Micro-size Cryocooler Control Electronics

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ABSTRACT

Focal Plane Array cooling for small satellites presents a very challenging need for power dense cryogenic refrigeration and drive electronics. Critical performance metrics include small size, low mass, low vibration, high efficiency, and radiation tolerance. In addition to excellent technical performance, universal designs are needed to support a variety of missions with short development time and minimal cost. This paper describes the development and demonstration of Micro-size Cryocooler Control Electronics (MCCE) suitable for small satellite cryogenic refrigerators. Our MCCE provides dual, independent drives for pulse tube and Stirling cryocoolers which can be customized for each application with software changes. The MCCE package is small and lightweight, with a volume of 140 cm^3 and mass of 220 g, and has been designed to flight requirements. We have demonstrated the following through brassboard tests: (1) operation with three different cryocoolers; (2) output power levels up to 30 W; and (3) efficiency of 85–95%.[1-3]

INTRODUCTION

Cubesats are becoming a very desirable imaging sensor platform due to low cost, short development time, and allowance for use of commercial components. However, challenging performance requirements such as power density and reliability still apply. For example, an entire 3U cubesat must fit within a 10 x 10 x 30 cm, 4 kg package, and achieving the required power density is quite challenging. Medium earth orbit (MEO), geostationary orbit (GEO), and low earth orbit (LEO) missions require radiation-hardened components; and for extended duration MEO missions, tolerance levels up to 1 Mrad are required. For cubesats that use infrared sensors, miniaturization and cost reduction of the cryocooler are a significant challenge. Typical cubesat cryogenic refrigerator requirements are summarized in Table 1. Creare is addressing this challenge by working collaboratively with Lockheed Martin Advanced Technology Center (LM-ATC) to develop a cryogenic refrigerator comprising LM-ATC microcryocooler technologies and an adaptation of Creare's low-cost Tactical Cryocooler Drive (TCD) electronics. This paper describes development and testing for a next generation MCCE suitable for typical miniature cryocoolers.

MICRO-SIZE CRYOCOOLER CONTROL ELECTRONICS

To accomplish this goal, Creare is leveraging low-cost, micro-size electronics, and cryocooler technologies and capabilities previously demonstrated on prior programs. The refrigerator com-

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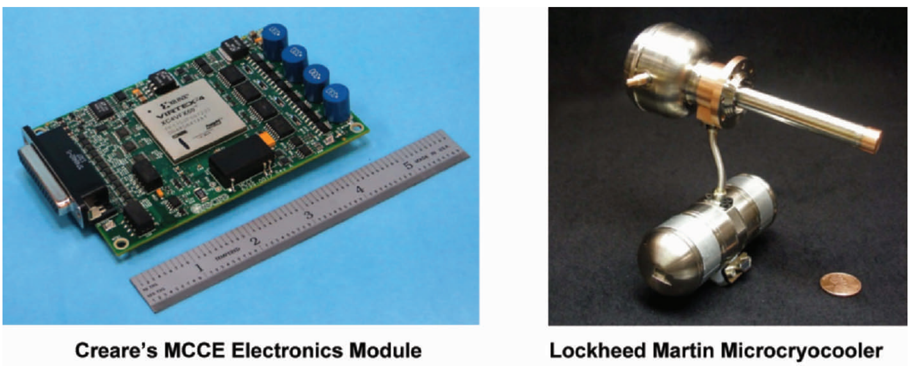
Table 1. Cryogenic Refrigerator Requirements

Parameter	Requirement
Application	• 3U cubesat or microsat, with the following overall characteristics: – 4 kg total mass – 10 x 10 x 34 cm total size – 50 W total power
Mission	• 10-year GEO or MEO • 5-year LEO
Radiation Hardness	• 150 krad at component level • Path toward 1 Mrad for MEO
Cooling Temperature	100 K
Cooling Load	1 W
Rejection Temperature	275 – 325 K
EMI/EMC	According to GSFC-STD-7000% [1-3]



Features of Creare's MCCE/Microcryocooler Approach:

- Small size: 370 cm^3 (cryocooler 230 cm^3 & MCCE 140 cm^3)
- Low mass: 560 g (cryocooler 340 g, MCCE 220 g)
- High refrigerator system reliability: 5 years: 0.98, 10 years: 0.96
- Active vibration control
- Universal design is easy to adapt for each mission

Figure 1. Creare's approach for developing a cryogenic refrigerator for cubesats.

prises a space-flight version of our universal TCD electronics and a Lockheed Martin micro-size pulse-tube Thermo-Mechanical Unit (TMU).[4-7]

Figure 1 shows photographs of the micro-size electronics module and cryocooler subsystems envisioned for the refrigerator. Our TCD electronics have been previously demonstrated with Lockheed Martin's 4 K four-stage tactical cryocooler, Sunpower's CryoTel CT and GT cryocoolers, and Ricor's 527 and 535 cryocoolers. As part of our most current work, the TCD was miniaturized and designed for compatibility with cubesat power levels. The LM-ATC microcryocooler has recently been qualified to TRL 6 and can be optimized to achieve 1 W cooling at 100 K.[8] With a highly integrated design, the refrigerator package is much smaller than previously reported products. To validate the miniaturized design, we fabricated a representative set of MCCE hardware and demonstrated performance at power levels up to 20 W per channel with the Ricor K527 and K529 cryo-

Table 2. Cryogenic Refrigerator Key Parameters

MCCE	
Size (cm^3)	140
Mass (g)	220
MTBF (Mhrs)	3.1
Conversion Efficiency (%)	92
Lockheed Martin Cooler	
Size (cm^3)	230
Mass (g)	340
MTBF (Mhrs)	6.1
Cooling at 100 K	1 W (35 W_e)
System	
Size (cm^3)	370
Mass (g)	560

coolers and the LM-ATC miniature cryocooler. Table 2 summarizes the technical accomplishments. The most important determinations are that the overall refrigerator volume fits comfortably within a fraction of the 3U cubesat envelope, mass, and electrical power allotment. These results demonstrate that this approach is feasible for creating a micro-size cubesat refrigerator.

TEST RESULTS

Load testing has included a lumped resistance-inductance (RL) equivalent motor simulator, low-cost in-house cryocoolers such as the Ricor K527 and K529 single compressor cryocoolers, and the Lockheed Martin dual piston minicryocooler. Figures 2a, 2b and 2c show the MCCE electrical output voltage, current, power, and efficiency characterization data. Overall, we have been able to achieve an output power level as high as 30 W per channel for a single channel lumped RL load with 12 V(rms) and 3 A(rms). The Fig. 2 figures show that input impedance for the cryocoolers is highly nonlinear depending on whether the piston is moving or not; and at low drive voltages, the current is quite low and efficiency is nearly 100%.

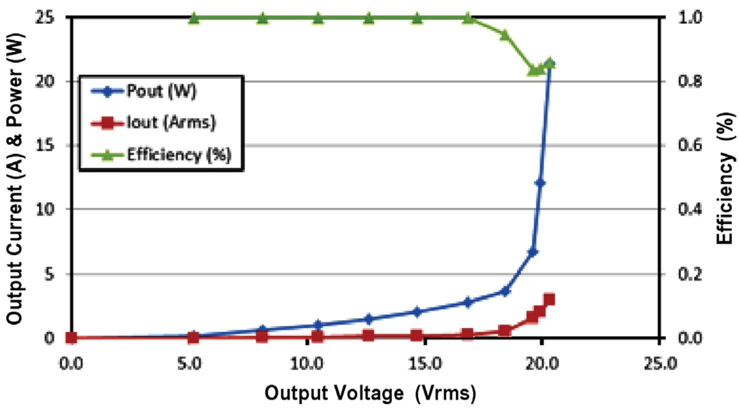


Figure 2a. MCCE electrical performance with a Ricor K527 Cryocooler.

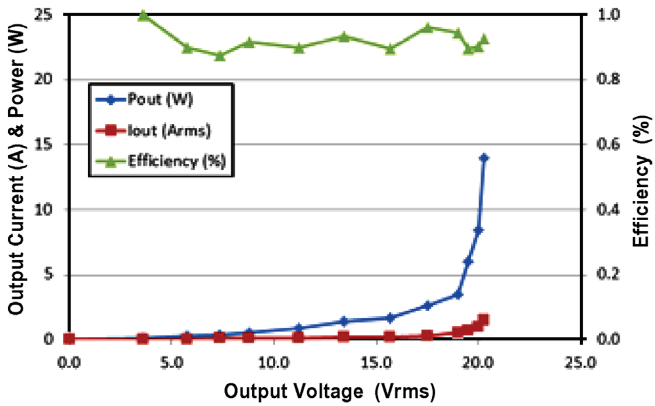


Figure 2b. MCCE electrical performance with a Ricor K529 Cryocooler.

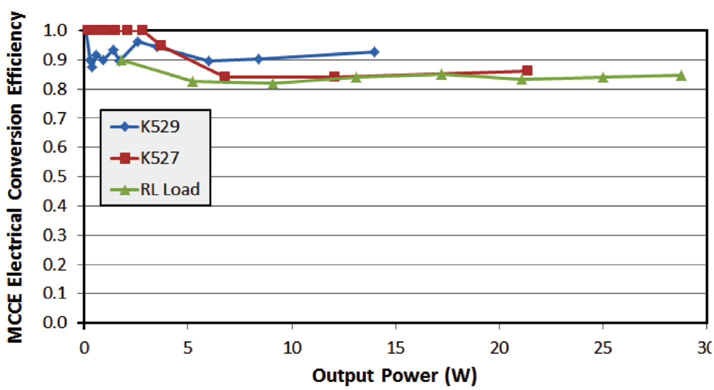


Figure 2c. MCCE electrical conversion efficiency for an RL load, K527, and K529 cryocoolers.

Figure 2c summarizes the efficiency performance for the RL load and the K527 and K529 cryocoolers. Efficiency is typically 85–95% at power levels between 3 W and 20 W, and at typical power levels of between 10–20 W per compressor, we expect efficiency to be 90–95%. The Lockheed Martin minicryocooler and microcryocooler typically require an electrical input power of approximately 10–15 W per channel, which is easily met by the MCCE. Figure 3 shows the test setup with the MCCE and K527 and K529 cryocoolers. We have successfully verified that the control logic signals are properly generated by the FPGA and fed to the Pulse Width Modulation (PWM) circuits. We have also verified that the PWM circuits create a pseudo-sinusoidal current which is applied to the compressor motor.

Figure 4 shows a photograph of the test setup where we evaluated MCCE performance with the LM-ATC minicryocooler. For this benchtop test, we integrated the MCCE with the minicooler and provided adequate coldhead multi-layer insulation and a foam insulation layer to enable demonstration of successful cooldown at prototypical power levels. The minicryocooler coldfinger was not in a vacuum for this test. To evaluate feasibility, our aims were to demonstrate (1) minicooler functional operation and (2) MCCE ability to control the minicooler during cooldown at prototypical power levels and with acceptable electrical conversion efficiency.

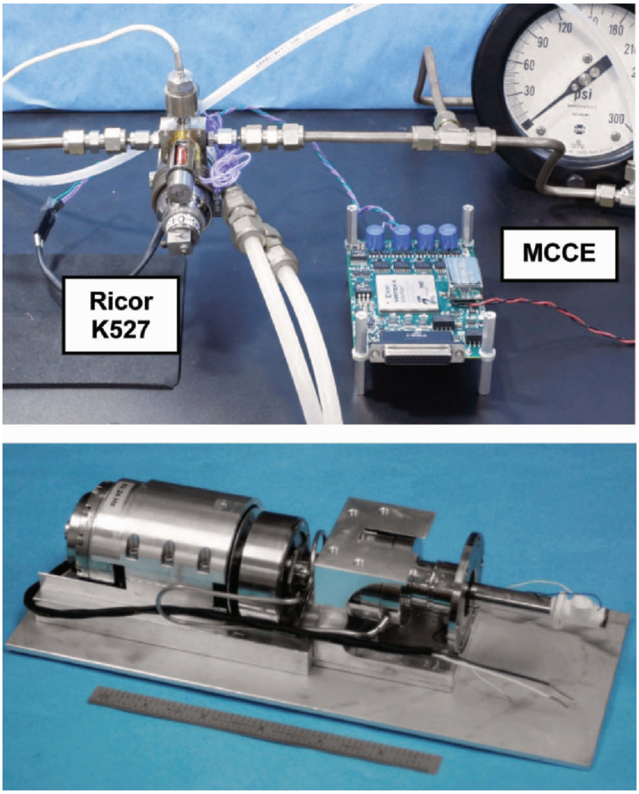


Figure 3. Ricor K527 (top) and K529 (bottom) cryocoolers used during testing.

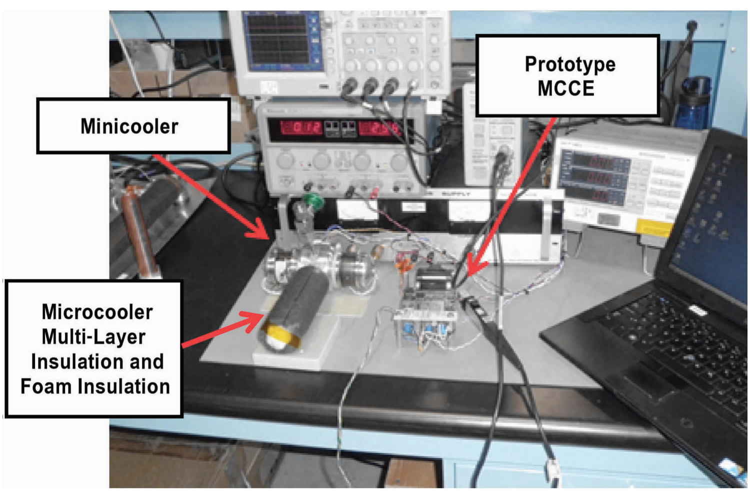


Figure 4. Photograph of the test setup.

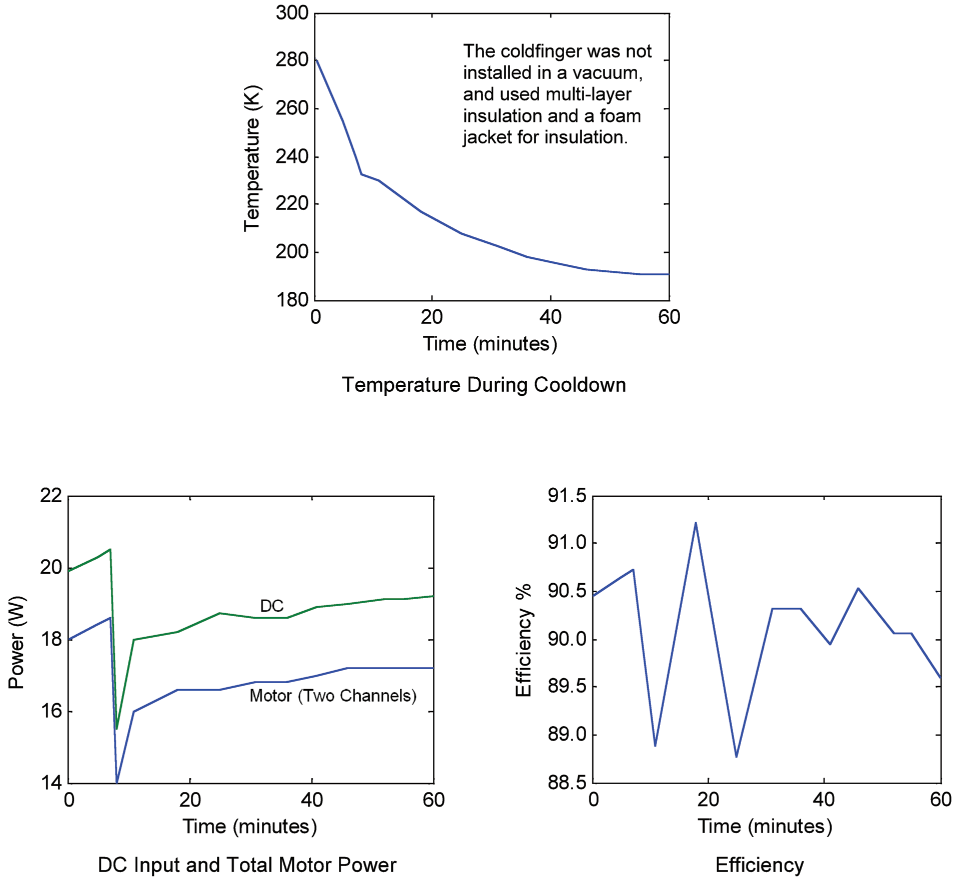


Figure 5. Temperature, power, and efficiency as a function of time during cooldown.

Figure 5 shows the most important results. The top graph shows cooldown performance from roughly 280 K to 190 K over the course of approximately one hour. The bottom left panel shows a total DC input power between 16–21 W and the total output power for the two compressors between 14–19 W during the test. The initial cooldown rates are as expected for the LM-ATC minicryocooler, and the overall cooldown time and ultimate cold tip temperature are in line with expectations when operating the pulse tube cooler horizontally (an unfavorable orientation for the cryocooler with respect to gravitational convection within the pulse tube) and without high vacuum around the cryocooler. The bottom right graph shows that the MCCE electrical conversion efficiency was between 89–91% throughout the test.

This test successfully demonstrated the proper functional operation and compatibility of the minicooler and MCCE electronics, and also that the MCCE provides the required power levels with good efficiency during cooling.

CONCLUSIONS

The result of this program will be a refrigerator that is suitable for use on cubesats, small satellites, and small aircraft. A very small cryogenic refrigerator will enable imaging, surveillance, and scientific investigation in micro-sized payloads. The key result described in this paper is successful development and testing of the MCCE required to drive a range of miniature and micro-size cryogenic refrigerators.

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