CRYOCOOLERS 13
Preface

The last two years have witnessed a continuation in the breakthrough shift toward pulse tube cryocoolers for long-life, high-reliability cryocooler applications. New this year are papers describing the development of very large pulse tube cryocoolers to provide up to 1500 watts of cooling for industrial applications such as cooling the superconducting magnets of Mag-lev trains, cooling superconducting cables for the power industry, and liquefying natural gas. Pulse tube coolers can be driven by several competing compressor technologies. One class of pulse tube coolers is referred to as “Stirling type” because they are based on the linear Oxford Stirling-cooler type compressor; these generally provide cooling in the 30 to 100 K temperature range and operate at frequencies from 30 to 60 Hz. A second type of pulse tube cooler is the so-called “Gifford-McMahon type.” Pulse tube coolers of this type use a G-M type compressor and lower frequency operation (~1 Hz) to achieve temperatures in the 2 to 10 K temperature range. The third type of pulse tube cooler is driven by a thermoacoustic oscillator, a heat engine that functions well in remote environments where electricity is not readily available. All three types are described, and in total, nearly half of this proceedings covers new developments in the pulse tube arena.

Complementing the work on low-temperature pulse tube and Gifford-McMahon cryocoolers is substantial continued progress on rare earth regenerator materials. These technologies continue to make great progress in opening up the 2 -10 K market. Also in the commercial sector, continued interest is being shown in the development of long-life, low-cost cryocoolers for the emerging high temperature superconductor electronics market, particularly the cellular telephone base-station market. At higher temperature levels, closed-cycle J-T or throttle-cycle refrigerators take advantage of mixed refrigerant gases to achieve low-cost cryocooler systems in the 65 to 80 K temperature range. Tactical Stirling cryocoolers, the mainstay of the defense industry, continue to find application in cost-constrained commercial applications and space missions; the significant development here is the cost-effective incorporation of Oxford-like flexure spring piston supports so as to achieve an extended-life, low-cost product.

The objective of *Cryocoolers 13* is to archive these latest developments and performance measurements by drawing upon the work of the leading international experts in the field of cryocoolers. In particular, this book is based on their contributions at the 13th International Cryocooler Conference that was held in New Orleans, Louisiana, on March 29 - April 1, 2004. The program of this conference consisted of 123 papers; of these, 88 are published here. Although this is the thirteenth meeting of the conference, which has met every two years since 1980, the authors’ works have only been made available to the public in hardcover book form since 1994. This book is thus the sixth volume in this new series of hardcover texts on cryocoolers.

Because this book is designed to be an archival reference for users of cryocoolers as much as for developers of cryocoolers, extra effort has been made to provide a thorough Subject Index that covers the referenced cryocoolers by type and manufacturer’s name, as well as by the scientific or engineering subject matter. Extensive referencing of test and measurement data, and application and integration experience, is included under specific index entries. Contributing organizations are also listed in the Subject Index to assist in finding the work of a known institution, laboratory, or manufacturer. To aide those attempting to locate a particular contributor’s work, a separate Author Index is provided, listing all authors and coauthors.
Prior to 1994, proceedings of the International Cryocooler Conference were published as informal reports by the particular government organization sponsoring the conference — typically a different organization for each conference. A listing of previous conference proceedings is presented in the Proceedings Index, at the rear of this book. Most of the previous proceedings were printed in limited quantity and are out of print at this time.

The content of Cryocoolers 13 is organized into 15 chapters, starting with papers describing the development of a new class of space cryocoolers to provide cooling in the 4-18 K temperature range. The next several chapters address cryocooler technologies organized by type of cooler, starting with regenerative coolers; these include Stirling cryocoolers, pulse tube cryocoolers, Gifford-McMahon cryocoolers, thermoacoustic refrigerators, and associated regenerator research.

Next, recuperative cryocoolers including Joule-Thomson, and sorption cryocoolers are covered. The technology-specific chapters end with a chapter on unique sub-Kelvin, magnetic, and optical refrigerators. The last three chapters of the book deal with cryocooler integration technologies and experience to date in a number of representative space and commercial applications. The articles in these last three chapters contain a wealth of information for the potential user of cryocoolers, as well as for the developer.

It is hoped that this book will serve as a valuable source of reference to all those faced with the challenges of taking advantage of the enabling physics of cryogenics temperatures. The expanding availability of low-cost, reliable cryocoolers is making major advances in a number of fields.

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Acknowledgments

The International Cryocooler Conference Board wishes to express its deepest appreciation to the Conference Organizing Committee, whose members dedicated many hours to organizing and managing the conduct of the Conference, and wishes to express its appreciation to Lockheed Martin for its financial contribution. Members of the Organizing Committee of the 13th ICC included:

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In addition to the Committee and Board, key staff personnel made invaluable contributions to the preparations and conduct of the conference. Special recognition is due Laurie Huget, Executive Director of the Cryogenic Society of America, who managed the registration activities.
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Ball Aerospace 4-10 K Space Cryocoolers

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ABSTRACT

This paper describes the design, development, testing and performance at Ball Aerospace of long life, 4-10 K temperature space cryocoolers. For temperatures down to 10 K, Ball has developed long life Stirling cycle cryocoolers. For temperatures to 4 K and below, Ball has developed a hybrid Stirling/J-T (Joule-Thomson) cooler. The hybrid cooler has been verified in test to 3.5 K on a Ball program and a 6 K Development Model is in development on the NASA/JPL ACTDP (Advanced Cryocooler Technology Development Program). The Ball ACTDP cooler Development Model will be tested in 2005. The ACTDP cooler provides simultaneous cooling at 6 K (typically, for either doped Si detectors or as a precooler for sub-Kelvin refrigerators) and 18 K (typically, for optics or shielding), with cooling stages also available at 40 and 180 K (typically, for thermal shields or other components). The ACTDP cooler is under development for the NASA James Webb Space Telescope (JWST), Terrestrial Planet Finder (TPF), and Constellation X-Ray (Con-X) missions. The 4-10 K coolers are highly leveraged off previous Ball space coolers including multiple life test and flight units.

INTRODUCTION

Ball Aerospace has specialized in space cryogenics, and specifically low temperature applications (<60 K) for over 40 years. This includes over 150 space flights of cryogenic hardware to date, 18 years of mechanical refrigerator or cryocooler development, and over 11 years of development of multistage Stirling coolers. Consistent with the application trend to replace cryostat or dewar cooling systems with cryocoolers, Ball has concentrated their technology developments in the cryocooler area over the last decade. This has resulted in multiple cryocooler product lines. Each product is optimum for different application envelopes, and each is based on proven long-life designs. Our Stirling cryocoolers are very compact and power efficient. Our Joule-Thomson coolers have inherent load leveling capability and are optimum for providing stable temperatures over distributed cooling interfaces. Our hybrid cryocoolers combine the advantages of both Stirlings and J-Ts and are optimum for low temperature (<10 K) applications.
Figure 1. 2-Stage SB235 is designed for simultaneous cooling of detectors at 35 K and optics at 110 K.

Figure 2. 2-Stage SB235E is a higher capacity model derivative of the SB235 and is designed for simultaneous cooling of detectors at 35 K and optics at 110 K.

STIRLING CRYOCOOLERS

Coolers for Moderate to Higher Cryogenic Temperatures

Ball Aerospace has been building long life, multi-stage Stirling coolers since 1989. These include flight qualified 1, 2, and 3-stage coolers.

At temperatures above about 60 K, our 1-stage SB160 cooler is preferred. Two SB160 units (flight and engineering model/flight spare) were delivered (in 1999 and 2000) for the HIRDLS (High Resolution Dynamic Limb Sounder) instrument on the NASA (National Aeronautics and Space Administration) Aura EOS (Earth Observation System) platform scheduled for launch in June 2004.1 To date, several thousand hours have been accumulated on the HIRDLS engineering model and over 27,000 hours on the SA160 development unit predecessor.

Below 60 K and/or for simultaneous cooling of two different temperatures, our next generation 2-Stage coolers are more optimum and include the SB235 model and the SB235E derivative, shown in Figures 1 and 2, respectively. These are build-to-print, qualified coolers that
are designed for simultaneous cooling of detectors at 35 K and optics at about 110 K and were
the baseline for the TRW/Raytheon Space Based Infra-Red System–Low (SBIRS-low) Program
Definition and Requirements Review (PDRR) program. The SB235 has a nominal performance
of 1.0 W at 40 K and 2.0 W at 110 K for 85 W of motor power. The SB235 has passed
qualification level environmental test verification and is in life test at the Air Force Research
Laboratory (AFRL) with about 2500 hours of accumulated run time. The SB235E has a nominal
performance of 1.0 W at 41 K and 7.0 W at 110 K for 100 W of motor power. The SB235E is
currently in assembly at Ball.

Our previous generation 2-stage cooler, the 30 K or SB230, was environmentally qualified
and delivered to NASA GSFC (Goddard Space Flight Center) for life test. It currently has
accumulated over 20,000 hours with over 11,000 hours on the displacer after a design change.

Low Temperature Stirling Coolers

Ball's 3-stage Stirling coolers are optimum for cooling of multiple stages and/or below
30 K. For the Air Force Research Laboratory (AFRL), Ball developed a 3-stage cooler, the
35/60 K or SB335, which was highly leveraged off the GSFC SB230 design. This cooler has a
nominal performance of 0.4 W at 35 K simultaneously with 0.6 W at 60 K for about 60 W of
motor power. An SB335 unit completed environmental testing and is on life test at AFRL with
close to 25,000 hours accumulated to date.

A development unit of the SB335 was also employed on the Ball NASA 6 K Explorer
Cooler program to develop technology advances for cooling to below 15 K. The 6 K Explorer
Program demonstrated cooling with a relatively small cooler to temperatures below 12 K. These
enhancements were incorporated into the current SB315 or Advanced Cryocooler Technology
Development Program (ACTDP) precooler shown in Figure 3. The SB315 combines the high
capacity of our SB235 coolers with the 3-stage cold tip design from the SB335 to produce a high
capacity <15 K low temperature cooler. A Development Model of the SB315 cooler is being
built on NASA/JPL's ACTDP program. On the ACTDP program, the SB315 will serve as a
precooler for a Joule-Thomson (J-T) cooler that provides simultaneous cooling at 4-6 K and
18 K. The nominal performance of the ACTDP SB315 is 0.3 W at 15 K simultaneously with
1.0 W at 40 K and 2.0 W at 180 K for 180 W of motor power.

A Breadboard (BB) of the SB315 is also being built on an internal Ball program. This BB
should verify the thermodynamic performance of the ACTDP precooler. In addition, the BB will
be modified and tested for 10 K cooling. Predictions indicate that the SB315 should be capable
of 100 mW or more of cooling at 10 K. Initial verification with the BB of both the ACTDP precooler and 10 K performances should be completed by August 2004.

**HYBRID CRYOCOOLERS**

**Introduction**

For very low temperature (<10 K) cooling, Ball has combined our Stirling and J-T products to create a line of hybrid coolers. As shown in Figs. 4 and 5, Ball’s latest ACTDP hybrid is a cooling system that combines the best features of each thermodynamic cycle to produce low temperature cooling. The system uses the mass and power efficient Stirling as a precooler to perform the bulk of the cooling to temperatures around 15 K. Then, it uses the low temperature efficiency of the recuperative (vs. regenerative for the Stirling) J-T cooler to perform the last stages of cooling to 6 K and below. An additional benefit is the ability of the J-T to provide remote cooling (for both the 4-6 K and 18 K stages) through long, very thin, flexible lines. Thus,
Figure 6. ACTDP 4-6 K Cooler is highly leveraged off previous developments.

Figure 7. 4-6 K Breadboard Cooler hardware.

the J-T allows the cooling system to remotely locate the compressors over 20 meters from the cryogenic instrument.

4-6 K or ACTDP Cooler

The hybrid J-T/Stirling design is the baseline for the NASA/Ball ACTDP cooler. The nominal performance of the Ball ACTDP cooler is 30 mW at 6 K (or 20 mW at 4 K) simultaneously with 150 mW at 18 K for 125 W of motor power. Figure 5 shows a potential integration of the Ball ACTDP cooler into the NASA Terrestrial Planet Finder (TPF) mission. As shown in Figure 6, a key aspect of the ACTDP cooler is that it is highly leveraged off previous developments at Ball. In fact, every component in the system has been proven in test at some level. During the ACTDP Study Phase, this culminated in the successful integration and test of a breadboard cooling system (refer to Fig. 7 for hardware photos and Fig. 8 for test data plot). This breadboard has demonstrated cooling at 6 K (35 mW), 5 K (21 mW), and 4 K (12 mW).
Figure 8. 6 K Breadboard Cooler testing showing simultaneous 6 and 18 K cooling with temperature stability even through a step change in the 18 K load.

Integration Features

Unique features in our hybrid coolers facilitate their mission integration. As previously mentioned, they have capabilities for very remote heat transport (and with no moving cold head parts). Our hybrids have also been designed to not require cryogenic radiator precooling assistance. This allows them to be equally applicable to Earth and non-Earth orbit missions and to minimize stray light and thermal back load on the cryogenic instruments. As a result of integration studies performed on the JWST, Constellation-X, and other systems, we have developed relatively mature thermal/mechanical integration designs, including structural supports and thermal insulation that have been accounted for in the thermodynamic performance. Understanding that the integration of a 4-6 K cooler will usually cross several system interfaces, we have built-in quick disconnects with proven heritage on our Cryogenic On-Orbit Long Life Active Refrigerator (COOLLAR) and NICMOS flight programs. Our hybrid coolers use only a single phase, gaseous working fluid and have no zero-g concerns or 1-g testing limitations. We also have independent control of 6 and 18 K heat loads and the capability, in real-time on-orbit, to adjust to factor of two changes in the ratio of the 6 and 18 K loads.

CONTROL ELECTRONICS

Ball understands that a cryocooler is the combination of a mechanical refrigerator system and the control electronics to drive it. We have paid special attention to the development of high reliability electronics for over a decade. This covers three generations of electronics. The E100 is in life test with the SB230 and SB335 coolers. The E200 (shown in Figure 9) was delivered with the SB160 on the HIRDLS program. The E300 is our electronics for SB235, SB315, and hybrid coolers. The E300 features include closed loop temperature and vibration control, high reliability (95% at 10 years), radiation tolerance to 100 krad and beyond, a comprehensive set of telemetry, an isolated power supply ground, and active current ripple suppression.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the various government agencies and personnel that have sponsored cooler technology developments at Ball through the years. This includes JPL, NASA GSFC, AF SMC SBIRS Low, and AFRL. We would also like to recognize the contributions of our teammates on the ACTDP: Redstone Engineering and CTS.
REFERENCES


NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System

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ABSTRACT
The NGST ACTDP cooler system features a three-stage integral pulse tube cooler coupled, as a precooler, to a 6 K Joule-Thomson (JT) cooler. The system is configured to provide remote cooling (12 m) at 18 and 6 K. The cooler is being developed under contract to the Jet Propulsion Laboratory with the objective of providing cooling for future NASA space observatory missions such as Terrestrial Planet Finder (TPF), Constellation X, and James Webb Space Telescope (JWST). The cooler development effort is to deliver an engineering model cooler with rack electronics that provide a flight-simulated interface.

This paper presents a cooler system overview and data collected during cooler development testing to date. Designed conservatively for a 10-year life, the hybrid cooler is required to provide 150 mW of cooling at 18 K together with 30 mW of cooling at 6 K while rejecting to 300 K and minimizing input power to the electronics. The total mass of the cooler and electronics system is less than 40 kg. The software driven control electronics provide the cooler control functions that are fully re-configurable and based on the NGST flight-qualified Advanced Cooler Electronics (ACE) with minor modification to measure and control temperatures in the 6 K range.

INTRODUCTION
The NASA Advanced Cryocooler Technology Development Program (ACTDP) objective is to develop active cooling systems for cooling remote sensors of space applications in the 5 to 10 K temperature range. Additionally, the ability to provide a second cooling temperature in the 18 K range is required. The NGST ACTDP cooling system consists of a three-stage pulse tube precooler, a JT cooler, and control electronics—all based on flight heritage NGST hardware that has been adapted to the sub-10 K cooling requirements of the ACTDP program. The NGST effort is under contract with the Jet Propulsion Laboratory, with the current phase 9 months into a program scheduled for 31 months.

A schematic representation of the key components of the NGST ACTDP cooler system is shown in Figure 1. A valved compressor is used for the JT loop and incorporates the use of reed valves integrated with a flight qualified HEC (High Efficiency Cooler) compressor. The pulse tube precooler also uses an existing HCC (High Capacity Cooler) compressor design integrated with a three-stage pulse tube that provides gas precooling at 85, 35, and 17 K for the JT cooler. The JT
precooling is achieved with the use of three recuperators operating from 300 K to 85 K (recuperator R4), 85 K to 35 K (recuperator R3), and 35 K to 17 K (recuperator R2). A 17 K to 18 K recirculating gas heat exchanger (HX) is used to provide cooling at 18 K with the exiting gas connected to an 18 K to 6 K recuperator (R1). The 6 K cooling for the sensor is provided by expansion through a JT valve. The 18 K cooling stage and JT valve are remotely located (12 to 20 m typically) from the pulse tube gas precooler. Also included in the JT cooler are room temperature getters, room temperature and cryo particulate filters, a JT decontamination heater, and a 100 K to 18 K bypass valve. The bypass valve is required to cool down potentially large (90 kg) thermal masses associated with the sensor. The JT cooler also has field joints that allow integration of the JT cooler coldhead into instrument systems independent of the JT compressor and pulse tube precooler. The JT cooler and pulse tube precooler are controlled with the Advance Cryocooler Electronics (ACE). The ACE for the JT cooler and pulse tube precooler use an existing flight-qualified design with minor modification to replace the PRT thermometry with cernox thermometry and to interface with the auxiliary electronics. The auxiliary electronics is required to provide additional thermometry and heaters required for the cooling system.

**COOLER SYSTEM**

The three stage mechanical precooler (Figure 2) rejects heat at the centerplate of the compressor. Inside the compressor, flexure springs support the moving-coil linear motor that drives the pistons. The springs maintain alignment for the attached non-contacting pistons that oscillate and compress gas into the pulse tube cold heads. A small clearance between the cylinder and the piston seals the compression space. Two opposed compressor halves vibrationally balance the compressor. The compressor is operated at a frequency between 35 and 40 Hz.

The pulse tube cold heads are bolted to the compressor centerplate and are sealed with metal seals. The centerplate conducts heat to the radiator. The cold head components are arranged coaxially: mounting flange, regenerator, cold block, with the pulse tube, and warm-end heat exchanger body (or orifice) internal to the mounting flange and regenerator. The cold heads are surrounded by the JT cooler recuperators and the 35 K and 17 K cold head are enclosed in an 85 K radiation shield. A stainless steel orifice line connects the gas from the orifice to the reservoir tank that is either incorporated into the compressor end cap (85 K and 35 K stages) or mounted on the 85 K cold head (17 K stage).
The internal wiring in the compressor is stranded PTFE (cross-linked Teflon) insulated wiring. All wiring exits the centerplate through ceramic-insulated pins in a D-shell feedthrough for the cooler drive power. A separate connector is used for redundant cernox thermometers on the 17 K cold block and a thermistor attached to the centerplate. An accelerometer is mounted on the compressor centerplate. Together with the signal conditioning electronics, the accelerometer provides a feedback signal to the vibration control algorithm in the ACE.

For the JT cooler (Figure 2) the compressor is as described previously for the precooler except it is the smaller HEC type. The compressor centerplate has been modified to incorporate reed valves to facilitate the DC flow required for JT operation. The JT cooler operates at 2X the precooler operating frequency. The JT gas flows through a zirconium room temperature getter, stainless steel tubing recuperators and transfer lines to the 18 K and 6 K cooling stages. The 18 K and 6 K cooling blocks are copper and have redundant thermometry and trim control heaters. Additionally the 6 K cold stage has the JT restriction for gas expansion and a decontamination heater.

An envelope for the bus-mounted cooler components, pulse tube precooler and JT compressor, is shown in Figure 3.

One of the two identical electronics boxes that are used to drive and control the precooler and JT cooler is shown in Figure 4. The electronics are a next generation of advanced cooler electronics based on our high-reliability flight designs currently on orbit and integrated on multiple instruments awaiting launch. The ACE represent a smaller, lighter weight, radiation hard (300 krad), and more reliable evolution of our previous cooler electronics. The functions of the electronics are to:

1. Convert the 28 Vdc primary power to the secondary isolated power,
2. Provide primary bus current ripple suppression,
3. Drive the cooler,
4. Provide communication with the host,
5. Control the cooler with a processor using software resident in EEPROM.

The software performs the following functions:

- Transmits spacecraft command and cooler telemetry via the RS422 data bus,
- Collects cooler state of health data,
- Controls cold block temperature,
- Balances vibration force by controlling the waveform of the pistons,
- Provides safety protection to the cooler.
Table 1 summarizes the cooler system weight and capabilities. Figure 5 shows the load line for the pulse tube precooler with data collected from 3rd stage unit testing. The requirement shown is a derived requirement that includes the required net cooling at the remote cold head as well as the required gas precooling for the JT cooler. Figure 6 shows a cool down curve based on analysis with the system performance model. The thermal mass used is 90 kg of aluminum. Because of the large thermal mass, a by-pass valve is incorporated into the design to allow JT helium flow to by-pass the JT restriction at temperatures greater than 18 K. Without the by-pass, the system would not cool down.

Figure 6 illustrates the system performance during cool down. Three key operating points on the cooling capacity specification define the system power. These points are steady state operation at 6 K and two pinch points during cool down at 18 K during the bypass mode and at 12 K during the JT orifice-controlled cool down.
Table 1. Cooler System Description.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Pre-cooler</td>
<td>18.5</td>
</tr>
<tr>
<td>JT Cooler</td>
<td>7.1</td>
</tr>
<tr>
<td>Electronics (2 ACE and AUX)</td>
<td>7.8</td>
</tr>
<tr>
<td>Cables</td>
<td>3.3</td>
</tr>
<tr>
<td>Integrating Structure</td>
<td>9.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37.1</strong></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Mass Capabilities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Operating Condition</td>
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</tr>
<tr>
<td>Cooling Load 18K</td>
<td>150mW</td>
</tr>
<tr>
<td>Cooling Load 6K</td>
<td>30mW</td>
</tr>
<tr>
<td>Heat Reject Temperature</td>
<td>300K</td>
</tr>
<tr>
<td>Bus Power steady state</td>
<td>228W</td>
</tr>
<tr>
<td>Peak cool down power</td>
<td>236W</td>
</tr>
<tr>
<td>Operating Temperature Range (TMU)*</td>
<td>-20 to 50°C</td>
</tr>
<tr>
<td>Non-operating Temperature Range (TMU)</td>
<td>-40 to 70°C</td>
</tr>
<tr>
<td>Operating Temperature Range (ACE)</td>
<td>-20 to 60°C</td>
</tr>
<tr>
<td>Non-operating Temperature Range (ACE)</td>
<td>-35 to 75°C</td>
</tr>
<tr>
<td>Launch Vibration (TMU)</td>
<td>14.2 Grms, 1 min</td>
</tr>
<tr>
<td>Launch Vibration (ACE)</td>
<td>14.2 Grms, 1 min</td>
</tr>
<tr>
<td>Launch Vibration JT cooler 18K and 6K comp.</td>
<td>25.8 Grms, 1 min</td>
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<tr>
<td>Bus Voltage Range</td>
<td>21V to 42V</td>
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<tr>
<td>Ripple Current</td>
<td>100 dB micro amps</td>
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<tr>
<td>Communication Protocol</td>
<td>RS422/1553B</td>
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<tr>
<td>Lifetime</td>
<td>10 years</td>
</tr>
</tbody>
</table>

*TMU = Thermal Mechanical Unit

Figure 5. Pulse tube pre-cooler third stage performance with 35 K reject temperature.

**CONCLUSIONS**

Northrop Grumman Space Technology has demonstrated the feasibility of providing cooling for space scientific instruments at 6K. The system currently in development is an evolution of existing flight-proven designs and hardware. This approach minimizes the technical and schedule risks of developing new designs.

**ACKNOWLEDGMENT**

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A Study of the Use of 6K ACTDP Cryocoolers for the MIRI Instrument on JWST

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ABSTRACT

The Mid Infrared Instrument (MIRI) of the James Webb Space Telescope (JWST) is a demanding application for the use of space cryocoolers. During calendar year 2003 an extensive study was carried out examining the application to this mission of hybrid 6K/18K J-T cryocoolers developed by NASA as part of their Advanced Cryocooler Technology Development Program (ACTDP). Among the most challenging requirements of the MIRI application were the requirements to cool down the ~90 kg 6 K cooling load in less than 30 days and to restrict the location of the compressors with their heat dissipation and vibration generation to a remote spacecraft position some 12 meters away from the cryogenic load. Because the hybrid 6K/18K J-T cryocoolers have unique load-carrying capability as a function of temperature, the cooldown requirement was the primary consideration in cooler sizing. This paper presents the lessons learned and performance achieved in the MIRI cryocooler application. In the final proposed configuration, all of the MIRI/JWST design considerations were successfully met. Although the cryocooler option was eventually deselected in favor of a solid-hydrogen stored cryogen system, the cryocooler study offered an important opportunity for understanding and refining the performance and integration capabilities of this important new class of low-temperature space cryocoolers.

INTRODUCTION

Chosen to replace the Hubble Space Telescope (HST), which was launched in 1990, the James Webb Space Telescope (JWST) 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, JWST is designed to be located in deep space in an Earth-tracking L2 orbit. This location, a fixed 1.5 million km from Earth, will allow JWST's large ~6-meter telescope (illustrated in Fig. 1) to be passively cooled to ~35K to enable unique new science.

The JWST instrument responsible for imaging the longest wavelengths is referred to as the Mid Infrared Instrument (MIRI). This instrument is being jointly developed by the European Space Agency (ESA) and NASA, with the Jet Propulsion Laboratory as manager. The MIRI instrument focal plane arrays require cooling to below 6.8 K, and its optics to below 15 K to suppress background noise levels to acceptable levels. Thus, unlike the other JWST instruments, MIRI requires supplemental active cooling to achieve temperatures on the order of 6 K.
During the cryocooler/dewar trade study, two alternative approaches were examined by the MIRI team to provide the needed cooling: 1) a solid hydrogen cryostat, and 2) a 6 K/18 K mechanical cryocooler, the latter based on the cooler concepts being developed as part of NASA's Advanced Cryocooler Technology Development Program (ACTDP). Although the solid hydrogen stored cryogen system option was eventually selected in favor of a cryocooler, the cryocooler study offered an extremely valuable opportunity for understanding and refining the performance and integration capabilities of the ACTDP cryocooler concepts in an actual flight application.

THE MIRI CRYOCOOLER DESIGN CONCEPT

The cryocooler design concept for the MIRI application derives from three distinct areas: 1) the MIRI instrument itself, which represents the cooling load, 2) the overall JWST observatory, which provides most of the structural, thermal, electrical, and configurational interfaces, and 3) the ACTDP cryocoolers, which provide their own individual performance constraints. During the course of the cryocooler study the JWST observatory, and the MIRI instrument in particular, underwent modest configurational iterations typical of this stage in any project's development. Thus, the details presented here reflect the state of development in the spring of 2003, and are likely to be somewhat different from the design that exists at this time—a year later—or will exist in the future.

JWST Integration Concept

Figure 2 illustrates some of the configurational details of the JWST observatory at the time of this cooler integration study. In the JWST concept, the science instruments, including MIRI, are housed in the large ~35 K Integrated Science Instrument Module (ISIM) enclosure on the back of the ~35 K telescope. During launch, the telescope reflector is in a folded position with the telescope tower hard-mounted to the top of the spacecraft bus. After launch, the telescope reflector unfolds, and the entire tower and ISIM rise up approximately 1.5 m from the spacecraft bus to provide thermal and vibration isolation between the two. Thus, all cabling or plumbing connecting the ISIM instruments to the spacecraft must undergo this ~1.5 meter deployment, must be highly flexible, and must have minimal thermal conductance.

The overall JWST thermal compartmentalization places a constraint that any room-temperature cryocooler compressors be located in the spacecraft bus approximately 12 meters away from the cryogenic loads in the ISIM. Thus, the compressor-coldhead connection must also accommodate the 1.5 meter in-space deployment of the telescope away from the spacecraft following launch. One key advantage of this deployment is a much relaxed requirement on cryocooler-generated vibration compared with, for example, HST. For JWST, the cryocoolers are assumed to be vibration-isolated from the spacecraft structure using standard vibration isolation mounts with perhaps a 15 Hz mounting frequency.
In terms of reliability and redundancy, an important implication of JWST’s orbital location is that periodic repair and refurbishment, like was successfully used many times on HST, will not be possible with JWST. Thus, reliability and long life will be particularly important for this mission.

MIRI Instrument Concept

Figure 3 illustrates the generic concept of the MIRI instrument at the time of this cooler integration study. Structurally, the instrument is supported from the Integrated Science Instrument Module (ISIM) on the back of the JWST telescope via three pairs of low-conductivity struts. Strictly speaking, the instrument consists of three relatively low-power focal planes (~1 mW each) that require cooling to <6.8 K, plus a ~90 kg Optical Bench Assembly (OBA) that has to be cooled to below ~15 K. However, to avoid requiring two cooling temperatures, the instrument design in 2003 had the entire instrument integrated at roughly the same 6 K temperature.

In terms of refrigeration capacity, the primary cryogenic load presented to the cooler is approximately 10 mW, associated with conduction down the struts from the ~35 K ISIM structural interface, plus approximately 12 mW of radiation load to MIRI from the ~40 K ISIM enclosure, plus 5 mW (inc. margin) for the focal planes. The radiation loading assumes the presence of MLI blankets