An Overview of Ball Aerospace Cryocoolers

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ABSTRACT

Over the last 20 years, Ball Aerospace & Technologies Corp. has developed very high efficiency Stirling and hybrid cryocoolers for aerospace and tactical applications. The single-stage HIRDLS cryocooler has been operating successfully on orbit for nearly eight years (> 69,000 hours) with no on-off cycles. The two-stage SB235E TIRS cooler provides two stages of cooling with measured performance of 2.25 W at 42 K, 13.3 W at 100 K for 159 W motor power at a rejection temperature of 0°C. Hybrid coolers have been demonstrated for low temperatures, low exported disturbances, and load leveling.

INTRODUCTION

Ball Aerospace has been designing and building cryocoolers since 1990. During this time, the cryocoolers have evolved from single stage units with small capacity to multiple stage units with very large capacity (Figure 1). Our cumulative life run time is over 212,000 hours or 24 years of operation. In addition to growing in size, our cooler efficiency has also increased over this period and is compared to the empirical curve fit of vendor efficiency data from Aerospace in Figure 2[1]. The High Resolution Dynamic Limb Sounder (HIRDLS) flight cryocooler is a single-stage unit that has been operating continuously since August 10, 2004. The SB235 cryocooler is the next generation of cooler at similar capacity and mass but with two stages. The latest larger capacity unit, the SB235E, has been built four times, and a flight version was delivered to Goddard Space Flight Center (GSFC) for the Thermal InfaRed Sensor (TIRS) instrument scheduled to launch in January 2013.

HIRDLS CRYOCOOLER SUBSYSTEM (CSS)

The HIRDLS instrument is on the NASA Aura spacecraft, which was successfully launched on July 15, 2004 aboard a Delta 2 from Vandenberg Air Force Base, California into a 705 km sun synchronous orbit with a 98° inclination and a 1:45 PM equator crossing time. HIRDLS is an infrared limb-scanning radiometer with 21 photoconductive Mercury Cadmium Telluride (HgCdTe) detectors, which are cooled to 61 K with the Ball cryocooler. After initial instrument checkout, the cryocooler was ramped up to 80% stroke on August 10, 2004. Since that time, the cryocooler has been in continuous operation.

Ball Aerospace was responsible for designing and building the Cryocooler Subsystem (CSS), which consists of the cryocooler, cold plumbing, ambient radiator, and vacuum enclosure. The HIRDLS cryocooler is a single-stage Stirling design with its primary design point at 57 K.

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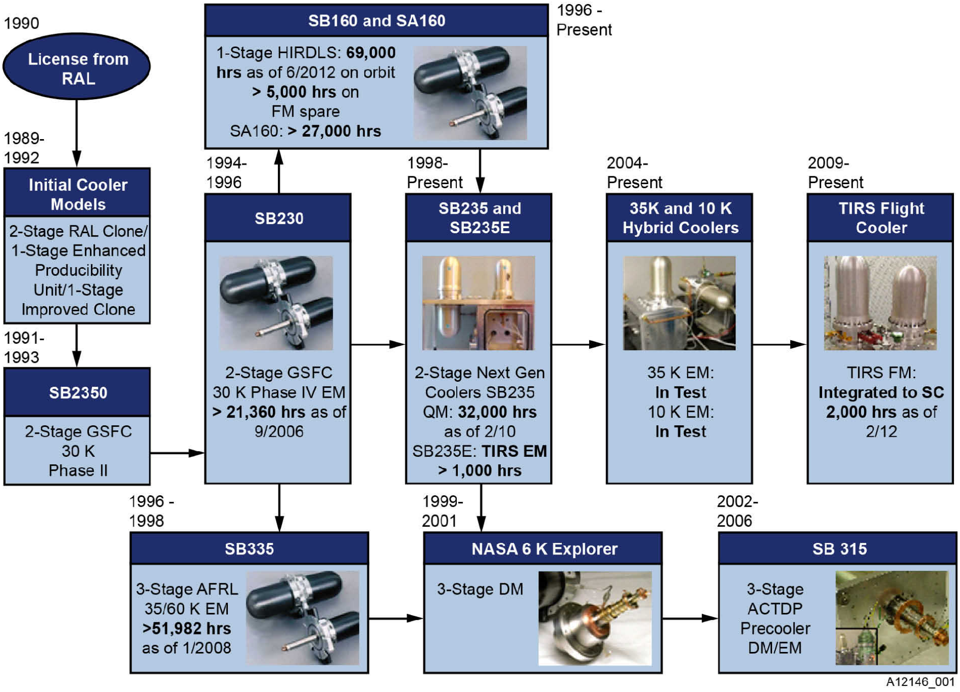

Figure 1. Ball Aerospace has over 20 years of experience developing long life, multi-stage flexure bearing based Stirling cryocoolers with cumulative run time of over 24 years including nearly 8 years on orbit for the HIRDLS mission.

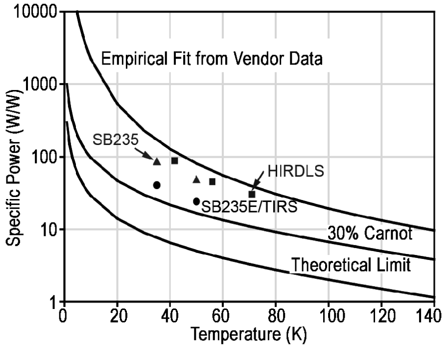

Figure 2. Over time, the efficiency of Ball cryocoolers has increased significantly resulting in higher than 20% Carnot efficiency. Here the efficiencies of HIRDLS, the SB235 and the SB235E are compared to an empirical line created from the Aerospace cryocooler survey and a goal line of 30% Carnot[1].

The HIRDLS cryocooler is mounted directly to an ambient radiator to reduce integration complexity and the total mass of the system. The radiator panel provides the waste heat rejection while also acting as the structural mount for the cryocooler. The close proximity between the radiator and the cryocooler eliminates the thermal bus that would otherwise be necessary and that would increase both the mass and the parasitic heat loads. The radiator mounts to the spacecraft through four blade-style flexures to mitigate effects of thermal expansion differences between the spacecraft and the radiator and to reduce the instrument to radiator heat leak path. Figure 3

Figure 3. HIRDLS cryocooler mounted into radiator.

shows the HIRDLS cryocooler mounted into the radiator. The mass of the CSS including electronics is 27 kg. A cryogenic vacuum housing surrounds the cold finger. A more detailed description of the CSS can be found elsewhere[2,3]. The engineering unit of the CSS was delivered in August 1999 and the flight unit in November 2000.

Unrelated to the CSS, the HIRDLS instrument had an on-orbit anomaly that initially resulted in significantly degraded instrument performance and instrument science. The instrument's aperture view is approximately 85% blocked most likely due to a 2-layer Kapton contamination closeout shield that became dislodged during ascent. The HIRDLS team developed a correction scheme to allow for significant useful high vertical resolution scientific data collection that only the HIRDLS instrument can provide. In March 2008, the instrument chopper stopped working. Subsequent attempts to resolve the issue were not successful, and the instrument has not produced any scientific data since that time. However, the cryocooler is still operating, and housekeeping data are provided to confirm its performance[4].

MLI has been used in the CSS design to minimize radiation heat transfer as opposed to the use of bare or uncovered low emissivity surfaces. Compared to a low emissivity surface design, the CSS MLI design results in improved performance (measured effective emittance (ε^*) of 0.015) and inherent robustness against external contamination. Previous cryocooler space systems that have suffered from degraded performance due to contamination all had design areas that relied on no or very few layers of MLI. These systems were susceptible to significantly increased loads as the low emissivity surface emittance increased. Because of this design approach, the HIRDLS cryocooler has never required a decontamination cycle on-orbit.

The HIRDLS cryocooler has been operating since initial ramp up on August 10, 2004. On-orbit data are collected each day; Figure 4 is created from points taken at midnight GMT every day. From the figure, one can see the operational effects on the CSS by the chopper including chopper heater set point change and the effect of various attempts at fixing the chopper. The detector temperatures have varied less than 6.8 mK peak-to-peak for nearly 8 years. A typical requirement for detector stability might be < 10 mK peak-to-peak over a 30-minute period. Figure 5 shows the detector temperatures for a two-hour window starting on June 15, 2012 at midnight GMT with a peak-to-peak temperature variation of 5.45 mK over two hours. Figure 4 also shows the cryocooler stroke as a function of time. Cryocooler stroke is an indication of how hard the cryocooler has to work to meet the detector temperature requirement. As the stroke

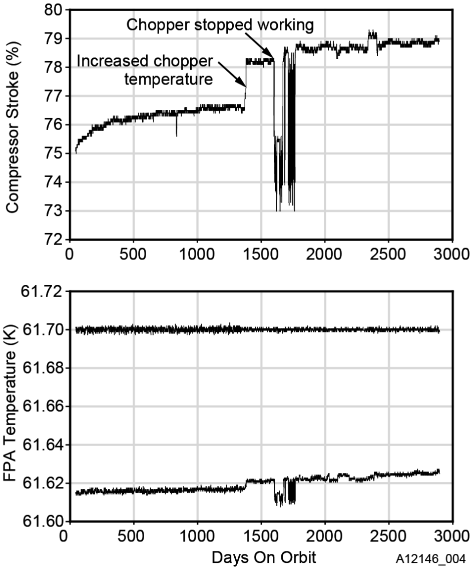

Figure 4. On-orbit performance for cryocooler stroke and detector temperature over the entire mission. Detector temperature stability has varied ±3.4 mK.

increases, the input power required for constant detector temperature also increases. Figure 4 shows a slight increase in stroke over time to keep constant detector temperature. This load increase is due to contamination on the cryogenic surfaces changing the surface emissivity and therefore increasing the loads. In general, cryocooler stroke would be allowed to rise to approximately 90% before decontamination operational modes would be used to remove condensation on the cryogenic surfaces. Alternatively, input power limitations might drive a decontamination cycle before the 90% level is reached. Preflight operational plans for the HIRDLS instrument called for decontamination cycles every few weeks during the first year of operation. Such a decontamination cycle has never been required because the stroke has increased less than 4% from 75.0 to 79.0% when including the chopper operational changes. This extremely small level of contamination is unprecedented in cryocooler operational data released into the public domain.

SB235E/TIRS CRYOCOOLER

After the HIRDLS cryocooler, our first two-stage cooler, the SB230, carried 0.6 W at 35 K. Its productized derivative, the SB235, carried 1.0 W at 35 K and 2.0 W at 85 K for slightly more

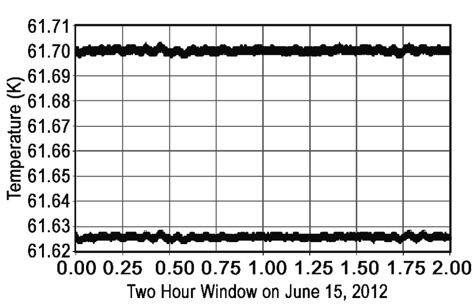

Figure 5. Over shorter time scales that are more typical of temperature stability requirements, the detector temperatures are stable to 5.45 mK peak-to-peak for a two-hour window on June 15.

mass and power. An even larger version was started in 2002 to meet the growing performance requirements. The resulting cooler, called the enhanced version of the SB235 or the SB235E, is shown in Figure 6. It has been characterized in a number of configurations. A flight unit of the SB235E was built and delivered to GSFC for the TIRS instrument. Table 1 compares the SB235 and the SB235E from general design points. Figure 7 compares the SB235 and SB235E cooling capacity over a wide range of operating parameters. In this figure the performance data have been sliced to show the cooler performance at constant motor power for a variety of mid-stage and cold-stage temperatures. The 125 W power level for the SB235 is close to its maximum while that same motor power is at the low end of the SB235E. Stroke for this case varies from 45% to 65%. This performance is at a mid-range power meaning that the increase in capacity is even larger than depicted in the figure. It is also apparent that efficiency has increased and refrigeration has doubled and tripled for the same motor power. Part of the improvement came from an economy of scale, but the remainder is due to design changes incorporated from lessons learned during the SB235 build.

To quantify the efficiency of the cooler, the Carnot efficiency is computed for the 2-stage machine in the following equation:

$$\text{Carnot efficiency} = \frac{1}{\text{Motor power}}\left(\frac{(\text{Treject} - \text{Tcold})}{\text{Tcold}} \cdot \text{Qcold} + \frac{(\text{Treject} - \text{Tmid})}{\text{Tmid}} \cdot \text{Qmid}\right) \qquad (1)$$

where Q is the measured capacity at each stage, Treject is the rejection temperature, Tcold is the cold-stage temperature, and Tmid is the mid-stage temperature. For an ideal cooler, this efficiency factor approaches unity. Figure 7 shows the Carnot efficiency of the SB235 and SB235E showing the efficiency of the SB235E is twice that of the SB235.

Performance mapping of the TIRS cryocooler was completed during thermal vacuum testing in March 2011[5,6]. Figure 9 shows contour plots of the cooling capacity and Carnot efficiency at

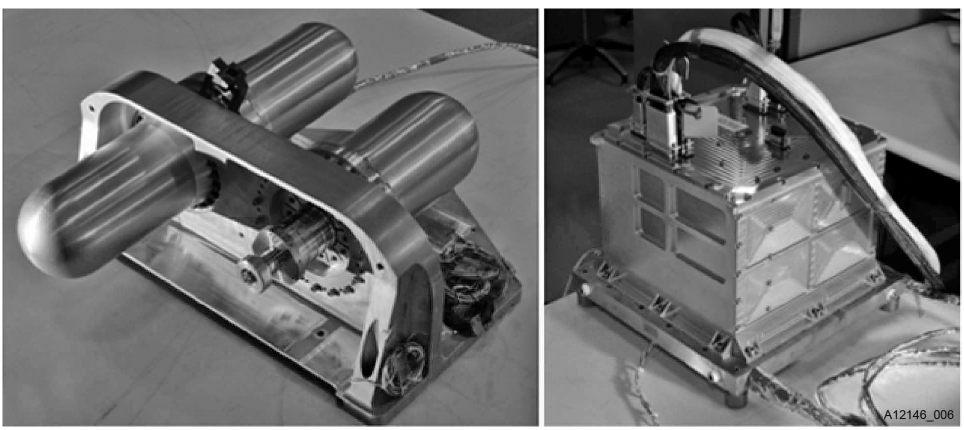

Figure 6. The TIRS cryocooler is the SB235E version of Ball 2-stage coolers scheduled for flight in January 2013.

Table 1. A comparison of Ball's multi-stage 35 K/85 K cryocoolers.

Test Parameter	SB235	SB235E
Nominal 35 K cooling capacity (W)	1.0	2.5
Nominal 85 K cooling capacity (W)	2.0	10
Nominal motor power (W)	150	245
Cooler mass (kg)	10.5	17.43
Life test hours	> 32,000	> 1,000 TIRS EM >1,000 each 35 K/10 K Coolers > 2,000 TIRS FM

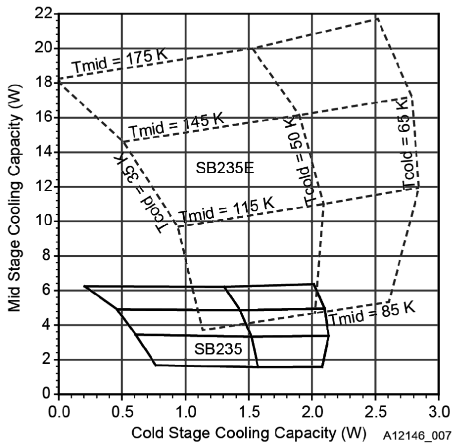

Figure 7. Comparison of the SB235 and SB235E both operating at 125 W motor power. Both arrays cover the same temperature range. Phase angle is 75 deg, frequency is 39 Hz, and rejection temperature is 289 K.

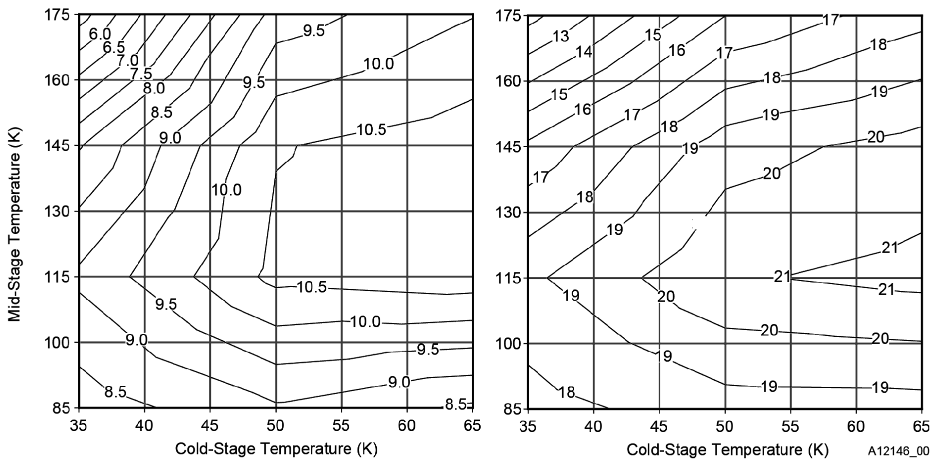

Figure 8. Comparison of the Carnot efficiency for the SB235 (left) and SB235E (right) operating at phase angle 65°, frequency is 39 Hz, rejection temperature is 289 K and stroke of 65%.

150 W and 200 W motor power. For that additional 50 W, the cold-stage capacity increases by 50% and mid-stage capacity by 40%. The Carnot efficiency is very similar between the two points. As expected, the cold-stage capacity varies significantly with cold-stage temperature while the mid-stage capacity is relatively constant. Below 80 K on the mid-stage, the Carnot efficiency is relatively independent of cold-stage temperature. Above 80 K, the efficiency is highly dependent on both temperatures. These curves can be used by the instrument designer in assessing the preliminary cryogenic system level design to determine system level size, weight and power (SWaP) requirements. This cooler has been added to hybrid systems in the 35 K and 10 K Cryocooler programs demonstrating both load leveling capability and very low temperature operation. Finally, a scheme for very low exported force and torque mounting has been demonstrated[7].

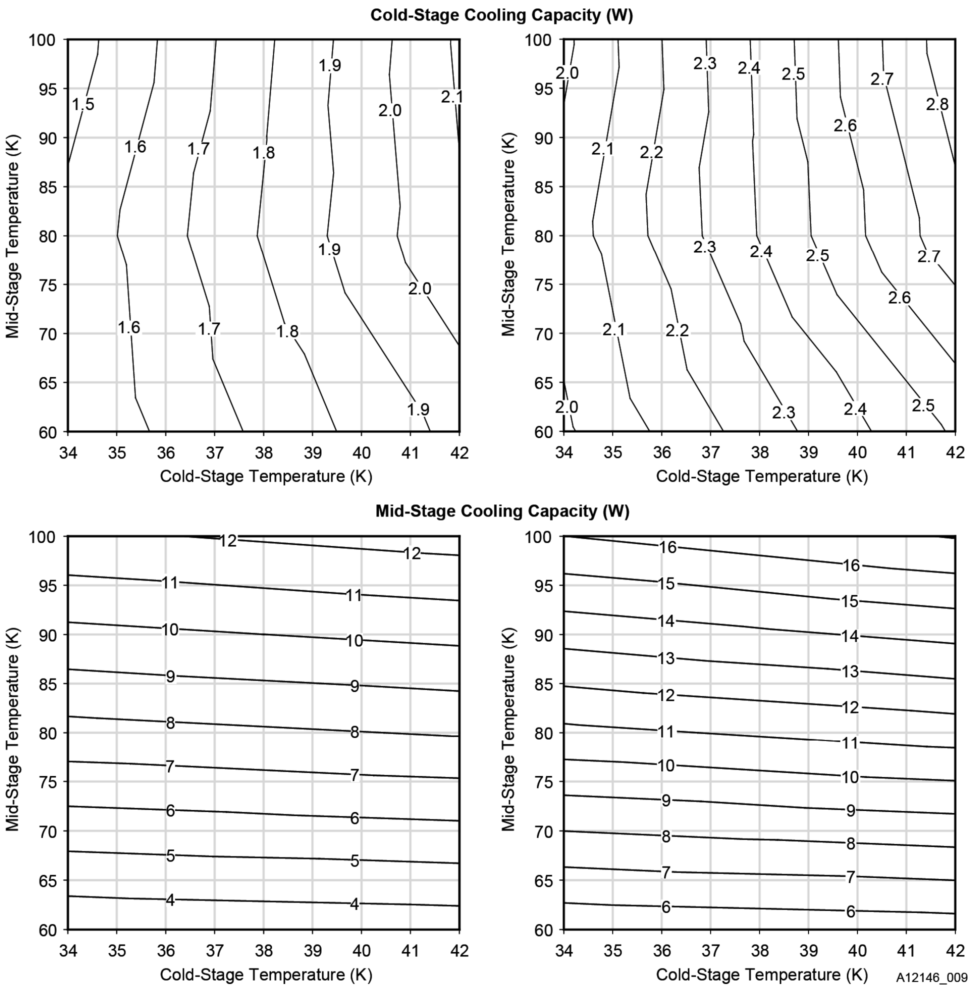

Figure 9. TIRS cooler performance at 150 W motor power (left) and 200 W motor power (right) at 0°C rejection temperature, 65° phase angle and 40 Hz frequency.

CONCLUSION

Ball cryocoolers have a demonstrated history of excellent performance. The HIRDLS cryocooler has been operating for nearly 8 years without a single on-off cycle. In that period the detector temperature has varied less than 5.45 mK peak-to-peak over two hours. In the cryocooler design evolution of the last 20 years, Ball's high capacity flight cryocooler, the SB235E, is now capable of over 20% efficiency. Its first flight is in January 2013. Further refinement has included the addition of circulation systems to enable load leveling capability, very low temperature, and exported force and torque mitigation.

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REFERENCES

1. Curran, D.G., Cha, J.S., & Yuan, S.W. "Space Cryocooler Vendor Survey Update: 2007," Aerospace Report No. TOR-2008(1033)-7691, The Aerospace Corporation, January 2008, pp. A-3.
2. Berry, D.J., Gutow, D., Richards, J., and Stack, R., "Cryocooler Subsystem Integration for the High Resolution Dynamic Limb Sounder (HIRDLS) Instrument," *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 761-769.
3. Kiehl, W., Berry, D.J., Glaister, D.S., Richards, J., and Stack, R.G., "HIRDLS Instrument Flight Cryocooler Subsystem Integration and Acceptance Testing," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 769-773.
4. Hurtt, G., Barros, A., Bevilacqua, R., Bourassa, M., Comstock, J., Cornillon, P., et. al., "NASA Earth Science Senior Review 2011," NASA Earth Science Directorate (June 30, 2011).
5. Marquardt, E., Gully, W., Marquardt, J., Boyle, R., and Hale, T., "Qualification test results for the TIRS cryocooler," *Adv. in Cryogenic Engineering*, Vol. 57, Amer. Institute of Physics, Melville, NY (2012), pp. 147-153.
6. Boyle, R., Marquardt, E., and Marquardt, J., "TIRS Cryocooler Integration and test at the Instrument Level," *Cryocoolers 17*, ICC Press, Boulder, CO (2013), (this proceedings).
7. Marquardt, E.D., Glaister, G., Marquardt, J.S., Raab, J. and Durand, D., "Testing Results for Low Exported Force and Torque Cryocooler Mounts," *Cryocoolers 17*, ICC Press, Boulder, CO (2013), (this proceedings).