Flight Qualification Testing of Cryocooler Electronics

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ABSTRACT

The Low Cost Cryocooler Electronics (LCCE) has been developed by Iris Technology under United States Air Force (USAF) funding to provide a radiation hardened, high performance, modular, affordable set of cryocooler electronics. To date, the LCCE has been used to drive and control a wide range of 100W class linear coolers, including the AIM SF100 (pulse tube and Stirling versions), Thales LPT 9510, Lockheed Martin Microcryocooler, Northrop Grumman Micro Pulse Tube Cooler, and the Ricor K527. This paper describes the Flight Qualification Testing to which the LCCE was subjected to achieve a Technology Readiness Level (TRL) 6 rating. The LCCE survived thermal cycling, thermal vacuum, and applied vibration environments without damage or degradation. MIL-STD 461F electromagnetic interference (EMI) testing was also successfully completed. Performance testing was performed throughout the test sequence with the AIM SF100 pulse tube and dummy resistive loads to ensure that degradation was not occurring. The test profiles and performance of the LCCE are discussed.

INTRODUCTION

Cryogenic refrigeration systems ("cryocoolers") are an enabling technology for many space-based infrared sensors, particularly those operating at mid-wave infrared (MWIR) and longer wavelengths. As the state of the art in long-life cryocooler technology advances, cryocoolers are supplanting cryoradiators and stored cryogen solutions for an ever-increasing range of applications. Cryocoolers provide by far the most mass-efficient means to produce refrigeration at cryogenic temperatures, so their use has become the standard as the lifetime and reliability issues that challenged older designs have been resolved.

Past industry and government efforts to advance the state of the art, unfortunately, have often overlooked the electronics required to drive the cryocoolers, much to the detriment of the United States Government (USG) space infrared sensor customer community. At present, the lead time (and often the cost) for a space cryocooler system is driven by the electronics, and for many cryocoolers of interest to the USG, space flight cryocooler electronics are not available. Ongoing government-funded programs at Iris are helping address this need by providing modular, scalable space cryocooler electronics that are broadly applicable to a wide range of cryocoolers and payloads. This is the proper focus given that past funded research and development efforts have focused

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almost solely on the mechanical cryocooler, yet approximately half the cost of a space cryocooler system is in the electronics.

The Low Cost Cryocooler Electronics (LCCE) Program is focused on providing space-qualified cryocooler electronics for cost-sensitive payloads and missions, such as those of interest for spaceflight experiments and Operational Responsive Space (ORS). Indeed, as federal budgets are increasingly squeezed, almost every payload and mission presently in the formative stages might be classifiable as "cost-constrained." Therefore, as the development effort has progressed through the Phase II, the Iris team has taken a broader view with respect to applicability and are now advocating the use of LCCE and LCCE-based solutions for a wide range of missions including missile defense, Earth weather, and planetary exploration.

LCCE is unique from any other cryocooler electronics available by providing a fully space-qualified, radiation hardened (>300 krad total ionizing dose (TID)) solution at an affordable price. This has been accomplished primarily through designing out complexity that is not required for many missions (e.g., exported vibration control), and in so doing achieving tremendous reduction in radiation-hardened parts cost and software.

LCCE, shown in Figure 1, is architected to support both traditional long-life space cryocoolers and tactical cryocoolers, providing the payload integrator with a wide range of radiation hardened cryocooler system options. Demonstrative of this broad applicability, LCCE was recently tested with two different AIM cryocoolers (Stirling and pulse tube), a Thales cryocooler (LPT 9510), and a Sunpower cryocooler (Sunpower CT). Previous versions of LCCE have successfully operated and controlled a Ricor Stirling, a Northrop Grumman Aerospace Systems (NGAS) micro pulse tube, and a Creare spin rig. These past integration successes have been described previously[1, 2, 3].

References 1, 2, and 3 describe the performance of early COTS-based brassboard versions of the LCCE. This paper documents the maturation of the design to its present status as Technology Readiness Level (TRL) 6. A prototype LCCE was designed and constructed using radiation hard, space qualified electronic piece parts. The enclosure and assembly features were designed to meet the strict environmental requirements of spaceflight. The LCCE prototype was then subjected to performance testing with a long-life AIM SF100 Pulse Tube Cryocooler, which is representative of the type of cooler which the LCCE might be paired for a low cost spaceflight mission. Finally, the LCCE was subjected to, and passed, a full suite of environmental tests, the results of which are summarized herein.

IRIS CRYOCOOLER ELECTRONICS (ICE) OVERVIEW

Present day cryocooler electronics marketplace

Cryocooler control electronics, particularly for space, have traditionally been developed for Thermo-Mechanical Unit (TMU)-specific and mission-specific applications. This paradigm has

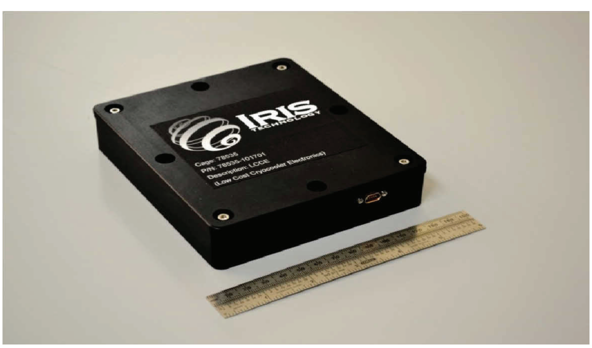

Figure 1. Photograph of Low Cost Cryocooler Electronics (LCCE). Dimensions are 12.6 x 14.2 x 3.1 cm. Mass = 750g.

been driven in part by technical factors. The Cryocooler Control Electronics (CCE) and TMU must be well-matched in order to constitute an optimized cryocooler system solution. The motor drives must be properly sized for the impedance of the mating electromagnetics; oversized motor drives lead to inefficiency through a combination of increased resistive and tare losses. The number of motor drives is another variable; a pulse tube or passive Stirling cryocooler with a single compressor motor requires but one motor drive, while a typical space Stirling cryocooler requires four (two independent compressor motors, the displacer, and the expander balancer). The signal excitation and conditioning circuitry and connector pin outs must be consistent with the physical telemetry sensors. The telemetry stream provided by a TMU informs the health, status, and control aspects of the operational firmware, so it is reasonable to expect that interface optimization between TMU and CCE firmware is also essential. The challenge of matching the CCE and the TMU across all these metrics evidently increases with the complexity of the cryocooler.

Market factors have also been important, and the authors contend dominant, in defining this present day "point design" framework. The CCE, almost without exception, is provided by the cryocooler manufacturer, who thus lacks a business rationale for providing a CCE that can also support his competitors' products. While the tactical cryocooler community has been fairly successful in developing electronics that work for a range of their own products[4], the space cryocooler manufacturers face additional impediments which make even this a challenge:

- With much longer product development cycles arising from the typical 5 to 10 year payload program duration, parts obsolescence often necessitates changes between design cycles/ programs;
- Different programs with different lifetimes and orbits have different component requirements for total ionizing dose (TID), single event latch-up (SEL), and extended low dose rate sensitivity (ELDRS);
- While tactical applications are typically in the comparatively narrow operating range of 0.1 W to 1.0W capacity with single-stage operation between 70K and 150K, space applications go down to 4K or below, often require multiple stages of cooling, have capacities that range widely, and as a result have input power ranges from as low as 10W to over 500W;

Perhaps most importantly, traditional space cryocooler manufacturers have been reluctant to provide any technology solutions they perceive as potentially enabling to a competitor. For these reasons and others, the present marketplace is largely characterized by point design CCE solutions, particularly for the more complex space cryocoolers.

Modular and scalable CCE solutions

Higher build quantities and design reuse lead to lower acquisition cost for any technology, cryocooler electronics included. Therefore, it is in the acquisition customer's interest to support the development of modular, scalable CCE designs that span across the widest possible range of cryocooler technologies and manufacturers. Missile Defense Agency and the United States Air Force began funding the Modular Advanced Cryocooler Electronics (MACE) in 2008, addressing this need by standing up Iris Technology as a merchant supplier of cryocooler electronics for the entire community[5]. This eventually led to the LCCE work described herein.

As shown in Table 1, LCCE is but one point on a continuum of Iris Cryocooler Electronics (ICE) designs spanning from 10W microsat/cubesat applications up to 800W for very high power space cryocoolers, like the Ball SB235[6] and the Northrup Grumman High Capacity Cryocooler[7]. To reduce NRE, a common motor drive architecture is reused with only minor rescaling to envelope the power range. A modular slice architecture is used so that the number of motor drives and auxiliary circuits, such as specialized input current ripple filters, is easily achieved by combining the slices into the desired operational configuration. Consider the simplified MACE configuration shown in Figure 2. Only the five (5) motor drives present were required for this application; input ripple filtering was not required and the control logic was implemented with a separate controller. Populating the empty card slots evident in the test chassis with the input ripple and controller slices enables a different, more complex configuration. In this fashion, solutions that cover a wide

Table 1. Iris Cryocooler Electronics (ICE).

Product:	**mLCCE**	**LCCE**	**LCCE-2**	**HP-LCCE**	**MACE**
Power range:	10 to 50W	50 to 150W	50 to 150W	150 to 300W	300 to 800W
# motor drives:	1	2	2	2 or 4	Up to 5
Supported controls:	temperature	temperature	temperature, vibration	temperature, vibration	temperature, vibration, piston position
Input ripple filtering:	N	N	Y	Y	Y
TRL:	4	6	4	3	4+
Typical mating TMU:	AIM SX-030, LM Micro-cryocooler	AIM SF-100, AIM SX-095, Thales LPT 9510	Thales LPT 9510, AIM SF-100	Thales LPT 9310, NG HEC	LM 3-stage pulse tube, Thales LPT 9710, NG HCC, Ball SB-235, Raytheon RSP2

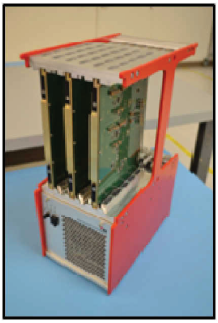

Figure 2. Modular Advanced Cryocooler Electronics (MACE) in a laboratory configuration 6U card rack. This simplified configuration consists of two identical high power (400W) motor drive slices and one three-channel low power (20W each) slice. The remote telemetry aggregation unit (TAU), used for data acquisition and signal conditioning, is not shown.

range of power and complexity are being addressed. LCCE-2 and HP-LCCE, which are in development and planned for future publication, are similarly straightforward adaptations of LCCE with an additional slice added for the input ripple filtering.

FLIGHT DESIGN LOW COST CRYOCOOLER ELECTRONICS

The LCCE is designed to support a wide range of low cost spaceflight experiment-type missions, requiring nominally 100W of input cryocooler power, closed loop temperature control, temperature set point and operational frequency set point adjustment from the ground, and a robust two-way command and communication protocol to support on orbit operations. This represents, in short, the essential subset of space CCE operating characteristics. Additional capabilities such as vibration control and input current ripple filtering, were omitted for the sake of cost, an acceptable trade-off since the spaceflight experiments for which LCCE is primarily intended do not require these functions. (Note: In reference to Table 1, NASA/JPL is presently funding the incorporation of these functions into a two-board version of LCCE called "LCCE-2.") The basics of the design and early brassboard results have been previously presented[1, 2, 3]. The top level LCCE requirements are summarized in Table 2, and a block diagram is provided in Figure 3.

The initial performance testing was accomplished using purely resistive loads. This intermediate step, prior to operation with an actual cryocooler, is performed to isolate non-idealities of the cryocooler from the characterization of the LCCE itself. For example, high motor inductance can result in a large phase angle between the current and voltage waveforms during operation (i.e., power factor << 1), reducing the efficiency of the drive circuits. It is desirable to eliminate such potential variables during the characterization of the electronics. A resistance value of 5.2 ohms was selected for each drive channel so as to approximately match the targeted class of cryocoolers.

A calibrated TDK LAMBDA ZUP60-14 DC power supply was used to set and provide the input bus voltage. The drive level (i.e., the amount of demanded input current) was set using a lab

Table 2. Low Cost Cryocooler Electronics (LCCE) top level specification

Performance Features	Specification Value
Operating input voltage	22 to 37 VDC
Operating temperature range	-34ºC to +71C continuous operation case temperature
Output voltage @ 27C ambient	Up to 41 V peak to peak (2 channels)
Output voltage quality	Sine wave output with less than 0.3V DC offset and < 1% total harmonic distortion (THD) up to 5 kHz
Soft start	Output voltage ramps from 0 Vpp to max in 10 seconds
Total output power	> 100WAC maximum at 28VDC (>50 WAC per channel)
Efficiency	> 92%
Operating frequency control	30 to 150 Hz with 0.1 Hz resolution
Cold Temperature Sensor	Determine temperature over a temperature range of 30K to 325K (2 channels)
Cold end temperature control	≤ +/- 0.05K over the temperature range of 30K to 100K
Temperature set point	Settable in range from 30K to 200K with 0.1K resolution
Ionizing space environment	300 krad total ionizing dose (TID); single event latch-up (SEL) immune up to 75 MeV/mg/cm2
Mass	750 g
Volume	12.6 cm x 14.2 cm x 3.1 cm

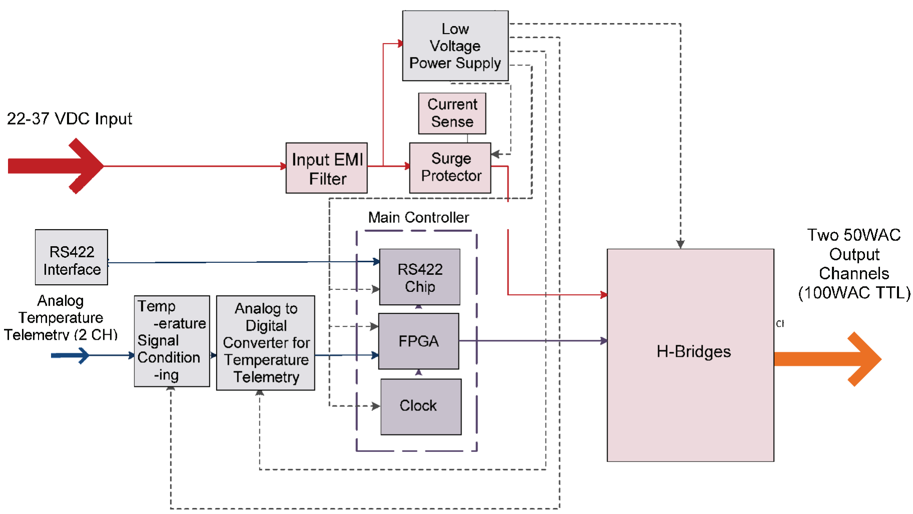

Figure 3. Low Cost Cryocooler Electronics (LCCE) functional block diagram.

computer, communicating to the LCCE through the onboard RS422 communication circuit in accord with the LCCE spaceflight communication protocol. The output AC drive frequency of 45 Hz was similarly set through the lab computer, which is essentially taking the place of the payload or spacecraft computer in this test setup. The input and output currents were measured using a Tektronix TCPA312 current probe and TCPA300 amplifier. Resistive losses in the connecting cables are taken into account so that reported efficiencies are for the LCCE only, i.e., independent of cable length. The LCCE was operated over the specified range of input voltage and output power levels up to current handling capability of the electronics. The results are shown in Figure 4. Of particular note is that the typical power conversion efficiency is >92% over the range of interest. The approximated uncertainty using the present measurement system is +/- 1.5%. (Additional efficiency testing is planned for the near future using a recently received Yokogawa WT300 digital power analyzer; this is expected to narrow the uncertainty band relative to the present test setup.)

The tare power, which is the power draw of the LCCE when it is powered to receive and transmit data but is not driving the motors, was also measured. Tare is a weak function of the input voltage with measured values of 0.91W, 1.03W, and 1.31W for 22VDC, 28VDC, and 37VDC, respectively. These tare powers were subtracted from the input drive power in determining the efficiency values reported in Figure 4.

Following this successful box-level characterization, the LCCE was prepared for integrated testing with an AIM SF100 single-stage pulse tube cryocooler.

LCCE INTEGRATED PERFORMANCE TESTING

Integrated testing of the LCCE was performed with an AIM SF100 Pulse Tube cryocooler[8]. The compressor motors are wired together internally in the AIM SF100, so a single motor drive channel (channel A) on the LCCE was used to drive the cooler. During the testing, a fan was used to cool the compressor to help maintain a nominally constant room temperature rejection temperature. The cryocooler was provided with an integrated vacuum dewar for the cold head, greatly simplifying the testing.

As shown in Figure 5, the TMU was initially cooled down to 135K with an imposed drive limit that restricted the maximum power to ~30WAC, per the manufacturer's recommendation, to avoid piston knock. At 135K the power limit was increased to 55WAC, again in accord with the TMU specifications. The cooler settled in at the programmed 77K set point in about 20 minutes from initiation of cooldown under a "no load" condition, meaning no external heat load was being applied to the cold tip during cooldown. (It should be noted that the TMU is physically capable of a more rapid cooldown, but that was not a criterion for this test.)

The output drive level is indicated in Figure 5, and in the similar plots to follow as the measured peak voltage of the "A" drive output, which is measured with onboard LCCE telemetry. The approximate corresponding power, determined using external power meters, is indicated with figure notations as appropriate. Following cooldown, a test was performed on the temperature control servo in which a 0.50W load, implemented through a resistive heater on the cold tip of the cryocooler, was applied and then subsequently removed (see Figure 6). As expected, the drive output increases to the limit value with the application of the heat load to try to drive back down to the 77K temperature set point. Conversely, the drive output decreases with the removal of the heat load.

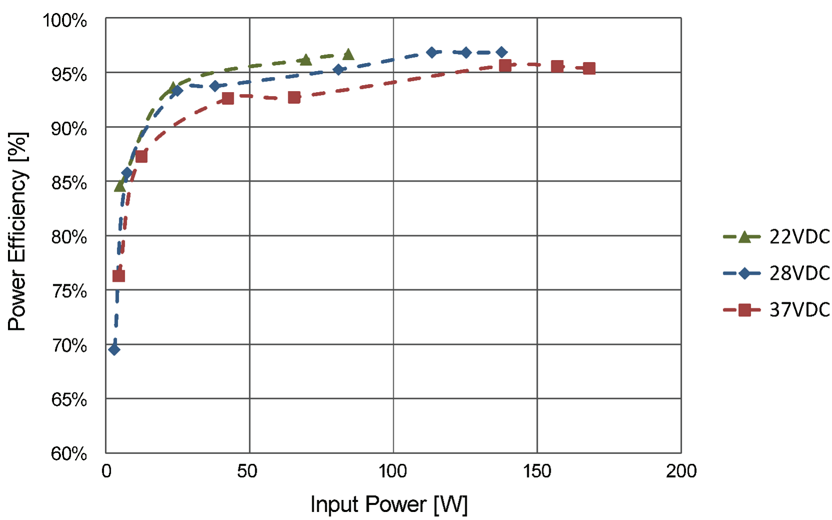

Figure 4. LCCE efficiency versus input power and input (bus) voltage. Current limiting on the input circuit reduces the maximum input power to ~85W at 22 VDC.

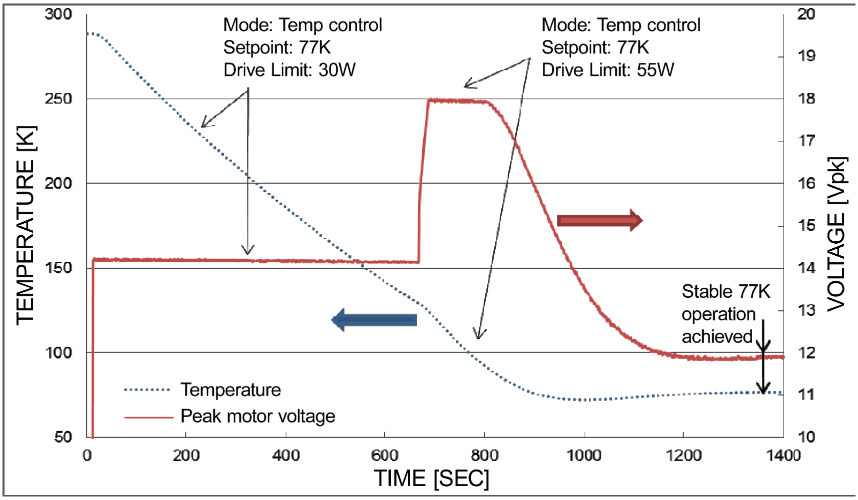

Figure 5. Cool down of the AIM SF100 pulse tube cooler with the LCCE. Temperature control mode with set point temperature = 77K throughout. Power limit increased at approximately 670 seconds.

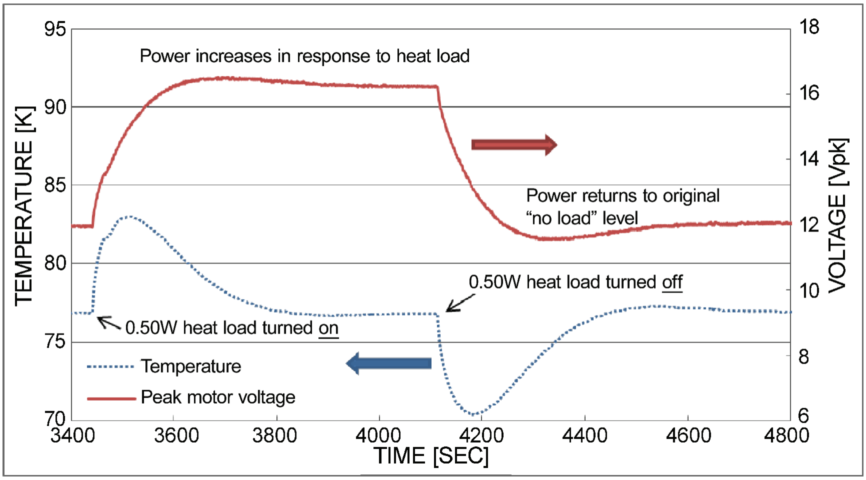

Figure 6. LCCE temperature set point control testing with the AIM SF100 pulse tube cooler. Temperature set point equals 77K throughout test sequence.

Finally, a test was performed at a constant 0.25W applied heat load at the same 77K set point to assess temperature stability. As shown in Figure 7, better than +/- 15mK was achieved, which is typical for LCCE.

ENVIRONMENTAL TESTING

Overview

Following successful performance testing both at the electronics and cryocooler integration levels, the radiation hard prototype LCCE was subjected to environmental testing. Working in consultation with USAF and various prime contractors, test levels were established which were

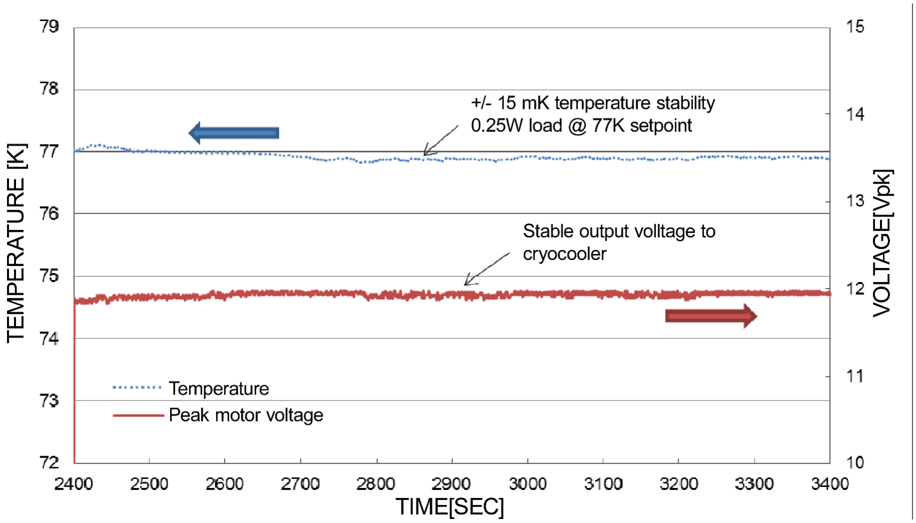

Figure 7. LCCE temperature stability testing with the AIM SF100 pulse tube cooler.

deemed representative of the types of anticipated flight missions. The test flow is shown in Figure 8. The Performance Testing performed at the beginning and end of the test sequence exercised the unit under test (UUT) to the full operational voltage range (22VDC to 37VDC) and frequency range (40Hz to 150 Hz). The symmetry of the drive waveforms, power conversion efficiency, and other such metrics were used to verify the compliant operation of the UUT. The Functional Check-out performed mid-sequence was simply a shortened version of the test. No degradation of performance was observed throughout the testing.

EMI

MIL STD 461F testing for CE101, CE102, CS101, RE102, and RS103 was performed at a local certified EMI laboratory. Testing was performed at the maximum rated output (100W) and nominal bus voltage (28VDC) for the UUT. No excursions or anomalies were encountered for CE101, CS101, and RS103. For RE102, there were some excursions above the 461F limit line.

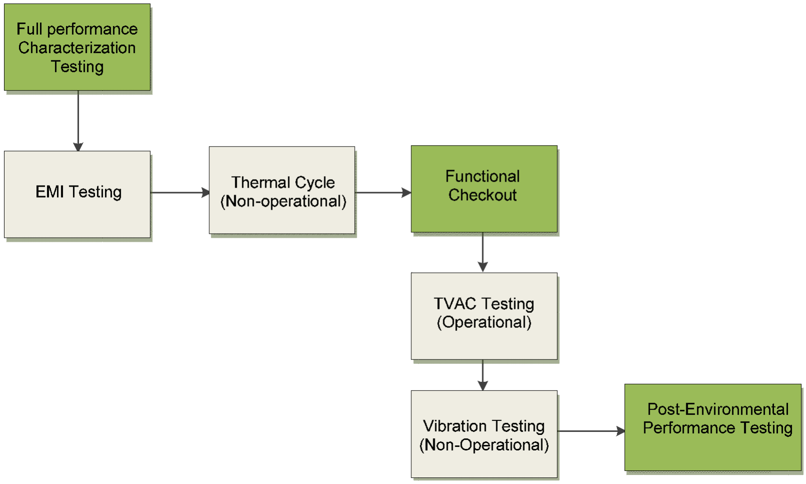

Figure 8. LCCE qualification test sequence.

Iris Technology is highly confident that this is a test artifact due to the use of non-spaceflight external cables. Early screening testing with the brassboard LCCE yielded results well above the limit line, an example of which is shown in the lower left corner of Figure 9. The brassboard test was performed with unshielded loads and cables, as shown in the top left. When the testing was performed for EM2, we made an attempt to shield the load and cables. The load (resistors) were placed into a closed aluminum housing, which was effective. The cables were covered with copper tape and terminated onto the connector backshells as best we could as an approximation of flight-level shielded cables. See top right. Just with these ad hoc modifications, the improvement relative to the brassboard was dramatic, as shown in the bottom right. It is our expectation that all of the RE102 spectrum will fall below the limit line when flight cables are incorporated into the test setup. This testing is budgeted and planned for early 2015.

For the conducted emissions testing, the high side and low side power lines are measured separately. As shown in Figure 10, the low side is well under the limit line, but the high side is slightly (3 dB) over at the 96 kHz PWM switching frequency. Ideally, the two sides would be balanced and both under the limit line. Two potential improvements have been identified, one involving balancing the capacitive network on the source and return lines, the other firmware related. Both are presently being investigated with the eventually selected approach scheduled for testing, along with RE102, in early 2015.

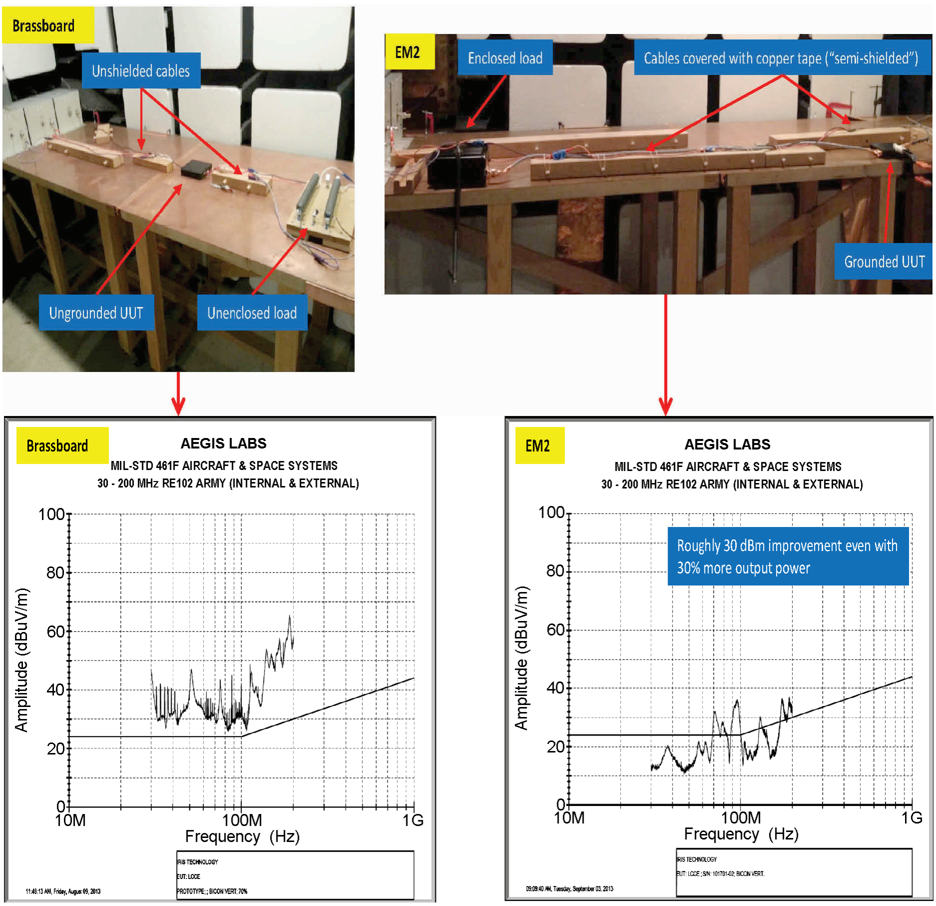

Figure 9. Brassboard to EM2 comparison of RE102 testing

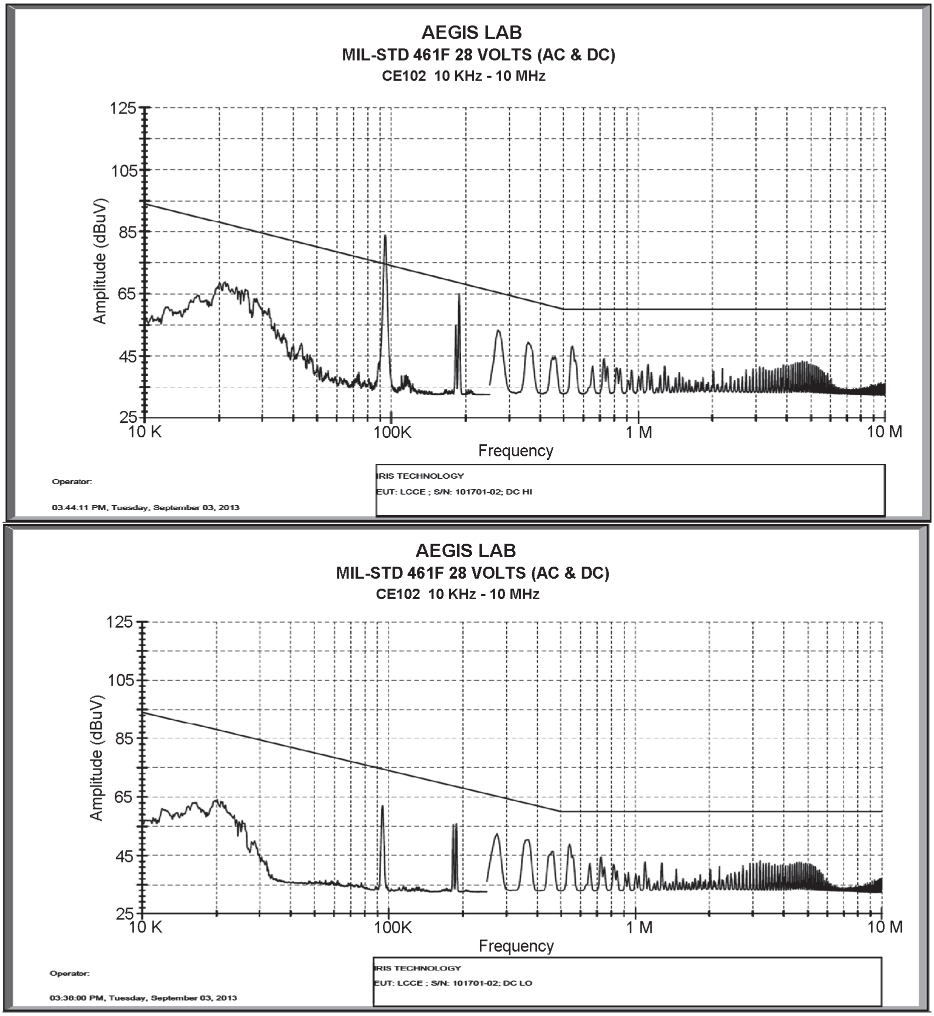

Figure 10. High side to low side comparison of CE102 test results**.** Low side (bottom) well within spec. High side (top) ~3dB over.

Thermal Cycling

Thermal cycling testing was performed at ambient pressure in a thermal chamber at the Iris facility. Six (6) thermal-cycles between -34°C and +77°C with a transition rate of 4°C / minute and a soak time at each temperature of nominally one hour were performed. See Figure 11. A reduced functional test, as described in 5.1, was performed while the unit was in the oven after the first complete cycle and after the sixth cycle. The results of these functional tests were positive, indicating that the LCCE had successfully passed the Thermal Cycle test.

Thermal Vacuum

The LCCE (EM2) was subjected to a Thermal Vacuum Test in accordance with Iris Acceptance Test Procedure 10036 at Wyle Laboratories. The LCCE completed the Thermal Vacuum Test with four cycles between +71 ± 2°C and -34 ± 2°C with one hour dwell at each. Functional testing was

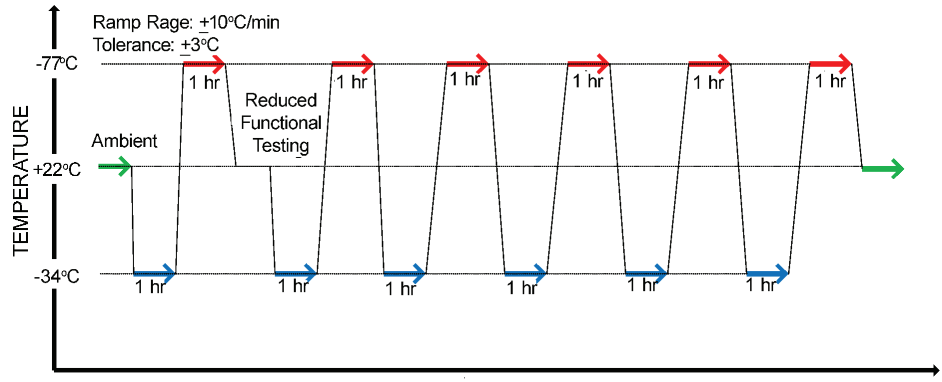

Figure 11. LCCE Thermal Cycle Test profile

performed during the fourth cycle; once at hot and once at cold. See Figure 12. A post-TVAC functional test was performed at ambient temperature.

The Thermal Vacuum Test was a complete success. The unit exhibited no degradation as a result of the testing, and it continued to operate flawlessly at both temperature extremes. The peak DC-to-AC power conversion efficiency was measured to be 95% for all test conditions, which greatly exceeds the 85% specification value. The only notable observation that warrants consideration for future builds is that the overcurrent protection tripped at just above the 100W specification value for the cold case. For future missions with high power demand and similarly cold low end environmental, some adaptation of the input current limit circuit may be required.

Applied Vibration

Following the successful TVAC testing, the LCCE EM2 was prepared for applied vibration testing. Large components and internal wires were staked down using space-approved EC-2216 epoxy. The LCCE was taken through induced vibe at Wyle labs. The qualification levels used for the basis of this qualification testing, provided in Table 3, come from a proposed upcoming JPL mission and are deemed representative of likely LCCE applications.

Three-axis accelerometers were placed on the lid, the chassis and the test fixture during the vibe testing. The fixture accelerometer was used as the vibe input control. The response was as expected with no discernible changes in dynamic response after exposure to applied vibration in each orthogonal axis. The successful post-vibe functional testing confirmed that the LCCE had survived this last environment without damage or degradation.

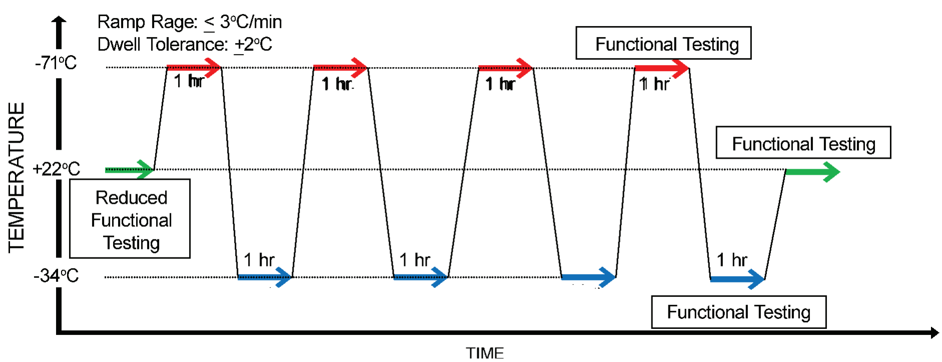

Figure 12. LCCE Thermal Vacuum Test profile

Table 3. LCCE was tested to the levels in the Qualification column

Frequency (Hz)	Power-Spectral Density (G2/Hz)		
	Acceptance	Protoflight	Qualification
20	0.013	0.026	0.026
20-50	+6 dB/octave	+6 dB/octave	+6 dB/octave
50-300	0.080	0.160	0.160
300-2000	-6 dB/octave	-6 dB/octave	-6 dB/octave
2000	0.0019	0.0037	0.0037
Overall	6.4 Grms	9.1 Grms	9.1 Grms
Duration, per axis	1 minute	1 minute	2 minutes

CONCLUSION

A low cost, radiation hard, space qualified cryocooler electronics module has been developed and demonstrated. This fairly simple set of electronics is geared towards cost-constrained spaceflight missions requiring just basic functionality, such as temperature control and ground-resettable operating points, namely temperature and frequency. These electronics are characterized by high power conversion efficiency, low tare, physical robustness, and high reliability. Most notably, these electronics have been shown to work with an extremely wide range of Stirling and pulse tube cryocoolers from a variety of cryocooler manufacturers.

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