Ball Aerospace 4-10 K Space Cryocoolers

D.S. Glaister[1], W. Gully[1], R.G. Ross, Jr[2], R. Stack[1], E. Marquardt[1]

[1]Ball Aerospace and Technologies Corporation
Boulder, CO 80306
[2]Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

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.

Presented at the 13th International Cryocooler Conference
New Orleans, Louisiana, March 29 - April 1, 2004. In *Cryocoolers 13*, pp. 1-7.

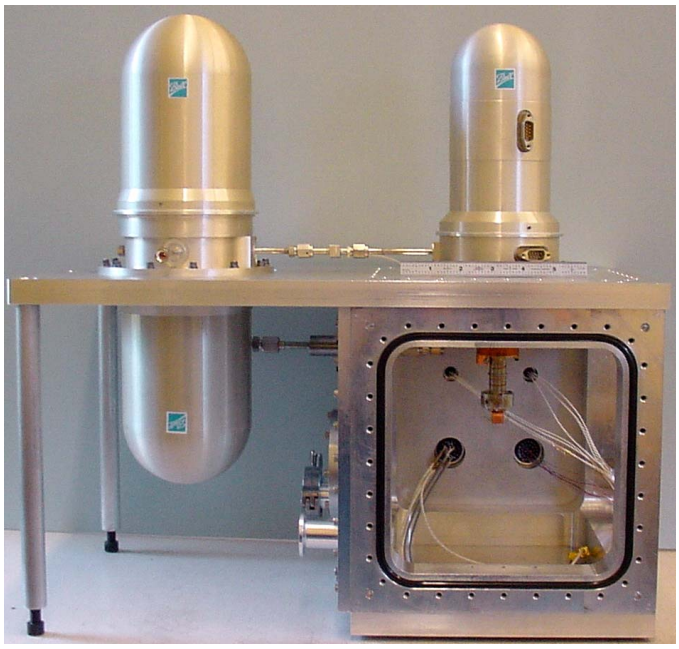

Figure 1. 2-Stage SB235 is designed for simultaneous cooling of detectors at 35 K and optics at 110 K

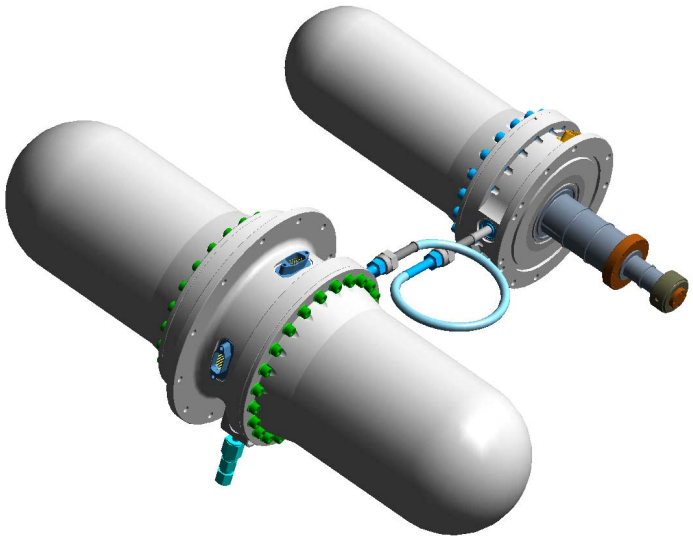

Figure 2. 2-Stage SB235E is a higher capacity model derivative of the SB235 and is designed for simultaneous cooling of detectors at 35 K and optics at 110 K.

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

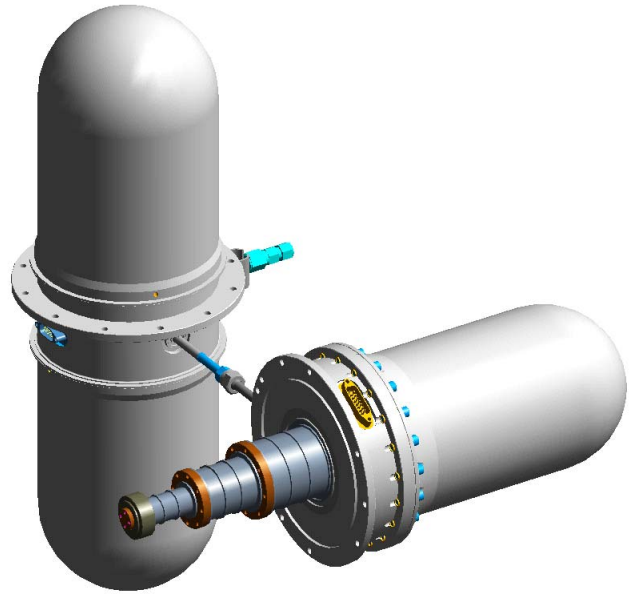

Figure 3. 3-Stage SB315 is a high capacity cooler optimized for cooling below 15 K.

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.[2] 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.[3,4] 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.[5]

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.[6] 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.[7,8] 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

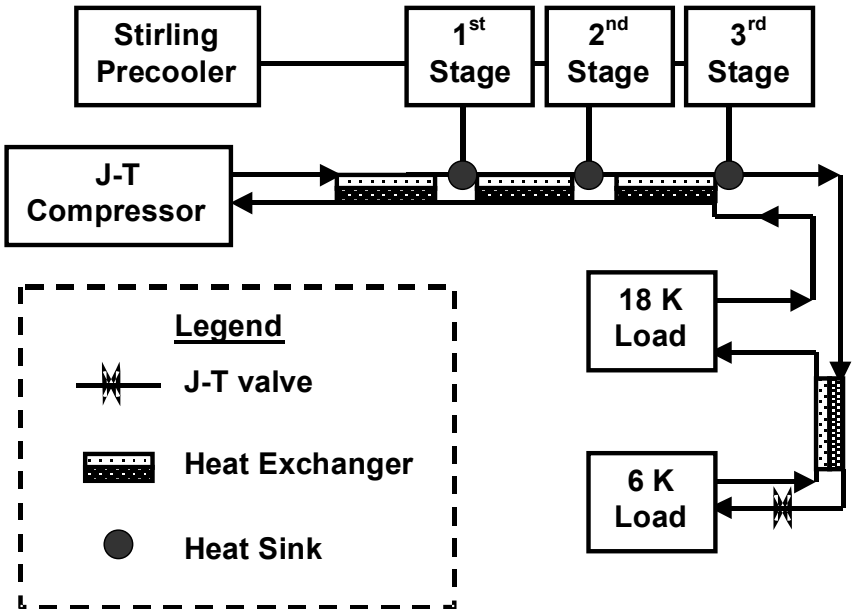

Figure 4. Ball hybrid cooler designs our Stirling and J-T cycles to produce very low temperature cooling.

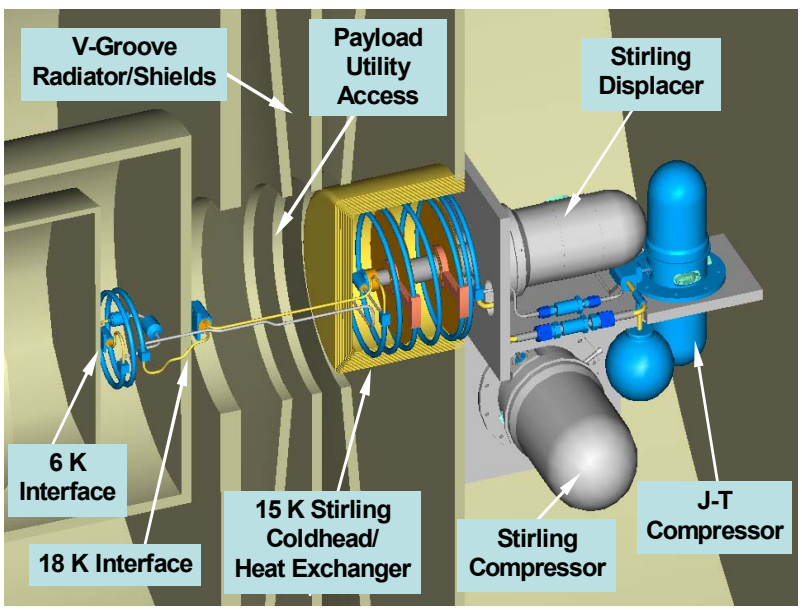

Figure 5. Ball 4-6 K Cooler integrated into TPF type application.

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.[9,10,11] 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,

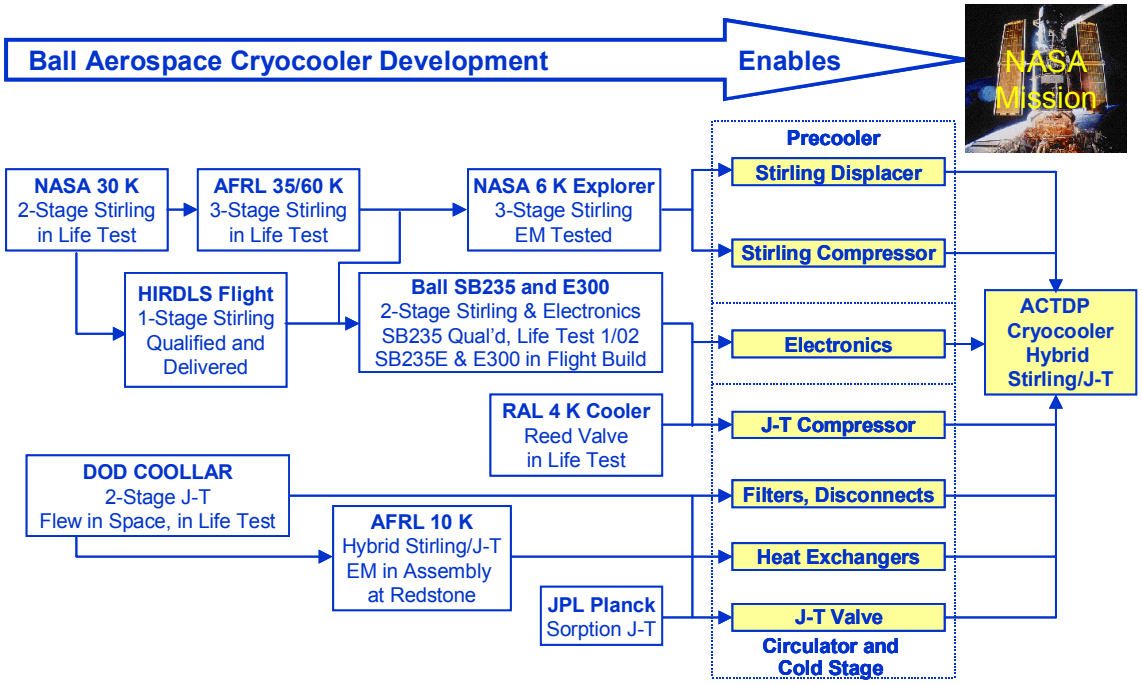

Figure 6. ACTDP 4-6 K Cooler is highly leveraged off previous developments.

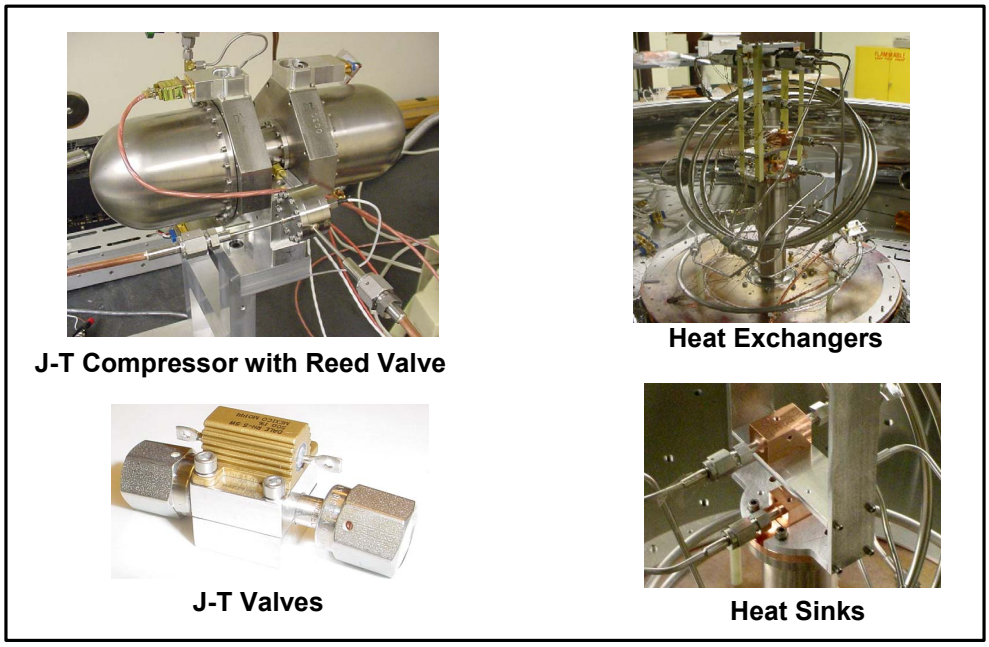

Figure 7. 4-6 K Breadboard Cooler hardware.

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).

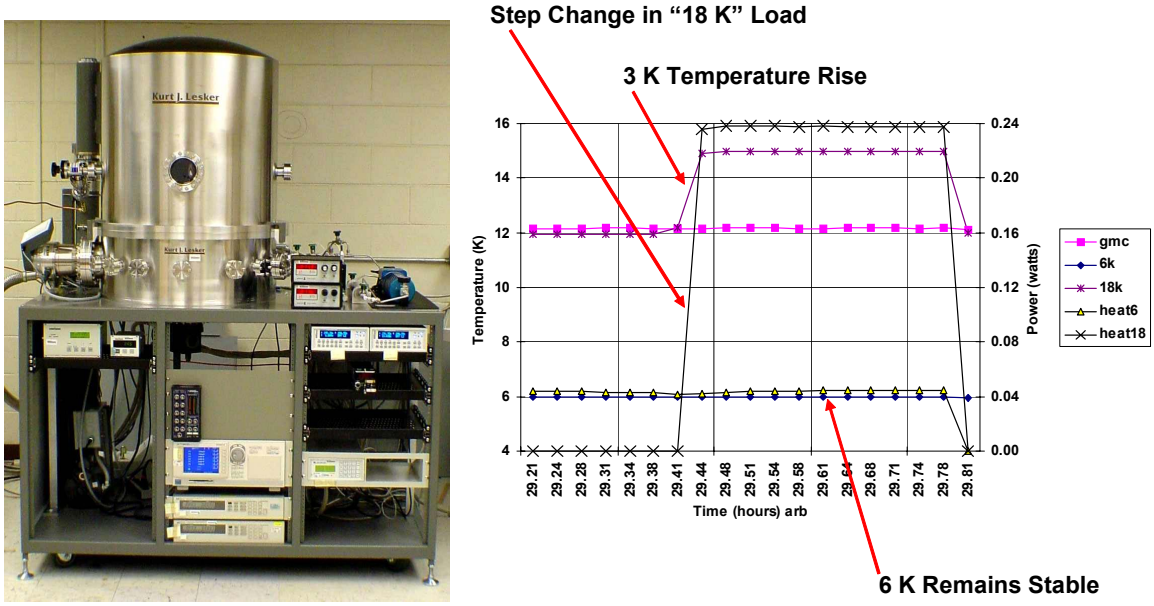

Figure 8. 6 K Breadboard Cooler testing showing simultaneous 6 and 18 K cooling with temperature stability even through a step change in the 18 K load.

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[12], 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)[13] 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 18K 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.

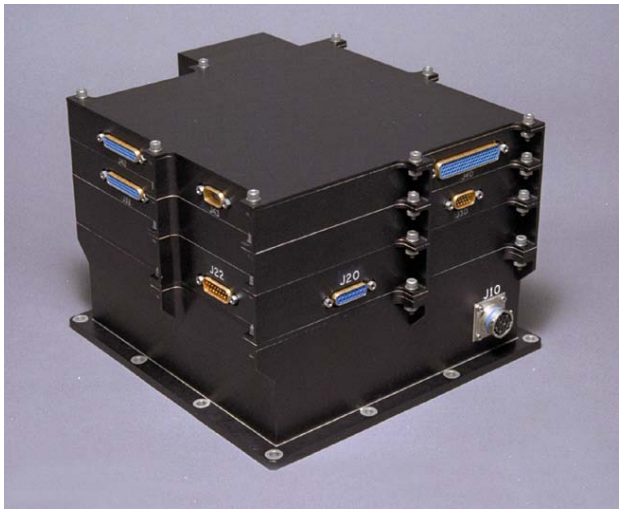

Figure 9. Ball E200 electronics delivered on the HIRDLS flight program.

REFERENCES

1. Kiehl, W.C., "HIRDLS Instrument Flight Cryocooler Subsystem Integration and Acceptance Testing," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 769-773.
2. Gully, W.J. et al., "Thermodynamic Performance of the Ball Aerospace Multistage Stirling Cycle Mechanical Cooler," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 45-50.
3. Berry, D. et al., "System Test Performance for the Ball Two-Stage Stirling-Cycle Cryocooler," *Cryocoolers 9*, Plenum Press, New York (1997), pp. 69-77.
4. Gully, W.J et al., Qualification Test Results for a Dual-Temperature Stirling Cryocooler," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 59-65.
5. Bruninghaus, C.H.Y., Tomlinson, B.J., and Abhyankar, N., "Performance Characterization of the Ball Aerospace 35/60K Protoflight Spacecraft Cryocooler," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 51-58.
6. Gully, W.J., "Development of a 12K Stirling Cycle Precooler for a 6K Hybrid Cooler System," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 63-68.
7. Ross, R.G., Jr., Boyle, R.F., Key, R.W. and Coulter, D.R., "NASA Advanced Cryocooler Technology Development Program," *Proceedings of the International Society of Optical Engineering (SPIE) Conference*, Waikoloa, Hawai, August 22-28, 2002.
8. Ross, R.G., Jr., Boyle, R.F., and. Kittel, P., "Overview of NASA SPACE Cryocooler Programs — A 2003 Summary," *Adv. in Cryogenic Engin.*, Vol 49B, Amer. Inst. of Physics, New York, 2004, pp. 1197-1204.
9. R. Levenduski, R., Gully, W. and J. Lester, J. "Hybrid 10 K Cryocooler for Space Applications," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 505-511.
10. Glaister, D.S. et al., "A 10 K Cryocooler for Space Applications," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 577-586.
11. Oonk, R.L., "Low-Temperature, Low-Vibration Cryocooler for Next Generation Space Telescope Instruments," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 775-782.
12. Ross, R.G., Jr. "A Study of the Use of 6K ACTDP Cryocoolers for the MIRI Instrument on JWST," *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), this proceedings.
13. R. Fernandez, R. and R. Levenduski, R., "Flight Demonstration of the Ball Joule-Thomson Cryocooler," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 449-456.