NASA SPACE CRYOCOOLER PROGRAMS: A 2003 OVERVIEW

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ABSTRACT

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science missions. An overview is presented of ongoing cryocooler activities within NASA in support of current flight projects, near-term flight instruments, and long-term technology development. NASA programs in Earth and space science observe a wide range of phenomena, from crop dynamics to stellar birth. Many of the instruments require cryogenic refrigeration to improve dynamic range, extend wavelength coverage, and enable the use of advanced detectors. Although, the largest utilization of coolers over the last decade has been for instruments operating at medium to high cryogenic temperatures (55 to 150 K), reflecting the relative maturity of the technology at these temperatures, important new developments are now focusing at the lower temperature range from 4 to 20 K in support of studies of the origin of the universe and the search for planets around distant stars. NASA's development of a 20K cryocooler for the European Planck spacecraft and its new Advanced Cryocooler Technology Development Program (ACTDP) for 6-18 K coolers are examples of the thrust to provide low temperature cooling for this class of missions.

COOLERS ON NEAR-TERM EARTH AND SPACE SCIENCE MISSIONS

In spring 2002 three new cryocooler systems were launched into space to support NASA missions. Two of the three were based at least partially on the Oxford cooler technology that first flew on the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument in 1991; this type of cooler has demonstrated multi-year lifetime in orbit, and has been adopted by many long-life instruments to enable new and improved science. The third cooler, the NICMOS cooler, was the first space application of a long-life turbo-Brayton cooler.

These recently launched coolers, which are reviewed below, have each now achieved over a year of successful operation in space, adding to the growing number of long-life space coolers enabling the acquisition of important new space-science data. These recent applications build upon the coolers of earlier NASA missions, such as those on the MOPITT, ASTER and Hyperion instruments that have achieved over two years of space operation at this point.[2] Additional coolers, such as the Northrup Grumman (TRW) pulse tube coolers on the TES instrument and the Ball Aerospace Stirling cooler on the HIRDLS instrument, are in the queue for launch aboard NASA missions in early 2004 and are also described below.

RHESSI Gamma-Ray Spectrometer

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. The detector

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Figure 1: *Sunpower M77B Stirling cryocooler mounted on RHESSI cutaway radiator structure.*

Figure 2: *The flight NICMOS Cooling System mounted on temporary structure during buildup.*

array is cooled to 75 K by a Sunpower M77B Stirling cooler (Fig. 1) running at 65 K.[3,4] This mission represents the first application of a low-cost commercial cooler to achieve multi-year operation in space.

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. This technique thus provides the capability of a two-stage cooler with an off-the-shelf single-stage cooler. Since launch, the cooler has maintained the gamma-ray detectors at their required 75K temperature, with a goal of up to two years on orbit.[5]

NICMOS Cooling System

The Creare NICMOS Cooling System (NCS) was designed to cool the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument of the Hubble Space Telescope. It was successfully launched and integrated into the Hubble Space Telescope during the HST's fourth servicing mission (SM3B) in March 2002.[6] This followed an earlier flight test of the entire cooling system aboard a week-long Shuttle mission in October 1998.[7] The NCS, shown in Fig. 2, is a large turbo-Brayton cooler with a nominal cooling capacity of 7 W at 80 K with 400 W input power. The NICMOS instrument was originally launched in 1997 using a solid Nitrogen dewar to cool its sensitive infrared focal plane. However, after a dewar failure led to a shorter than expected on-orbit life, the NCS was identified as a way to extend the mission and recover the original science objectives. Thus, the NCS was developed to be retrofitted to the NICMOS instrument during a subsequent HST servicing mission in space.

The NCS is designed to maintain the instrument's detectors in the range of 75-85K by circulating refrigerated neon gas through the NICMOS dewar's existing liquid helium freeze lines. The very large (7 W at 80 K) heat load is associated with the inefficiencies of using existing in-space Bayonet couplings on the NICMOS dewar to connect with the gas lines.

To date, the system has performed flawlessly and the NICMOS instrument has been returned to its job of gathering infrared images of the far reaches of space.

Atmospheric Infrared Sounder (AIRS) instrument

JPL's Atmospheric Infrared Sounder (AIRS) instrument was launched in May 2002 on NASA's Earth Observing System Aqua platform. Its mission is to measure the atmospheric air temperature using a HgCdTe focal plane cooled to 58 K by a redundant pair of 55 K TRW pulse tube coolers.[8,9] The instrument was designed and built under JPL contract by Lockheed Martin Infrared Imaging Systems, Inc. (now BAE Systems IR Imaging Systems) of Lexington, MA.

Initiated in 1994, the cryocooler development effort was the first space application to select a pulse tube cryocooler. The highly collaborative development effort, involving cryocooler development at TRW and extensive cryocooler testing at JPL and Lockheed Martin, has served as the pathfinder for much of the pulse tube development to date. The AIRS flight pulse tube coolers, shown in Fig. 3, were originally

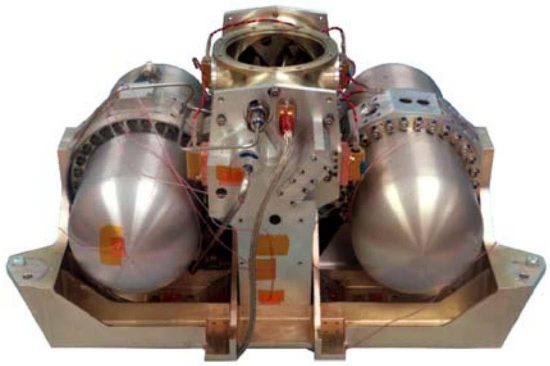

Figure 3: AIRS cooler system.

Figure 4: TES cooler system.

delivered to JPL for testing in October 1997, and completed spacecraft-level testing in September 2001. Since being launched in May 2002 the coolers have been performing flawlessly.[10]

TES Cooler Development

The EOS Tropospheric Emission Spectrometer (TES) instrument is the next large JPL cryogenic instrument. TES is an infrared instrument designed to measure the state of the earth's troposphere. It is scheduled for launch into polar orbit aboard NASA's third earth observing systems spacecraft (EOS-Aura) early in 2004.

TES uses two 57 K coolers to cool two separate focal planes to 62 K. The two coolers are identical and are a variant of the TRW AIRS pulse tube cooler, but configured with the pulse tube hard mounted to the compressor.[11,12] The coolers were fabricated by NGST (formerly TRW) under contract to JPL, and have recently completed system-level testing on the Aura spacecraft in preparation for launch.

HIRDLS Cooler Development

On the same spacecraft as the TES instrument, the High Resolution Dynamics Limb Sounder (HIRDLS) instrument uses a single-stage Stirling cryocooler manufactured by Ball Aerospace under contract to Lockheed Martin. The HIRDLS cooler, which provides 720 mW at 55 K for an infrared array covering 21 bands between 6-17μm, uses technology developed under a number of NASA and DoD contracts.[13] It incorporates radial position sensors for establishing and monitoring the clearance seals in the cooler, prior to closeout of the housing. It is similar in design to a two-stage 30 K cooler delivered to GSFC in 1997, and life tested to 13,000 hours.

AMS-2 Charged-Particle Spectrometer

A set of four Sunpower M87 coolers has been baselined to fly on the Alpha Magnetic Spectrometer–2 (AMS-2) mission in October 2004. The instrument, mounted on the International Space Station, will use a large superconducting magnet assembly in a search for antimatter nuclei from cosmic sources. The coolers will be used to intercept heat at the outer thermal shield on a 2500 liter helium tank. With a mass of over 2000 kg for the superconducting magnets and helium tank, it is extremely challenging to provide enough thermal isolation to allow a 3-year lifetime, even with the coolers operating at nominal power. The four coolers, each capable of 6-7 W of heat lift at 77 K, will be run at reduced power to provide a total of 20-25 W of cooling on the shield at 77 K. The coolers, operating in the stray field of the magnet system, will be specially qualified for operation in a magnetic field of 750-1000 gauss.

Planck Cooler Development

As a precursor to the US low-temperature cryocooler missions, JPL is presently working on the development of a 1 W at 18-20 K hydrogen sorption cryocooler for the Planck mission of the European Space Agency. The objective of the Planck mission is to produce very high resolution mapping of temperature anisotropy in the cosmic microwave background (CMB) radiation. Planck's Low Frequency Instrument (LFI) will have an array of tuned radio receivers to detect radiation in the range 30-100 GHz. These receivers will be operated at a temperature of about 20 K. The High Frequency Instrument (HFI) will use bolometers operated at 0.1 K for frequencies from 100 GHz to 900 GHz.

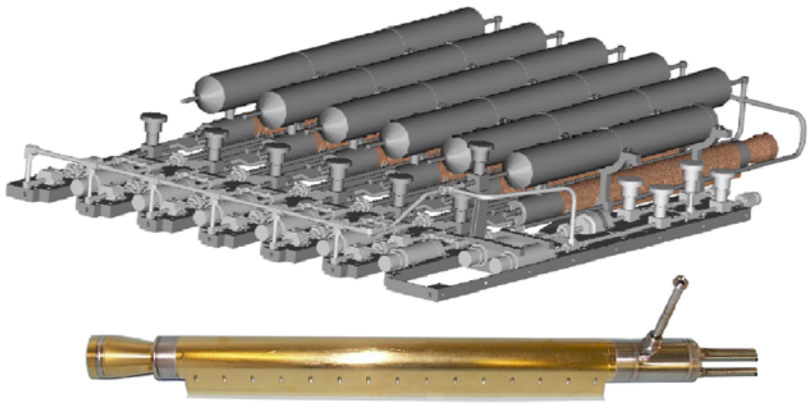

Figure 5: *20K Planck sorption compressor system (top) and fabricated compressor element (bottom).*

The redundant hydrogen sorption cryocoolers are being designed to cool the LFI detectors to 18 - 20 K and to precool the Rutherford Appleton Lab (RAL) 4 K helium J-T that cools the 0.1 K dilution refrigerators in the HFI cooling system. A successful test of the breadboard Planck sorption cooler was conducted in February 2002,[14] following significant development of the refrigerators compressor elements.[15] The flight coolers are currently in fabrication, with the first qualification/flight unit scheduled for delivery and instrument integration in early 2004, followed by the second flight unit a year later.

Other Applications

Another NASA application for space cryocoolers is in propulsion systems. NASA's Glenn Research Center and Ames Research Center are studying the use of cryocoolers to enable zero-boiloff storage of cryogenic propellants in space flight systems.[16,17] At the Johnson Space Center, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project is designing a system that will use high-temperature superconducting coils for plasma containment and acceleration.[18]

CRYOCOOLER DEVELOPMENT FOR FUTURE NASA MISSIONS

Over the years, NASA has collaborated with the US Air Force to develop new cryocooler technologies for future space missions. Recent achievements include the NCS, AIRS, TES and HIRDLS cryocoolers described previously, and new smaller pulse tube coolers at NGST/TRW[19-21] and Lockheed Martin.[22,23] The largest technology push within NASA right now is in the temperature range of 4-10 K. Missions such as the James Webb Space Telescope (JWST) and Terrestrial Planet Finder (TPF) plan to use infrared detectors operating between 6-8 K, typically arsenic-doped silicon arrays, with telescopes of greater than 5 m diameter. Other missions use bolometers and X-ray microcalorimeters operating as low as 50 mK.

Advanced Cryocooler Technology Development Program

To develop the needed cryocooler technology for this mission set NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) in 2002 under the leadership of JPL and in collaboration with the NASA Goddard Space Flight Center.[24] In 2002, four contractors conducted initial study-phase contracts to develop preliminary cryocooler designs capable of providing cooling in the 6-20 K temperature range. Following the study phase, three of the cooler concepts were selected to proceed into Engineering model development. The three contractors include Ball Aerospace & Technologies Corp., Lockheed Martin ATC, and Northrup Grumman Space Technology. The three concepts being pursued by these contractors are illustrated in Fig. 6 and summarized below:

Ball ACTDP Cryocooler Concept. Ball Aerospace's ACTDP cryocooler concept utilizes a multistage Stirling refrigerator to precool a J-T loop powered by a linear-motion Oxford-style compressor. The J-T loop provides remote cooling of the 6 K and 18 K loads and isolates the loads from compressor-generated vibration and EMI.; the compressor elements are easily separated by over 10 meters from the cryogenic

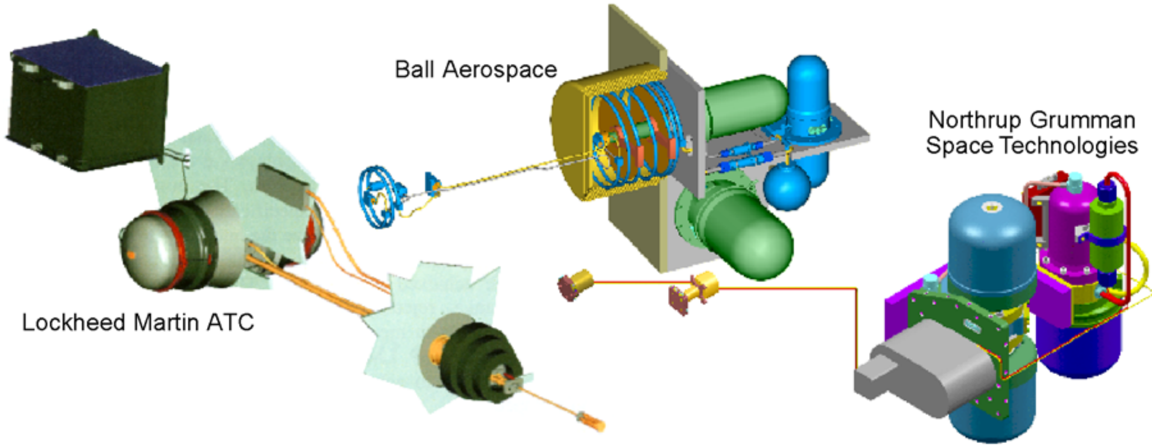

Figure 6. ACTDP Cryocooler Concepts.

loads. The multistage refrigerator is based on leveraging existing Ball flight-quality Stirling compressors, J-T cold-end technology, and drive electronics; these technologies are configured and adapted to meet the specific needs of the ACTDP mission requirements.

NGST ACTDP Cryocooler Concept. The Northrup Grumman Space Technology (NGST) concept is similar to the Ball Aerospace ACTDP concept in that it uses a combined 6K/18K J-T loop to provide the remote cooling of the 6 K and 18 K loads, thus isolating the loads from any compressor-generated vibration and EMI. However, the NGST concept utilizes a multistage pulse tube refrigerator for precooling the J-T loop. The multistage refrigerator is powered by linear-motion Oxford-style compressors and is based on leveraging existing NGST/TRW flight-quality pulse tube compressors and drive electronics, and developmental J-T cold-end technology. These components are configured and adapted to meet the specific needs of the ACTDP cooler requirements.

Lockheed Martin ACTDP Cryocooler Concept. Lockheed Martin's ACTDP cryocooler concept utilizes a multistage all-pulse-tube refrigerator to directly cool the 6 K and 18 K loads. Though not compatible with highly remote coldloads, this concept has the potential for improved reliability with fewer drive motors and less complex electronics. The single-unit multistage refrigerator leverages existing Lockheed flight-quality pulse-tube compressors, cold heads, and drive electronics, and laboratory pulse tube technology[25] that has demonstrated direct cooling down to ~5K; these are being configured and adapted to meet the specific needs of the ACTDP mission requirements.

Basic Research in Support of Low Temperature Refrigeration

To support the development work on 4-20 K cryocoolers, NASA ARC is exploring new rare earth alloys that hold the promise of significantly improving cryocooler efficiency. For example, modeling of a pulse tube cooler using either Er_3Ni or layers of some new materials shows that using random wires of the new materials results in a 2.8x higher efficiency than Er_3Ni powders. Similarly, substituting a new material for lead spheres in the second stage predicts an additional 1.37x improvement. Thus, a cooler making use of the new materials would require 4x less power from the spacecraft and would reject 1/4 of the heat. The newer materials also offer advantages in terms of cost, manufacturability, and long-term reliability. In particular, the new materials neither fracture, as Er_3Ni does, nor flow, as Pb does, under the repeated pressure and temperature oscillations that occur within cryocooler regenerators. In a cooler operating at 40 Hz, the pressure gradient in the regenerator reverses $4x10^8$ times over a 10-year period.

SUMMARY

Cryocoolers are increasingly being adopted for usage in NASA science instruments, with a total of 10 cryocoolers launched into orbit over the past 10 years, and several more scheduled for the next few years. With flight cryocoolers widely available for the 30 K to 150 K temperature range, NASA-funded technology development is now focusing primarily on coolers in the 4-20 K temperature range, and on coolers for special applications such as storage of cryogenic propellants in space.

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