

Development of a Miniature Cryocooler System for Cubesats

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ABSTRACT

The Microsat Cryocooler System (MCS) is a key enabling technology for a suite of single FPA dewar solutions on microsat and cubesat platforms. The overall effort addresses the entire cryocooler system, i.e., the thermo-mechanical unit and the electronics. The focus of this paper is the cryocooler control electronics. The range of missions of interest for the MCS is broad, thus it is essential that the electronics be modular and configurable. By leveraging the fully space-qualified Low Cost Cryocooler Electronics (LCCE) and by employing advanced component technologies, Iris Technology has developed a miniaturized version of the LCCE (mLCCE). The mass of the mLCCE is less than 200 grams and the volume is 90 cm³, representing an 80% reduction in size relative to the LCCE. The mLCCE has been integrated and tested with four (4) different cryocoolers including dual and single compressor piston configurations and pulse tube and Stirling expanders. Although the mLCCE was tested as high as 55 W, it was designed for a nominal output power of 25 W with a measured efficiency greater than 95% in a wide range around its design point. The design and test data are presented.

INTRODUCTION

As the scientific requirements of microsattellites migrate closer to those of larger more expensive traditional satellites, the technical requirements on the key enabling components and subsystems are becoming more demanding. Radiation hardness and reliability are receiving greater attention, and addressing these concerns tends to conflict with the other expressed needs for reduced Size, Weight and Power (SWaP) of these subsystems. For example, many microsattellites with optical payloads have been developed and deployed, but they tend to feature only modest resolution visible cameras. In order to improve the optical resolution and increase bandwidth, active cryogenic cooling of the photon-detector arrays is required. Solutions for active cryogenic control on microsats are presently limited because advanced active techniques, such as closed-cycle cryogenic refrigerators (cryocoolers), violate the SWaP and/or reliability requirements of the modern microsats. If the utility of microsattellites is ever expanded to include high performance mid-wave infrared (MWIR) and short-wave infrared (SWIR) sensors, significant advancement in the state of art of small cryocooler systems is required.

The vision of the Microsat Cryocooler System (MCS) Program is to provide the key technology building blocks that will enable a suite of solutions for single focal plane array (FPA) dewars on microsat, cubesat, and UAV platforms. The range of missions of interest is broad. Therefore, it

is essential that the proposed approach be modular and configurable. Iris Technology has employed advanced component technologies and new electronic architectures to develop a miniature (nominally 25W) version of our highly successful Low Cost Cryocooler Electronics (LCCE)¹. As with LCCE, the developed mini-LCCE (mLCCE) will support a wide range of mechanical cryocooler solutions, making it the ideal solution to meet the industry's wide range of intended cubesat and microsat missions and orbits.

Iris has been successfully designed, manufactured, and tested (see Figure 1) a brassboard set of miniature cryocooler electronics for the Microsat Cryocooler System. These electronics were integrated and tested with four (4) different cryocoolers (AIM SX-030², AIM SF100^{3,4}, Thales LPT9510⁵, and Lockheed Martin Microcryocooler⁶) of various configurations (pulse tube and Stirling, single compressor piston and dual-compressor pistons). Integration was achieved with little complication.

MINIATURE LCCE OVERVIEW

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 2 and the preliminary top level specifications in Table 1. The version tested in support of this research is a COTS brassboard, which is an intermediate step for the flight-design, radiation hardened version. The flight mLCCE is planned for release in 2016.

The mLCCE utilizes the same FPGA, 12-bit ADC, and RS-422 driver integrated circuits as the LCCE so that the firmware is essentially identical between the two designs, reducing nonrecurring engineering (NRE). The primary design differences relate to the motor drives and the electromagnetic interference (EMI) filtering. The primary advantage of dual motor drives is that it allows for the implementation of active vibration cancellation by applying a correction waveform to one of the two opposing motors to cancel exported force in the drive axis. For the mLCCE, this is not a requirement. The objective cryocoolers are small, so the uncompensated vibrations for the dual-opposed piston miniature coolers are already low. In the case of the single-piston AIM SX-030 cryocooler discussed herein as well as others of similar construction, there is only one compressor motor and the exported vibrations are damped passively. For this reason, the mLCCE only has a single motor drive circuit. The lower power rating allowed for a dramatic reduction in the input and output EMI filtering. These were the primary sources of the demonstrated size reduction.

The assembled mLCCE brassboard circuit card measures 2.2 inches by 2.2 inches and only weighs 20.4 grams. This represents an approximate reduction in area of 80% relative to LCCE. When integrated into a chassis, the mLCCE is about 160 grams, under the requirement of 200 grams and much less than the 750 gram weight of the LCCE. Preliminary tare and efficiency measurements were performed at the nominal bus voltage value of 28VDC. The tare power was measured



Figure 1. The mLCCE (right) is 80% smaller than the LCCE (left).

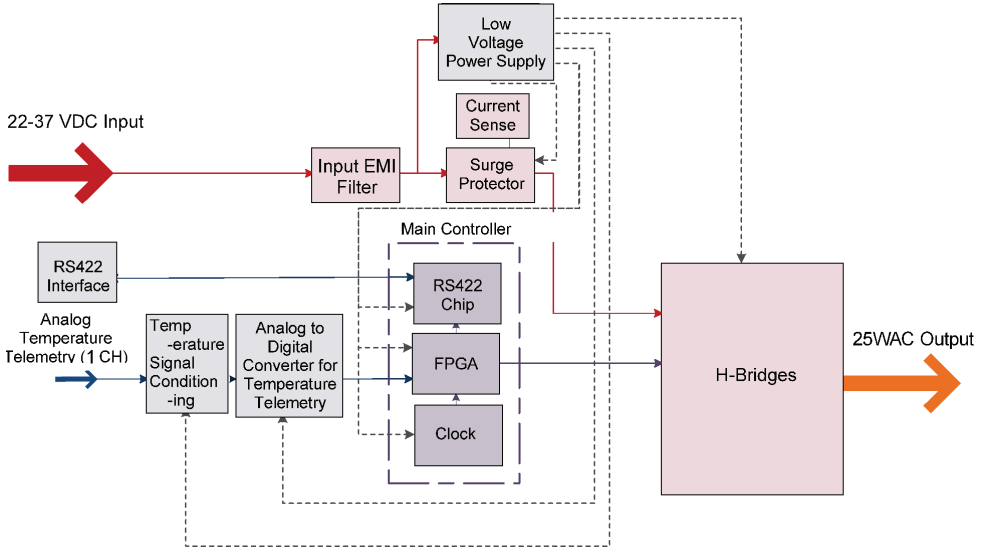


Figure 2. Miniature Low Cost Cryocooler Electronics (mLCCE) functional block diagram

Table 1. Miniature Low Cost Cryocooler Electronics (mLCCE) Top Level Specification

Performance Features	Specification value
Operating input voltage	22 to 37 VDC
Operating temperature range	-34°C to +71°C 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	< 200 g
Volume	6 cm x 6 cm x 2.5 cm (TBR)

at 0.80W, comparable to the LCCE, which is not unexpected because the digital control portion of the design is essentially identical to its larger predecessor. The efficiency plot for the single motor drive at 28VDC is provided in Figure 3. 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 4.

INTEGRATED SYSTEM DESIGN

The AIM SX030 was selected as a test vehicle for verification of the performance of the initial brassboard mLCCE. AIM is well known for manufacturing miniature, long-life tactical cryocoolers, and the performance and power level of the SX030 are well matched for the targeted missions. Looking ahead to the eventual flight missions, it was necessary to perform an initial assessment of

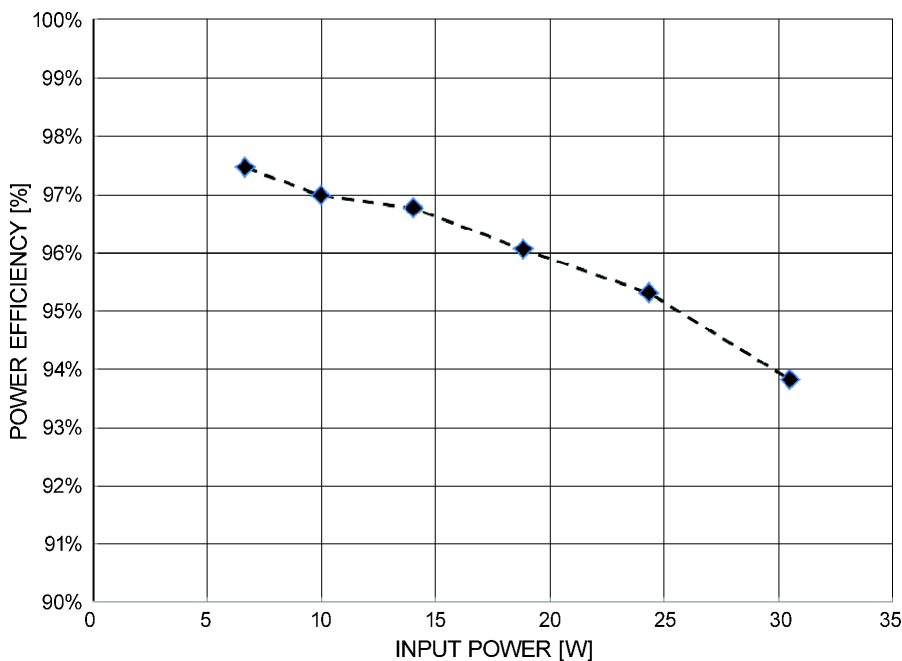


Figure 3. Miniature LCCE efficiency versus input power at 28VDC bus voltage. >93% efficiency achieved over entire power range of interest.

the CubeSat payload integration challenges to determine if the use of the SX030 is indeed viable for the intended applications.

Traditional space cryocoolers utilize dual-opposed piston compressors to achieve first order dynamic balance to reduce exported vibrations, which can be a major source of jitter in a spaceborne imager. In the case of the AIM SX030, which features a single-piston compressor with a passive tuned-mass balancer, the compressor must essentially be “floated” relative to the payload so that the balancer can properly function; a rigid mount to the structure would result in shunting the single-piston induced vibrations to the payload. This means that the primary structural support, heat rejection, and cold tip thermal strap must all be designed to achieve their functional requirements while “floating” in terms of mechanical attachment to the structure. One proposed notional solution is seen in Figure 4. The compressor mount is secured to the payload structure across vibration isolators. The cold tip is connected to the focal plane detector with a typical flexible thermal strap. These are not atypical integration features. Of note is that the heat rejection from the compressor is also accomplished with a high-flexibility thermal strap, like the cold tip. This is possible for the AIM SX030 because the power level is so low (~10W) as compared to a traditional space cryocooler, where heat rejection loads on the order of 100W necessitate high thermal conductance integration schemes, characterized by large bolted interfaces and stiff structures. Some relevant integration technologies are indicated in Figure 5.

Another factor working in favor of this scheme is that tactical coolers are generally rated for higher operating temperature than traditional space cryocoolers. In the case of the AIM SX030, it is qualified up to 85°C. Using a typical 55°C maximum payload heat rejection interface temperature, this allows for up to a 30°C temperature drop through the thermal strap. A compliant thermal strap with a 0.5 °C per watt (C/W) thermal resistance is readily attainable from proven providers such as Space Dynamics Laboratory, which for the nominal 10W load would yield a comfortable 20°C temperature drop (10°C margin).

Using an integration scheme along these lines, Iris is highly confident that an AIM SX030 (or similar cooler) can readily be integrated into a Cubesat while properly accounting for both the heat rejection and the vibration isolation concerns.

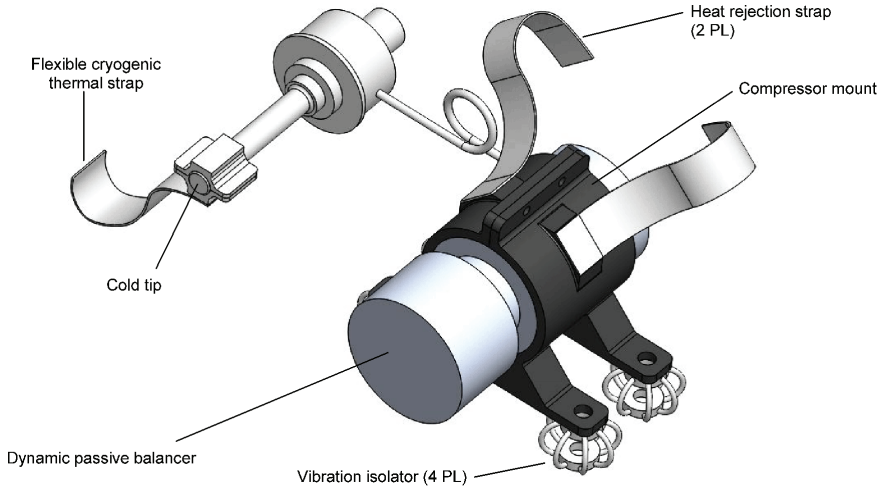


Figure 4. Notional integration scheme for a tactical cryocooler with a passive balancer, shown here with the SX030. (“PL” denotes places in figure.)



Figure 5. Relevant cryocooler integration technologies. (L) Copper foil flexible thermal link from Space Dynamics Laboratory. (R) Vibration isolator from Wuxi Hongyuan Devflex.

INTEGRATED ELECTRONICS AND CRYOCOOLER TEST RESULTS

The mLCCE is firmware-configurable, and thus broadly supportive of a wide range of cryocoolers for tactical and space applications, as had been demonstrated already for its larger LCCE predecessor. This continued approach will support both extremely cost-sensitive missions by enabling the use of small tactical cryocoolers and long-life strategic missions by providing compatibility with miniature versions of traditional flexure bearing, clearance seal type long-life space coolers. Demonstrative of this, mLCCE has been paired with four separate cryocoolers (AIM SX030, AIM SF100, Thales LPT9510, and a Lockheed Martin Microcryocooler). Integration with each cooler was essentially “plug-and-play,” meaning changes to the mLCCE firmware were not required. One firmware build fully supported all testing with the only changes between test setups being wiring to the cooler and different operational set points as entered from the payload computer simulator (i.e., the graphical user interface).

Brassboard mLCCE with AIM SX030

The SX030 provides a cooling capacity of more than 0.6 W at 140 K with the targeted detector technology being the emerging hot mid-wave infrared (HMWIR). The SX030 consists of a single piston linear compressor with a moving magnet linear motor and an optional passive balancer. The separated cold finger is a pneumatically-driven Stirling expander (see Figure 6).

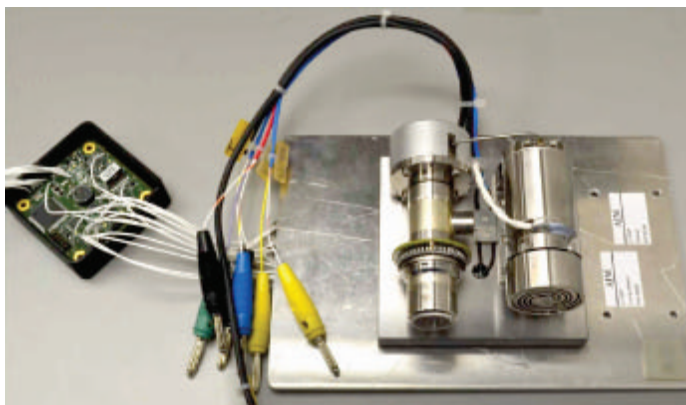


Figure 6. The mLCCE shown next to AIM SX030 cryocooler.

To date, only preliminary integrated cryocooler testing has been done with the mLCCE. The initial results are encouraging. As shown in Figure 7, 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 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 SX030 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.

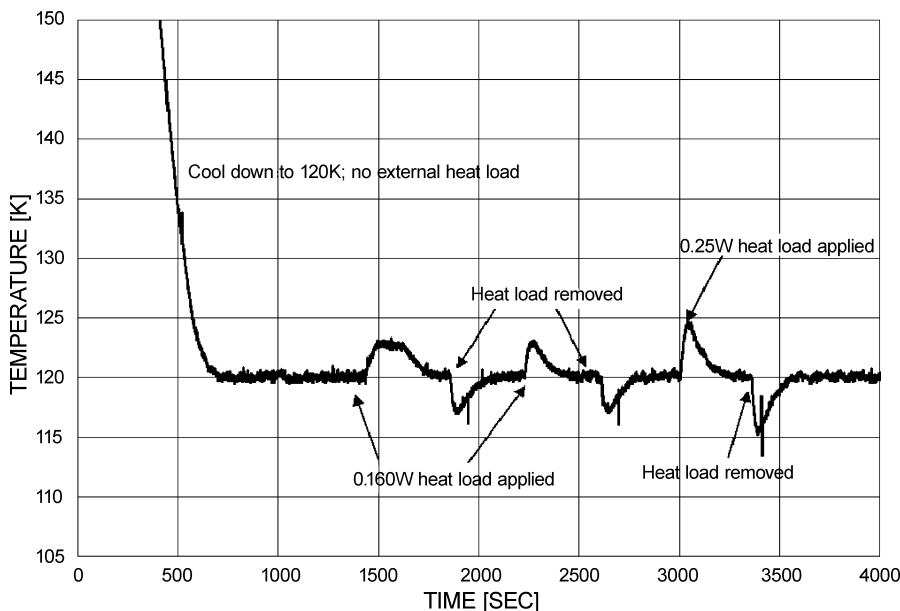


Figure 7. CubeSat CCE and AIM SX030 Cryocooler: response to heat load at 120K setpoint. Two cycles performed with 160 mW, one with 250 mW.

Brassboard mLCCE with AIM SF-100

The mLCCE was also integrated with an AIM SF-100 cryocooler. Although this cooler is too big for an actual microsat application, this was an important test because it demonstrates the ability of the mLCCE to drive a dual compressor motor configuration in addition to the single compressor motor configuration (i.e., SX030). The SF100 is a pulse-tube cryocooler, thus the cold-head configuration (Stirling or pulse-tube) is immaterial to the mLCCE; either can be driven without complication. Additionally, running this larger cooler allows us to push the mLCCE to 25 W of output power, the nominal design point, since the SX030 is designed for lower input powers. Shown in Figure 8 is a cool-down curve demonstrating closed loop control. (Note: “Drive limit” refers to an internal software setting that can be adjusted with the GUI for test purposes. Higher drive limit corresponds to higher maximum output power.) As seen in the figure, the mLCCE demonstrated closed-loop temperature control at 110K with heat loads ranging from 25mW to 250mW. It is important to note that no changes were made to the hardware, firmware or software when switching between the SX030 and the SF-100. Like with the SX030, the temperature control coefficients have not been optimized.

Brassboard mLCCE with Thales LPT9510

As with the AIM SF-100, the Thales LPT9510 test was to further demonstrate the plug-and-play philosophy that has been designed into the mLCCE architecture. This proof of concept test was run in open air, as seen in Figure 9, with the focus of running the mLCCE to higher powers (~40W). Performance testing will be performed once the integrated dewar has been received and the results will be presented in a later publication.

Brassboard mLCCE with Lockheed Martin Microcryocooler

The mLCCE was successfully integrated and tested in Palo Alto with the Lockheed Martin Microcryocooler. Like with all the other cryocooler testing efforts, integration with the Lockheed

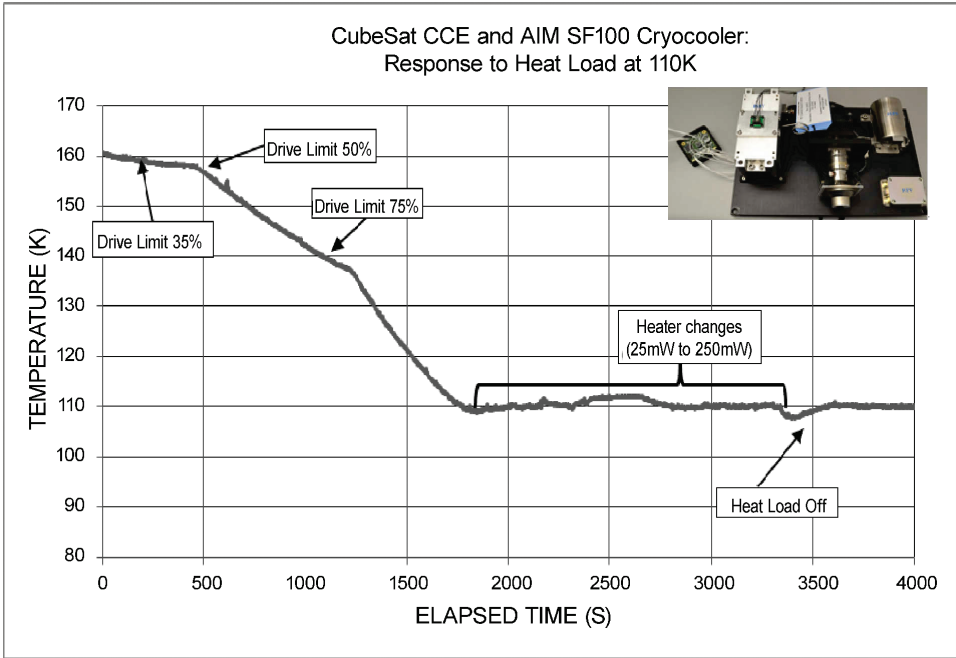


Figure 8. mLCCE and SF100 cool-down curve demonstrating closed-loop temperature control.

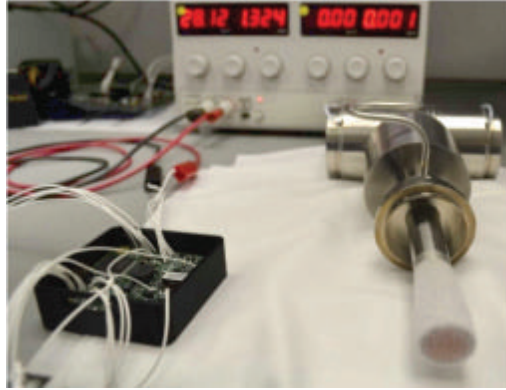


Figure 9. Ice forming on cold-tip of LPT9510 while being powered by mLCCE.

Martin Microcryocooler was accomplished in just a couple of hours. This test, coupled with the successful testing of the AIM SX030, AIM SF100, and Thales LPT9510 cryocoolers, further demonstrates the modular “plug-n-play” architecture designed into the mLCCE. During the LM integrated testing, performance data was taken with a steady heat load of 662 milliwatts (mW) applied to the cold-head. Preliminary data can be found in Figure 10.

CONCLUSION

A product line of cryocooler electronics has been developed to support a wide range of spaceborne cryocooler system applications. This paper describes a brassboard set of miniature cryocooler electronics for the Microsat Cryocooler System. These electronics, mLCCE, were integrated and tested with four different cryocoolers (AIM SX030, AIM SF-100, Thales LPT9510, and Lockheed Martin Microcryocooler) of various configurations (pulse-tube and Stirling, single-compressor piston and dual-compressor pistons). Initial testing indicates that high 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. In addition, because the mLCCE is a scaled down variant of the

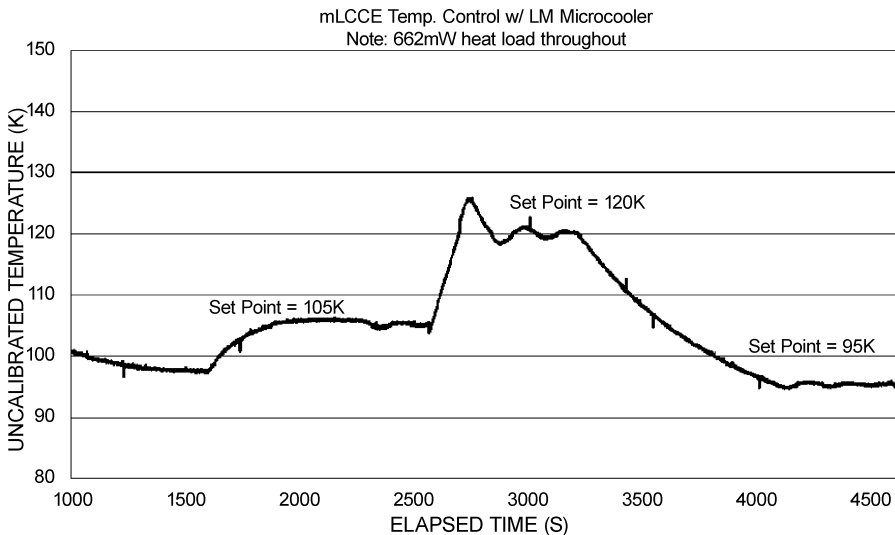


Figure 10. Integrated testing with LM Microcryocooler and mLCCE was successful

LCCE, a defined path for space flight exists with part-for-part radiation hard integrated circuits already identified. Several high-probability commercialization paths have been identified with industry partners and are being pursued for both space (microsat) and tactical (UAV) platforms.

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