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High efficiency digital cooler electronics for aerospace applications

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ABSTRACT

Closed-cycle cryogenic refrigerators, or cryocoolers, are an enabling technology for a wide range of aerospace applications, mostly related to infrared (IR) sensors. While the industry focus has tended to be on the mechanical cryocooler thermo mechanical unit (TMU) alone, implementation on a platform necessarily consists of the combination of the TMU and a mating set of command and control electronics. For some applications the cryocooler electronics (CCE) are technologically simple and low cost relative to the TMU, but this is not always the case. The relative cost and complexity of the CCE for a space-borne application can easily exceed that of the TMU, primarily due to the technical constraints and cost impacts introduced by the typical space radiation hardness and reliability requirements. High end tactical IR sensor applications also challenge the state of the art in cryocooler electronics, such as those for which temperature setpoint and frequency must be adjustable, or those where an informative telemetry set must be supported, etc. Generally speaking for both space and tactical applications, it is often the CCE that limits the rated lifetime and reliability of the cryocooler system.

A family of high end digital cryocooler electronics has been developed to address these needs. These electronics are readily scalable from 10W to 500W output capacity; experimental performance data for nominally 25W and 100W variants are presented. The combination of a FPGA-based controller and dual H-bridge motor drive architectures yields high efficiency (>92% typical) and precision temperature control (+/- 30 mK typical) for a wide range of Stirling-class mechanical cryocooler types and vendors. This paper focuses on recent testing with the AIM INFRAROT-MODULE GmbH (AIM) SX030 and AIM SF100 cryocoolers.

Keywords: cryocooler, cryocooler electronics, CCE, digital controller

1. INTRODUCTION

Cryocoolers are used widely throughout the world's military forces, primarily for the cooling of focal plane arrays (FPA) for infrared sensors. Although there is variability associated with the specific platforms and sensor technologies, and also with a realization that FPA technological development is ongoing and thus broad statements are no doubt subject to exceptions, it is generally true that a cryocooler is required for intrinsic semiconductor-type photon detectors operating at mid-wave (3 μm) and longer wavelengths. The classic definition of cryogenics restricts its temperature realm of applicability to 123K and below. However, the type of mechanical system used to produce these "cryogenic" temperatures is essentially the same at that used to produce 150K refrigeration for the emerging class of hot mid-wave infrared (HMIR) detectors, so we consider refrigeration from 150K and below to be the range of applicability for the technology described herein.

The military cryocooler marketplace has traditionally been segmented into tactical (terrestrial) and space categories. From the perspective of the electronics, the primary difference between these two classes is the radiation hardness and quality requirements for the electronic components themselves. The challenge is well described by Hamiter [1] in a 1991 article, which reveals that although the specific relevant military specifications have changed over the past 20 plus years, the basic supply and cost challenges remain. For the TMU portion of the system, operating lifetime has long been considered the primary discriminator between tactical and space. Whereas tactical cryocoolers are typically qualified for operational lifetimes of around 5,000 hours, space cryocooler lifetimes are generally in the range of 7 years (>60,000 hours). With the additional consideration that space cryocoolers are operated continuously upon deployment until end of spacecraft life, operational lifetime has been the critical discriminator between these classes.

This paper describes ongoing development activities directed at overcoming the sort of challenges described by Hamiter by developing modular, plug-and-play electronics solutions that work for multiple cryocoolers. With respect to the TMU, the gap between the "tactical" and "space" cryocoolers has already closed dramatically in recent years. This eventuality was foreshadowed by Hon and others in 2007 [2,3]. More recently, several traditional tactical cryocooler

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manufacturers have published endurance test data surpassing 20,000 hours of operation without degradation [4,5]. These designs employ essentially the same long-life techniques as the traditional space cryocooler manufacturers, such as flexure suspensions and clearance seals. The AIM SF100 and Thales LPT9510 cryocoolers are characteristic of the success the high-end tactical cryocooler providers have achieved by extending their operational lifetime well into the regime of the traditional space cryocooler providers.

While tactical cryocoolers are closing the lifetime gap, there is still a continuing need for the traditional space cryocoolers, particularly for high power, multi-stage, low temperature, high efficiency, and very low vibration applications. The Ball Aerospace two-stage 35K /80K Stirling cryocooler recently deployed on TIIRS is exemplary of space cryocooler state of the art [6]. The three-stage MIRI 6K Cryocooler for JWST is another example of an extremely complex, high performance space cryocooler [7]. The Northrop Grumman High Efficiency Cryocooler (HEC) is the most widely deployed space cryocooler with nine (9) presently flying on orbit [8]; this legacy of proven on orbit performance engenders continued strong interest in HEC for a wide range of missions. For all of these and similar cryocoolers, the electronics tend to be equally complicated and just as expensive. Relative to tactical cryocooler electronics, space cryocooler electronics have additional technical requirements (e.g., exported vibration control), the aforementioned extreme demands on the component reliability requirements, and a present lack of modularity and the reuse in the present industry offerings.

Even in the case of tactical cryocooler electronics for tactical applications, there are regrets in the marketplace. Based upon independent market research by these authors, tactical cooler electronics tend to be lower in reliability than the mating TMU, particularly given that the TMU technology is improving in reliability, as already discussed. High-end tactical applications, such as on a mission critical airborne IR targeting pods, would benefit from the sort of robust command and communications protocol more typical of space cryocooler electronic, primarily from the standpoint of health and status information for diagnostics and prognostics. It is becoming evident that there is a need for more reliable, more capable tactical cryocooler electronics.

As described in an earlier paper by Kirkconnell, there is no “one size fits all” cryocooler solution [9]. A given payload may be more optimally served by a pulse tube, Stirling, or Brayton. Different cryocooler manufacturers have different strengths and weaknesses with respect to mass, efficiency, exported vibration, etc. Of essential interest for this paper is that some space payloads, particularly those with cost constraints, require the use of long-life tactical cryocoolers to meet the budgetary requirements. Some high-end tactical applications reside in the gray space between lower cost space cryocooler solutions and traditional tactical cryocoolers. One common element in all cases is the need for a modular, high performance, affordable set of mating cryocooler electronics.

To avoid nonrecurring engineering (NRE) excesses, a modular, flexible cryocooler electronics solution is needed. The efforts described herein describe progress towards achieving that end. The objective of this research is to provide the aerospace cryocooler user community with a “generic” cryocooler electronics option, which can be directly implemented either with little or no modification, for the widest possible range of mechanical cryocoolers. This enables integrators to perform cryocooler source selection without being constrained by the lack of mating electronics, opening up the flexibility to choose the optimum TMU selection to meet the technical requirements within the available budget.

2. IRIS CRYOCOOLER ELECTRONICS (ICE) OVERVIEW

2.1 Present day cryocooler electronics marketplace

Cryocooler control electronics, particularly for space, have traditionally been developed for TMU-specific and mission-specific applications. This paradigm has been driven in part by technical factors. The 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 pinouts 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 [10], 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), extended low dose rate sensitivity (ELDRS), etc.;
- 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.

2.2 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. Early successes on MACE [11] led to the Low Cost Cryocooler Electronics (LCCE) Program. In 2012 Freeman, Murphy, and Kirkconnell described the successful testing of a LCCE brassboard set of cryocooler electronics with four different types of cryocooler in a previous paper [12]. The LCCE Program concluded as planned with the successful demonstration and Technology Readiness Level (TRL) 6 qualification of a radiation hard spaceflight design. A brief overview of the environmental testing and a thorough examination of the performance data are provided herein.

As shown in Table 1, MACE and LCCE now represent important milestones on a continuum of Iris Cryocooler Electronics (ICE), solutions 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 1. 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 range of power and complexity are being addressed.

This paper focuses on the two low power ICE designs, namely the LCCE and the miniature LCCE (mLCCE). LCCE is the most mature, having attained TRL 6 in 2013. The mLCCE is a close derivative of LCCE with plans to achieve TRL 6 in 2015. These two products, which together represent only the low power tail of the complete ICE spectrum, support a very wide range of technologies and manufacturers, as demonstrated by the data herein.

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
Number of 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-cryocooooler	AIM SF-100, 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

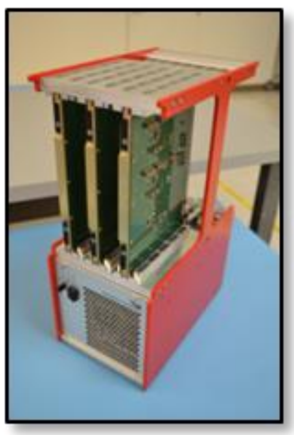

Figure 1. Modular Advanced Cryocooler Electronics (MACE) in a laboratory configuration 6U card rack. This simplified configuration consists of two identical high power (400W) motor drive slices and one three-channel low power (20W each) slice. The remote telemetry aggregation unit (TAU), used for data acquisition and signal conditioning, is not shown.

3. 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 setpoint and operational frequency setpoint 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 [12,13,14]. The top level LCCE requirements are summarized in Table 2, and a block diagram is provided in Figure 2.

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

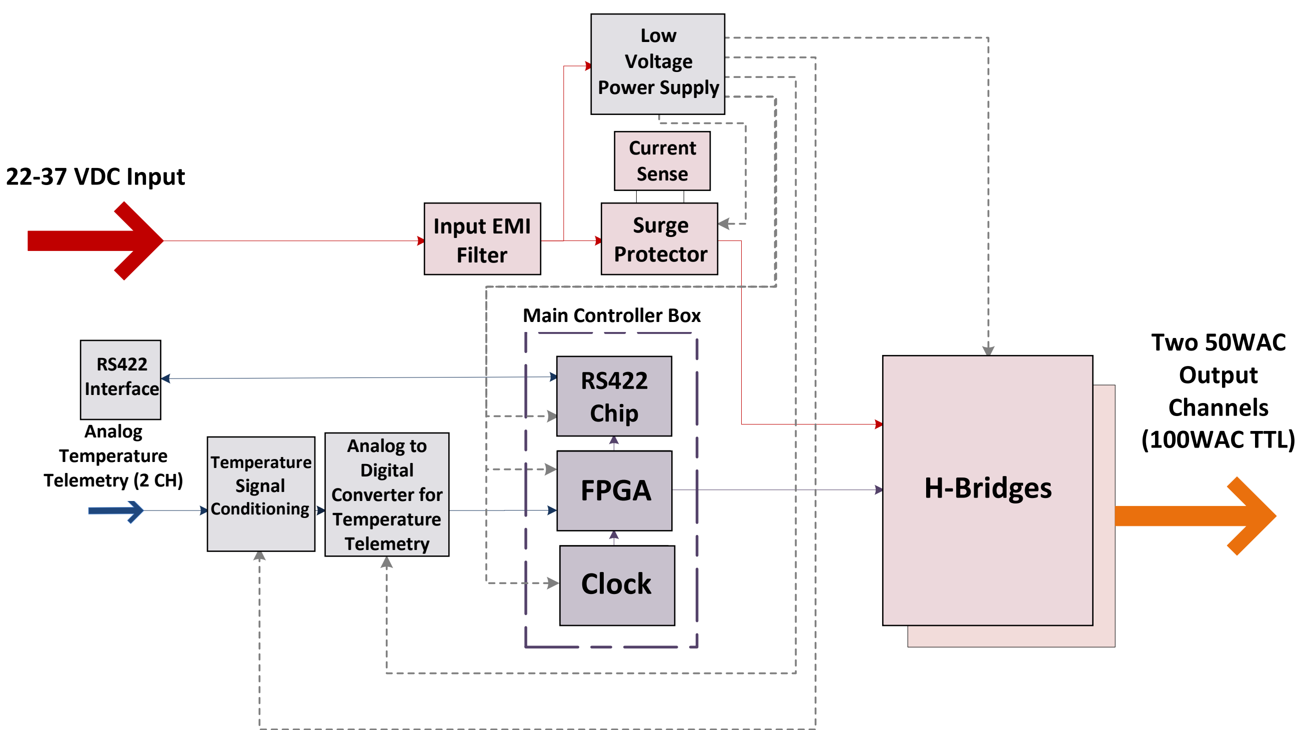

Figure 2. Low Cost Cryocooler Electronics (LCCE) functional block diagram.

Figure 3. Photograph of Low Cost Cryocooler Electronics (LCCE). Dimensions are12.6 x 14.2 x 3.1 cm. Mass = 750g.

This paper includes the first published performance results for the flight-design, radiation hard LCCE, shown in Figure 3. Whereas the earlier published test data was for COTS-based brassboard versions, this LCCE was assembled using radiation hard, spaceflight prototype integrated circuits, meeting the environmental requirements described in Table 2. This design has been subjected to full environmental qualification testing, including thermal cycling, thermal vacuum, and applied random vibration. The details of that testing are planned for presentation at the 2014 International Cryocooler Conference.

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 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. That testing is described later in Section 6.

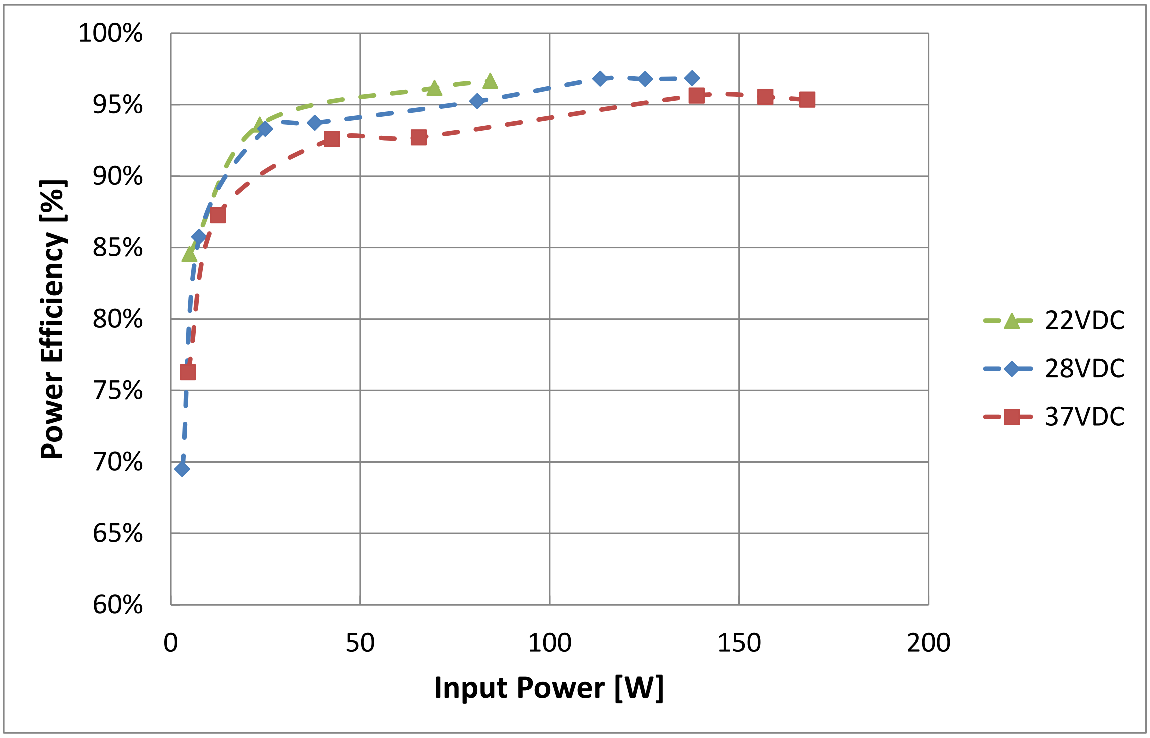

Figure 4. LCCE efficiency versus input power and input (bus) voltage. Current limiting on the input circuit reduces the maximum input power to ~85W at 22 VDC.

4. SECOND GENERATION LCCE (LCCE-2) BRASSBOARD

As indicated in the ICE overview Table 1, the LCCE-2 is an advanced version of the LCCE, with the key additional capabilities being exported vibration control and input ripple filtering. The LCCE-2 is a two-board version of the LCCE with the "main" board retaining the control and motor drive functions and the additional board being the input ripple filter. The new exported vibration control requirement necessitated a minor redesign on the main board relative to LCCE, which incorporated a signal conditioning circuit for the new accelerometer input, and a larger FPGA to handle the additional vibration control computations. A COTS version of the upgraded main board was designed and built on a recent NASA Phase I SBIR Program. The results are provided herein. The complete two-board, radiation hard LCCE-2 will be completed on the recently awarded Phase II Program, with scheduled qualification testing in 2016.

The characterization test setup and procedure for the LCCE-2 main drive board were the same as that used for LCCE, described in the previous section. Not unexpectedly, the tare power is ~ 50 mW higher than LCCE, which is attributable to the larger FPGA. The power efficiency data are summarized in Figure 5. The higher efficiencies relative to LCCE are due to the more efficient COTS MOSFETs used in this brassboard, as compared to the radiation hard equivalents in the flight LCCE.

Additional testing was performed to ensure that the efficiency is insensitive to drive frequency. The 28VDC testing was repeated at operating frequencies of 30 Hz and 60 Hz. The measured efficiencies for a given input power were all within 0.5% of each other, which is within the measurement accuracy of this test setup.

Integrated test results with the same AIM SF-100 pulse tube cryocooler used in the LCCE characterization testing follow in Section 6.

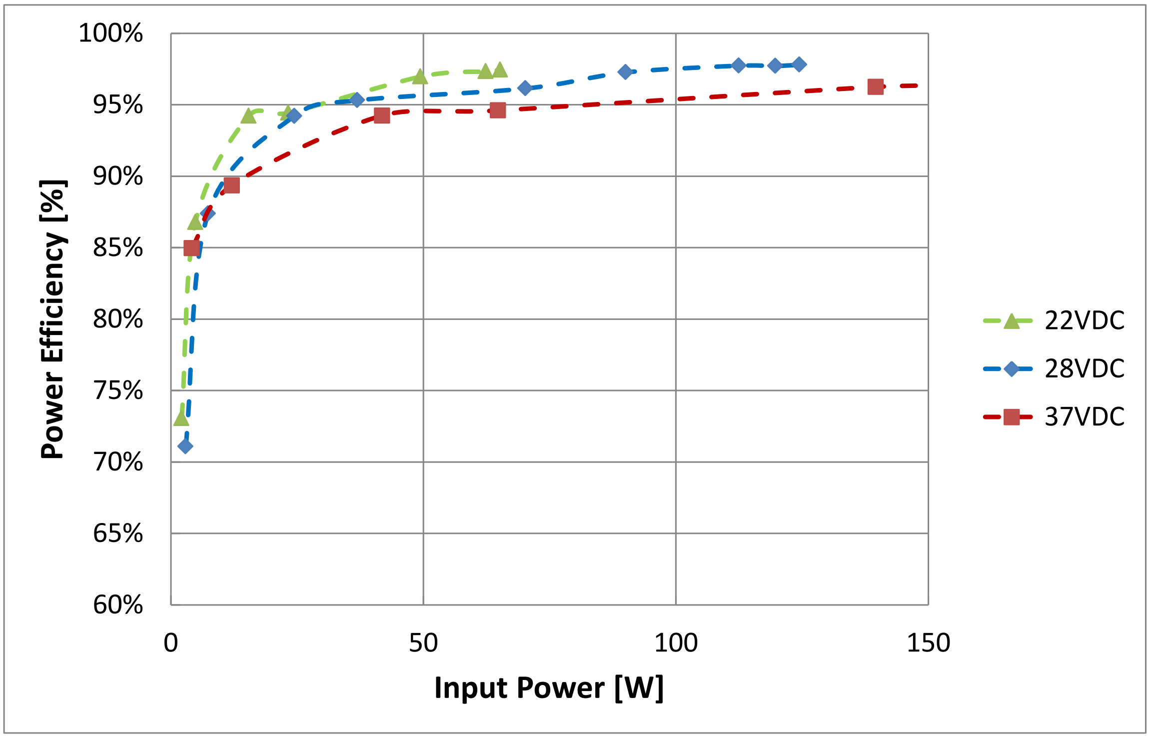

Figure 5. LCCE-2 main board efficiency versus input power and input (bus) voltage. Current limiting on the input circuit reduces the maximum input power to ~65W at 22 VDC. This limit value will be increased to85W for the flight version.

5. MINIATURE LCCE

The miniature LCCE (mLCCE) is precisely as the name implies, a reduced-scale version of its larger predecessor. Starting from the base LCCE design, the mLCCE has a single, nominally 25W drive instead of two ~50W drives. The temperature control functionality is identical, as are the command and control capabilities and associated protocol. The block diagram is provided in Figure 6 and the preliminary top level specifications in Table 3. The version tested in support of this research is a COTS brassboard, which like the LCCE-2 is an intermediate step for the flight-design, radiation hard version. The flight mLCCE is planned for release in 2016.

Following the previously described LCCE and LCCE-2 setup and procedures, preliminary tare and efficiency measurements were performed at the nominal bus voltage value of 28VDC. The tare power was measured at 0.80W, comparable to the LCCE, which is not unexpected because the FPGAs have similar gate counts. The efficiency plot for the single motor drive at 28VDC is provided in Figure 7. With the initial characterization tests successfully completed, a complete suite of efficiency characterization tests versus bus voltage, frequency and input power are now underway and will be presented when available.

Preliminary integrated test results with a single-stage AIM SX-030 Stirling cryocooler follow in Section 6.

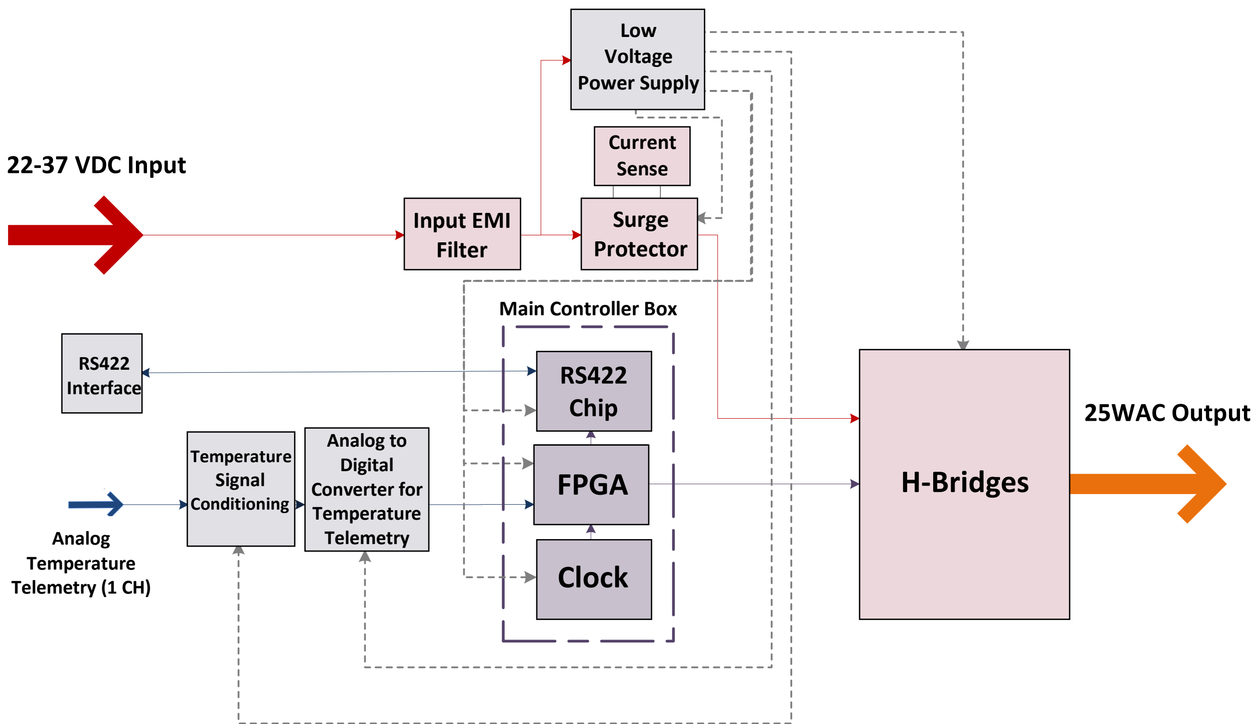

Figure 6. Miniature Low Cost Cryocooler Electronics (mLCCE) functional block diagram.

Table 3. Miniature Low Cost Cryocooler Electronics (mLCCE) 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 (1 channel)
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	> 25WAC maximum at 28VDC
Efficiency	> 92%
Operating frequency control	40 to 140 Hz with 0.1 Hz resolution
Cold Temperature Sensor	Determine temperature over a temperature range of 30K to 325K (1 channel)
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	150 krad total ionizing dose (TID); single event latch-up (SEL) immune up to 75 MeV/mg/cm2 (TBR)
Mass	< 250 g
Volume	6 cm x 6 cm x 2.5 cm (TBR)

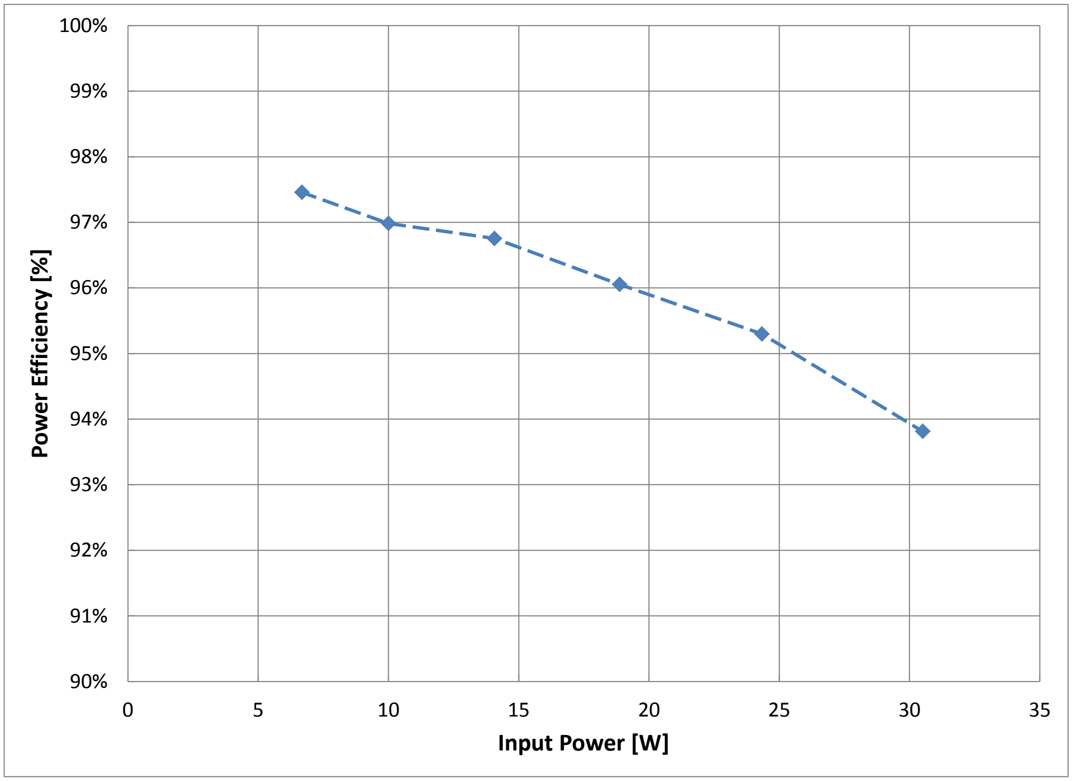

Figure 7. Miniature LCCE efficiency versus input power at 28VDC bus voltage. >93% efficiency achieved over entire power range of interest.

6. INTEGRATED CRYOCOOLER SYSTEM TEST RESULTS

6.1 Flight-design LCCE with AIM SF100 Pulse Tube Cryocooler

Integrated testing of the LCCE was performed with an AIM SF100 Pulse Tube cryocooler [15]. 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 8, 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 setpoint 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 8, 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 9. 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 setpoint. Conversely, the drive output decreases with the removal of the heat load. Finally, a test was performed at a constant 0.25W applied heat load at the same 77K setpoint to assess temperature stability. As shown in Figure 10, better than +/-15mK was achieved, which is typical for LCCE.

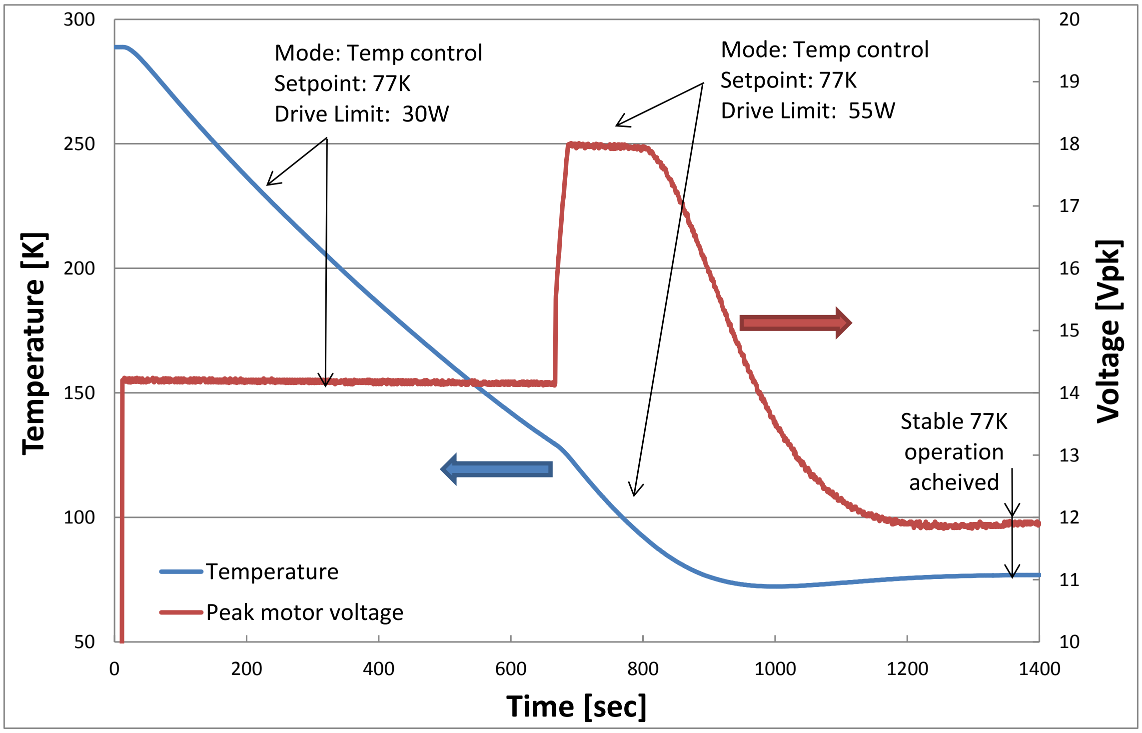

Figure 8. Cool down of the AIM SF100 pulse tube cooler with the LCCE. Temperature control mode with setpoint temperature = 77K throughout. Power limit increased at approximately 670 seconds.

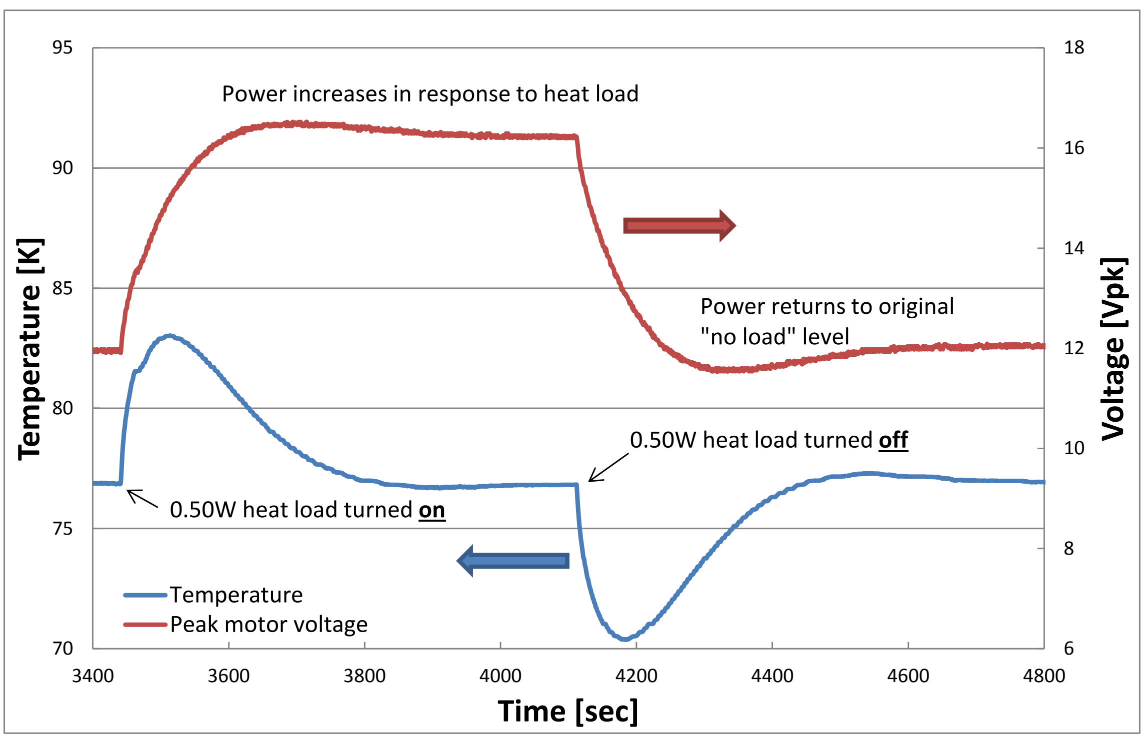

Figure 9. LCCE temperature setpoint control testing with the AIM SF100 pulse tube cooler. Temperature setpoint equals 77K throughout test sequence.

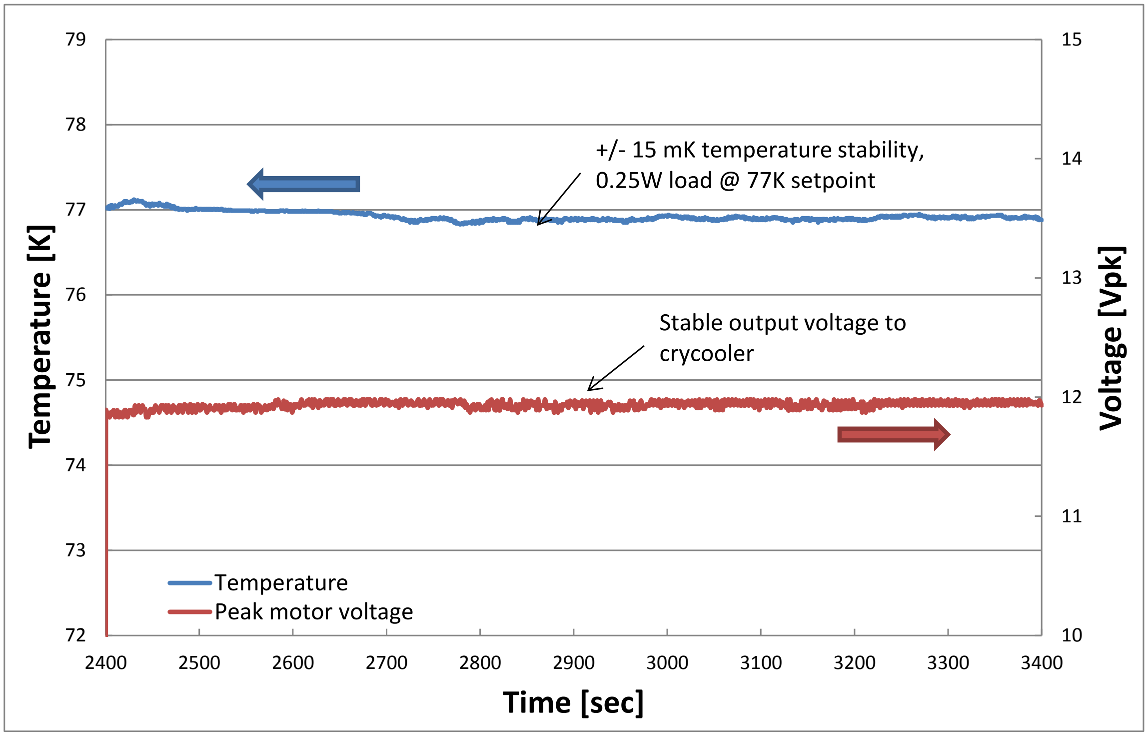

Figure 10. LCCE temperature stability testing with the AIM SF100 pulse tube cooler.

6.2 Brassboard LCCE-2 with AIM SF100 Pulse Tube Cryocooler

The tests described in Section 6.1 were repeated for the LCCE-2. The only notable difference in the test setups is that a developmental input ripple filter circuit, shown in Figure 11, was placed between the input power supply and the LCCE-2 main drive board. The purpose of the input ripple filter is to reduce the amplitude of the current ripple imparted back onto the input power bus. For example, for one typical data point during this testing, the induced current ripple was reduced from 5.80App (amps, peak to peak) to 0.2App. Additional design details and more extensive characterization of the ripple filter are planned for a future publication. The purpose of this testing was to verify that the inclusion of this circuit in the power path did not have any impact on the performance of the main drive electronics. This objective was achieved. The results of the complete test profile described in 6.1 is provided in Figure 12. The observed integrated cryocooler system performance is essentially identical.

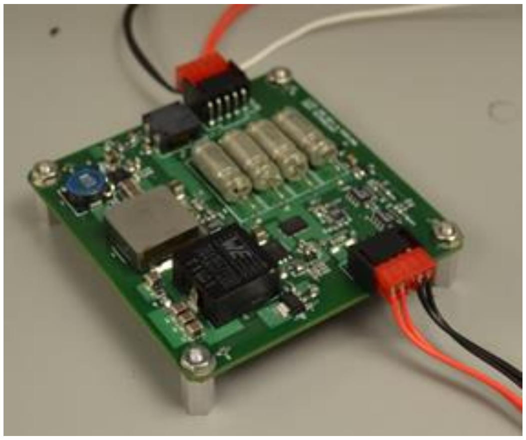

Figure 11. Input ripple filter test circuit (COTS). This is a proof of concept test article. The flight design is underway.

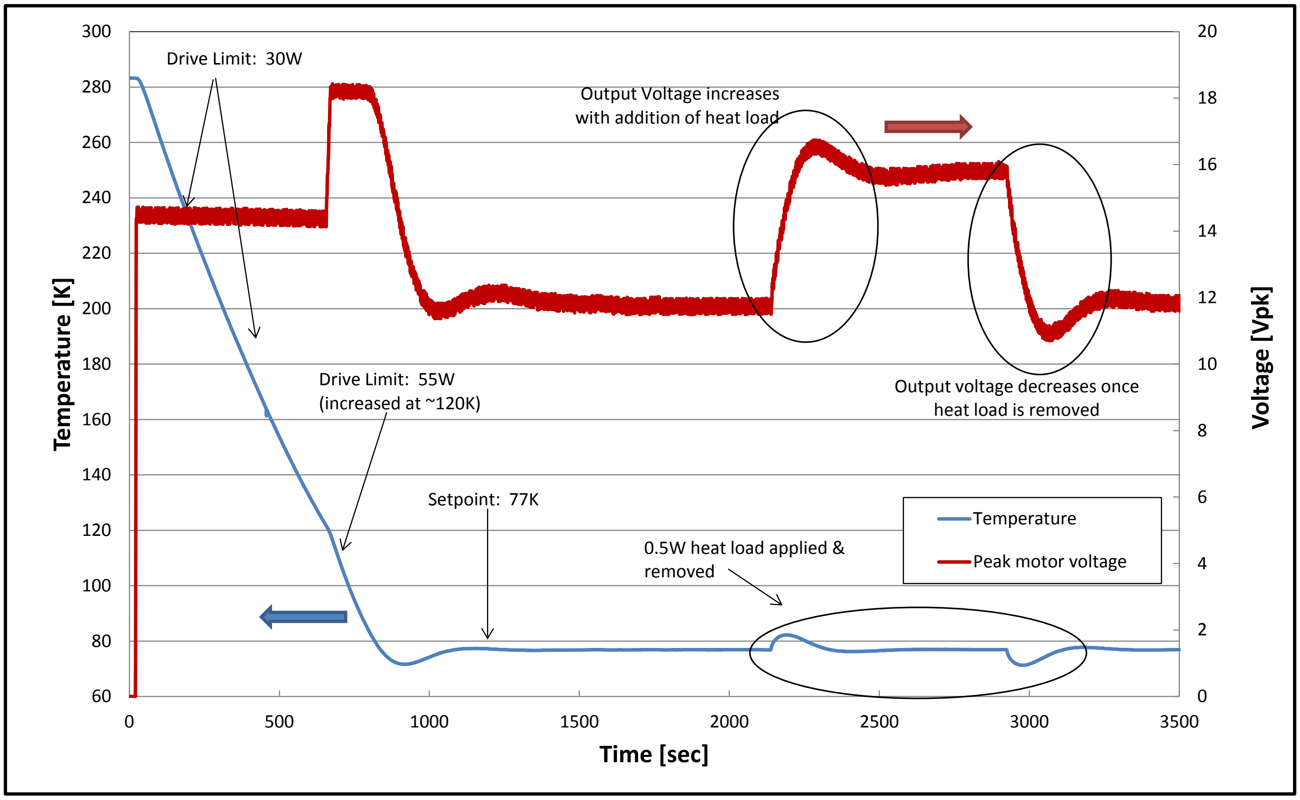

Figure 12. Results of LCCE-2 Full System Operation with AIM SF100 pulse tube cooler. This effectively is a combination of the testing depicted in Figures 8 and 9 (automated cooldown plus temperature response).

6.3 Brassboard mLCCE with AIM SX-030

To date, only preliminary integrated cryocooler testing has been done with the mLCCE. The initial results are encouraging. Following the same basic procedures described in 6.1. and 6.2 for the other two LCCE variants, the mLCCE has been tested with an AIM SX-030 single piston compressor driven Stirling cryocooler [16]. As shown in Figure 13, the temperature control loop has been demonstrated to cool a programmed setpoint (120K) and automatically adjust to the application and removal of an external heat load. The temperature stability achieved for these preliminary measurements was +/- 0.5K, which is considerably less stable than what has been achieved with LCCE, this difference will be investigated during the next round of testing. This could be attributable to the fact that the much smaller AIM SX-030 has considerably less thermal mass than the SF-100. This would inherently complicate stability, but it might be addressable in software. No attempts have yet been made to improve the temperature stability through adjustment of the temperature control coefficients. The authors expect to report on these findings in a later publication as the development effort progresses.

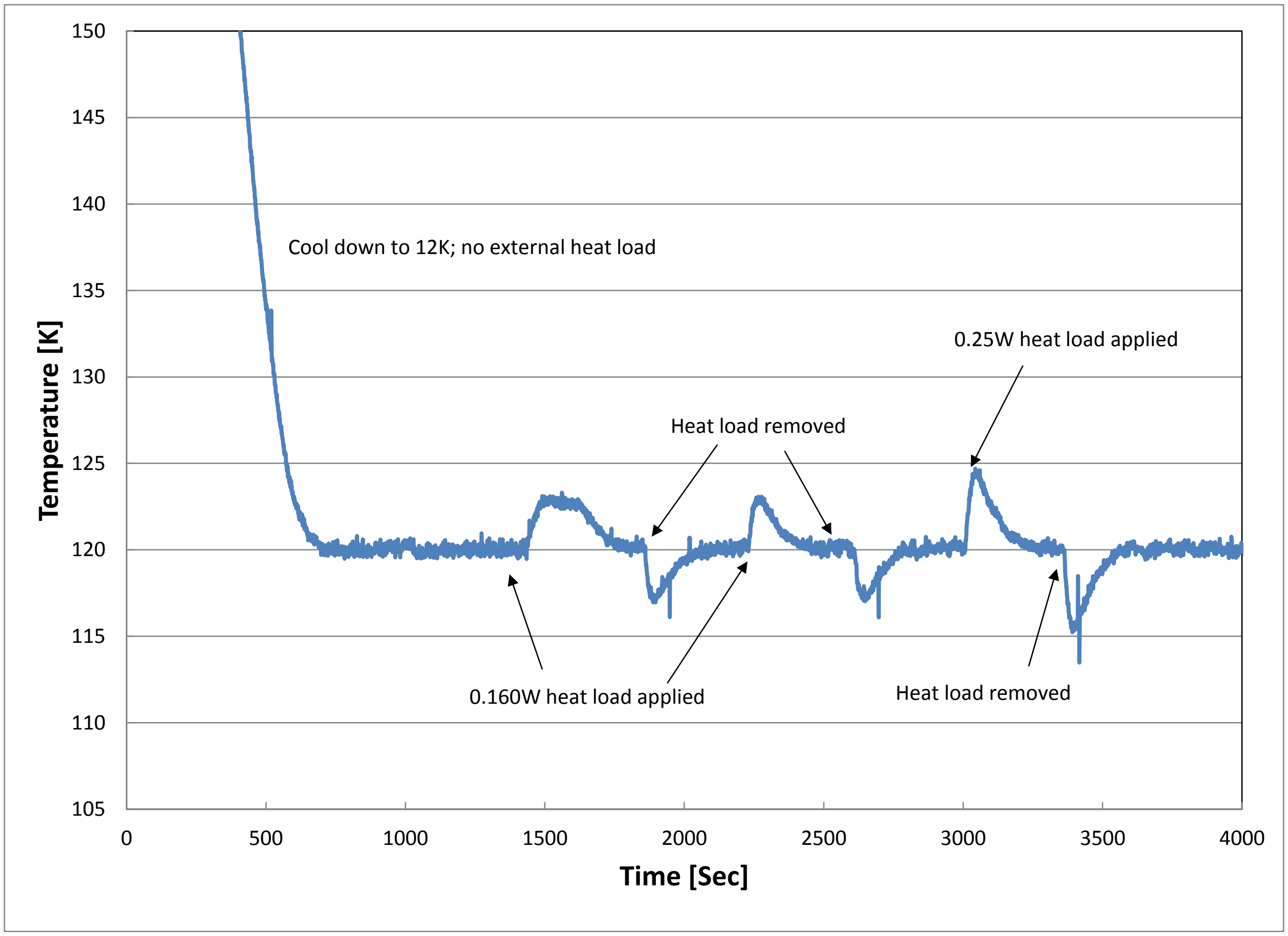

Figure 13. CubeSat CCE and AIM SX030 Cryocooler: response to heat load at 120K setpoint. Two cycles performed with 160 mW, one with 250 mW.

7. CONCLUSION

A product line of cryocooler electronics are being developed to support a wide range of spaceborne cryocooler system applications. The 100W-class LCCE, which has achieved TRL 6 maturity, has been shown to be a high efficiency controller with precision temperature control capability. A second generation LCCE-2 is being developed for applications requiring an input ripple filter and/or vibration cancellation. Testing reported herein confirms that the presence of the ripple filter between the spacecraft voltage bus and the main cryocooler drive electronics does not adversely impact the controllability of the cryocooler. A miniature LCCE, about 1/3 the size and mass of the LCCE, is in the intermediate stages of development. Initial testing indicates that comparable drive efficiency (~94%) can be achieved in this scaled down package. The temperature stability achieved to date is not as tight as for LCCE, a characteristic that is presently under investigation and expected to be resolved prior to achieving TRL 6.

All of the testing reported herein was for AIM cryocoolers, which are a good match for the intended low cost space missions. These coolers were provided to Iris with the cold heads packaged within sealed test dewars, and pre-instrumented with cold tip temperature sensors and heaters, which greatly simplified testing. The Thales LPT 9510 is another cryocooler of great interest for low cost space missions. Vacuum test equipment is presently on order to support near term testing of the LCCE and LCCE-2 with the LPT 9510.

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