Development and Qualification Testing of Cryocooler Systems for Affordable Space Missions

D.W. Fogg[1], R.W. Kaszeta[1], J.F. Gregoire[1], M.V. Zagarola[1], C. Kirkconnell[2]

[1]Creare LLC
Hanover, NH, USA 03755

[2]West Coast Solutions
Huntington Beach, CA, USA 92647

ABSTRACT

An increased number of space missions are utilizing constellations of small satellites to replace larger and more costly strategic satellites. These constellations offer enhanced coverage and resilience in comparison to one or several exquisite satellites. To address this growing market, Creare and our collaborators at West Coast Solutions developed low-cost space cryocooler systems based on our micro-sized cryocooler control electronics (MCCE). These electronics were qualified in 2020 and soon baselined for several space missions. This paper describes the qualification of these systems for space missions utilizing the MCCE with two tactical cryocoolers, the AIM SF070 and Thales LPT9510.

INTRODUCTION

Since 1991, Creare has been developing electronics to drive multiple types of cryocoolers, including turboBrayton, Stirling, Pulse Tube, and JouleThomson varieties. In 2008 we began developing dual channel Stirling and Pulse Tube cryocooler drive electronics, starting with a universal Tactical Cooler Drive (TCD) to support a range of tactical DoD applications. These electronics have since been adapted to drive multiple cryocoolers at different power levels and configurations. In 2014, Creare completed work for the Air Force to develop a miniaturized version of the TCD electronics, which resulted in designs for two versions. The first version utilizes commercial grade, high reliability parts (MCCECOM) and was demonstrated in the laboratory with Ricor K527, Ricor 529, Thales LPT9510, and Lockheed Martin minicryocoolers. As an extension of the MCCECOM demonstration, a radiation hardened (MCCERH) design for small satellites, which require the highest level of reliability and radiation tolerance for long duration space missions, was also conceptualized and is now being realized as a flight design prototype on an ongoing program. This design uses all S-class and radiation hardened components and meets the requirements for the most stringent space applications, including strategic platforms and long duration missions.

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Figure 1. The MCCETS is a single board assembly designed to fit on a side of a 1U CubeSat.

Table 1. Summary of MCCE TS specifications.

Input Voltage	28 VDC nominal, 22 VDC–36 VDC unregulated. 11 VDC–40 VDC input possible with inclusion of Input Ripple Filter
EMI	MILSTD461, optional input ripple filter for CE101/CE-102 ripple reduction.
Max AC Output Current	4 A_{RMS} (2 channels @ 2 A_{RMS} per channel)
Max AC Output Power	80–100 W (2 channels @ 40–50 W per channel at 28 VDC input voltage) depending on cryocooler impedance
CCE Thermal Management	Conductive cooling
Size (including chassis)	5.2 in. x 4.8 in. x 2.0 in. w/o ripple filter
Mass (including chassis)	800 grams w/o ripple filter and standard packing
Operating Temperature Range	-40ºC to 71ºC
Radiation Hardness (TID)	Min TID: 30 kRad (Si)
Radiation Hardness (SEL)	Min SEL threshold (LET_{th}): 40 $MeVcm^2/mg$
Reliability (MILHDBK217)	96% for twoyear mission with standard BOM. Potential for improved reliability with BOM upgrades.
Active Vibration Control	Optional with inclusion of radiation-tolerant charge amplifier
Command and Control	RS422
Motor Launch Lock	Optional
Programming	Hardware Description Language (HDL) firmware
Temperature Sensors	2 kΩ PRT or comparable sensors
Control Temperature Range	50 K to 200 K
Temperature Control	+/ 0.1 K
Temperature Accuracy	+/ 1 K from 70 K to 150 K

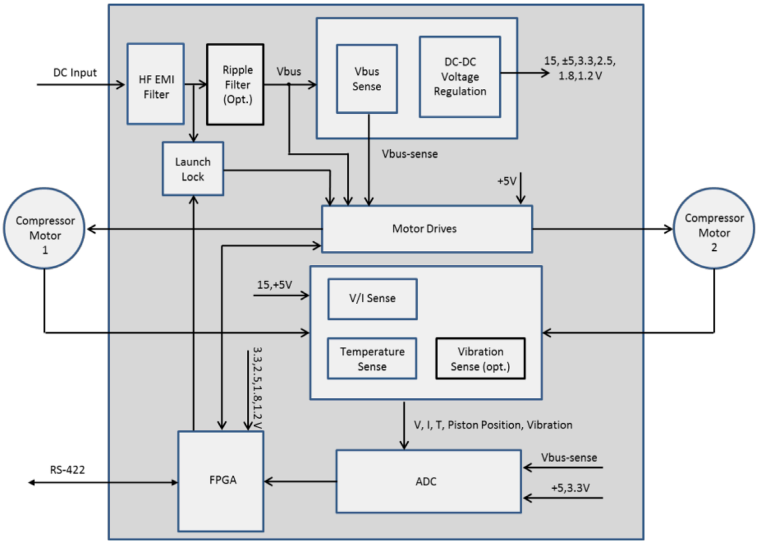

Figure 2. The MCCE-TS Drive Architecture.

MCCETS – LOWCOST ELECTRONICS FOR SPACE

In 2017, we started development of the MCCETS (Figure 1) on NASA Contract 80NSSC18C0059 [1]. This unit is a derivative of our MCCECOM and MCCERH units. Falling between MCCECOM and MCCERH in terms of reliability and radiation hardness, the MCCETS is intended for radiation tolerant, lowcost space missions where commercial electronics are not suitable. These electronics are being developed with our partner, West Coast Solutions (WCS), for NASA's Class C/D missions.

The important characteristics are shown in Table 1 and architecture is shown in Figure 2. The unit is designed for current levels up to 2 ARMS per channel and can drive linear cryocoolers with total maximum AC input power of up to 100 W.

CRYOCOOLER TEST FACILITY

For cryocooler testing, the cold finger for each cryocooler is installed in a vacuum dewar constructed from Con-Flat (CF) vacuum crosses. The dewar assembly allows up to four crosses to be connected to a central vacuum port for testing as many as four units simultaneously. The vacuum dewar achieves better than 10^{-6} torr. The cryocoolers and MCCEs are mounted to thermoelectrically-controlled cold plates to maintain constant heat rejection temperatures.

A simulated sensor load comprising a 4-wire resistive heater and a 4-wire PRT for MCCE temperature control is attached to the cold tip. The sensor load also includes an additional 4-wire PRT used by the support test equipment to independently monitor and record cold tip temperatures.

Monitoring equipment includes a Yokogawa WT-230 for measuring MCCE input and output powers; an SRS CTC100 cryogenic temperature controller for monitoring the cold tip temperature; and GW Instek GDM 8341 digital multimeters to measure cold tip thermal load powers.

TESTING OVERVIEW

Flight qualification of MCCE-TS drive electronics involves functional testing, EMI, vibration, and thermal environment testing. Functional testing focuses on MCCE-TS drive efficiency, set point control, and temperature stability. EMI testing assesses MCCE-TS compliance against industry standards. The vibrational and thermal environments are representative of worse-case conditions.

Most testing described in this paper is performed with the Thales LPT9510 cryocooler. Prior testing with the AIM SF070 cryocooler is given in reference [2]. The Thales LPT9510 can provide more than 1.4 W of cooling at 80 K and over 4.0 W of cooling at 130 K. It has an estimated mean time to failure of 90,000 hrs and has been previously qualified for use in space [3].

EMI

The MCCE-TS without an input ripple filter was characterized in accordance with MILSTD-461G EMI/EMC requirements to establish a baseline. Designs providing CE101 compliance have been implemented using both passive and active ripple filter circuits but were not included in the baseline testing.

The baseline EMI/EMC characterization was performed under varied operating parameters using simulated compressor loads. The PWM switching frequency was set to 25, 50, 100, or 200 kHz with a 0 or 5 µs phase delay between the two motor channels, for a total of eight configurations. In all tests, the MCCE drove a simulated load at approximately 45 W with a 28.0 V_{DC} supply. The simulated load is constructed with a combination of resistance and inductance that closely matches the impedance of the Thales LPT9510 cryocooler.

CE101 Assessment

The CE101 test was performed using a Stanford Research SR780 Network Signal Analyzer. We characterized performance over the CE101 bandwidth in two chunks, dubbed Lower and Upper. There is some overlap in the frequency spans, which can be seen in the data plots. For each test condition, four samples were taken one at a time, a Lower and an Upper sample for both the power (red) and return (black) conductors. We combined these four data sets into a single plot for each test condition.

The results show one 29 dB exceedance of the CE101 limit line at 90 Hz. This peak is an expected outcome and consistent with prior testing of driving the cryocooler motors at 45 Hz with an H-bridge, where there are two switching events per period. Harmonic peaks remain below the limit. The spectrum shown in Figure 3 is consistent across all eight test conditions. The CE101 limit line is shown in blue.

Cooldown Performance with Thales LPT9510

The MCCE-TS/LPT9510 cryocooler system rapidly cools down a thermal load simulator attached to the cold tip. A typical cool down event is shown in Figure 4. Starting at room temperature with no cold tip thermal load, the cooler is commanded to operate at the LPT9510 maximum drive voltage to 80 K. The cool down time is approximately 40 mins.

At t=48 min, 2.5 W of heat is applied to the cold tip thermal load simulator via a resistive heating element, and the cryocooler is commanded to regulate the cold tip temperature to 130 K.

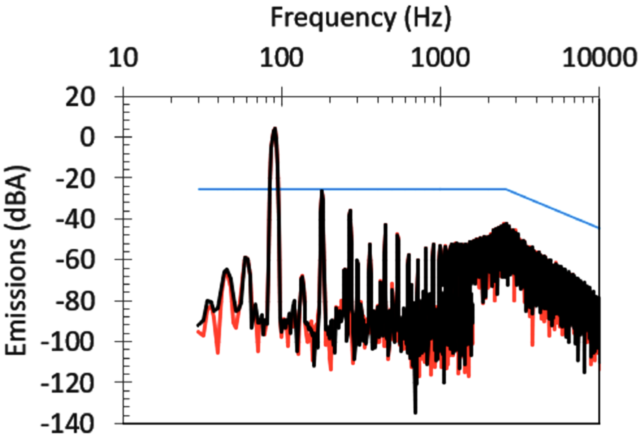

Figure 3. CE101 Emission Spectrum, 50 kHz.

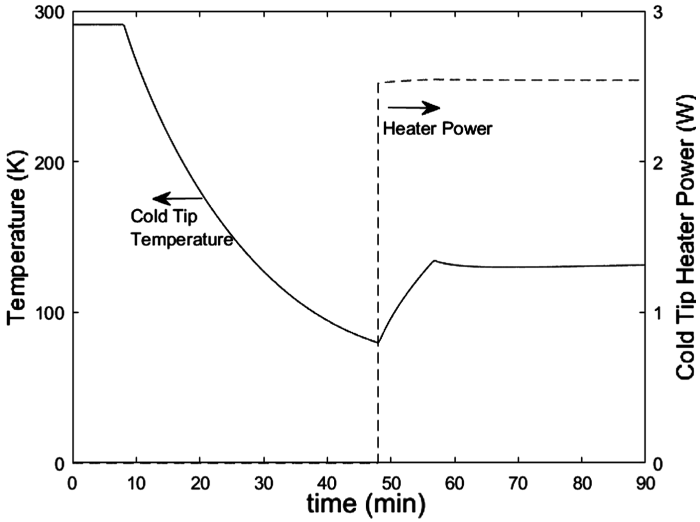

Figure 4. Cooldown and characterization of the LPT9510 cooler driven at maximum drive voltage with external heat between 0 and 2.5 W applied to the cold tip.

The PID controller in the MCCE-TS reduces the LPT9510 output to its minimum drive voltage while the cold tip climbs from 80 to 130 K. After a slight overshoot to 134.1 K, the PID algorithm ramps up the cryocooler drive voltage allowing the cooler to match the thermal load and settle into the setpoint temperature range (130 K +/- 1 K) within 4 minutes of the overshoot peak.

Setpoint Configurability and Stability with Thales LPT9510

The MCCE-TS supports configurable cold tip setpoints (Figure 5). The ability to control at a given setpoint depends on the cold tip thermal load and the cryocooler cooling capacity at the target setpoint for the maximum and minimum allowable drive voltages. The LPT9510 can cool in excess of 4.0 W at 130 K and above, but starts dropping in capacity as the set point temperature decreases with capacities approaching 1.0 W at 80 K.

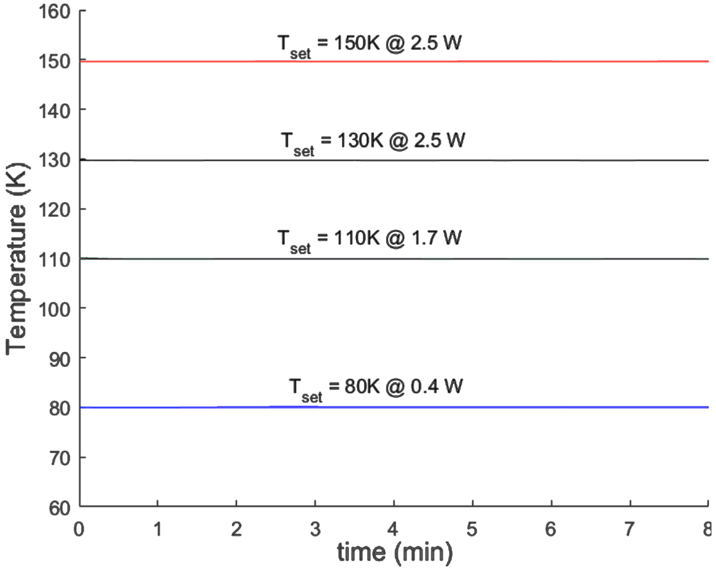

Figure 5. Setpoint control and stability.

The MCCE-TS measures the cold tip temperature via a resistance temperature detector (RTD) with common choices being platinum resistance thermometers (PRT) in the 1 to 10 kOhm range. Testing indicates setpoint accuracy and stability is within one bit of resolution on the temperature measurement circuit (+/-0.01 K in the tested configuration). For specific applications, the MCCE can be customized for other resistive temperature detectors as mission requirements dictate.

Power Conversion Efficiency

Power dissipation in MCCE-TS drive electronics is due to operational overhead and inverter inefficiencies. The operational overhead includes the power requirements to maintain board-level power supplies, instrumentation circuitry, and processors. Operational overhead is fixed and contributes approximately 2.6 W to the total power budget.

The MCCE produces the AC output to drive the cryocooler motors via a radiation-hardened H-bridge inverter. Inverter inefficiencies are related to H-bridge switching events and scale with input voltage and output power demands. Both standalone testing with the MCCE-TS driving simulated loads, as well as full system testing with the MCCE integrated with cryocoolers, yield average inverter efficiencies better than 90% at a cryocooler input power level of 45 W and up to 95% at 90 W.

Vibration Susceptibility

Creare assessed the survivability of the MCCE-TS to random vibrations associated with launch events. For vibration testing, each MCCE-TS module was rigidly mounted to an electrodynamic shaker (Ling Electronics Model V895-440-LPT-SP) and subjected to random vibration profiles characteristic of satellite launches. Each axis was shaken for 60 seconds. Acceptance criteria dictated that the vibration environment cannot degrade operational performance. For these tests, the MCCE-TS performance was baselined before and after vibration testing by simulating a cryocooler using the simulated loads. The MCCE-TS units were not operational or powered during vibration testing. The performance baselines prior to and following vibrational exposure showed no degradation due to the vibration profiles. Furthermore, no visible damage, including loosening of connectors, assembly hardware, or mounting bolts, was detected.

Thermal Environment Testing with LPT9510

MCCE-TS operation has been demonstrated over environmental temperatures ranges from -35 to +60°C with the LPT9510 (Figure 6). The cryocooler system was subjected to eight thermal cycles with a minimum of 2-hour soak durations at each temperature per cycle. Operational periods were interspersed with non-operational soaks. Thermal testing also included non-operational testing at temperature extremes of -50 and +70°C (Figure 7). Cold starts at -25°C confirmed the system can restart after exposure to severe non-operational conditions. No degradation in performance was detected after thermal testing.

INTEGRATION AND TESTING WITH AIM SF070

The MCCE-TS drive electronics can be readily integrated with other cryocoolers. West Coast Solutions (WCS) has been testing the MCCE with the AIM SF070 cryocooler since 2018. The AIM SF070 is a Stirling cryocooler based on Moving Magnet Technology and Flexure Bearing suspension on both ends of the driving mechanism. A computerized alignment process combined with an optimized material composition inside the helium vessel results in lifetimes exceeding 30,000 hrs. The cooler is designed for high performance IR-detectors. The SF070 is compact, lightweight, and provides a cooling capacity of more than 0.4 W at 80 K. The cooler can support detector temperatures down to 70 K.

Initial efforts utilized the SF070 as a test cooler to support the Creare NASA Phase II (Contr. No. 80NSSC18C0059) program on which the MCCE-TS was developed. The SF070 was procured with an instrumented cold tip (temperature sensor and heater) within a sealed vacuum

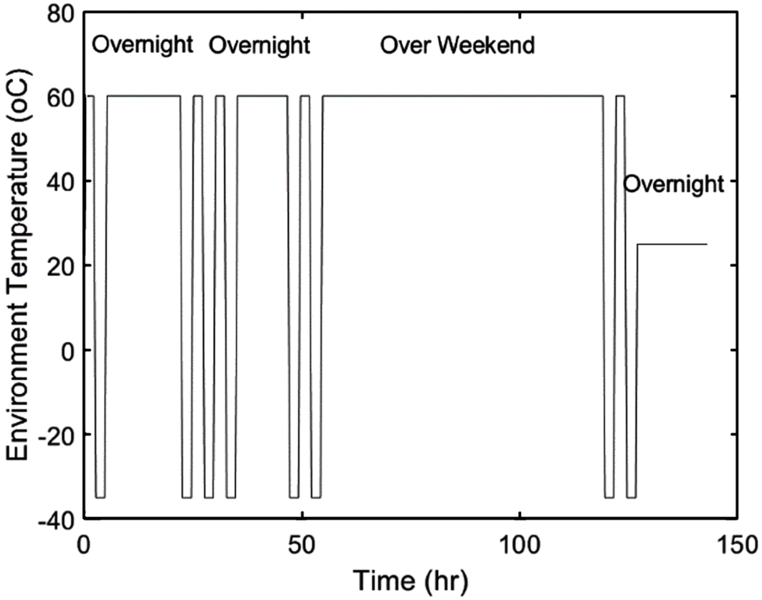

Figure 6. Operational Environment Test Conditions

dewar, which provides the ideal benchtop configuration for cryocooler electronics development. The MCCE-TS natively utilizes a PRT for temperature control, so minor circuit rework modifications were performed to permit integration with the 2N2222 temperature diode with which the SF070 was provided.

This combination of the MCCE-TS and SF070 was selected by the Hawaii Space Flight Laboratory (HSFL) in 2020 for the Hyperspectral Thermal Imager (HyTI) program. The SF070 test bed was used extensively in 2020 and 2021 to perform program specific integrated testing to help assess the thermal and cryocooler subsystem concept of operations, as well as verify the successful integration of the Creare-WCS Input Ripple Filter [2].

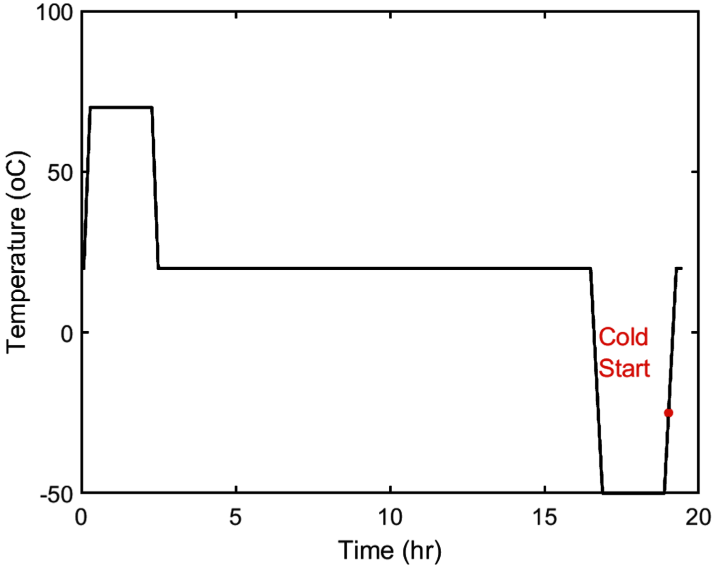

Figure 7. Non-Operational Environment Test Conditions

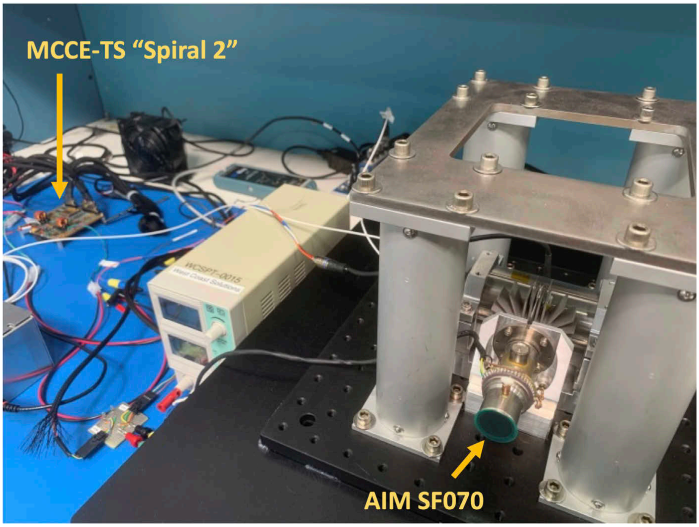

Figure 8. MCCE-TS shown integrated with AIM SF070 cryocooler at WCS during exported vibration mitigation testing. Cooler is mounted on a Minus K Technology 25BM8 vibration isolation table within a custom structure designed to locate the center of gravity (CG) on the compressor drive axis.

More recently, the MCCE-TS has been used together with the SF070 as the test bed for maturation of exported vibration reduction algorithms. A photograph of the test setup is provided in Figure 8. The cryocooler is mounted to a vibration isolation table. Not visible in this photograph are two PCB Piezotronic accelerometers. A PCB 357B3 feeds back into the MCCETS through a WCS designed charge amplifier for the closed-loop vibration control system, and a PCB 352B is connected to a force-calibrated National Instruments LabView system for measurement of the achieved results.

CONCLUSIONS AND NEXT STEPS

The MCCE-TS radiation tolerant cryocooler electronics drive module can be paired with any of several COTS or semi-COTS tactical cryocoolers to provide a relatively low-cost tactical cryocooler system for critical spaceborne sensors. Groundbased testing has successfully demonstrated MCCE-TS and cryocooler comply with various flight system specifications when paired with the Thales LPT9510 or AIM SF070 cryocooler.

ACKNOWLEDGEMENT

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