cryogenics accomplishments of the Western world with only passing reference to some of the Russian accomplishments.

Cryogenic Applications in Space

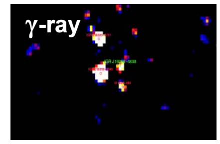
Before reviewing the accomplishments over the past 50 years it is useful to first briefly summarize the space applications that are enabled by space cryogenics and their needs as they have evolved over time. From a broad perspective there are two classes of space applications, cryogenic-liquid rocket propellants (such as liquid hydrogen and oxygen) and science applications such as fundamental physics experiments and infrared, gamma-ray and x-ray instruments with cryogenically-cooled detectors. This paper focuses only on the latter applications, which are typically “operated in space,” as opposed to being used to “get to space.”

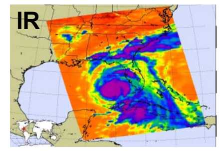
Infrared Sensors. As a result of the mutual benefit across the Earth, space-science, and reconnaissance communities, cryogenic infrared instruments are by far the largest application of space cryogenics. Viewing scenes in the infrared provides unique abilities in a number of fields: from measuring chemical constituents in the atmosphere, to viewing distant galaxies and stars, to identifying and tracking targets within a missile-defense system. Table 1 highlights the various wavelengths of the electromagnetic spectrum, the blackbody temperatures that emit such wavelengths, the applicable detector technologies used to see such wavelengths, and the temperatures to which such detectors must be cooled to achieve their required performance. Important regions for infrared observations include room temperature (300 K) objects that emit in the 10-15 micron region, and very cold celestial objects that emit in the 20-500 micron region. In these infrared wavelengths, it is not only necessary to cool the detector to cryogenic temperatures, but to also cool the optical system that illuminates the detector. As a result, infrared applications generally involve multistage cooling over a range of temperatures from 150 K down to near absolute zero.

Gamma-ray Detectors. The second most popular subject for cryogenic space instruments is gamma-rays. As shown in Table 1, gamma-rays are extremely short wavelength photons emitted from substances involved in very high energy reactions (equivalent to temperatures of 100,000,000 K). The remote detection of gamma-rays emitted from planetary surfaces allows the spatial mapping of the abundances of surface elements such as O, Mg, Fe, Al, Si, Ti, K, Ca, Th, and U. Knowing the elemental composition on the surface of a planet is very important to understanding the origin and the evolution of the planet and also for understanding the origin and the evolution of the solar system.

Table 1. Types and wavelengths of electromagnetic radiation, the blackbody temperature that emits such radiation, and applicable detector types and their required operating temperature.

Radiation Type	Wavelength (microns)	Blackbody Temp. (K)	Detector Technology	Detector Temp. (K)
γ-rays	10^{-5}	3×10^{8} K	Ge Diodes	80 K
γ-rays	10^{-4}	3×10^{7} K	Ge Diodes	80 K
x-rays	10^{-3}	3×10^{6} K	micro calorimeters	0.05 K
x-rays	10^{-2}	3×10^{5} K		0.05 K
UV	0.1	30,000 K	CCD/CMOS	200-300 K
visible	1	3000 K	CCD/CMOS	200-300 K
IR	2	1500 K	HgCdTe	80-130 K
IR	5	600 K	HgCdTe	80-120 K
LWIR	10	300 K	HgCdTe	35-80 K
LWIR	15	200 K	HgCdTe	35-60 K
LWIR	20	150 K	Si:As	7-10 K
LWIR	50	60 K	Ge:Ga	2 K
LWIR/μwaves	100	30 K	Ge:Ga	1.5 K
microwaves	200	15 K	Bolometers	0.1 K
microwaves	500	6 K	Bolometers	0.1 K





Unlike optical or even x-ray photons, gamma-rays simply pass through most materials and thus cannot be reflected by a mirror. The most common detectors are room-temperature sodium iodide scintillation crystals that emit a burst of light when struck by a gamma-ray, and cryogenically-cooled germanium-crystal diodes that release an electrical charge when struck by a gamma-ray. Germanium detectors, each the size of a tea cup, offer better energy resolution, less noise, and better spatial resolution than room-temperature scintillators. However, they must be cooled to around 80 K to achieve their performance advantage.

X-ray Detectors. X-rays are very short wavelength photons, much shorter than ultraviolet light, but not as short as gamma-rays. Many celestial objects such as stars and black holes generate x-rays in extremely violent processes such as when stars are born or explode. However, because Earth's atmosphere blocks out x-rays, celestial x-ray research must rely heavily on high-altitude balloon and space observations. The most common detectors are room-temperature gas scintillators that emit a burst of light when struck by an x-ray, and cryogenically-cooled microcalorimeters that heat microscopically due to the absorbed energy of the incoming x-ray photons. To achieve useful performance, x-ray microcalorimeters must be cooled to around 50 mK—just 1/20 of a degree above absolute zero.

Chapter Organization

The next five sections of this chapter review the history of space cryogenics over the past fifty years, with primary emphasis on the accomplishments in the Western countries. The work is organized by decade, starting 50 years ago in 1955, which also corresponds, more or less, with the beginning of the space program. Each decadal section describes the major space milestones of that decade, the key cryogenic missions carried out, and the research focus of the development work of that decade.

1955 TO 1965 — THE BIRTH OF THE SPACE PROGRAM

The space age began to be considered as early as 1946, as scientists started using captured German V-2 rockets, and later Aerobee rockets, to make measurements in the upper atmosphere after the end of World War II. The US considered launching orbital satellites as early as 1945 under the Bureau of Aeronautics of the US Navy. A 1946 Rand report to the Air Force further blessed the idea.

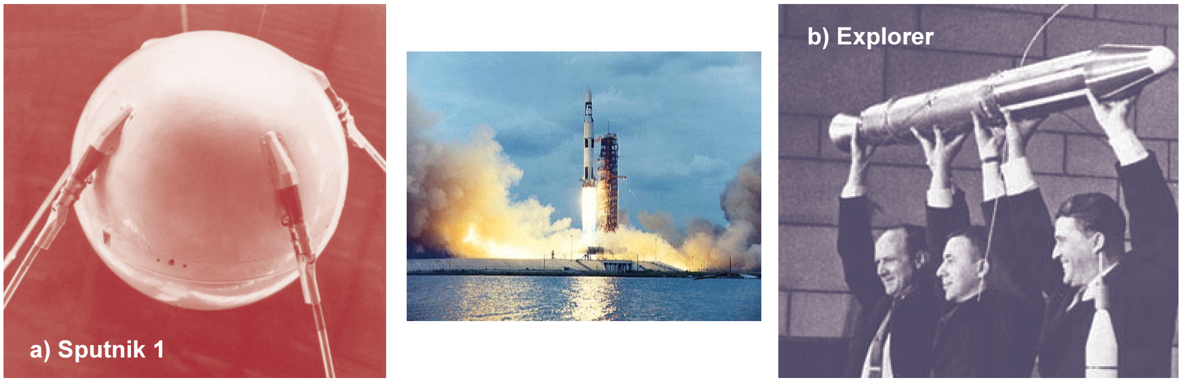


Figure 1. The successful launch of Russia's Sputnik I and the United States' Explorer satellites into orbit in the 1957-58 timeframe represented the start of the space program.

By 1955 the Air Force and Navy were working on Project Orbiter, which involved using a Jupiter C rocket to launch a small satellite into orbit. With growing interest in the International Geophysical Year, which was to last from July 1957 through December 1958, the White House, on July 29, 1955, reported that the US intended to launch satellites into orbit by the spring of 1958. To the great surprise of the Western world, Russia successfully launched their first satellite, Sputnik I (Figure 1a), into Earth orbit in October 1957, and followed it soon after with Sputnik II carrying a much heavier payload, including a dog named Laika. Four months later, in January 1958, The US successfully placed Explorer I into orbit (Figure 1b).

Building on these first successes, the space race was off and running, and grew to over 50 satellite launches per year over the next few years. By 1962 the US had a first flyby to Venus, Mariner 2, and discussions were ongoing in many circles on the scientific advances that could be made from satellite-based instruments. In 1964, Mariner 4 made the first close-up photographs of Mars, and Nimbus 1 was launched to carry out the first Earth-science observations.

Though the first cryogenic applications in space were still a few years away, development work was initiated on the first space cryocoolers for military applications [1]. Work on Brayton-cycle refrigerators started at Arthur D. Little in Cambridge, MA in 1962 based on the rotary-reciprocating refrigerator (R^3) concept [2]. The R^3 design incorporated gas bearings, with the promise of reducing wear and extending refrigerator lifetime. Work on Vuilleumier (VM) cryocoolers was also started in the 1960s at Hughes Aircraft in California and at Philips Laboratories in Briarcliff Manor, New York [1].

Work on future space-science cryogenic missions also began, including initial funding of Gravity Probe B in 1963. In the late 1950s, astronomers were using lead-sulfide (PbS) detectors to study infrared radiation. To increase the sensitivity of the PbS cell it was cooled to 77 K. This allowed infrared observations out to wavelengths of about 3 microns. In 1961 the first germanium bolometer was developed by Frank Low, and was hundreds of times more sensitive than previous detectors. It was capable of detecting far-infrared radiation when cooled to 4 K. In 1963, a germanium bolometer was attached to a balloon to make infrared observations of Mars.

1965 TO 1975 — RACE TO THE MOON, FIRST CRYOGENICS IN SPACE

This was the decade of the great race to the Moon and the first cryogenics in space. The year 1966 brought the landing of the Surveyor spacecraft on the surface of the Moon and the launch of Nimbus 2 for a next level of Earth-science observations.

Also in 1966, the Goddard Institute of Space Sciences used balloons to conduct infrared surveys at 100 μm and discovered about 120 bright infrared sources. In 1967, cooled infrared telescopes were placed on rockets that could observe the sky for several minutes before reentry. The first infrared all-sky map resulted from a series of rocket flights by the Air Force

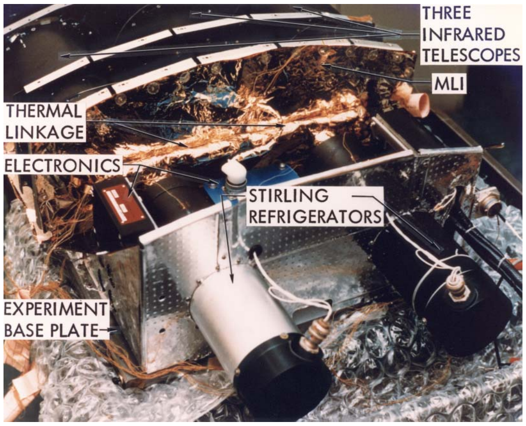


Figure 2. Malaker Stirling coolers flown on RM-19 in July 1971.

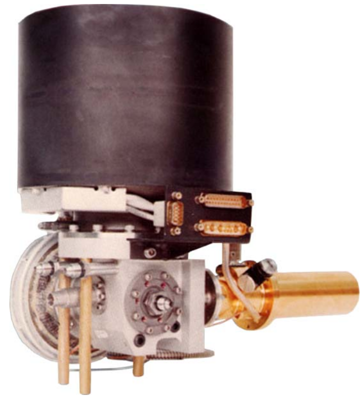


Figure 3. Hughes Aircraft two-stage Vuilleumier (VM) cooler flown on SESP 71-2 in October 1971.

Cambridge Research Laboratory. Although the total observation time accumulated by these Hi Star flights was only about 30 minutes, they successfully detected 2363 reliable infrared sources.

In 1968 Apollo orbited the moon and Nimbus B was launched for more Earth observations. Apollo 11 landed on the moon in 1969, followed by Apollo 12, and the Apollo 13 mishap in 1970. While the follow-on Apollo missions were frequenting the moon, the first cryogenics missions to space were being launched.

1965-1975 Cryogenic Missions

1968—Apollo Fuel Cell LH_2 and LO_2 Dewars. The first space dewars were probably those built by Beech Aircraft to hold supercritical liquid hydrogen and liquid oxygen for use in the Apollo Service Module fuel cells and breathing oxygen supply. It was one of these that was involved in the historic Apollo 13 mishap of 1970, though the problem was unrelated to the performance of the dewar. A total of 145 units were built in support of the Apollo program.

1969—Mariner 6 and 7 N_2/H_2 J-T Cooler. July-August 1969 brought the first cryocooler missions in space; these were two-stage nitrogen/hydrogen open-cycle Joule Thomson cryocoolers designed to cool the Mars infrared spectrometers on Mariner 6 and 7 to 22 K during the spacecrafts' flyby encounters with Mars [3]. Developed by the University of California, Berkeley, the spectrometers incorporated Ge:Hg detectors to allow infrared spectral surveys of Mars to be taken over the wavelength range from 6 to 14.3 μm. The Mariner 7 flight was totally successful with the detector remaining below 22 K for about an hour; however, the N_2 J-T stage of the Mariner 6 system failed to operate.

1971—RM-19 Malaker Stirling. July 1971 brought the first closed-cycle mechanical cryocooler in orbit — a Malaker Stirling cooler that cooled an Earth-background infrared radiometer built by Lockheed Missile and Space Co. (LMSC) in Palo Alto for the DoD [1]. The RM-19 radiometer and the Malaker Stirling are shown in Figure 2. Three detector assemblies were thermally connected to the two Stirling refrigerators by means of a flexible thermal strap, while each of the temperature-compensated infrared telescopes was passively cooled to 240 K. During the several-month mission, the refrigerators, operating in tandem, periodically cooled the detectors to approximately 105 K in three- to four-hour periods preceding radiometer operation. The cooling capacity of each cooler was 2 W at 100 K with a 40-W input. This first mission of a closed-cycle cryocooler was an important milestone; however, the total accumulated run time on the coolers during the mission was less than 1000 hours.

1971—SESP 71-2 Hughes VM Cryocooler. In October 1971, only a few months after the RM-19 flight, the first advanced technology cryocooler, a two-stage Hughes Aircraft Vuilleumier (VM) cooler (Figure 3) was flown as part of the DoD's SESP 71-2 technology

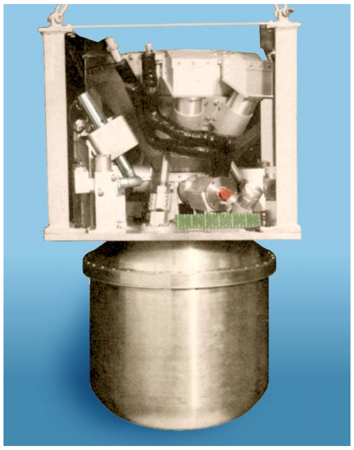


Figure 4. Lockheed Solid CO_2 cryostat flown on SESP 72-2 in October 1972.

Figure 5. Skylab was launched in 1973 and hosted two more cryogenic applications that used the Malaker Stirling coolers in space.

demonstration mission in conjunction with the Celestial Mapping Program [1]. The cooler provided 3.5 W at 60 K plus 0.15 W at 13 K for 427 watts of input power. The system accumulated 1179 hours of operation, which included 689 hours of prelaunch checkout and 490 hours of orbital operation. The system was operating at approximately nominal conditions when the heat-rejection coolant loop failed, thus causing system shutdown. During most of the orbital operation, the unit maintained the specified temperatures.

1972—SESP 72-2 Lockheed Solid CO_2 Cryostat. Shortly after the first Stirling and VM cryocoolers were launched to support infrared missions in 1971, the first cryostats flew on SESP 72-2 in October 1972 to support a DoD gamma-ray mission. The mission consisted of two single-stage solid carbon dioxide cryostats, each providing cooling of a separate gamma-ray detector at 126 K; the cryostats were 40.6 cm in diameter by 35.6 cm long and lasted for 7 and 8 months, respectively [4, 5]. Development of cryostats with both liquid and solid cryogens had been underway for nearly 10-years, and this first cryostat in orbit was built by Lockheed Palo Alto. A photograph of one of the cryostats is shown in Figure 4.

This first flight cryostat established Lockheed's cryostat design philosophy for many years [6]. Design elements include a folded cylinder support for the cryogen tank and a modular approach in which the detector and cooler could be separately developed and tested, and then integrated via a simple shrink-fit attachment that allowed a “drop in” mating of the two. To allow the detector to be maintained in a clean vacuum environment, the detector module was a sealed unit with its own vacuum system that consisted of a vac-ion pump. During ground operations and spacecraft integration, the cryogen was maintained in a non-vented condition by periodic circulation of LN_2 through the cooling coils at approximately one-week intervals.

With an orbital lifetime goal for the system of one year, the shorter 7-8 month lifetime achieved was attributed in part to contamination of the low-emissivity surfaces of the detector resulting from ice accumulation, and to initial heat rate predictions based on erroneous conductivity data for the support tube and the MLI insulating materials. Achieving longer life cryostats with better life prediction was a key technology focus for the next few years.

1973—Malaker Stirlings on Skylab. From May 1973 to February 1974, Malaker Stirling cryocoolers were used again in two Earth resources infrared experiments on Skylab (Figure 5) to evaluate the applicability and usefulness of sensing Earth resources from orbital altitudes in the visible through the far infrared spectral regions [7]. The two complimentary units were the S-191 Visible-Infrared Spectrometer, built by Block Engineering of Cambridge, MA, and the S-192 13-band Multispectral Optomechanical Scanner built by Honeywell Research Center of Lexington, MA [8]. Both used HgCdTe photoconductive detectors cooled to ~100K by Malaker

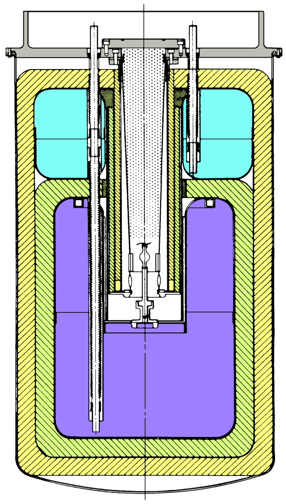


Figure 6. Lockheed Solid CH_4/NH_3 cryostat flown on Nimbus 6.

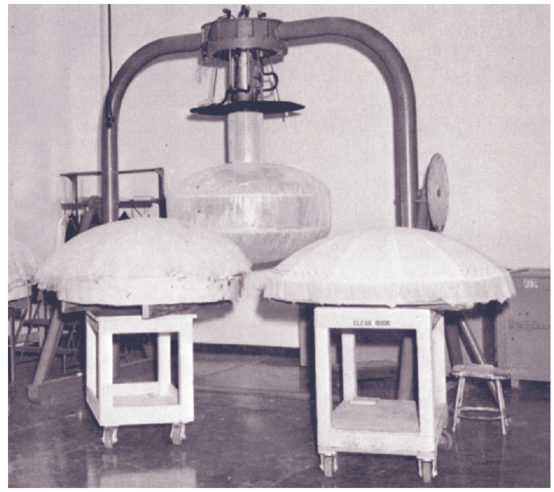


Figure 7. Early testing by Lockheed of candidate constructions of multilayer insulation (MLI).

Stirling cryocoolers to acquire data in their 6.2 – 15.5 μm and 10.2 – 12.5 μm far-infrared bands, respectively. The S-191 experiment was basically a two-channel visible and infrared spectroradiometer (manually pointed device), while the S-192 instrument utilized a 30 cm reflecting telescope with a rotating scan mirror.

1975—Nimbus 6 LRIR Cryostat. In June 1975, building on the success of their earlier solid CO_2 cryostat, Lockheed flew a dual-stage solid methane/solid ammonia cryostat on Nimbus 6 as part of the Limb Radiance Inversion Radiometer (LRIR) instrument. This cryostat, shown in Figure 6, provided cooling for a tri-metal detector array and the associated focusing optics and filters to 63 to 67 K (methane stage) and also provided cooling of other optical elements at 152 K (ammonia stage). Though the mission goal was one year, the detector remained within specified limits for approximately seven months, while the lifetime of the ammonia was twelve months [6, 9]. The design philosophy for this cryostat was similar to that of Lockheed's single-stage cooler in which the detector and secondary optics were housed in a separate capsule and interfaced with the cooler through shrink-fit elements. The cryogens were maintained in a non-vented mode by circulation of LN_2 at 10-day intervals. Once in orbit, explosive valves vented the cryogens and insulation vacuums to space.

Mid 1970s Liquid Helium Application. Although not in space, a far-infrared balloon-borne spectrometer was used for three flights in the mid-1970s to test the Big Bang theory. To increase its sensitivity, the instrument utilized germanium bolometers immersed in a cryostat cooled with superfluid helium. This is the first time that such a low temperature was used for infrared observations. The observations provided the most widely accepted support for the Big Bang theory until the launch of the COBE satellite in 1989. The first superfluid helium cryostat in space would be on IRAS in 1983.

1965-75 R&D Emphasis

During the late 1960s and early 1970s the focus of aerospace cryogenic research was on achieving long-life cryostats and cryocoolers for space use.

Cryostat Research. The major difficulty with the early solid cryogen coolers was the unpredictability of their lifetime, which was driven by the poorly quantified parasitic heat leaks associated with multilayer insulation (MLI) and support materials. Given the shortfalls in operational life, extensive research (illustrated in Figure 7) was conducted to improve the characterization and fabrication processes of MLI and support materials [10-12]. This work was supported jointly with the launch-vehicle community, which also needed low thermal

Figure 8. Hughes three-stage 12 K Vuilleumier cooler used dual opposed pistons.

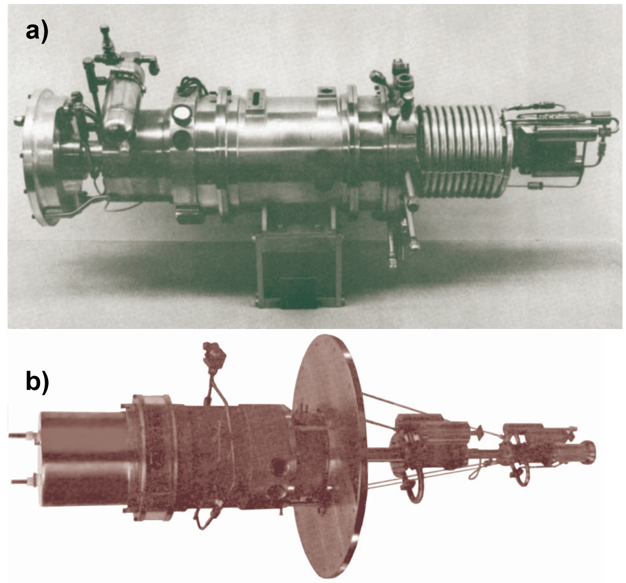


Figure 9. A.D. Little rotary-reciprocating refrigerators (R^3): a) single-stage 77 K system, b) 3.6 K hybrid Brayton/J-T system.

parasitics in cryogenic propellant tanks. Also, in support of Gravity Probe B, the porous plug was invented in 1970 for retention of superfluid helium in zero gravity [13].

Cryocooler Research. The major difficulty with the early cryocoolers was also their short unpredictable lifetime. The DoD's primary desire was to achieve long-life cooling at 10-12 K for the latest long wave infrared (LWIR) focal plane detector technologies, whereas NASA was concentrating on higher temperatures, around 65-80 K.

Vuilleumier Coolers. The work on Vuilleumier (VM) cryocoolers that was started by the Air Force in the 1960s at Hughes and Philips Laboratories was now focused on 3-stage machines capable of 0.3 W at 11.5 K, plus 10 W at 33 K, plus 12 W at 75 K, for an input power of 2700 W [14, 15]. The Philips unit had dual rotating shafts in a vibration-reducing rhombic configuration, while the Hughes unit, shown in Figure 8, used vibrationally-balanced opposed pistons. Because the VM cycle is thermally powered, operation of the cycle directly with radioisotopes or solar heat sources was considered feasible, and various studies of systems of this type were performed. In parallel, NASA GSFC started supporting single-stage Vuilleumier (VM) technology for higher-temperature NASA applications in 1969, resulting in a 7 W 75K for 300 W input cryocooler built by Garrett AiResearch and tested for 6000 hours [5].

10K Rotary Reciprocating Refrigerator (R^3). The work at A.D. Little initiated by the Air Force in 1962 on the rotary reciprocating (R^3) refrigerators led to the single-stage 77 K machine shown in Figure 9a. It utilized self-actuating, rotary gas bearings in both the compressor and expander sections, and linear motion to achieve the refrigeration. Thus, each moving member was both rotated and reciprocated. The machine also utilized clearance seals; thus, after startup, there were no rubbing surfaces in the machine.

In 1966, ADL was sponsored by the Air Force to extend the 77 K R^3 machine to achieve 1 watt at 3.6 K. A preliminary design of a complete refrigeration system suitable for spaceborne application was developed, and the expanders and associated drive system were tested. Shown in Figure 9b, this machine utilized a hybrid cycle coupling a Brayton upper stage with a 3.6 K Joule-Thomson bottom stage [2, 16].

Sorption Coolers. Initial studies of the feasibility of hydride sorption coolers also started during this decade with the work of Van Mal [17]. This work was primarily directed at conceptual design studies and quantification of the sorption isotherms of candidate hydride materials.

Figure 10. This was the decade of Shuttle development, leading to the first Shuttle launch in 1981.

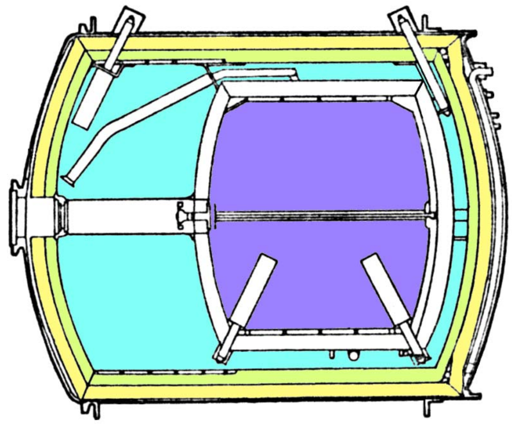


Figure 11. Ball methane/ammonia cryostat flown in 1978 on the High Energy Astronomical Observatories (HEAO-B and HEAO-C).

1975 TO 1985 — THE STRUGGLE FOR LONG-LIFE COOLERS

By the mid 1970s the space age was maturing, and work on the Space Shuttle was actively underway. Military personnel were busy designing large missile defense and reconnaissance satellite systems, and Earth and space scientists were planning various missions that could use the extensive access to space that would be provided by the Shuttle. Some of the proposed space-science studies focused on understanding the properties of superfluid helium in space and building on the early work to explore the Cosmic Microwave Background (CMB) of the universe.

Also, during this decade, the development of infrared array detectors (as opposed to single pixels) caused another giant leap in observational capability. This development greatly increased the efficiency of infrared observations and led to the development of infrared cameras that could produce images much more quickly than with a single element detector.

After several years of development, the first Shuttle launched in 1981 (Figure 10).

1975-85 Flight Applications

1978—Nimbus 7 LIMS Cryostat. The Limb Infrared Monitor of the Stratosphere (LIMS) instrument was flown aboard Nimbus 7 in October 1978 as a follow-on to the LRIR instrument that was flown in 1975 aboard Nimbus 6. Built by Honeywell, the instrument used an infrared detector and the same 65 K Lockheed methane/ammonia cryostat (shown earlier in Figure 6) used on LRIR [6, 9]. The objective of the LIMS experiment was to map the vertical profiles of temperature and the concentration of ozone, water vapor, nitrogen dioxide, and nitric acid in the lower to middle stratosphere range, with extension to the stratopause for water vapor, and into the lower mesosphere for temperature and ozone.

1978—HEAO-B/C CH_4/NH_3 Cryostat. About the same time that Lockheed flew their second methane/ammonia cryostat on Nimbus 7, Ball Aerospace flew their version of a methane/ammonia cryostat [5] on the High Energy Astronomical Observatories (HEAO-B and HEAO-C). The Ball cryostat, shown in Figure 11, had a loaded weight of 75 kg and measured 76 cm long by 56 cm in diameter. Cooling coils with LN_2 were used to freeze the cryogen during the fill operation and to maintain it during ground storage. After the final servicing before flight, the cryogens gradually warm up until the vent seal is opened in orbit. Heat exchange surfaces were located in both the primary and secondary tanks to promote even heat absorption by the cryogen.

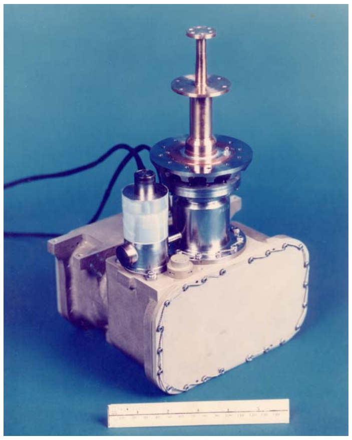


Figure 12. Philips rhombic-drive Stirling cooler launched on the STP 78-1 gamma-ray mission in 1979.

Figure 13. Over 60 of these Power Reactant Storage Assembly (PRSA) dewars were built by Beech Aircraft and Ball Aerospace to supply the Shuttle's fuel cells with hydrogen and oxygen.

1979—STP 78-1 Rhombic Drive Stirling. Launched as part of a DoD gamma-ray mission in 1979, this new 2-stage Stirling cooler (Figure 12) was developed specifically for long-term orbital operation by Philips Laboratories, with the Johns Hopkins Applied Physics Laboratory providing the electronic controls and space-qualification program. The overall gamma-ray system was developed by LMSC, and included two gamma-ray detectors, each with fully redundant cryocoolers, for a total of four coolers in the mission [18].

Each 7.2 kg cooler employed a grease-lubricated rhombic drive that utilized counter rotating weights to minimize generated vibration. Piston and displacer seals were glass-filled Teflon and Roulon. The cooling capacity of each cooler was 0.3 W at 77 K plus 1.5 W at 160 K, with an input power of 30 W. To support the redundancy approach, Lockheed developed self-actuating CTE-based thermal switches that disconnected the thermal link to the detector when a refrigerator was off (hot). However, the switches were not flown in the final configuration.

In total, the instrument was in orbit for 860 days, with a cumulative operating time for the four coolers of 4,700, 7,200, 13,000 and 16,020 hours, respectively [19]. Although this total run time was impressive, significant degradation in performance occurred. Consequently, after 130 days into the flight, both refrigerators were operated simultaneously in each instrument to provide the required cooling [19]. Not withstanding the performance degradation of the coolers, the utilization of the Stirling machines to provide instrument cooling over a continuous multi-year period was indeed a significant accomplishment. Up until this time no mechanical cooler had operated in space for more than 1000 hours.

1981—Shuttle PRSA Dewars. Originally developed by Beech Aircraft as a larger version of similar dewars first developed for the Apollo program (see 1968—Apollo Fuel Cell LH_2 and LO_2 Dewars) the Power Reactant Storage Assembly (PRSA) dewars (Figure 13) were developed to store supercritical liquid hydrogen and oxygen for use in the Shuttle's fuel cells to create electrical power and breathable oxygen. The LOX tank holds 317 liters with an operating pressure of 900 psia, while the LH_2 tank holds 606 liters at an operating pressure of 250 psia [20]. Over sixty PRSA dewars were delivered over the years, 28 by Beech Aircraft and 32 by Ball Aerospace following their acquisition of Beech in 1986.

1983—IRAS Helium Dewar. Shown in Figure 14, the Infrared Astronomical Satellite (IRAS) was launched in January 1983 with the first use of a superfluid helium dewar in space [21]. The 0.57-m IR telescope contained 62 detectors and was a joint project of the US, the UK, and the Netherlands. The American team built the telescope, detectors and cooling system, the British built the satellite ground station and control center, and the Dutch team built the spacecraft, which included the on-board computers and pointing system.

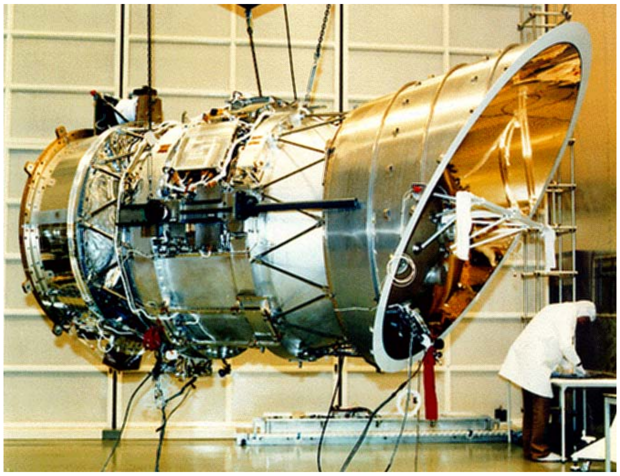


Figure 14. Launched in January 1983, the Ball Aerospace IRAS dewar was the first superfluid helium dewar in space.

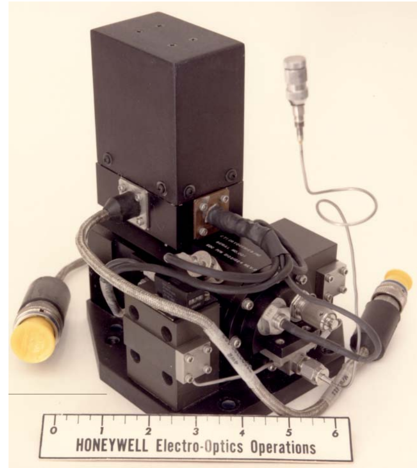


Figure 15. CTI Stirling cooler flown on the ATMOS instrument in 1985, 1992, and 1994.

The cryostat, which was filled with 480 liters of helium, was built by Ball Aerospace and involved the first space application of the porous plug that was invented at Stanford Univ. in 1970 [13]. The IR telescope was mounted in the center of the toroidal-shaped main cryogen tank, which was structurally supported through nine fiberglass-epoxy bands that attached to the outer vacuum shell. Additional thermal protection was provided by three vapor-cooled shields and multilayer insulation in the dewar's vacuum space. The outer shell operated at 170 K via radiant cooling to further reduce the parasitic heat load into the main cryogen tank.

During its 290-day life, IRAS scanned more than 96 percent of the sky four times, providing the first high sensitivity all sky map at wavelengths of 12, 25, 60 and 100 µm. IRAS increased the number of cataloged astronomical sources by about 70%, detecting about 350,000 infrared sources. Discoveries included a disk of dust grains around the star Vega, six new comets, and very strong infrared emission from interacting galaxies. IRAS also revealed, for the first time, the core of our galaxy—the Milky Way.

1985—ATMOS Stirling Cooler. The next mechanical cryocooler to fly was a CTI tactical Stirling cooler (Figure 15) that was part of the Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument on the 7-day Spacelab 3 flight in April 1985. The split Stirling coldtip cooled a HgCdTe IR detector within the ATMOS interferometer built by Honeywell of Lexington, MA. During three more space shuttle missions in 1992, 1993, and 1994, the instrument went on to measure solar absorption spectra from over 350 occultations from the upper troposphere to the lower mesosphere [22].

1985—Spacelab-2 Superfluid Helium Experiment. The Superfluid Helium Experiment (SFHE) was launched on Spacelab 2 in July 1985 to investigate the properties of superfluid helium in a microgravity environment [23]. An additional accomplishment was the qualification and characterization of the 120-liter space-compatible cryostat developed by Ball Aerospace as a reflyable dewar for liquid He microgravity experiments such as SFHE. In the future, the same dewar would be used for the Lambda Point Experiment (LPE) and Confined Helium Experiment (CHeX) in 1992 and 1997, respectively.

1985—Spacelab-2 Infrared Telescope. A second superfluid helium dewar on the July 1985 Spacelab-2 mission supported the Infrared Telescope (IRT) experiment. The IRT system was comprised of a 250-liter dewar, a helium transfer assembly, and a cryostat surrounding the IR telescope [24]. By utilizing a vacuum sealed rotary joint, the telescope could scan in one axis while the dewar remained stationary. A porous plug phase separator was located in the transfer assembly so that only gas was delivered to the cryostat assembly. The helium in the

Figure 16. Hughes Aircraft 3-stage "Hi Cap" Vuilleumier cooler.

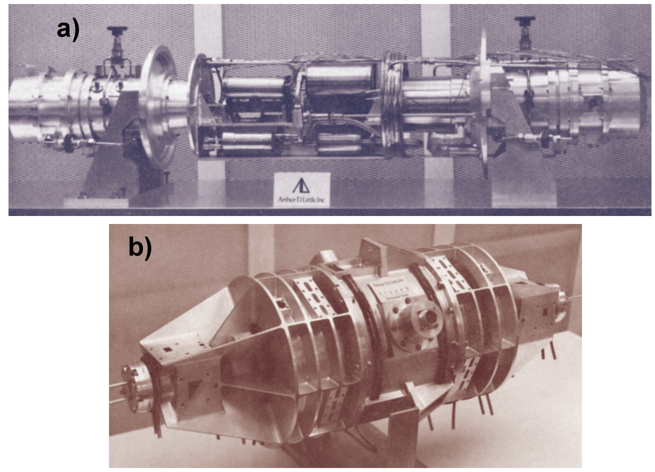


Figure 17. A.D. Little 2-stage Rotary Reciprocating Refrigerator (R^3): a) the expander assembly, b) one of two compressor modules.

dewar was maintained at 1.6 K while temperature requirements for the cryostat varied from 2.5 K at the detectors to 60 K at the upper telescope sections. The dewar and cryostat for the IRT system were manufactured by Cryogenics Associates, while NASA/Marshall Space Flight Center and the University of Alabama were responsible for the helium transfer assembly and subsequent integration.

1975-85 R&D Emphasis

A major factor in this decade was the DoD initiatives to develop a strategic missile defense system based on satellites using infrared tracking of intercontinental ballistic missiles. Having baselined the use of Silicon LWIR detector arrays that required significant 10-12 K cooling, major efforts were expended to bring large long-life 10-12 K cryocoolers into flight readiness [25]. In parallel, the civilian space agencies in the US and Europe supported the development of long-life cryocoolers for higher-temperature (60-80 K) Earth-science applications.

Large Long-Life Missile Defense Coolers for 10 K. Building on their ongoing space cooler development efforts and their strong need for long-life 10-12 K coolers, the DoD adopted a strategy of multiple parallel cooler development efforts:

Vuilleumier. The DoD's Vuilleumier cooler development program started back in the 1960s and led to a first flight cooler in 1971. By the 1980s the effort was focused on the development of the Hughes Aircraft Hi Cap machine (Figure 16) [5, 25]. Design requirements for this three-stage cooler were 0.3 W at 11.5 K plus 10 W at 33 K and 12 W at 75 K. Long-life operation was required with a maximum input power of 2,700 W. The Hughes approach used dry lubricated ball bearings (MoS_2) with a bearing retainer made of Roulon A (filled Teflon) with 5% MoS_2. The machine employed rubbing seals on both the hot and cold displacers and flexure pivots at the displacer drive-rod interfaces. Past problems included metal fatigue, internal contamination and seal wear. A major renewed effort to improve the reliability of the Hi Cap machine was undertaken in the mid 1980s [26]. This effort consisted of extensive testing of existing coolers to evaluate seals, regenerators, and other components.

10K Rotary Reciprocating Refrigerator (R^3). The goal for the 1980s 2-stage R^3 cooler shown in Figure 17 was a cooling capacity of 1.5 W at 12 K plus 40 W at 60 K for an input power of less than 2600 watts [27]. This development was an extension of the Air Force's long standing program developing rotary reciprocating Brayton coolers at A.D. Little dating from the 1960s [2]. Two of the first-generation machines were shown earlier in Figure 9. As with the earlier machines, this cooler also utilized self-actuating, rotary gas bearings in both the

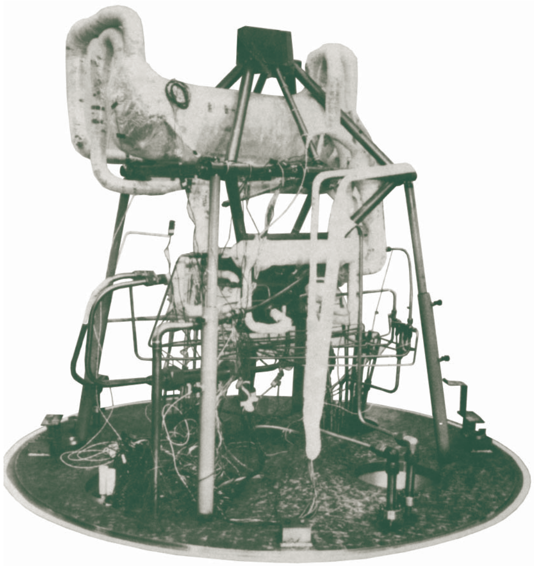


Figure 18. Garrett AiResearch turbo Brayton cooler.

Figure 19. Hughes rotary magnetic cooler for cooling between 10K and 20K.

compressors and the expanders to eliminate piston contact during the linear motion required to achieve refrigeration. By the mid 1980s the effort had been long and arduous, with a never-ending series of sophisticated problems requiring more advanced development [5].

10K Turbo Brayton. Because turbomachinery employing rotary gas bearings offered a high potential for long lifetime, a reverse-Brayton turbo-refrigerator for space was initiated in the early 1970s under DoD sponsorship as an alternative to the ADL R^3 concept. The system goals were cooling loads of 1.5 W at 12 K and 30 W at 60 K, with a 30,000 hour lifetime and a maximum power consumption of 4 kW [5]. The program resulted in a design of a four-stage turborefrigerator with gas bearings and included some component fabrication and testing. The contractor for the work was General Electric.

The Defense Advanced Research Project Agency (DARPA) initiated a follow-on turbo Brayton program in 1978 with Garrett AiResearch [28]. This system (Figure 18) was designed, fabricated and performance tested in the early 1980s. Although, it exhibited satisfactory operation, contamination and other issues prevented performance goals from being fully reached.

Large Rotary Magnetic Refrigerators. Given the difficulty of regenerative cryocoolers, such as Stirling coolers, achieving high efficiencies below 20 K, work was also initiated in the mid 1980s exploring the use of large magnetic coolers to bridge between 10 K and 20 K [26, 29, 30]. The coolers, such as the one in Figure 19, targeted the use of a new paramagnetic material $Gd_3Ga_5O_{12}$ (gadolinium gallium garnet or GGG) and higher-temperature superconducting magnet technology. All were rotary designs with a rotational rate of around 6-10 rpm. However, the development efforts faced extreme difficulties as internal losses and high forces from the magnets made it very difficult to achieve the promised efficiencies [31].

Long-life Stirling Coolers for 60-80 K. Building on the general success of the Philips Laboratories' rhombic-drive Stirling that flew in 1979 and on long-life pressure modulators developed at Oxford University, the Earth-science instrument community initiated development of 60-80 K long-life coolers focused at their higher-temperature needs.

Philips Magnet Bearing Stirling Cooler. In 1979, NASA/Goddard Space Flight Center initiated funding of Philips Laboratories for a next-generation Stirling cooler capable of producing 5 W at 65 K for 180 W of input power and with a lifetime of 3-5 years [5]. The basic design philosophy of the cooler was (1) to have no rubbing surfaces in the machine, (2) to electronically control axial position and piston/displacer phase angles, (3) to utilize a linear

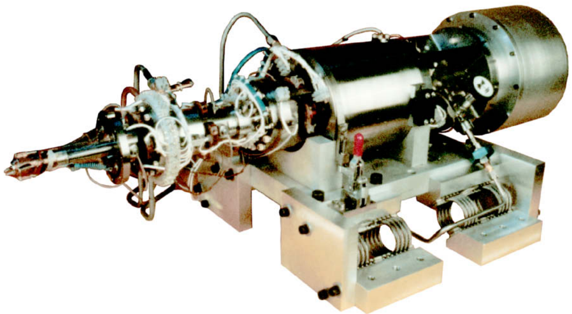


Figure 20. Magnetic bearing Stirling cooler built for NASA/Goddard Space Flight Center by Philips in 1979.

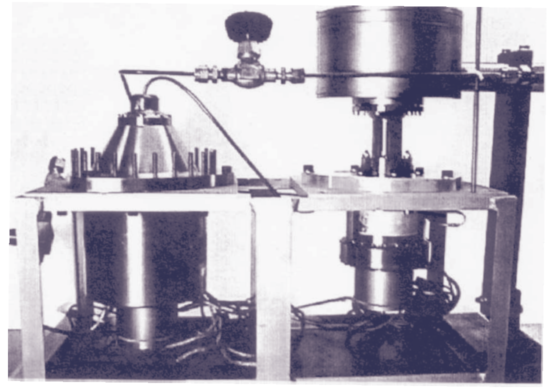


Figure 21. Original Oxford Stirling cooler built by Oxford University in the early 1980s.

drive system, and thus, eliminate mechanical linkages, (4) to reduce the potential for internal contamination by eliminating all organics inside the working gas, and (5) to provide an essentially dynamically balanced machine.

Shown in Figure 20, an Engineering Model single-stage device was developed using magnetic bearings and 25-µm clearance seals in the compressor and expander to eliminate all possible wear [32]. Although several hundred hours of operation were achieved, the resulting hardware was large and complex in comparison to the competing technology developed at the same time in England at Oxford University and Rutherford Appleton Laboratory (RAL).

Flexure Stirling Coolers at Oxford University and RAL. In 1980, Oxford University began work on a long-life Stirling cryocooler concept [33] that built on the flexure-bearing linear drive with clearance seals that was used for the pressure modulators that Oxford flew on PMR on Nimbus 6, SAMS on Nimbus 7, and VORTEX on Pioneer Venus [34-36]. The basic design philosophy of the so-called Oxford cooler was essentially the same as that enumerated above for the Philips Stirling. However, the implementation was much simpler, with passive flexure springs providing the piston support, as opposed to complex magnetic bearings. The Oxford cooler, shown in Figure 21, was also smaller, with a back-to-back pair targeted at 1.0 watt of cooling at 80 K, a mass of 10 kg, and an input power of 80 W [37]. During the early 1980s, in conjunction with RAL, this concept was developed into two slightly different flight coolers: one for use on the ATSR instrument on ERS-1, and the other for the ISAMS instrument on NASA's UARS spacecraft [38, 39, 40]. A cross-section showing the Oxford cooler internal construction features is shown in Figure 22.

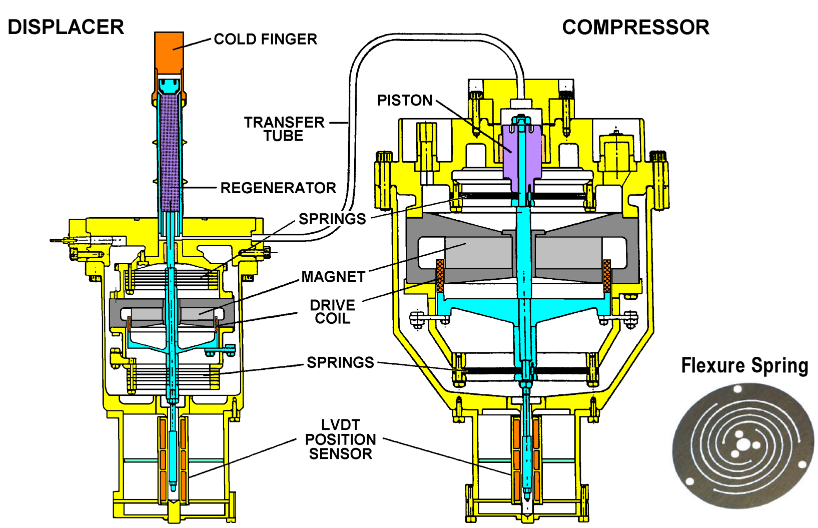


Figure 22. Cross-section of the Oxford Stirling cooler concept developed for ISAMS.

Figure 23. JPL 20 K Charcoal / H_2 sorption compressor of 1983.

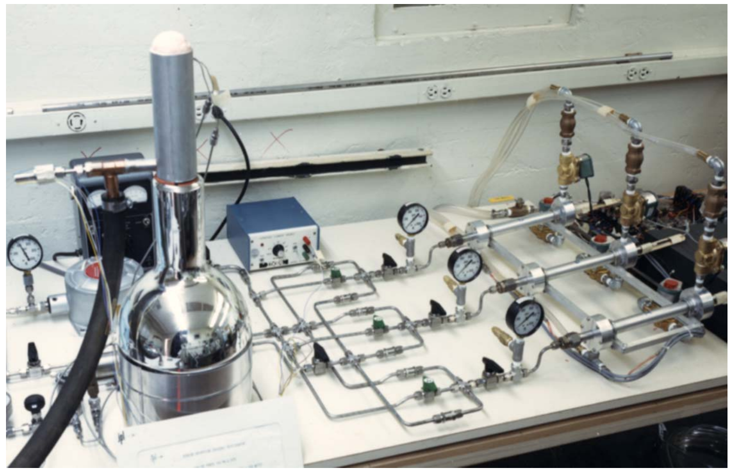


Figure 24. 1982 JPL Breadboard Hydride/H_2 cryocooler (650 mW at 29 K).

Long-life Sorption Coolers. Sorption technologies also started receiving modest recognition in the early 1980s as an alternative to the mechanical cooler concepts that were experiencing increasing difficulties in achieving long life. Work at the Jet Propulsion Laboratory and Aerojet Corp. of Azusa CA centered on both He/charcoal physical sorption concepts as shown in Figure 23, and on hydride chem-sorption concepts as shown in Figure 24 [41, 42].

Long-life Cryostats. By the 1980s cryostat technology had substantially matured based on the extensive research conducted in the 1970's on MLI and conductive material properties. Based on these advances, new long-life ammonia/methane cryostats were developed by Lockheed and referred to as the Extended Life Cooler or Long-Life Cooler, and the Advanced Long-Life Cooler [6, 43, 44]. These cryostats used solid methane as the primary cryogen, solid ammonia as the secondary, and could use passive radiators as a low-temperature guard for the ammonia. One system had a total weight of around 245 kg and a cooling capacity of 1.36 W-yr at the 60 K methane temperature, and 1.18 W-yr at the 145 K ammonia temperature [6].

Another important area of cryostat research was the use of solid hydrogen [6]. In these studies, the fill and vent of a solid hydrogen cooler was demonstrated and detailed safety analyses were performed. As an add-on to this effort, a para-to-ortho hydrogen catalytic converter to greatly improve effluent gas cooling was developed [45].

At this point solid hydrogen was being proposed as the cooling system for two instruments for the Upper Atmospheric Research Satellite (UARS) originally scheduled to launch in 1988. The Challenger accident in 1986 would delay the UARS launch and rule out the use of hydrogen dewars on future Shuttle flights. However, a few years later the solid hydrogen cryostat technology would be flown on the DoD's SPIRIT III mission in 1996.

1985-1995 — LONG-LIFE CRYOCOOLERS BECOME A REALITY

By the late 1980s the aggressive spending on defense technology during the Cold-War period was rapidly subsiding and the focus was beginning to shift toward smaller, more cost-effective approaches to missile defense. By the early 1990s the large DoD programs would be focused toward Brilliant Pebbles and Brilliant Eyes. However, the civilian space program, slower to feel the downsizing, was focused on great observatories like the Hubble Space Telescope (HST) launched in 1990, the Shuttle Infrared Telescope Facility (SIRTF), the Advanced X-ray Astrophysics Facility (AXAF), and the Gamma Ray Observatory (GRO). In this decade, the Earth scientists thoroughly embraced long-life cryocoolers and proposed dozens of instruments, many using cryocoolers, for NASA's huge Earth Observing System (EOS) platforms proposed for their Mission to Planet Earth.

Figure 25. Ball Aerospace superfluid helium dewar used for COBE was derived from the IRAS dewar flown in 1983.

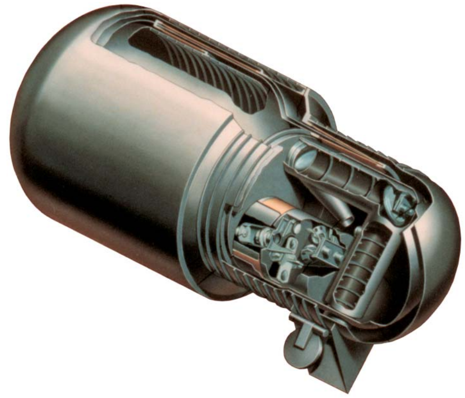


Figure 26. Two-stage SNe/CO_2 dewar built by Lockheed for the CLAES instrument launched in 1991 on UARS.

A sobering event at the beginning of this period was the explosion of the Challenger Shuttle in 1986. This led to a careful reexamination of mission safety and put a halt to the use of liquid fueled rockets carried aloft in the Shuttle for use in missions beyond low-Earth orbit. A return to a greater reliance on unmanned launch vehicles was the trend of the future.

1985-1995 Cryogenic Missions

1989—Cosmic Background Explorer (COBE). The Cosmic Background Explorer (COBE) mission launched in November 1989 using a superfluid helium dewar (Figure 25) based on the IRAS dewar with some small modifications [46]. COBE's objective was to map the infrared and microwave characteristics of the cosmic background radiation (CMBR) — the remains of the extreme heat of the Big Bang. Discovery of the universe's primordial "seeds" (cosmic microwave background anisotropy) by COBE's microwave receivers was reported worldwide as a fundamental scientific discovery. The cooled instruments, the Far IR Absolute Spectrophotometer and the Diffuse Infrared Background Experiment, measured the spectrum of the CMBR and discovered that the universe is filled with diffuse IR radiation.

1991—UARS CLAES Instrument. NASA's Upper Atmospheric Research Satellite (UARS) was launched in September 1991 with the Cryogenic Limb Array Etalon Spectrometer (CLAES) instrument that, before the Challenger accident, was scheduled to be cooled by a Lockheed cryostat with 944 liters (78 kg) of solid hydrogen [5]. After Challenger, the solid hydrogen cryostat was changed into a 15 K solid neon/carbon dioxide cryostat (Figure 26) that weighed 1035 kg with 152 liters (436 kg) of solid neon, and 326 liters (220 kg) of solid CO_2 [47, 48]. Part of NASA's Earth-sciences program, CLAES measured temperature profiles and concentrations of ozone, methane, water vapor, nitrogen oxides, and other important species, including CFCs, in the stratosphere using measurements of limb emission spectra in the 3.5 to 12 micrometer infrared wavelength range. These measurements were analyzed to better understand the photochemical, radiative, and dynamical processes taking place in the ozone layer. The dewar operated for 19 months in orbit, exceeding its 18-month design life.

1991—The First Oxford-style Coolers Reach Space. In July 1991 the Europeans launched their Earth Resources Satellite (ERS-1) with the Along Track Scanning Radiometer (ATSR-1) instrument that was cooled to 80 K via the RAL-version (Figure 27a) of the Oxford flexure-bearing Stirling cooler [40]. Two months later, in September, the Oxford University version of the 80 K Stirling cooler (Figure 27b) was launched as part of their Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument on NASA's Upper Atmospheric Research Satellite (UARS) [38, 39]. The success of these first long-life flexure-bearing Stirling coolers with clearance-type piston seals would lead to a dramatic change in the cryocooler world.

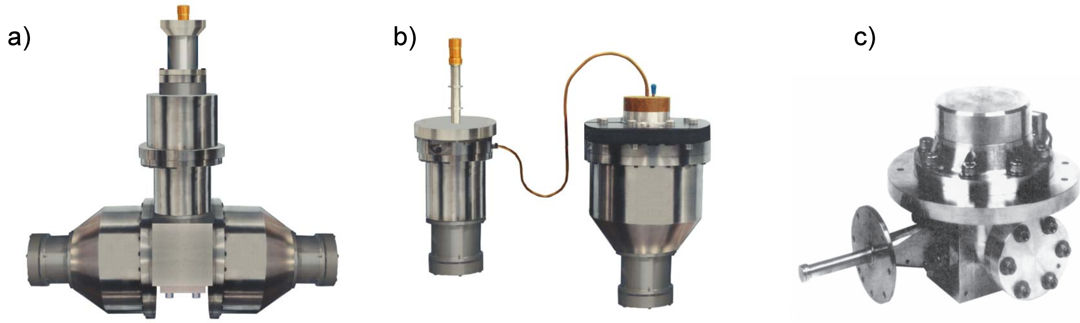


Figure 27. Space Stirling cryocoolers developed in the late 1980s: a) RAL 80K integral "Oxford" cooler flown on ATSR-1 and ATSR-2, b) Oxford University 80K ISAMS cooler flown on UARS, and c) Fujitsu 80K Stirling cooler flown on JERS-1.

1992—First Japanese Stirling in Space. In February 1992, the Japanese company Fujitsu launched their first space Stirling cooler on the Japanese Earth Resources Satellite (JERS-1). Used to cool the Short-Wave Infrared Radiometer (SWIR), the cooler had a cooling capacity of 1W at 80 K and was used to support 4000 short-period intermittent operations over a 2-year mission in space. The cryocooler design (Figure 27c) used an integral construction with rotary crank and had a measured mean lifetime of 3500 hours [49].

1992—Lambda Point Experiment. The Lambda Point Experiment (LPE) was a Shuttle payload dedicated to the study of the properties of superfluid helium in zero gravity. LPE flew on STS-52 as part of the US Microgravity Payload (USMP-1) in October 1992 and used the same dewar as used by SFHE in 1985 [50].

1993—HTTSE I. The first High Temperature Superconductivity Space Experiment (HTSSE I) was designed as a technology demonstration experiment to validate HTS components in a space-based system. It was developed by the US Naval Research Laboratory (NRL) and launched in 1993 using a British Aerospace 80 K cryocooler to cool its payload of superconducting devices. Unfortunately, the mission was lost before on-orbit startup when the host spacecraft failed [51].

1993—SHOOT. The Superfluid Helium On-Orbit Transfer (SHOOT) experiment successfully flew on STS-57 in 1993 and demonstrated using the fountain effect as the basis of a thermal mechanical pump for transferring superfluid helium between two tanks in a microgravity environment [52].

1994—Clementine. Launched in January 1994, the Clementine spacecraft was built by the US Naval Research Laboratory as a joint DoD/NASA technology demonstration flight focused at gathering data on the Moon and a near-Earth asteroid Geographos. Its sensor payload included a near-infrared camera cooled to 70 K and a long-wave infrared camera cooled to 65 K. Both were cooled by small Ricor K506B tactical cryocoolers [53].

1994—STRV-1b. Launched in June 1994, the STRV-1b spacecraft was developed by the Defense Evaluation Research Agency (DERA) of the UK Ministry of Defence as a small space technology testbed. The spacecraft carried a JPL-built cryocooler vibration-suppression experiment that demonstrated three-axis closed-loop control of the coldtip motion of a small 0.2-watt 80 K TI tactical Stirling cooler [54]. The cooler achieved over 3000 operational cycles, and was still functional when the mission was terminated after 4.5 years.

1995—ATSR-2. Launched on board the European Research Satellite (ERS-2) in April 1995, the second Along Track Scanning Radiometer (ATSR-2) was a follow-on instrument to ATSR, which was launched in 1991 to conduct sea surface temperature measurements with the accuracy required for climate research [55]. ATSR-2 used the flight spare of the RAL-built Oxford-style Stirling cryocooler that flew on ATSR-1 in 1991 (Figure 27a).

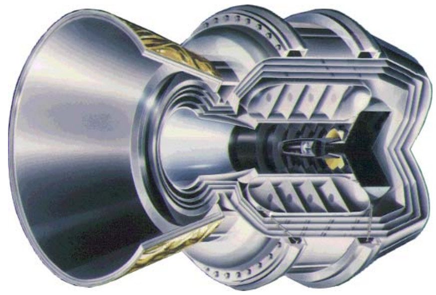


Figure 28. Japanese Infrared Telescope in Space (IRTS) launched in 1995.

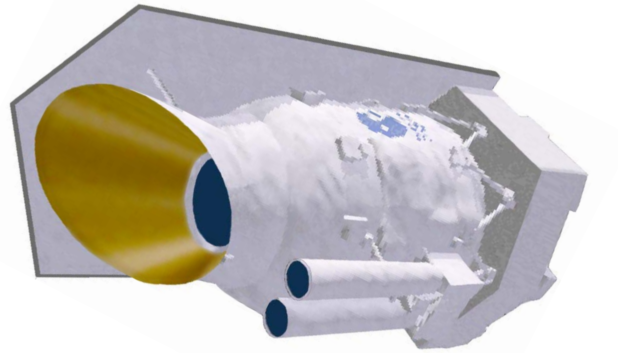


Figure 29. ESA Infrared Space Observatory (ISO) launched in 1995.

1995—CSE. The Cryo System Experiment (CSE) was launched on STS-77 in February 1995 as part of NASA's InSpace Technology Experiments Program (IN-STEP). CSE demonstrated the successful operation in space of a Hughes 2W 60 K SSC Stirling cooler and an experimental diode oxygen heat pipe also made by Hughes [56]. Such a heat pipe provides means of conducting heat from a remote cryogenic load and thermally disconnecting the load when the cooler is off.

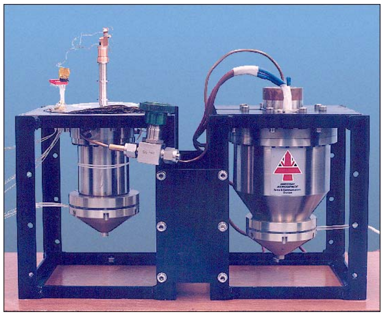
1995—IRTS. The Infrared Telescope in Space (IRTS) was the first Japanese orbiting telescope dedicated to infrared astronomy. The 0.15-m telescope, shown in Figure 28, was cooled to 1.8 K in a superfluid helium cryostat. It was launched aboard a Japanese multipurpose space platform SFU (Space Flyer Unit) spacecraft in March 1995 [57, 58] and surveyed approximately 7% of the sky with a relatively wide beam during its 28-day mission.

1995—ESA Infrared Space Observatory (ISO). Shown in Figure 29, ESA's Infrared Space Observatory (ISO), was launched in November 1995 and operated for 2.5 years. At the time it was the most sensitive infrared satellite ever launched, 1000 times more sensitive than IRAS, and observed over a wide range of infrared wavelengths (2.5 to 240 μm). The 0.6-m diameter cryogenic telescope was mounted within a large dewar containing 2200 liters of superfluid helium. The telescope held four instruments: an infrared camera, a photometer and two spectrometers working in different wavelength ranges. The instruments made use of different photo-conductors based on InSb, Si and Ge that operated between 1.8 and 10 K [59].

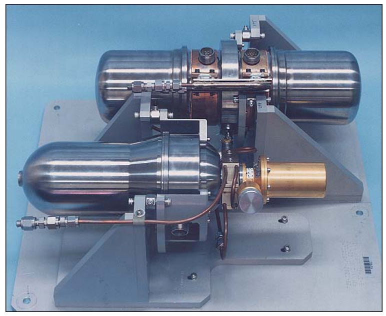
1985-95 R&D Emphasis

During this decade the aggressive spending on missile-defense cryocooler technology made a major shift toward smaller more cost-effective approaches. By 1992 the large DoD programs on the VM, 12 K Braytons, and 10-20 K magnetic refrigerators all ended, and none were ever used in space. Instead, the focus shifted toward smaller higher-temperature (50-80 K) cryocoolers that were also in demand by the civilian space community to support their desire for increasingly sophisticated Earth-science instruments. As part of its Mission to Planet Earth, the civilian space program was planning an extensive Earth Observing System (EOS) involving up to nine space platforms, each involving several large instruments—many with cryocoolers. At one point it was estimated that as many as 75 cryocoolers could be needed to support the full suite of nine EOS platforms. Cryostats, at this point, were considered fairly mature technology, and what little development was carried out was focused on specific missions like CLAES and ISO, which were building flight hardware.

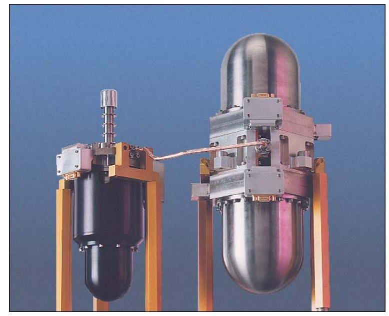
Long-Life 60-80 K Stirling coolers. Building on the success of the Oxford linear flexure-bearing Stirling coolers shown in Figures 22 and 27, a number of development contracts were awarded to expand this technology to the larger 2 W 60-80 K heat loads estimated for the new DoD and NASA EOS applications. The Air Force, through their Standard Space Cryocooler



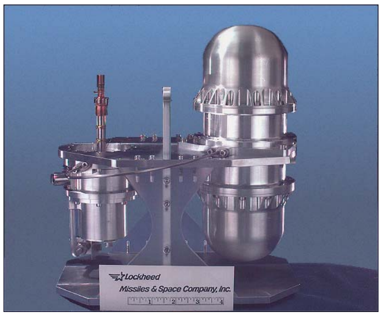
a) BAe 50-80K



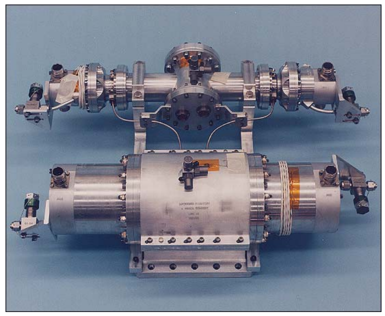
b) Hughes SSC 2W 60K



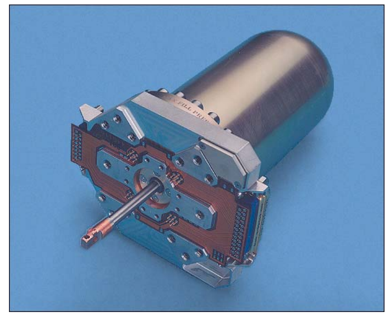
c) Ball 2W 60K



d) Lockheed 1710



e) Lockheed SCRS



f) TRW mini Stirling

Figure 30. Oxford-heritage Stirling cryocooler developments in the 1985-1995 timeframe.

(SSC) initiative [60], and NASA through the JPL Atmospheric Infrared Sounder (AIRS) [61] and GSFC development [62] efforts, funded new cooler designs at Hughes, Lockheed/Lucas, British Aerospace, and Ball Aerospace. The coolers, shown in Figure 30, all used variants of the Oxford flexure-spring supported linear drive with clearance seals. In Japan, Fujitsu and Mitsubishi also developed their versions of the Oxford cooler for the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument [63]. For smaller applications, TRW developed a miniature 1.4 kg Oxford-style Stirling cooler (Figure 30f) capable of 0.25 W at 65 K [64]. As an alternative to the Oxford design, the Air Force funded work on a diaphragm Stirling [65] at Creare (Figure 31) and work on a diaphragm compressor at Mechanical Technology, Inc. [60].

4 K Hybrid Oxford Stirling / J-T at RAL. In the late 1980s, the Rutherford Appleton Laboratory (RAL) in England began work on a two-stage Oxford-style Stirling cooler [66] for cooling in the 20-50 K range, and then mated it with a 4 K J-T bottom stage based on a two-stage Oxford-style compressor that used reed valves to achieve the required 9-to-1 compression-ratio DC gas flow [67]. Shown in Figure 32, the resulting 10 mW at 4 K cooler was targeted at the needs of future ESA space-science missions such as FIRST, Herschel and

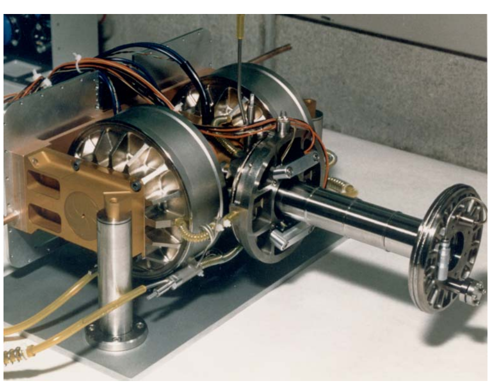


Figure 31. Creare 65 K diaphragm Stirling cooler.

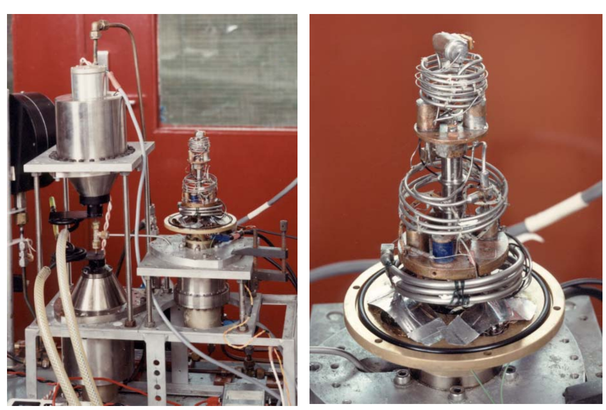
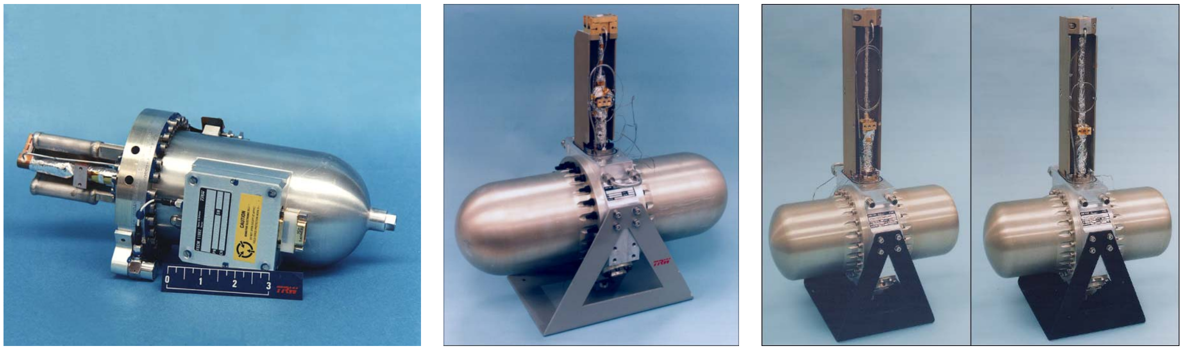


Figure 32. RAL 4 K brassboard cooler.



a) TRW mini pulse tube b) TRW 1W 35K pulse tube c) TRW 3503 and 6020 pulse tubes

Figure 33. TRW pulse tube cryocoolers using Oxford-heritage linear compressors.

Planck. Although the Russians flew a hybrid 4 K J-T/Stirling in 1981 [68], the unique aspect of the RAL design was the expected long life derived from using Oxford-style flexure-springs and clearance seals in both the J-T and Stirling compressors. This cooler served as the inspiration for future hybrid J-T/Stirling and Pulse Tube coolers developed by Ball Aerospace and NGST many years later for the NASA 6 K ACTDP cooler program [69].

Long-Life Pulse Tubes at TRW. Under Air Force sponsorship, TRW (now Northrop Grumman Space Technology) began work around 1989 to mate emerging pulse tube expander technology to Oxford-style linear compressors. In 1992 they developed a mini-pulse tube cooler [70] capable of 0.3 W at 73 K (Figure 33a), and in 1993 achieved the first really high-efficiency pulse tube cooler with the introduction of an inertance tube into their 20 cc 1W-35 K cryocooler [71] (Figure 33b). This and follow-on high efficiency pulse tube coolers such as the 3503 and 6020 [72,73] (Figure 33c) awakened the world to the merits of pulse tube coolers and led to a whole series of follow-on cooler designs that were flown in space over the next several years. Other work at TRW in the early 1990s examined multistage pulse tubes for use at temperatures as low as 10 K.

Long-Life Brayton coolers. Although all the large 10 K Brayton cooler development work at Garrett AiResearch and A.D. Little was stopped in 1991, interest continued in a smaller single-stage version of a turbo-Brayton cooler for providing around 5 W at 65 K. Starting with a series of Small Business Innovative Research (SBIR) contracts for component development, Creare, Inc. of Hanover, NH developed and delivered a complete Engineering Model cooler (Figure 34) in the 1993 timeframe under contract with NASA/GSFC and the Air Force [74,75]. An upgraded version of this cooler eventually flew as the NICMOS cooler on the Hubble Space Telescope in 2002 [76].

Figure 34. Creare 5 W 65 K Turbo Brayton cryocooler.

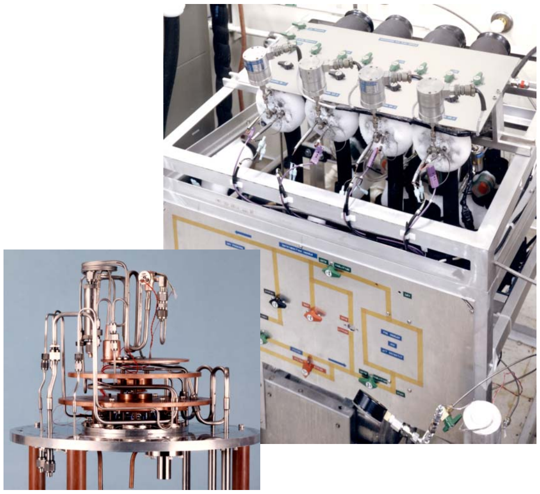


Figure 35. JPL's 70K HIMS PCO/O_2 life-test sorption cooler.

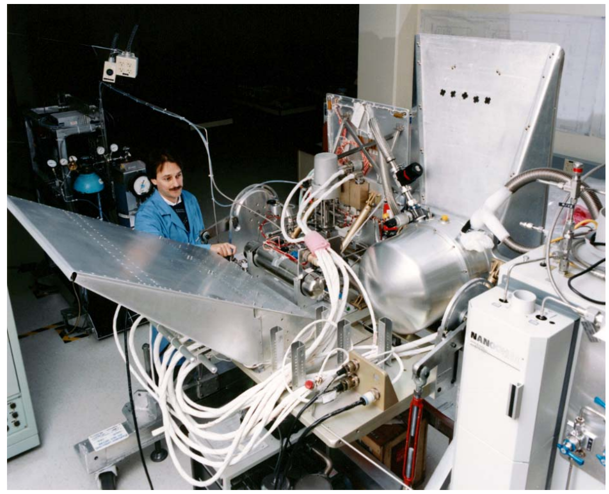


Figure 36. JPL's 10K BETSCE SH_2 sorption cooler flown on STS-77 in 1996.

Long-life Sorption Coolers. Sorption cooler technologies received increasing interest during the 1985-1995 timeframe for two applications: periodic 10 K cooling for missile defense, and for zero-vibration cooling for precision telescopes such as the Hubble Space Telescope (HST); the HST was launched in 1990 without an IR imaging capability.

PCO O_2 Sorption cooler for HIMS. Within NASA/JPL, development work was carried out on a two-stage sorption cooler for the Hubble Imaging Michelson Spectrometer (HIMS) instrument that was proposed as an IR replacement instrument for HST. The cooler utilized an Oxygen J-T to provide vibration-free cooling at 70 K based on a Praseodymium Cerium Oxide (PCO) chem-sorbent compressor, teamed with a Krypton/charcoal third stage at 140 K and thermoelectric cooler upper stages at 200 and 225 K [77]. Work continued through life testing of the brassboard unit shown in Figure 35, but was stopped when the competing NICMOS instrument, which used a solid nitrogen dewar, was selected for HST.

10 K Hydride Sorption cooler for the DoD. In a combined program, JPL and Aerojet developed a hydride sorption cooler for periodic cooling to 10 K for the SDIO Brilliant Eyes mission. Following a successful breadboard test in 1991 [61], the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) cooler, shown in Figure 36, was developed and flown on STS-77 as an in-space cryocooler demonstration in 1996 [78].

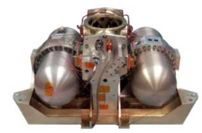
Regenerative Sorption concepts. Prior to the work on PCO and Hydride compressors, a variety of regenerative physical-sorption compressors were studied and tested at JPL and Aerojet using methane (65 K) and krypton (140 K) together with charcoal as the sorbent material. Despite the use of regeneration, the low efficiency of the physical sorption process eventually led to these technologies being passed over [79].

1995-2005 — LONG-LIFE CRYOCOOLERS AND LARGE CRYOSTATS BECOME MATURE SPACE TECHNOLOGIES

By the late 1990s 5-year-life space cryocoolers built on the Oxford-cooler compressor concept were considered a reality, and pulse tube cryocoolers became a focus of cryogenic research worldwide. Starting in December 1999, the three large NASA Earth Observing System platforms (Terra, Aqua and Aura) were launched, as was the large European ENVISAT platform. Together, they included over ten long-life cryocoolers in seven separate instruments. As shown in Table 2, by 2005 over 25 Oxford-style coolers were in orbit on multi-year missions — the majority were Stirling, but nine were pulse tubes. Also, a first turbo-Brayton cooler was launched for a vibration-sensitive application on the Hubble Space Telescope.

Table 2. Recent space cryocooler flight operating experience as of December 2005.

Cooler / Mission	Running Hours	Comments
Ball Aerospace 60K Stirling (HIRDLS)	12,000	Turnon: 8/04; ongoing no degrad.
Creare Turbo Brayton (NICMOS)	34,000	Turnon: 3/02; ongoing no degrad.
Fujitsu and Mitsubishi Stirling		
ASTER (2 units)	51,000	Turnon: 3/00; ongoing no degrad.
NGST (TRW) Cryocoolers		
CX (Mini PT (2 units))	69,000	Turnon: 2/98; ongoing no degrad.
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, miss'n end, no degr.
MTI (6020 10cc PT)	51,000	Turnon: 3/00; ongoing no degrad.
Hyperion (Mini PT)	44,000	Turnon: 12/00; ongoing no degrad.
SABER (Mini PT)	35,000	Turnon: 1/02; ongoing no degrad.
AIRS (10cc PT (2 units))	31,000	Turnon: 6/02; ongoing no degrad.
TES (10cc PT (2 units))	12,000	Turnon: 8/04; ongoing no degrad.
JAMI (6cc HEC PT)	6,000	Turnon: 4/05; ongoing no degrad.
Oxford/BAe/MMS/Astrium Stirling		
ISAMS (80 K Oxford)	15,800	Turnon:10/91; instrument failed 7/92†
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, miss'n end, no degr.
MOPITT (50-80K BAe (2 units))	47,000	Turnon: 3/00; one displacer failed at 10,300 hours; other still running†
ODIN (50-80K Astrium (2))	42,000	Turnon: 3/01; ongoing no degrad.
AATSR (50-80K Astrium (2))	33,000	Turnon: 4/02; ongoing no degrad.
MIPAS (50-80K Astrium (2))	23,000	Turnon: 4/02; ongoing† no degrad.
INTEGRAL (50-80K Astrium (4))	28,000	Turnon: 11/02; ongoing no degrad.
Rutherford Appleton Laboratory		
ATSR 1 (80K Integral Stirling)	44,000	7/91 thru 6/96, mission end, no degr.
ATSR 2 (80K Integral Stirling)	93,000	Turnon: 5/95; ongoing no degrad.
Sunpower RHESSI Stirling	34,000	Turnon: 2/02; ongoing no degrad.



† Cooler operating hours less than calendar hours due to instrument downtime

Complementing the excellent progress of long-life cryocoolers at temperatures above 20 K, dewars provided the foundation for low temperature missions requiring temperatures of 10 K and below during this timeframe. Cryostats were also used in missions like the Hubble Space Telescope that require near-zero vibration. However, the cryostats, unlike the cryocoolers, suffered a mixed history of reliability, with over a third of the civilian cryostat missions suffering critical mishaps.

During this decade, cooler research and development was generally associated with building and qualifying the many coolers that were used in the missions. Thus, the majority of the funding for cooler research transferred away from pure-R&D budgets, and was carried as part of flight-project funding for the specific space missions. This was largely true for both the civilian space-cooler development efforts as well as the military efforts [80].

1995-2005 Flight Applications

Long-life Cryocoolers for 50-80 K. Building on the success of the Oxford flexure-bearing linear-drive Stirling that first flew in 1991 together with the high-efficiency pulse tube coolers demonstrated at TRW in 1993, a large number of 50-80 K cryocooler missions were flown between 1998 and 2005. Nearly all of the coolers achieved multi-year lives in space as noted in Table 2.

1997—Lewis. The first two pulse tube cryocoolers launched into space were on this NASA spacecraft that failed prior to turn-on of the payloads. The spacecraft contained a TRW

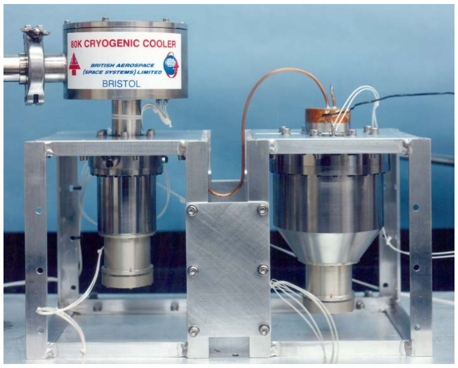


Figure 37. BAe 80 K Stirling cooler.

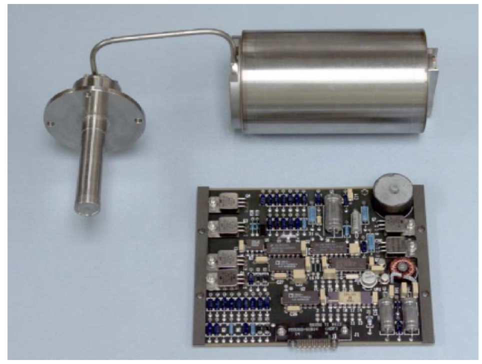


Figure 38. DRS 1W-80K Tactical cooler.

mini pulse tube cooler (shown earlier in Figure 33a) for TRW's HSI hyperspectral imager and a second TRW mini pulse tube cooler for the NASA Goddard LEISA instrument.

1998—CX. Launched in January 1998, this Sandia-developed DoD payload was cooled by a pair of the same TRW mini pulse tube cryocoolers (Figure 33a) that were used on the above Lewis mission. These were the first pulse tube cryocoolers to operate in space [81].

1999—HTSSE II. The High Temperature Superconductivity Space Experiment (HTSSE II) was launched on the US Air Force's ARGOS (Advanced Research and Global Observation Satellite) in February 1999 as a second technology demonstrator to validate high temperature superconductor (HTS) components in space-based systems. The experiment, managed by the US Naval Research Laboratory (NRL), used a British Aerospace 80 K cryocooler (Figure 37) to cool a number of HTS-based devices in the main experiment, and included a second experiment cooled by a TRW mini Stirling cooler (see Figure 30f) [82].

1999—MOPITT. The Measurements Of Pollution In The Troposphere (MOPITT) instrument was launched on NASA's EOS Terra space platform in December 1999. It contains a pair of back-to-back British Aerospace 50-80 K cryocoolers (see Figure 30a) that cool two separate sensors to 80 K [83]. Although one displacer failed after 11,000 hours of operation, the compressors and second displacer remain running as indicated in Table 2.

1999—ASTER. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument was also launched on NASA's EOS Terra space platform in December 1999. It contains a pair of sensors each cooled by a Japanese 80 K Oxford-style Stirling cooler; one cryocooler was made by Fujitsu, and the other was made by Mitsubishi [84].

2000—MTI. Launched in March 2000, the Sandia developed Multi-Spectral Thermal Imager (MTI) instrument is cooled by a 2 W- 60 K TRW pulse tube cryocooler referred to as the TRW 6020 (shown in Figure 33c) [85].

2000—STRV-2. The Space Technology Research Vehicle (STRV-2) was launched June 2000 as the primary payload of the USAF TSX-5 spacecraft. The instrument was designed to detect aircraft from space and to collect imagery enabling the characterization of various IR background types. The instrument's IR focal plane was cooled to 80 K using an off-the-shelf DRS 1W- 80 K Stirling cycle tactical cryocooler (Figure 38). The instrument also incorporated the test of a novel six DOF active vibration isolation and suppression system (VISS) that could be used to isolate a precision payload from spacecraft-borne disturbances [86].

2000—Hyperion. Launched on NASA's New Millennium EO-1 spacecraft in November 2000, the Hyperion instrument was a technology demonstrator to support evaluation of hyperspectral technology for future Earth observing missions. It has a single telescope and two spectrometers, one of which covers from 0.9 to 2.5 microns and is cooled to 110 K by a TRW mini pulse tube cryocooler (shown in Figure 33a) [81, 87].

Figure 39. Sunpower M77B Stirling cooler flown on RHESSI in 2002.

Figure 40. Creare NICMOS turbo-Brayton cryocooler flown on HST in 2002.

2001—ODIN. Launched in February 2001, Sweden's 250 kg science satellite, Odin, carries both radiometers and spectrometers for investigations of celestial objects as well as the Earth's atmosphere. Its Sub-Millimeter Radiometer (SMR) consists of four submillimeter channels and a 1-mm wave channel. The mixers and IF amplifiers are inside a cryostat and are cooled to approximately 130 K by a British Aerospace 80 K Stirling cooler (Figure 37) [88].

2001—SABER. Launched in December 2001 on the TIMED spacecraft, SABER uses a 10-channel IR radiometer operating from 1.27 to 17 μm to investigates the relative importance of radiative, chemical, and dynamical sources and sinks of energy in Earth's atmosphere. Its focal plane is cooled to 75 K by a TRW mini pulse tube cryocooler (Figure 33a).

2002—RHESSI. Launched in February 2002, the Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) uses an array of nine large germanium gamma-ray detectors to observe solar flares from 3 keV to 25 GeV [89]. The detector array is cooled to 75 K by a Sunpower M77B Stirling cooler (Figure 39) operating at 65 K. This mission represents the first application of a low-cost commercial cooler to achieve multi-year operation in space [90]. Additionally, the cooler uses a heat intercept strap clamped to the Stirling coldfinger to provide simultaneous cooling to the instrument's higher-temperature radiation shields at 155 K.

2002—NICMOS Turbo-Brayton Cryocooler. After the damaged solid-nitrogen dewar of the NICMOS instrument ran out of cryogen in January 1999, there was interest in restoring the instrument to life using a cryocooler. The 5 W 65 K turbo-Brayton cooler developed by Creare in the early 1990s was the only cooler candidate with the cooling power and near-zero vibration required for use on HST. By adding a turbine-pumped fluid loop to the turbo-Brayton cooler (Figure 40), a system was devised to cool the instrument to 77 K via its cooling coils originally used to freeze the cryogen in the dewar [76]. Astronauts installed the cooler, fluid loops, and a capillary-pumped-loop (CPL) heat rejection system in February 2002. Prior to installation on HST, the cooler was flown in 1998 on STS-95 as part of the Hubble Orbital Systems Test (HOST). The cooler retrofit was a resounding success, and NICMOS is now expected to continue to operate throughout the remainder of Hubble's life [91].

2002—AATSR. The Advanced Along Track Scanning Radiometer (AATSR) instrument continues the ATSR-1 and ATSR-2 observations of precise sea surface temperature providing a 10-year near-continuous data set at the levels of accuracy required for climate research. Launched in March 2002 on the ESA Envisat spacecraft, AATSR is an imaging radiometer, sensing at thermal infrared, reflected infrared, and visible wavelengths. The focal plane for the thermal infrared wavelength region is cooled to about 80 K by a pair of Astrium 50-80 K cryocoolers similar to those shown previously in Figure 30a [92].

2002—MIPAS. The Micholson Interferometer for Passive Atmosphere Sounding (MIPAS) is a Fourier transform spectrometer for the measurement of high-resolution gaseous emission

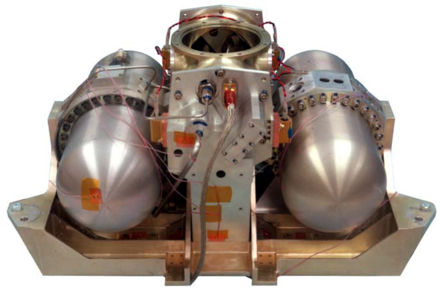


Figure 41. TRW 1.5W-55K pulse tube coolers flown on AIRS in 2002.

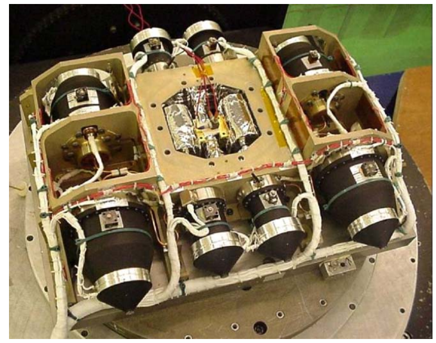


Figure 42. Suite of four Astrium 50-80 K coolers used to cool the INTEGRAL instrument.

spectra at the Earth's limb. Launched in March 2002 on the European Envisat spacecraft, it operates in the near to mid infrared where many trace-gases that play a major role in atmospheric chemistry have important emission features. The IR focal planes are cooled to 70 K by a back-to-back pair of Astrium 50-80 K cryocoolers [93].

2002—AIRS. JPL's Atmospheric Infrared Sounder (AIRS) instrument was launched on NASA's EOS Aqua space platform in May 2002 [94-96] to make precision global measurements of Earth's air temperature. It contains a redundant pair of TRW 1.5 W-55 K pulse tube cryocoolers (Figure 41) and was designed and built under JPL contract by Lockheed Martin Infrared Imaging Systems, Inc. (LMIRIS) of Lexington, MA (now BAE Systems IR Imaging Systems). AIRS was the first flight instrument to commit to a pulse tube cryocooler, and in so doing, ushered this important new technology into space cryogenics.

2002—INTEGRAL. The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is a medium size ESA science mission launched in October 2002 and dedicated to gamma-ray spectroscopy and imaging between 15 keV and 10 MeV. The γ-ray spectrometer on the spacecraft uses a 30-kg array of germanium detectors maintained at 85 K by the suite of four Astrium 50-80 K Stirling cryocoolers shown in Figure 42 [97].

2004—VIRTIS. Launched on board the European Space Agency's Rosetta spacecraft in March 2004, the VIRTIS instrument [98] contains two infrared spectrometers, each cooled to around 70 K by a miniature Ricor K508 tactical Stirling cryocooler (Figure 43). Rosetta is the first mission designed to both orbit and land on a comet; its target is a rendezvous with the comet Churyumov-Gerasimenko in 2014.

2004—TES. JPL's Tropospheric Emission Spectrometer (TES) instrument was launched on NASA's EOS Aura space platform in July 2004 to measure the chemical processes in the Earth's troposphere. It uses two identical TRW pulse tube coolers (Figure 44) to cool two separate IR focal planes to 62 K [99]. The coolers are a variant of the TRW 1.5 W-55 K AIRS pulse tube cooler, but with the pulse tube hard mounted to the compressor [100].

Figure 43. Tiny Ricor K508 tactical cooler flown on VIRTIS in 2004.

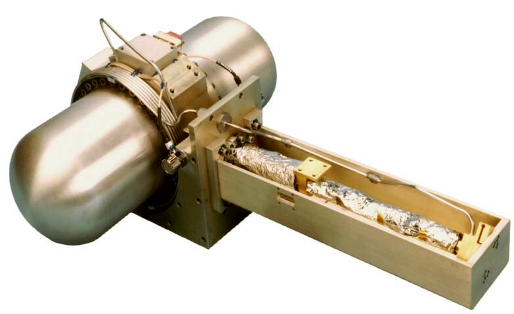


Figure 44. TRW 1.5W-55K pulse tube cooler flown on TES in 2004.

Figure 45. Ball Aerospace HIRDLS cryocooler.

Figure 46. TRW HEC pulse tube cooler flown on JAMI in 2005.

2004—HIRDLS. The High Resolution Dynamics Limb Sounder (HIRDLS) instrument is an international joint development between the USA and UK and was launched on NASA's EOS Aura spacecraft in July 2004. Though, during launch, the instrument suffered an optical blockage that has severely restricted the acquisition of science data, its infrared detectors continue to be cooled to 65 K by an integral back-to-back Ball Aerospace Oxford-style Stirling cooler with single dynamically balanced displacer (Figure 45) [101].

2004—Messenger. NASA's first trip to Mercury in 30 years was launched in August 2004 with a small Ricor K508 (see Figure 43) tactical cryocooler that will cool a germanium gamma-ray detector to 90 K to conduct a study of gamma-ray emissions from the Mercurian crust as well as solar winds and cosmic rays as it flys by the planet in 2008 and 2009, and eventually orbits around Mercury in 2011.

2005—JAMI. The Japanese Advanced Meteorological Imager (JAMI) instrument was launched on the Japanese MTSAT spacecraft in March 2005 and was developed by Raytheon SBRS (Santa Barbara Remote Sensing) under contract to Space Systems/Loral. The overall objective of the mission is to provide meteorological data for operational weather needs for Japan, East Asia, and Australia. The instrument focal plane views the 0.55 to 12.5 μm spectral region and is cooled to 67 K using two TRW HEC pulse tube coolers (Figure 46) [102].

2005—CRISM. Launched on NASA's Mars Reconnaissance Orbiter spacecraft in August 2005, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument uses a set of three parallel Ricor K508 tactical cryocoolers similar to the one shown previously in Figure 43 to cool the instrument's 105 K focal plane; operation of the coolers will occur upon arrival at the planet in 2006. To provide for switching between the three cryocoolers, each cryocooler is connected to the focal plane using a methane diode heatpipe.

Cryostat Missions. Complementing the excellent progress of long-life cryocoolers at temperatures above 20 K, dewars provided the foundation for low temperature missions requiring temperatures of 10 K and below during this timeframe. Cryostats were also used in missions like the Hubble space telescope, which require near-zero vibration. Table 3 summarizes the key flight cryostat missions.

1996—SPIRIT III Solid Hydrogen Cryostat. In April 1996 the DoD Ballistic Missile Defense Organization (BMDO) conducted a Midcourse Space Experiment (MSX) mission that included the Spatial Infrared Imaging Telescope III (SPIRT III) cooled by a Lockheed 10 K solid-hydrogen cryostat (Figure 47) [103]. In addition to testing technologies to identify and track ballistic missiles during flight, the mission also performed many scientific investigations of the Earth's atmosphere and outer space. SPIRIT III contained a long-wave infrared telescope with a high off-axis-rejection, a five-color radiometer, and a six-channel interferometer. It studied the infrared emission from the gas and dust that permeates the universe, and sur-

Table 3. Recent space cryostat flight operating experience.

Mission	Cryogen	Launch Date	Operate Hours	Comments
Ball Aerospace				
COBE (650 ℓ)	Sf He	1989	7,300	Similar to IRAS 1983 dewar
PRSA (on Shuttle)	ScH_2, ScO_2	1991-04	500	60 dewars for Shuttle fuel cells
BBXRT (shuttle)	solid Ar	1991-98	200	Multiple Shuttle experiments
NICMOS (on HST)	solid N_2	1998	12,000	Damaged during launch
Spitzer (360 ℓ)	Sf He	2003	17,500	As of 8/05, projected life 5 years
Lockheed Martin				
CLAES (on UARS)	Ne-CO_2	1991	13,900	Was solid H_2 before Challenger
MSX (Spirit III)	solid H_2	1996	7,300	DoD mission, lasted 10 mths
WIRE	solid H_2	1999	15	Failed on deployment in orbit
GPB (2400 ℓ)	Sf He	2004	12,600	As of 10/05 at end of mission
GSFC				
XRS (25 ℓ)	Sf He	2005	750	Design life 3 years; lasted 30 days
ESA				
ISO (2200 ℓ)	Sf He	1995	22,000	Operational 30 mths





veyed areas of the sky that were missed by IRAS. In November 1994, just prior to launch, the cryostat suffered a loss of vacuum in the insulation space; this resulted in extensive damage to it and the instrument. Although it was repaired prior to launch, some possible remaining damage to the MLI together with not filling the dewar the entire way and a higher shell temperature than planned in orbit were felt to have been responsible for the mission life of 10 months compared to the 18-month design life.

1997—NICMOS Solid Nitrogen Cryostat. In February 1997, the Near-Infrared Camera and Multiple-Object Spectrometer (NICMOS) instrument was installed on the Hubble Space Telescope during its second servicing mission to provide an infrared imaging capability from 0.8 to 2.5 microns. Its HgCdTe photoconductive detectors were cooled to 65 K by a Ball Aerospace cryostat (Figure 48) using 120 kg of solid Nitrogen [104]. Unfortunately, during repeated warming cycles prior to and during launch, the expanding nitrogen warped the dewar and led to a thermal short to one of the vapor-cooled shields [105]. As a result of the increased heat leak, the mission lasted 23 months, far short of its 5-year design life. Five years later, the NICMOS instrument was brought back to life through the installation of the low-vibration Creare turbo-Brayton cryocooler installed during HST servicing mission 3B [76].

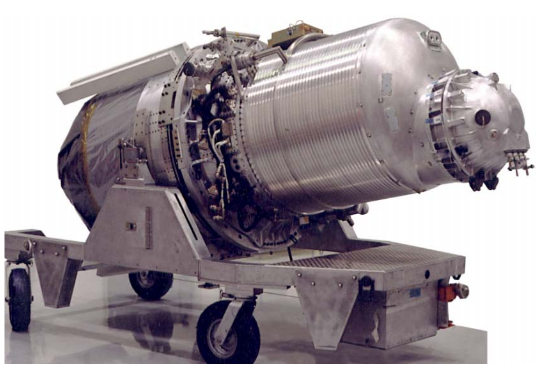


Figure 47. SPIRIT III solid H_2 Cryostat.

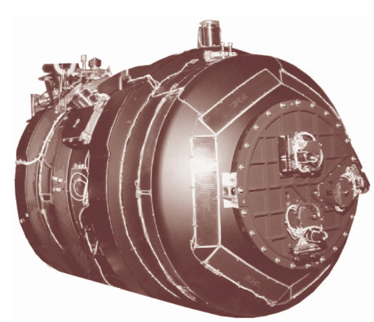


Figure 48. NICMOS solid N_2 cryostat.

Figure 49. WIRE 7K solid H_2 dewar.

Figure 50. SIRTF superfluid He dewar.

Figure 51. GPB superfluid He dewar.

1999—WIRE 7.5 K Solid Hydrogen Cryostat. Launched in March 1999, the Wide-Field InfraRed Explorer (WIRE) was one of NASA's small explorer series, a 'faster, better, cheaper' mission designed to spend 4 months surveying the sky at mid-infrared wavelengths between 12 and 25 microns with a sensitivity 1000 times better than IRAS. The Lockheed-built cryostat shown in Figure 49 consisted of two solid-hydrogen stages, one at 13 K to cool the telescope and serve as a thermal guard for the lower stage, and one at 7.5 K to cool the 128×128 Si:Ga detector array [106]. Unfortunately, an electronic glitch in the spacecraft resulted in the dewar lid getting ejected prematurely, prior to the telescope being stably pointed toward dark space. With sun shining into the telescope, in just 15 hours the entire four-month supply of hydrogen was vaporized, and the mission was lost.

2003—SIRTF 1.4 K Superfluid Helium Cryostat. One of NASA's great observatories, SIRTF began its development in 1983 as the Shuttle Infrared Telescope Facility, and over the years became the Space Infrared Telescope Facility when it was separated from the shuttle; it was renamed *Spitzer* after it was successfully launched in August 2003. Over its 20 years of development, SIRTF survived several changes in design philosophy including the "cheaper faster better" paradigm of the early 1990s. The final cryogenic design of the 0.85-m IR telescope (Figure 50) is remarkably well optimized and promises over 5 years of operation on 360 liters of superfluid helium; this contrasts with ISO's 2200 liters used for a 0.6-m IR telescope with a 30-month life [107]. Spitzer is much more sensitive than prior infrared missions and is studying the Universe over a range of wavelengths from 3 to 180 μm. Its three instruments together contain 11 detector arrays, operating from 1.4 to about 10 K, along with the attendant optics for imaging and spectroscopy. The detectors and instruments are cooled directly by the liquid helium cryostat, while the effluent gas is used to cool the telescope down to 6 K. Its key objectives are the study of brown dwarfs, superplanets, planetary systems revealed by protoplanetary and debris disks, and surveys of galaxy activity and the distant Universe.

2004—GPB 1.8 K Superfluid Helium Cryostat. Gravity Probe-B (GPB) began its life in 1963, even earlier than SIRTF, and was finally launched into orbit in April 2004 to test two unverified predictions of Einstein's general theory of relativity. Over its 40 years of development by Stanford University, GPB developed a wide array of cutting-edge technologies, one of which is the world's most precision gyroscopes. Two others are the 9-foot-tall Lockheed-built dewar [108] (Figure 51), which contains 2440 liters of superfluid helium, and its porous plug liquid-vapor phase separator [13]. The He dewar provides the 1.8 K required for the instrument's Superconducting Quantum Interference Device (SQUID) magnetometers that measure the drift of the gyroscope's spin axis, and for other superconducting elements used in the instrument to monitor and shield-out external magnetic fields. The liquid helium lasted until September 30, 2005 (17 months from launch) providing 12 months of science data to test Einstein's theory.

2005—XRS. The X-Ray Spectrometer (XRS) instrument was originally slated for NASA's x-ray observatory (AXAF) back in 1985. When AXAF was replanned, XRS became a part of the joint Japanese/US Astro-E mission, which failed to achieve orbit in February 2000. Unfortunately, the third time was not a success either, as XRS consumed its 3-year supply of helium within a month after being successfully launched as the prime instrument of the Japanese Suzaku (formerly Astro-E2) spacecraft in July 2005. XRS was designed to measure the spectrum of celestial objects in the "soft" X-ray range (200 to 10,000 eV) to much higher resolution than had been previously possible. The x-ray detectors were cooled to 65 mK using a GSFC Adiabatic Demagnetization Refrigerator (ADR) cooled by a superfluid helium dewar [109]. The 25-liter 1.3 K superfluid He dewar was in turn cooled by a 17 K solid neon dewar provided by the Japanese, which in turn was cooled by a Sumitomo Stirling cryocooler to achieve a design life in orbit of 2.5 to 3 years. Although the excessive heat load ended the mission in just 29 days, XRS achieved 58 mK steadystate — a new record low temperature for space.

Technology Demonstration Cryocooler Missions. In addition to the prime missions described above, the 1995-2005 period also had some important technology demonstration missions to test out new technologies or to run cryogenic experiments in space. These included both cryostat and cryocooler missions.

1996—MIDAS. The Materials in Devices as Superconductors (MIDAS) was a NASA cryogenic facility for the characterization of high temperature superconductors during extended flights. It was based on a Stirling cooler capable of 1 W cooling at 80 K, with a maximum power consumption of 60 W [110]. Launched on STS-79 it was installed on board the Russian space station MIR, where it operated for about 3 months before returning.

1996—BETSCE. In May 1996 the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) flew on board STS-77 (Figure 52) and demonstrated the capability to cool a 100 mW load to <11 K in less than two minutes, and then to continue to maintain the load at temperature for 10-20 minutes [111]. After this period, the closed-cycle Joule-Thomson sorption cryocooler recycled in preparation for another cooling cycle. The periodic nature of the cooler allowed the required input power to be averaged over the four-hour recycle time, thus providing a fast-cooldown 150 mW 10 K cooler for a relatively low average power. The cooler, also shown earlier in Figure 36, was built for SDIO by JPL and Aerojet and was based on metal-hydride sorption compressors combined with three Hughes 7044H tactical Stirling cryocoolers to precool the hydrogen J-T gas stream to 65 K before making solid hydrogen at 10 K in the system's coldtip reservoir.

1997—COOLLAR. In August 1997 the Cryogenic On-Orbit Long-Life Active Refrigerator (COOLLAR) flew on board STS-85 and demonstrated a cooling capacity of 3.5 W at 65 K together with 5 W at 120 K. COOLLAR (Figure 53) is an oil-lubricated multipiston closed

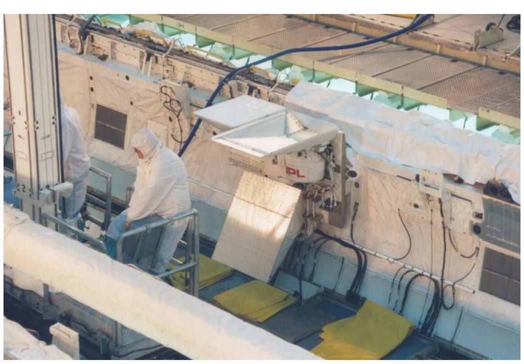


Figure 52. 10 K BETSCE cryocooler integrated onto space shuttle STS-77.

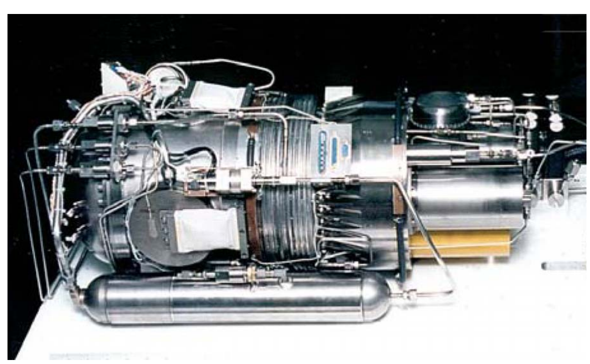


Figure 53. Ball Aerospace COOLLAR closed-cycle 77 K J-T cryocooler.

cycle nitrogen J-T developed by Ball Aerospace for the DoD [112]. It was an important pathfinder for long-life space J-T cryocoolers.

1997—CheX. Flown on STS-87 in November 1997 as part of USMP-4, the Confined Helium Experiment (CHeX) was a follow-on experiment that used, for the last time, the same superfluid helium dewar as LPE in 1991. The experiment investigated the behavior of He at the transition between superfluid and liquid state [113].

2000—STRV-1d. Launched in November 2000, the STRV-1d spacecraft was developed by the Defense Evaluation Research Agency (DERA) of the UK Ministry of Defence as a small space technology test-bed. The spacecraft carried a JPL-built Quantum Well Infrared Photodetector (QWIP) focal plane validation flight experiment cooled by a DRS 1W-80K tactical Stirling cryocooler (Figure 38) that cooled the detector to 50 K [114].

1995-2005 R&D Emphasis

During this decade of over 25 successful long-life space cooler missions, cooler research and development was principally associated with building and qualifying the many coolers that were used in the missions. Thus, the majority of the funding for cooler research transferred away from pure R&D budgets, and was carried as part of flight project funding for the specific space missions. This was largely true for both the civilian space-cooler development efforts as well as the military efforts.

Following this trend, most of the development efforts for future space cooler missions was funded by approved future flight missions. These are described below:

Long-Life 35-80 K Stirling and Pulse Tube Coolers. Building on the work in the early 1990s, extensive development of third- and fourth-generation Oxford-style linear flexure-bearing coolers and drive electronics took place at NGST (formerly TRW), Ball Aerospace, Lockheed Martin, and Raytheon (formerly Hughes) between 1995 and 2005. Included in this work was the incorporation of active vibration cancellation [115], closed-loop control of coldtip temperature [116], and active suppression of current ripple fed back onto the spacecraft power bus. The TRW 1.5 W 55 K AIRS [95] and 0.5 W 55 K IMAS [117] pulse tube coolers served as pathfinders for many of these new performance-enhancement technologies incorporated into the cryocooler drive electronics.

Military applications such as SBIRS-low also sponsored extensive development of single and multi-stage coolers for a variety of applications — all building on the general designs of the earlier Oxford coolers. This included designs such as the NGST and Lockheed pulse tube cryocoolers shown in Figure 54; these have input power ratings as high as 600 watts with cooling capacities up to 2 W at 35 K plus 20 W at 85 K [118, 119]. The primary focus of Ray-

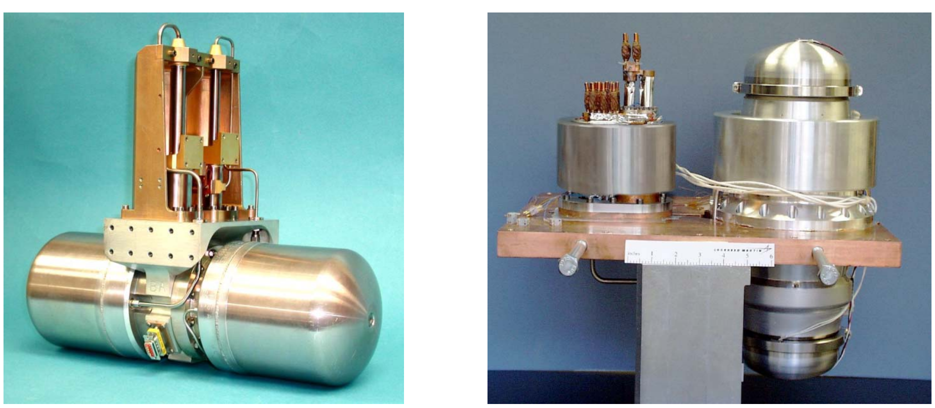


Figure 54. NGST (left) and Lockheed (right) two-stage HCC pulse tube cryocoolers are designed for power levels up to 600 watts.

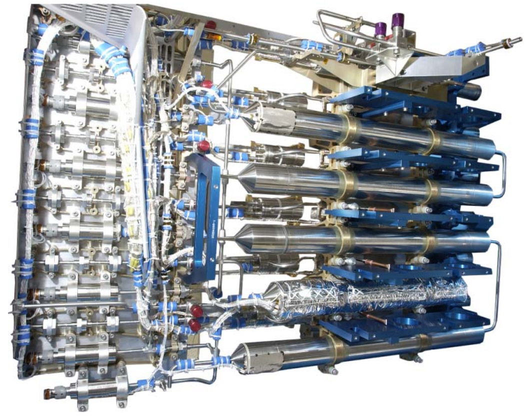


Figure 55. Planck sorption cryocooler compressor assembly as delivered for spacecraft integration.

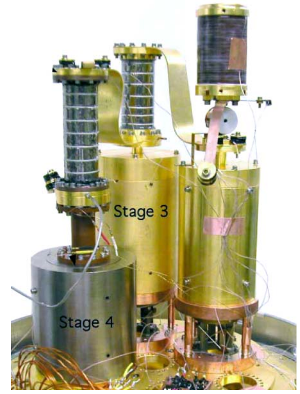


Figure 56. Sub-Kelvin ADR refrigerator for Constellation-X.

theon and Ball Aerospace was on high efficiency single and multi-stage Stirling coolers targeted at the 35 K temperature range [120,121].

Hybrid J-T Sorption Cooling for Temperatures down to 4 K. The European Planck mission, scheduled for launch in the 2007 timeframe, sponsored the flight development of JPL hydride sorption coolers building on the work started by Jones, et al. as early as 1982 [42]. The main objective of Planck is to map the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky with high sensitivity. Achieving this goal requires bolometers operating at 100 mK, HEMT devices operating at 20 K, and a low-emissivity cooled telescope at 60 K. The cryogenic system being developed for Planck is based on precooling to 60 K by passive radiators, cooling to 20 K with the JPL hydride sorption cooler [122, 123] (Figure 55), cooling to 4 K with an RAL He Joule-Thomson cooler based on Oxford mechanical compressors, and final cooling to 100 mK using an open-loop dilution refrigerator (discussed in the next paragraph under sub-Kelvin cooler developments). The RAL 4 K cooler is a derivative of the developments started in the 1980s, shown previously in Figure 32 [124, 125]. The planned mission lifetime for Planck is 15 months.

Sub-Kelvin Cryocoolers for Cooling down to 50 mK. To enable sub-Kelvin detectors on XRS, Herschel, Planck, and future space-science missions, a variety of sub-Kelvin refrigerators were developed for flight between 1995 and 2005. This includes the 1999 launch of the NASA Goddard single-stage ADR used to provide 65 mK cooling from a 1.3 K He bath for the X-ray detectors on XRS. After the failure of the 1999 XRS launch, a second XRS ADR cooler was built for the re-flight in 2005. This XRS single-stage ADR cooler had been under development since the early 1980s [109].

Additional sub-Kelvin refrigerator development included an open cycle ^{3}He sorption cooler to provide the 0.3 K cooling required by FIRST/Herschel [126], and the open-loop dilution refrigerator [127, 128] designed by CRTBT in Grenoble and manufactured by Air Liquide to provide 100 mK cooling for Planck. Building on the concepts developed for XRS, NASA Goddard also began development of a prototype four-stage ADR (Figure 56) for cooling X-ray microcalorimeters to 50 mK for the future NASA Constellation-X mission [129].

Hybrid J-T Stirling and Pulse Tube Cooling for Temperatures down to 4 K. To enable a suite of ever more capable science observatories, NASA initiated funding in 2001 for long-life coolers in the 4-20 K temperature range. With three future missions as its focus, the Advanced Cryocooler Technology Development Program (ACTDP) was funded under the Terrestrial Planet Finder (TPF) project to develop long-life mechanical cryocoolers with the necessary cooling power and integration features to accommodate the 6 K/18 K cooling of its target missions [130]. Three alternative concepts, shown in Figure 57, were selected for devel-

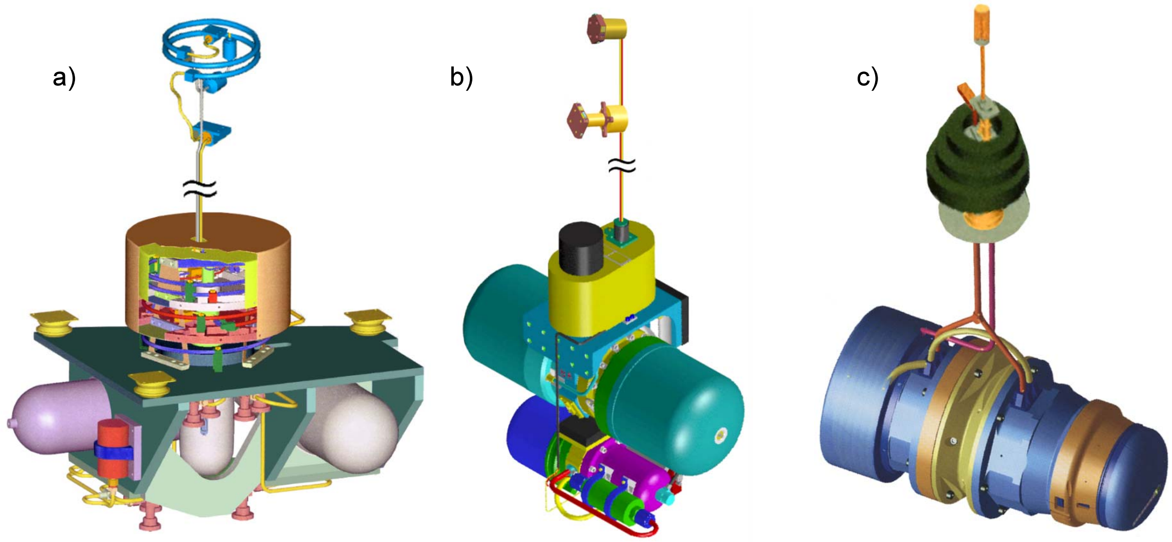


Figure 57. ACTDP coolers: a) Ball 6 K JT with 18 K Stirling precooler, b) NGST 6 K JT with 18 K pulse tube precooler, and c) Lockheed Martin 4-stage 6 K pulse tube.

opment: two hybrid systems using Stirling/Joule-Thomson and pulse tube/Joule-Thomson combinations, and a four-stage pulse tube with an optional integral flow loop. In 2005, based on the excellent progress made during breadboard fabrication and development testing, the ACTDP coolers were selected to cool the Mid Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST), scheduled for launch in the 2013 timeframe. At this time, in 2005, the ACTDP program has been transferred to JWST to be managed as a flight cryocooler development program.

SUMMARY

Since the beginning of the space program, in 1957, the world's aerospace industry has utilized cryogenic temperatures to enable infrared, gamma-ray and x-ray detectors to gather vast amounts of data for scientific, missile defense, and reconnaissance observations. Soon after the first satellites were in orbit, engineers and scientists began seeking means of providing multi-year cryogenic cooling for ever more sophisticated and sensitive detectors. Although passive cryoradiators were useful for temperatures above 150 K, stored cryogens and mechanical cryocoolers soon became the mainstay for extended low-temperature (0.1 K to 80 K) observation from space. Through the years, cryostat and cryocooler technology has advanced to a tremendous degree, providing a source of cryogenic cooling for a great many missions.

However, the path to reliable, multi-year cooling from space has been long and difficult. Over the years, perhaps hundreds of millions of dollars has been expended examining every conceivable technology capable of providing long-life cooling. Stirling, Vuilleumier, Brayton, magnetic, sorption, and pulse tube—all have been researched in great depth. But, at the end of the 50 years, not only do we have over two dozen long-life cryogenic missions currently circling the globe, we have enormous improvements in our understanding of the universe and Earth, including, from the DoD's perspective, vastly superior missile defense and reconnaissance observations. One can only conclude that over the past 50 years, the quest for long-life cryogenic cooling in space has been a great success.

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Brief Biographical Sketch

Dr. Ronald G. Ross Jr. joined NASA's Jet Propulsion Laboratory as a spacecraft development engineer in 1968 after receiving his Ph.D. in mechanical engineering from the University of California, Berkeley. Over the years he has served as a multi-discipline Technical Manager and Project Engineer on a wide variety of flight and R&D projects where he has specialized in transitioning emerging technologies into qualified flight hardware. For the past 18 years he has supervised JPL's Advanced Thermal and Cryogenic Technology Group with a primary focus on cryocoolers and cryogenic instrument design. He has published over 170 papers covering his technical experience, over 65 of which are in the field of cryocoolers and cryogenic instruments. He is a past General Chair of the International Cryocooler Conference and has been its Publications Chair and Proceedings Editor for the past 12 years.