Ball Aerospace Next Generation Two-Stage 35 K Coolers: The SB235 and SB235E

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ABSTRACT

This paper describes the design, development, testing, and performance of the Ball Aerospace SB235 and SB235E long-life, two-stage space cryocoolers. The SB235 and SB235E are two-stage coolers designed to provide simultaneous cooling at 35 K (typically for HgCdTe detectors) and 85 K (typically for optics). The SB235 qualification unit was delivered to Air Force Research Laboratory (AFRL) for life testing and has accrued more than 13,000 hours as of May 2006. The SB235E is a higher capacity derivative of the SB235 that has undergone initial performance testing. The SB235E is the precooler for the 35 K High Capacity Variable Load Cryocooler and 10 K High Capacity Cryocooler Programs under development at Ball Aerospace. Initial testing of the SB235E has shown performance of 2.64 W at 35 K and 10.4 W at 85 K for 255 W of power, which equates to Carnot efficiency about 50% higher than that of other published cryocooler data. Mass of the SB235E cooler is 14.4 kg for the compressor and displacer.

INTRODUCTION

As infrared systems grow in size, the power savings for cooling them with a multistage cryocooler becomes significant. The cryocooler has to absorb the electrical dissipation at the detector temperature. Parasitic heat loads originating at ambient that would otherwise fall on the detector can be intercepted by a second-stage operating at a higher temperature for a considerable savings in cooler input power. In addition, multistage coolers allow for multiple cooling temperatures so that for example, optics can also be cooled with a single unit. Ball has developed a series of two-stage Stirling cycle coolers for space that provide refrigeration at both 35 and 85 K in a single package to support these applications.

Loads have grown rapidly over the past decade because of larger formats and new features such as redundant coolers, and Ball Aerospace coolers have had to keep pace. 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 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 1. It has been characterized in a number of configurations, and the results will be presented in this paper. It is a significantly larger cooler, carrying over 3 W at 35 K and 10 W at 85 K. The growth in size of our two-stage coolers is documented in Table 1.

DESIGN AND DEVELOPMENT OF THE SB235E

Although they have grown in size, the coolers in Table 1 embody essentially the same technology. They are all long-life, high-reliability space coolers based on the "Oxford" linear drive technology, where

Table 1. A comparison of Ball's multistage 35 K / 85 K coolers.

	SB230	SB235	SB235E
Testing year	1996	2003	2006
Nominal 35 K heat lift (W)	0.6	1	3
Nominal 85 K heat lift (W)	0	2	10
Motor power (W)	55	150	255
Operating frequency (Hz)	36	40	40
Charge pressure (Bar)	8	10	10
Cooler mass (kg)	9.5	10.5	14.4
Compressor displacement (cc)	5	13.6	37
Life test hours	>22,000	>14,660 (6/5/06)	-

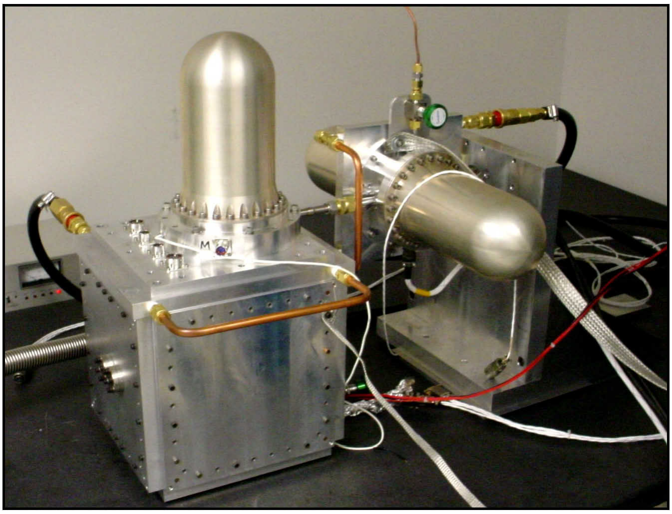

Figure 1. The SB235E cooler in ambient temperature performance characterization tests. Chillers held the baseplates to 20 °C during the tests reported below.

pistons supported on diaphragm springs are driven by linear motors. Our compressor components have been carefully scaled to ensure that the pistons remain non-contacting at these higher power levels. Our displacers still use fixed regenerators and light- weighted displacer pistons so they too remain noncontacting in all orientations on the ground, which facilitates system testing. Continued life testing of the earlier versions gives us confidence that these mechanisms are well understood.

The drive electronics have grown as well. Their peak power capability has increased from 100 W in the SB230 to 450 W in the latest design. They continue to be microprocessor controlled and operate from a 28 Vdc electrical bus. A constant current input now eliminates the substantial ripple that these coolers previously caused on the power lines. Our development circuitry and support equipment are shown operating the SB235E in Figure 2.

SB235E TEST RESULTS

The new SB235E cooler was extensively tested as a function of compressor and displacer strokes and phase angles over an assortment of mid-stage and cold-stage temperatures from 35 to 150 K. The data was used to construct a performance matrix that can be interrogated in various ways as will be illustrated below. The data matrix has supported a number of case studies and cryogenic system performance predictions.

The first performance plot is given in Figure 3. It illustrates the relative capacity between the SB235E and SB235. The SB235's performance has been discussed in detail in a previous report.[1] In this figure the

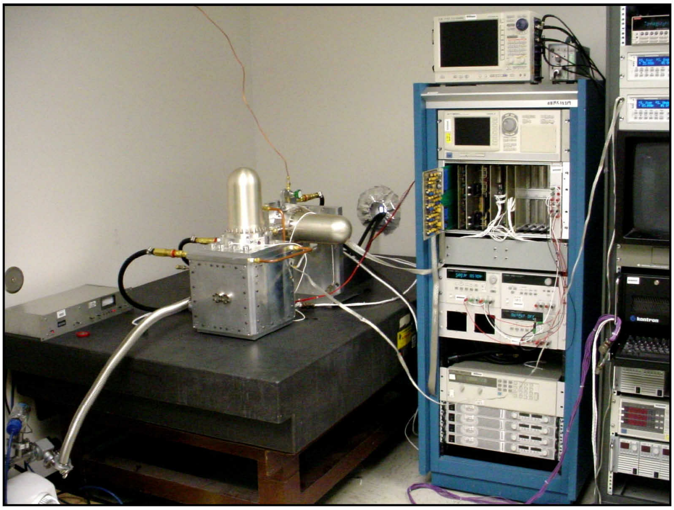

Figure 2. The SB235E cooler with its development electronics and support equipment.

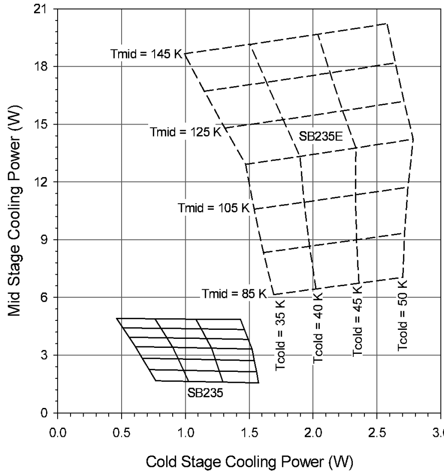

Figure 3. Comparison of the SB235 operating at 125 W with the new SB235E operating at 175 W.

data matrix has been sliced to show the cooler performance at constant motor power for a variety of mid-stage and cold-stage temperatures. The rule is that at any temperature set and phase angle, the stroke was calculated for the desired motor power. The 125 W power level for the SB235 is close to its maximum, whereas the 175 W power chosen for the SB235E is only 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 only a 40% increase in input power. Part of the improvement comes from economies of scale, but the remainder is due to design changes incorporated from lessons learned during the SB235 build.

Performance at somewhat higher power levels is shown in Figure 4. The cooling is similar to that reported in Figure 3 except that it now peaks at over 3 W at the cold stage and 21 W at the mid-stage for the appropriate temperatures. Even this does not represent full power in the cooler. The full dynamic range at 35 and 85 K is illustrated in Figure 5, where the heat lift at this single temperature set is plotted as a function of input power. The temperatures chosen are the coordinates of the lower left hand corner of the arrays in Figures 3 and 4. Figure 5 shows the cooling at both stages continues on without saturation to values at least 50% greater than those depicted in Figure 4. The SB235E is truly a much more powerful cooler than the SB235.

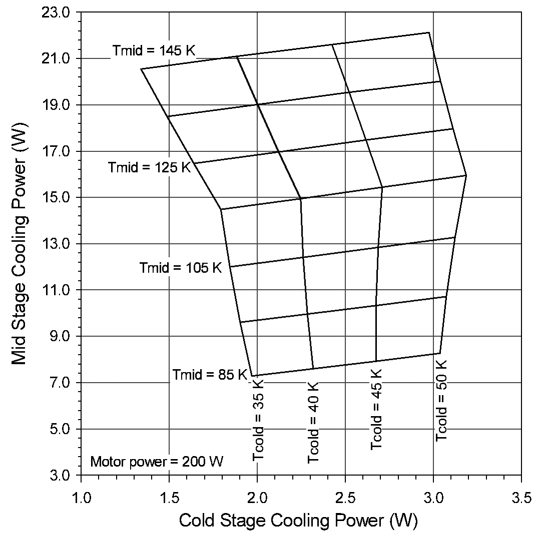

Figure 4. Performance of the SB235E at 200 W.

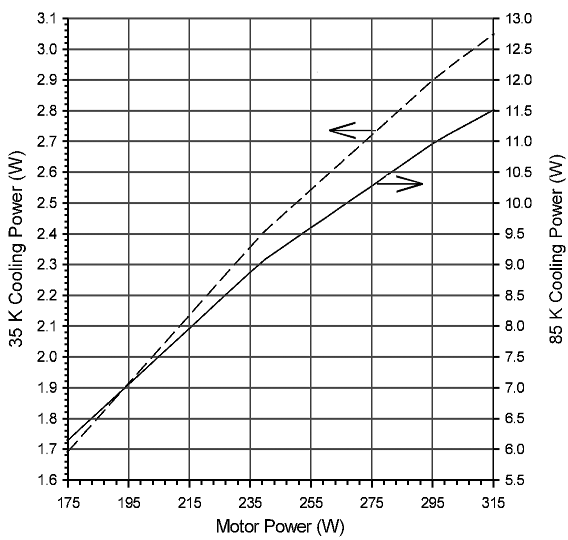

Figure 5. SB235E performance at 35 and 85 K, 39 Hz frequency and 75° phase angle.

Both arrays cover the same temperatures. Phase angle is 75°; frequency is 39 Hz.

To quantify the efficiency of the cooler, a "Carnot" power $P=Q^*(T_{ambient}/T_{cold}-1)$ can be calculated for a single stage from the measured capacity Q, its interface temperature T_{cold}, and the baseplate temperature, $T_{ambient}$. Powers derived for the individual stages are added. Dividing this theoretical Carnot cooler power by the measured motor power results in an "efficiency" factor that approaches unity for a perfect cooler. For 35 and 85 K, the SB235's efficiency was 14% while the SB235E's efficiency ranges from 16 to 18%. This efficiency is half again higher than efficiencies calculated from the reported performances of pulse tube coolers operating in the similar capacity and temperature range in the literature.[2,3]

The phase angle dependence of the SB235E's heat lift is shown in Figure 6. Both stages peak at about the same place so the SB235E has minimal ability to shift capacity from one stage to the other on orbit. In contrast, the SB235 is able to shift approximately 30% of its cooling between stages.[4] The difference can be explained by the greater disparity in the heat lift between the two stages on the SB235E and because the SB235 second-stage regenerator losses were more phase dependent.

THE SB235E IN THE 35 K HIGH-CAPACITY COOLER PROGRAM

The SB235E has been selected as the precooler for the 35 K High Capacity Variable Load Cryocooler Program. A schematic of this cryogenic system is shown in Figure 7. In this application, the sensor has to be kept at 35 K even though its thermal load varies dramatically during a 90-min. cycle. The cryogenic system regulates the sensor temperature by using two coolers and an internal thermal storage unit (ITSU). Refrigeration accumulated in the ITSU during the low load part of the cycle is quickly transferred to the sensor by a J-T cooler during the high load part of the cycle. Because of the load leveling characteristic of the ITSU, the SB235E precooler operates steadily to supply the average amount of refrigeration required by the sensor over the 90 min. Not only does this simplify the system, but it enables the precooler to refrigerate systems with much larger intermittent loads.

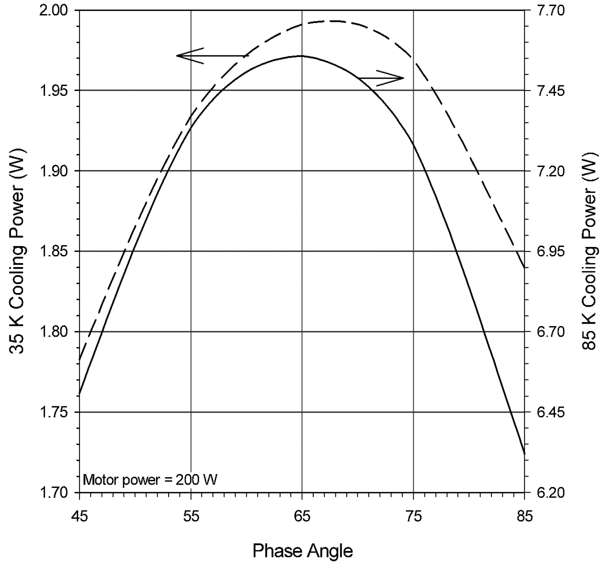

Figure 6. The cooling power of both stages of the SB235E peaks as a function of phase angle.

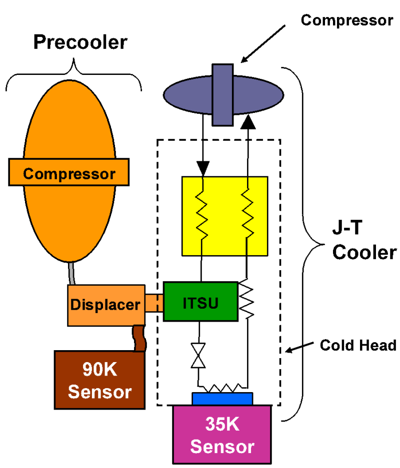

Figure 7. The 35 K High Capacity Program uses an internal thermal storage unit to augment precooler refrigeration during the "high load" part of a variable load.

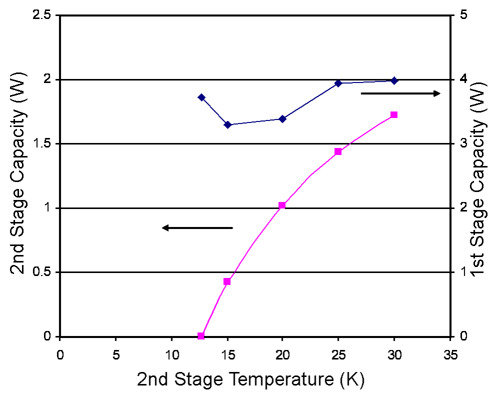

Figure 8. Measured 1st- and 2nd-stage cooling capacities for the SB235E with a modified 2nd-stage regenerator. The cooler carries 420 mW at 15 K for an input power of approximately 240 W.

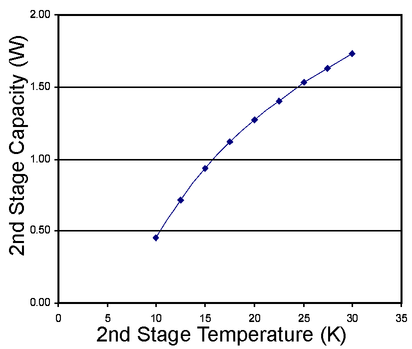

Figure 9. Predicted 2nd-stage cooling capacity for a 2nd-stage design optimized for 15 K cooling.

SB235E AS A 10 K PRECOOLER

Since the baseline SB235E cooler had a no-load temperature near 15 K, it was clear that it had the potential to become a very nice low-temperature cooler. To get a quick demonstration of its capability, the standard screen pack in its 2nd stage regenerator was replaced with a custom regenerator matrix with a high-heat capacity. Its low-temperature performance is shown in Figure 8. The cooler achieved 420 mW at 15 K simultaneously with approximately 4 W at 70 K for motor powers in the range from 223 to 248 W as the 2nd stage temperature decreased.

Given this promising result, a design study was undertaken to determine the best way to re-optimize the whole cooler for operation at 15 and 70 K instead of 35 and 85 K. The results are shown in Figure 9. The analysis shows that by tweaking the regenerator and altering the size of the second stage somewhat, the heat lift at the cold tip can double for the same input power and capacity at 70 K. A new unit is presently being fabricated and will be tested later this year.

Based on these results, the modified SB235E has been chosen as the precooler for our 10 K High Capacity Cooler Program. The 10 K cooler system is a hybrid in which the Stirling precooler refrigerates a helium J-T loop to 15 K. Our analysis shows that the system is capable of 200 mW at 10 K for less than 400 W of system power. The hybrid approach to 10 K cooling has many system advantages and is discussed at length in a companion article in the conference proceedings.[5]

SUMMARY

The new Ball Aerospace SB235E cooler has significantly greater capacity and is quite power efficient. The cooler has found a niche in several current applications.

ACKNOWLEDGMENTS

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