NASA advanced cryocooler technology development program

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ABSTRACT

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science Enterprises. Over the years, NASA has developed new cryocooler technologies for a wide variety of space missions. Recent achievements include the NCS, AIRS, TES and HIRDLS cryocoolers, and miniature pulse tube coolers at TRW and Lockheed Martin. The largest technology push within NASA right now is in the temperature range of 4 to 10 K. Missions such as the Next Generation Space Telescope (NGST) and Terrestrial Planet Finder plan to use infrared detectors operating between 6-8 K, typically arsenic-doped silicon arrays, with IR telescopes from 3 to 6 meters in diameter. Similarly, Constellation-X plans to use X-ray microcalorimeters operating at 50 mK and will require ~6K cooling to precool its multistage 50 mK magnetic refrigerator. To address cryocooler development for these next-generation missions, NASA has initiated a program referred to as the Advanced Cryocooler Technology Development Program (ACTDP). This paper presents an overview of the ACTDP program including programmatic objectives and timelines, and conceptual details of the cooler concepts under development.

Keywords: cryocoolers, ACTDP, JPL, NASA, pulse tube, Stirling, Brayton, Joule Thomson, NGST, TPF, Con-X

1. INTRODUCTION

NASA programs in Earth and space science observe a wide range of phenomena, from atmospheric physics and chemistry to stellar birth. Many of the instruments require low-temperature refrigeration to enable use of cryogenic detector technologies to improve dynamic range, or to extend wavelength coverage. Over the last two decades, NASA, often in collaboration with the US Air Force, has funded cryocooler technology development in support of a number of missions.[1,2,3] The largest utilization of coolers is currently in Earth Science instruments operating at medium to high cryogenic temperatures (50 to 80 K), reflecting the relative maturity of the technology at these temperatures. Since January 2002 we have seen three new cryocooler systems launched into space to support NASA missions: the TRW pulse tube coolers[4,5,6] on the Atmospheric Infrared Sounder (AIRS) instrument, the Creare NCS turbo Brayton cooler[7,8] on the Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument, and the Sunpower M77B Stirling cooler[9,10] on the Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) instrument.

These recently launched coolers build upon the coolers of earlier NASA missions such as those on the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument in 1991, the Measurements Of Pollution In The Troposphere (MOPITT) instrument and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument in 1999, and the Hyperion instrument in 2000.[2,3] Additional coolers, such as the TRW pulse tube coolers[11,12] on the Tropospheric Emission Spectrometer (TES) instrument and the Ball Aerospace Stirling cooler[13] on the High Resolution Dynamics Limb Sounder (HIRDLS) instrument, are in the queue for launch aboard NASA missions in the next couple of years. Also under development is a 1 watt at 18-20 K hydrogen sorption cryocooler for the Planck mission of the European Space Agency.[14,15] The objective of the Planck mission is to produce very high resolution mapping of temperature anisotropy in the cosmic microwave background (CMB) radiation. The redundant hydrogen sorption cryocoolers are being developed by NASA/JPL to cool the Low Frequency Instrument detectors to 18 - 20 K and to precool a 4 K helium J-T cryocooler that cools the 0.1 K dilution refrigerators in the High Frequency Instrument cooling system.

For the future, NASA is planning ever more capable space observatories to extend the science discoveries achieved with the Hubble Space Telescope and the anticipated discoveries from use of the Space Infrared Telescope Facility (SIRTF), which is preparing for launch this next year. These future observatories will be designed to investigate the structure and evolution of the universe and to search for the origins of galaxies, stars, planets, and, ultimately, life. Two of mankind's longest standing questions are: "*How did the universe begin?*" and "*Are we alone in the universe?*" The successful answer to these questions, including the detection of Earth-like planets with an environment suitable for life as we know it, will

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have dramatic implications for humanity's view of our place in the universe. Although for centuries these questions have been the topic of vigorous debate, only recently has our technology advanced to a state where technically meaningful measurements are beginning to be made. Answering these scientific questions will not only require continued advances in astronomy and space sciences, but also in the engineering disciplines necessary to achieve the needed observational sensitivities.

One of these critical engineering technologies that has been identified as common to many of these future observatory concepts is the capability to provide multi-year cooling of their unique low-noise detector systems at temperatures in the range of 6 K and below. To address cryocooler developments meeting these challenges, NASA has initiated a new program referred to as the Advanced Cryocooler Technology Development Program (ACTDP). This development program, which is the subject of this paper, is focused at 6 K/18 K two-stage cryocoolers, and builds on NASA's successful prior developments of Stirling, pulse tube and turbo Brayton technologies. The ACTDP effort is sponsored as a part of NASA's Astronomical Search for Origins and Planetary Systems (ASO) theme and the Structure and Evolution of the Universe (SEU) theme in its Space Science Enterprise.

2. THE ACTDP MISSION FOCUS

To provide a specific focus for the generation of detailed ACTDP requirements and prototype refrigerators, three specific observatory missions that require the ACTDP cooler technology have been identified. These observatories span the electromagnetic spectrum from the far infrared to X-rays and include the Next Generation Space Telescope (NGST), the Terrestrial Planet Finder (TPF), and the Constellation-X (Con-X) missions. All three missions have been identified as having similar requirements for cooling near 6 K, have similar needs for secondary cooling near 18 K, and have similar orbital thermal environments. An important part of the ongoing ACTDP program has been to carefully examine each of these missions to insure that the developed technology fulfills their needs. Prior to describing additional details of the ACTDP program it is useful to review the features of each of these three missions.

Next Generation Space Telescope

Chosen to replace the Hubble Space Telescope (HST), which was first launched in 1990, NGST is designed to examine the Universe in wavelengths between 0.6 and 28 microns during a mission lasting up to ten years. Unlike HST, which is in a Shuttle-accessible low-Earth orbit, NGST will be located in deep space in an Earth-tracking L2 orbit. At this location, a fixed 1.5 million km from Earth, NGST's huge ~5-meter telescope (illustrated in Fig. 1) can be passively cooled to on the order of 35 K to enable unique new science. However, another implication of this orbital location is that periodic repair and refurbishment, like was successfully used many times on HST, will not be possible with NGST. Thus, refrigerator reliability and long life will be particularly important. A second attribute of the NGST configuration is the need to locate

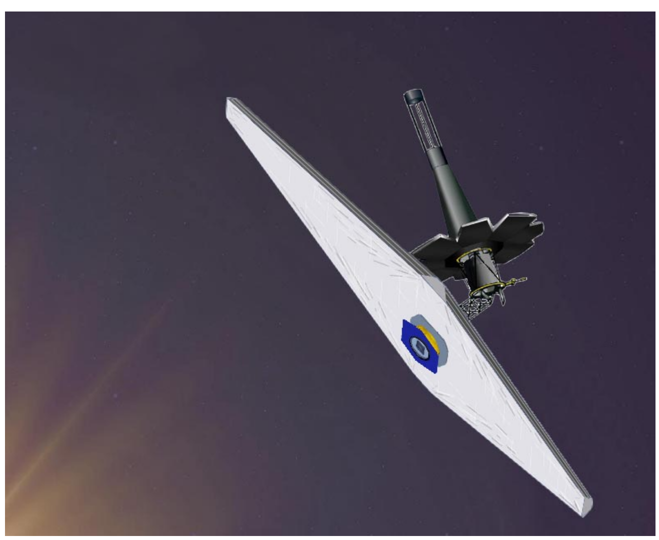

Figure 1. Concept drawing of a possible NGST configuration

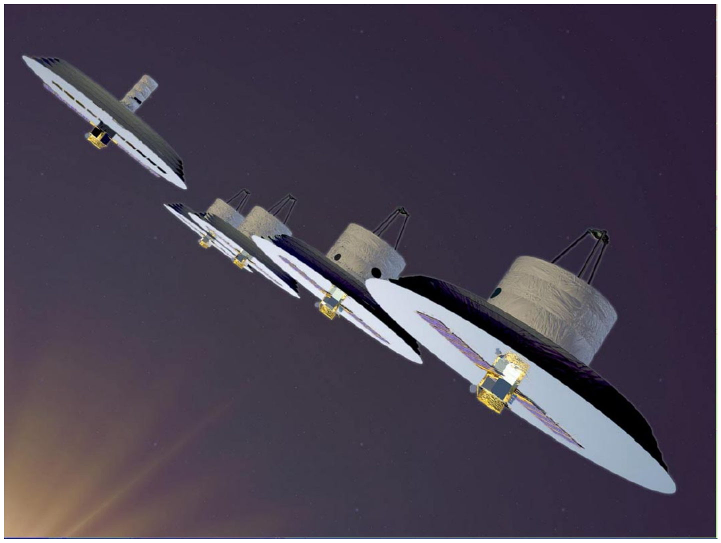

Figure 2. An artist's concept of the free-flying TPF constellation.

the cryogenic telescope some distance away from the room-temperature spacecraft bus. This places a constraint that the room-temperature refrigerator compressors be located perhaps meters away from the 6 K and 18 K cold heads, and, quite possibly, for the coldhead separation to be compatible with in-space deployment. Depending on the configuration chosen, and its deployment approach, the NGST coolers could be required to have compressor cold head plumbing lines as long as 25 meters.

A second sensitive instrument accommodation issue is the area of generated vibration and electromagnetic interference (EMI). Although, not as demanding as with HST, due to NGSTs large separation distance between the S/C and the telescope, very low vibration and EMI will be important requirements on the NGST coolers.

In the area of cooling loads and temperatures, MIRI, the low-temperature cryogenic instrument for NGST, proposes to use low-noise arsenic-doped silicon detectors operating at a temperature near 6 K, with total estimated cryogenic loads of 15-40 mW. Although alternative cooling concepts including a stored cryogen system are being examined for MIRI, a 6 K/ 18 K ACTDP cryocooler would have significantly lower mass and offer other tangible and important benefits. Since NGST will be flown prior to TPF, and the two missions are anticipated to have similar cryocooler requirements, the requirements of NGST's MIRI instrument are particularly important to the ACTDP effort.

Terrestrial Planet Finder

The TPF mission is focused at searching for earth-like planets around nearby stars, providing the first direct imaging of such planets, and performing low resolution spectroscopic studies of the planetary atmospheres. In addition, TPF will support general astrophysics studies by providing unprecedented imaging capability.[16] By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of planets as small as the Earth. In addition, TPF's spectroscopy will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet could someday, or even now, support life.

To meet these objectives, several TPF system architecture concepts have been under study over the past several years. These include both visible coronagraphs and infrared nulling interferometers, as well as several other related concepts. Final selection of a TPF architecture is planned for 2006, with the mission itself planned for the 2015 timeframe. Figure 2 illustrates one of the possible TPF spacecraft configurations, this one, a formation-flying, nulling infrared interferometer. This free-flying configuration consists of four spacecraft each supporting a 3.5-m telescope, and a separate spacecraft for the beam combiner. Like NGST, the optics on each spacecraft have a multilayer thermal shield to provide passive cooling to 35 K. With this concept, the spacecraft are positioned along a line oriented normal to the direction of observation, and they relay the starlight to a beam combiner to maintain the optical paths through the system equal to within a few centime-

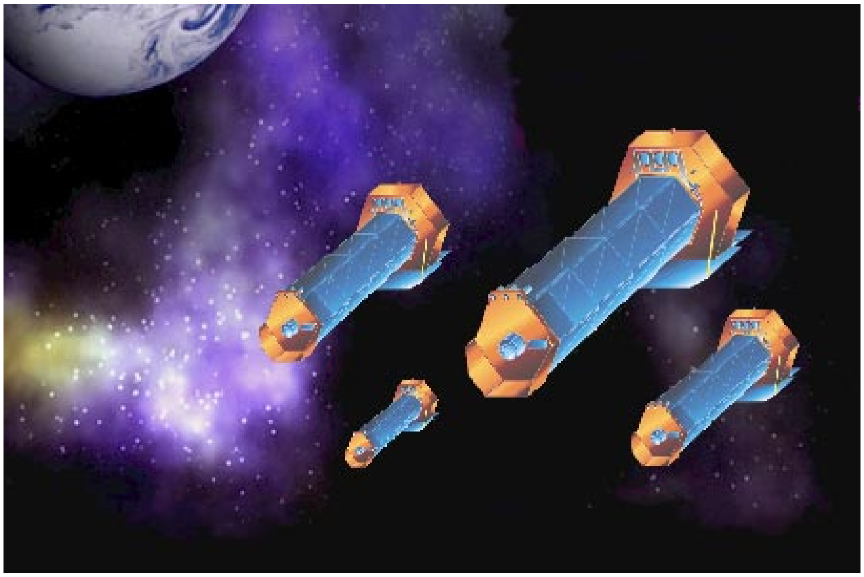

Figure 3. An artist's illustration of the Constellation-X concept.

ters. The array of spacecrafts is rotated around the line-of-sight over a 6-hour period while observing the source. The starlight is rejected in a nulling beamcombiner and the planet light is sent through a spectrometer.

For such a interferometric system, observing in the infrared from ~5-20 microns, cooling the detectors to around 6 K is required over a mission lifetime of 5 to 10 years. Also, like with NGST, room-temperature and vibration-prone refrigerator compressors will have to be located on the main spacecraft bus, possibly meters away from the cold and vibration-stabilized optics and detector module.

Constellation-X

The Constellation-X mission complements the previously described NASA missions by working in a different wavelength region of electromagnetic spectrum—X-rays. It supports NASA's exploration of the structure and evolution of the universe theme by focusing on unlocking the mysteries of black holes, galaxy formation, and the still undetected matter in the Universe, and testing Einstein's Theory of General Relativity in an environment of extreme gravity. It consists of a group of four spacecraft, conceptually shown in Fig. 3, each carrying two X-ray telescopes. The spacecraft would be launched in pairs, with roughly a year between launches, with four years of operation as a group.

The key science detectors in Con-X's Soft X-ray Telescopes are microcalorimeters. These must be maintained at 50 mK to achieve the very high spectral resolution required from 0.3 - 10 keV. To cool the detectors, a multistage refrigeration system is envisioned, consisting of a 6 K/18 K ACTDP cryocooler to cool from room temperature down to 6K, followed by a multistage magnetic refrigerator to cool from 6 K to 50 mK. Like NGST and TPF, the Con-X constellation will also be located in a remote L2 orbit. However, these X-ray telescopes lack the 35 K cold optics of the other two missions, and thus lack some of their compressor/cold head separation and deployment constraints. With respect to vibration and EMI, Constellation-X uses squids with a very high sensitivity to magnetic signatures and is thus quite sensitive to magnetic or magnetizable materials near the sensitive detectors.

3. ACTDP PROGRAMMATIC OVERVIEW

To develop the needed cryocooler technology for the above described missions NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) under the leadership of the Jet Propulsion Laboratory, and in collaboration with the NASA Goddard Space Flight Center. As shown in Fig. 4, the ACTDP effort has been structured as a two-phase process containing an initial study phase followed by a second hardware development and test phase. The effort started with the generation of detailed requirements and specifications in summer 2001, leading to a com-munity-wide request for proposals in November 2001, and the award of four parallel Phase I contracts by April 2002.

ID	Activity	FY2002				FY2003				FY2004				FY2005			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	**Study Phase**																
2	Receipt of Order by Contractor		▲														
3	Study Phase Kick-off Meeting			▲													
4	Mid-Term Study Progress Review			▲													
5	Preliminary Design Review				▲												
6	Study Phase Final Report				▲												
7	Study Phase Final Report Evaluation					Δ											
8	**Demonstration Phase**																
9	Receipt of Order by Contractor					Δ											
10	Demonstration Phase Kick-off Meeting					Δ											
11	Demonstration Phase Delta PDR						Δ										
12	Technical Interchange Meeting #1							Δ									
13	Critical Design Review								Δ								
14	EM Test Plan Pre-Test Review										Δ						
15	Technical Interchange Meeting #2											Δ					
16	Technical Interchange Meeting #3												Δ				
17	Technical Interchange Meeting #4														Δ		
18	System Test Report															Δ	
19	Acceptance Data Package																Δ
20	Pre-Ship Review																Δ
21	EM Cryocooler System																Δ
22	FM Cryocooler Development Plan																Δ

Figure 4. ACTDP schedule showing the two phases of the effort.

In the Study Phase, each contractor is developing a detailed preliminary design with supporting laboratory test data sufficient to confidently enter into the hardware development and demonstration phase. The study phase culminates with a Preliminary Design Review (PDR) in September 2002, with the proposed cooler documented in a final study report that will be evaluated by NASA and serve as the primary basis for down-selection to the Demonstration Phase. As structured into the contracts, only the technology providers selected for the Study Phase will be considered for the Demonstration Phase.

NASA plans to down-select to two to three concepts for the Demonstration Phase. The hardware development and demonstration phase will involve detailed design, fabrication, performance and environmental testing, and delivery of an Engineering Model (EM) cryocooler system by the end of FY2005. The requested EM mechanical cryocoolers are to be fully flight-like in form, fit, and function, and allow assessment of their ability to meet all key thermal, structural, and reliability/lifetime performance requirements. They must also be capable of providing the required cooling system performance over the full range of interface temperatures, and be suitable for multi-year life-testing, including assessment of susceptibility to self-contamination over time. Consistent with prototype hardware, the EM mechanical cryocooler will not have formal flight drawings, or flight-approved materials, electronic parts, or fasteners, except where they are critical to performance.

In order to drive and operate the EM mechanical cooler, the demonstration phase of the ACTDP effort also includes the development and delivery of Brassboard cooler drive electronics that are flight-like in function (e.g. power and control functionality), but not flight-like in form. In particular, the brassboard electronics are expected to be rack mounted for operation in a lab environment and need not address flight structural, thermal, or space radiation issues. Their fundamental job is to be capable of operating the EM mechanical cryocooler over its full range of capabilities to allow assessment of the cryocooler's overall design with respect to key efficiency, control, and refrigeration performance requirements. Any digital functionality of the brassboard electronics is expected to be simulated with PC-based hardware and software.

As a contract option, the contractors have also been asked to propose delivering an Engineering Model (EM) form of the cryocooler electronics. The EM electronics would fully demonstrate the form, fit, and function of flight model electronics to allow assessment of the ability of the circuit and mechanical design to meet key electrical, thermal, structural, and EMI performance requirements over the expected flight operating temperature range. The EM electronics circuit and packaging design would have to be based on flightworthy radiation hard, high reliability parts and processes that are compatible with the specified flight operating temperature, radiation, and SEE environments. However, the fabricated EM electronics unit would not need to have formal flight drawings, or flight-approved radiation hard, high reliability materials, electronic parts, or fasteners, except where they are critical to performance. The EM electronic unit would be suitable for powering the EM Mechanical cryocooler system during multi-year life-testing.

Flight Model (FM) hardware fabrication and delivery is not within the scope of the ACTDP effort. However, ACTDP participants have been asked as part of the second phase activities, to estimate what additional resources and schedule would be needed to develop and deliver a fully flight qualified system (mechanical and electronic) meeting all interface, test, and documentation requirements for flight application.

4. ACTDP CRYOCOOLER CONCEPTS

As noted above, four contractors have initiated the first study phase of the ACTDP effort to develop cryocooler designs capable of meeting the described requirements. Each of the coolers is designed to provide between 7.5 and 40 mW of cooling at 6 K, together with an additional 100-250 mW at 18 K. The four contractors include:

- Ball Aerospace & Technologies Corp. of Boulder Colorado
- Creare, Inc. of Hanover, New Hampshire
- Lockheed Martin ATC of Palo Alto, California
- TRW Space and Electronics of Redondo Beach, California

The four concepts being pursued by these four contractors are summarized below. These concepts represent the starting point for the contractors studies and can thus be expected to evolve and be refined as the study phase progresses. It is planned that at least two of these concepts will be selected for fabrication of engineering model hardware starting in the fall of 2002.

Ball ACTDP Cryocooler Concept

As shown in Fig. 5, 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. No intermediate radiative precooling is required, and the compressor elements are easily separated by over 3 meters from the cryogenic 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. The baseline concept has a projected total system mass of 27 kg (including flight drive electronics) and has an estimated input power of approximately 150 watts into the drive electronics with no intermediate radiative precooling.

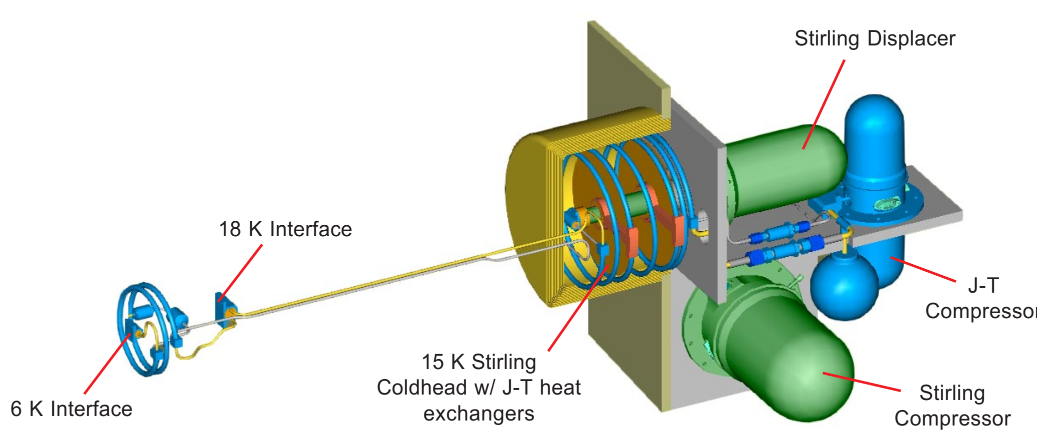

Figure 5. Ball Aerospace ACTDP Cryocooler Concept.

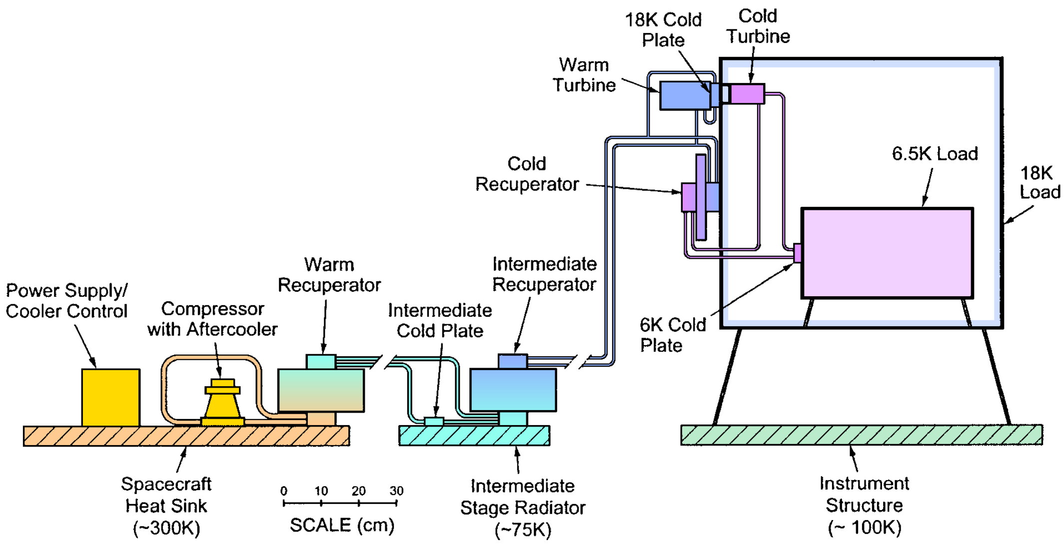

Figure 6. Creare turbo-Brayton ACTDP Cryocooler Concept.

Creare ACTDP Cryocooler Concept

Creare's ACTDP cryocooler concept utilizes a multistage turbo-Brayton refrigerator with optional precooling by a cryoradiator. The turbo-Brayton loop, which has remotely located turbo-expanders operating at 6 K and 18 K, generates minimal vibration and allows the 6 K and 18 K loads to be widely separated from the loop's room-temperature compressor and electronics. The multistage refrigerator is based on leveraging existing Creare flight-quality turbo-Brayton compressors, expanders, and drive electronics as well as new developmental hardware aimed at low temperature operation.[17,18] These hardware elements are configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept, shown in Fig. 6, has a projected total system mass of 27 kg (including flight drive electronics) and has an estimated input power of approximately 105 watts into the drive electronics, with approximately 1.3 W dissipated at a 75 K intermediate-temperature radiator.

Lockheed Martin ACTDP Cryocooler Concept

Lockheed Martin's ACTDP cryocooler concept (Fig. 7) utilizes a multistage pulse tube refrigerator, with optional cryoradiator precooling, to directly cool the 6 K and 18 K loads. The single-unit multistage refrigerator leverages existing

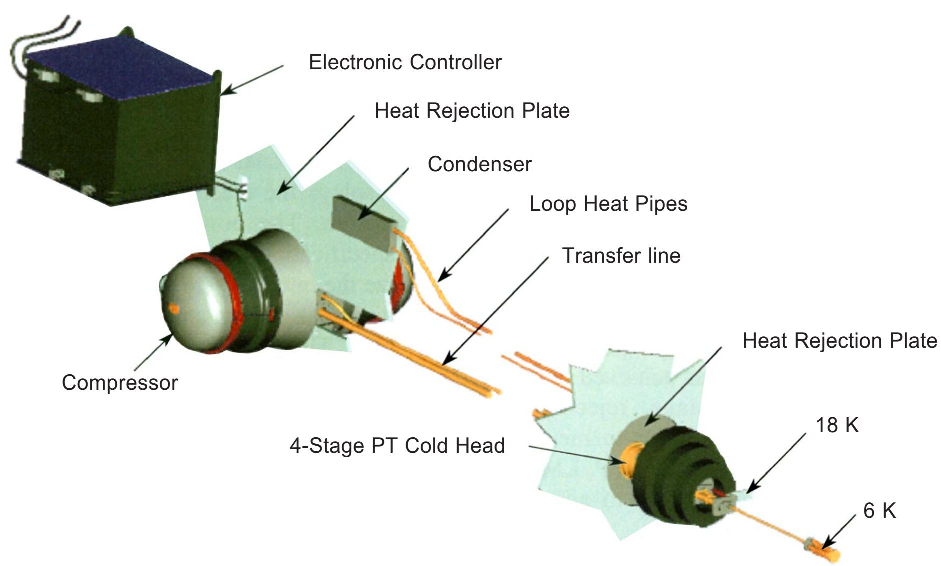

Figure 7. Lockheed Martin multistage pulse tube ACTDP cryocooler concept.

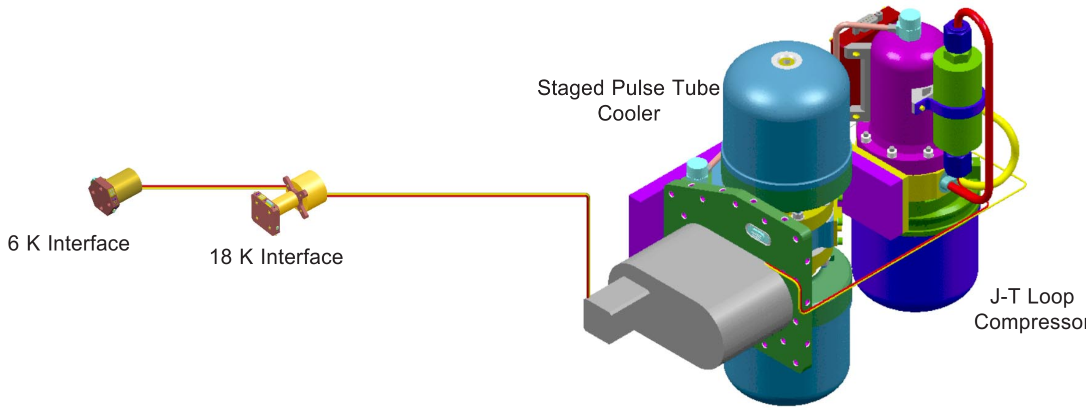

Figure 8. TRW ACTDP Cryocooler Concept.

Lockheed flight-quality pulse-tube compressors, cold heads, and drive electronics, and laboratory pulse tube technology[19] that has demonstrated direct cooling down to 4K; these are being configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept has a projected total system mass of approximately 26 kg (including flight drive electronics) and has an estimated input power of approximately 208 watts into the drive electronics when no intermediate radiative precooling is utilized. Use of a 120 K precooler dissipating 8 W is estimated to reduce the input power to on the order of 106 watts.

TRW ACTDP Cryocooler Concept

TRW's ACTDP cryocooler concept, illustrated in Fig. 8, utilizes a multistage pulse tube refrigerator, with optional cryoradiator precooling, 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 any compressor-generated vibration and EMI. The multistage refrigerator is based on leveraging existing TRW flight-quality pulse tube compressors and drive electronics, and developmental J-T cold-end technology; these are configured and adapted to meet the specific needs of the ACTDP mission requirements. The baseline concept shown in the accompanying illustration has a projected total system mass of approximately 17 kg (including flight drive electronics) and has an estimated input power of approximately 207 watts into the drive electronics, with 2 W dissipated at the 85 K intermediate temperature radiator.

5. SUMMARY

Cryocoolers are increasingly being adopted for usage in NASA science instruments, with a total of ten 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 to enable a suite of ever more capable science observatories similar in scope to the Hubble Space Telescope. To address the limitations associated with carrying stored cryogens into space to provide cooling for these 5 to 10-year-life missions, NASA/JPL has initiated the Advanced Cryocooler Technology Development Program (ACTDP). This program is directed at developing long-life mechanical cryocoolers with the necessary cooling power (~7.5 to 40 mW at 6 K together with 100 to 250 mW at 18 K) and integration features needed to accommodate these missions. Initiated in fall 2001, the program is currently funding four Study Phase contracts to define Engineering Model cryocoolers. These concepts include both pulse tube and turbo-Brayton coolers, as well as hybrid systems using Stirling/ Joule-Thomson and pulse tube/Joule-Thomson combinations. In fall 2002 two or more of the four concepts will be selected to proceed into the hardware demonstration phase, with tested coolers scheduled for delivery to NASA by the end of 2005.

ACKNOWLEDGMENT

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