Characterization testing of Lockheed Martin high-power micro pulse tube cryocooler

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Abstract. This paper describes the thermal vacuum, microphonics, magnetics, and radiation testing and results of a Lockheed Martin high-power micro pulse tube cryocooler. The thermal performance of the microcooler was measured in vacuum for heat reject temperatures between 185 and 300 K. The cooler was driven with a Chroma 61602 AC power source for input powers ranging from 10 to 60 W and drive frequency between 115 and 140 Hz during thermal performance testing. The optimal drive frequency was dependent on both input power and heat reject temperature. In addition, the microphonics of the cooler were measured with the cooler driven by Iris Technologies LCCE-2 and HP-LCCE drive electronics for input powers ranging from 10 to 60 W and drive frequency between 135 and 145 Hz. The exported forces were strongly dependent on input power while only weakly dependent on the drive frequency. Moreover, the exported force in the compressor axis was minimized by closed loop control with the HP-LCCE. The cooler also survived a 500 krad radiation dose while being continuously operated with 30 W of input power at 220 K heat rejection temperature in vacuum. Finally, the DC and AC magnetic fields around the cooler were measured at various locations.

1. Introduction
The Jet Propulsion Laboratory (JPL) is examining the Lockheed Martin micro pulse tube cryocoolers as low-cost candidates to provide active cooling on future scientific missions. The Lockheed Martin high-power coaxial pulse tube microcryocooler can be driven with up to 60 W at 140 Hz at 300 K and is optimized to provide 2 W of cooling at 105 K [1]. Its performance at 300 K heat rejection temperature was measured and was previously reported [1, 2, 3]. The cooler was qualified to Technology Readiness Level (TRL) of six for Earth orbiting missions by environmental testing including three-axis random vibration with a 50 gram mass on the cold tip and thermal vacuum (TVAC) cycling [1]. The cooler was also temperature cycled between 225 K and 338 K non-operating and 265 K and 300 K operating. This high-power cooler (Micro1-2) weighs 450 grams and is slightly larger than the 350 gram, 25 W standard version (Micro1-1) that has been thoroughly characterized previously [4, 5, 6, 7, 8]. These mass measurements include the compressor pedestal mounts. Both coolers are shown in the left photograph of Figure 1. The high-power cooler is baselined for the Mapping Imaging Spectrometer for Europa (MISE) instrument on NASA’s planned Europa Clipper mission. However, the Europa environment is much harsher than that of Earth, and thus the TRL 6 qualification done by Lockheed Martin [1] does not apply entirely for the planned Europa mission. MISE intends to take advantage of this cooler’s functionality at much lower heat rejection temperatures than the previous qualification levels in order to limit power consumption. In addition, the cooler has never been tested to the radiation levels it would experience during the planned Europa mission. This work seeks to advance the Lockheed Martin high-power microcooler to TRL 6 for the Europa environment. It also reports performance data for low heat rejection temperatures as well as measured microphonics data. All of the tests described in this work were performed on the same high-power unit that was previously qualified by Lockheed Martin to TRL 6 for Earth orbits [1] and underwent 7,700 hours of life-test at Lockheed Martin [2].
2. Thermal vacuum tests

2.1. Test setup and procedure

Figure 1 (right photograph) shows the high-power microcooler in the TVAC chamber at JPL. This test setup was very similar to that previously used and described in Ref. [8]. In this case, the high-power cooler was mounted to a large, solid aluminum block with a cylindrical section hollowed out for the coldfinger. This block was connected to a CTI 1050 coldhead by means of flexible copper straps. All of the cold surfaces including the microcooler coldfinger were wrapped in multiple layers of aluminized mylar. The microcooler was powered using a Chroma 61602 AC source supplying between 5 W and 55 W at frequencies between 115 Hz and 140 Hz. The heat rejection temperature was defined as that of the expander of the microcooler. It varied from 185 K to 300 K while the cold tip temperature varied from 70 K to 200 K. The compressor temperature was as much as 15 K warmer than the expander temperature for large input powers. The cold tip temperature was measured by a platinum resistance thermometer and controlled by a Lake Shore 340 temperature controller powering a resistive element. Both the heater and sensor were bonded to the cold tip and made use of four-wire measurements. Finally, Lockheed Martin provided a recommended maximum drive voltage based on the motor characteristics as a function of frequency, compressor temperature, and current. This maximum recommended voltage was not exceeded and limited the input power to the compressor at low heat reject temperatures and drive frequencies.

Figure 1. Left: the high-power microcooler (Micro1-2) and standard microcooler (Micro1-1). Right: high-power microcooler in TVAC chamber.

2.2. Effect of heat rejection temperature

Figure 2 shows a multivariable performance plot (Ross plot) of the high-power microcooler performance for two different heat rejection temperatures while driven at 140 Hz. The markers indicate measured data points and the isotherms are polynomial fits. It is evident that, for large cooling loads and cold tip temperatures, the microcooler had better performance at 300 K than at 250 K when driven at 140 Hz. This indicates that, for a given drive frequency, lowering the heat rejection temperature does not necessarily translate to an increase in performance. This is not the case for other pulse tube cryocoolers tested [8, 9, 10]. Moreover, the cooling capacity for a given input power and cold tip temperature at 300 K reject was approximately 0.25 W worse than that reported by Lockheed Martin previously [1, 2]. This performance difference may be attributed to differences in heat rejection environments between the two test setups. For an expander temperature of 300 K, the compressor temperature was within 3 K and 11 K for measurements made at Lockheed Martin and JPL, respectively.

2.3. Effect of drive frequency

Figure 3 shows the (a) motor efficiency and (b) specific power of the high-power microcooler as a function of drive frequency for an 80 K cold tip temperature, heat rejection temperature ranging from 185 K to 250 K, and compressor input power ranging from 10 W to 20 W. The motor efficiency was defined as the quantity of the Joule heating ($i^2R$) losses in the coils subtracted from the compressor input...
power divided by the compressor input power \([11]\). The coil resistance \(R\) was taken to be the value measured at 293 K multiplied by the compressor temperature and divided by 293 K. A 4-wire measurement found the resistance of each coil to be 5.4 ohms at 293 K. The specific power was defined as the compressor input power divided by the cooling load. Figure 3 illustrates that the optimal drive frequency, corresponding to the maximum motor efficiency and minimum specific power, was dependent on both input power and heat rejection temperature. For a given heat rejection temperature, the optimal drive frequency was weakly dependent on input power. However, for a given input power, the optimal drive frequency increased significantly with increasing heat reject temperature. Lockheed Martin indicated that the optimum frequency decreased with decreasing temperature due to a reduction in gas pressure which led to a decrease in resonant frequency of the compressor. In fact, the optimal drive frequency for a heat rejection temperature of 250 K was around 126 Hz. As the drive frequency increased to 132 Hz at 10 W, the motor efficiency fell by more than 4% and the specific power more than tripled. These factors indicate a deterioration in performance and confirm that the cooler had a better expected performance at 300 K than 250 K when driven at 140 Hz (Figure 2).

**Figure 2.** Ross plot showing the high-power microcooler performance while driven at 140 Hz for different reject temperatures. The circles represent measured data points.

**Figure 3.** (a) Motor efficiency and (b) specific power vs. drive frequency for different heat rejection temperatures and compressor input powers with the cold tip at 80 K.
2.4. Effect of temperature cycling

The cooler was temperature-cycled between non-operational temperatures of 125 K and 340 K and operating temperatures of 185 K to 250 K. The cooler was subjected to 8-hour non-operational soaks at 125 K and 340 K. The heat sink temperature profile also followed several hot-to-cold temperature cycles with cooler-operating plateaus of 250 K, 220 K, and 185 K. The microcooler was turned off and its heat rejection temperature was allowed to drift towards ambient overnight and on weekends. Overall, the microcooler accumulated 25 hours of operation at 185 K, 65 hours at 220 K, and 75 hours at 250 K. Figure 4 shows isotherms measured at 80 K and 105 K with a 220 K reject temperature at the beginning, middle, and end of the temperature cycling. The cooler was operated between 7.5 W and 35 W at 122 Hz. The measured cooling load did not change over the course of the temperature cycling indicating that the microcooler was not affected by the extreme temperatures to which it was exposed. Overall, the microcooler was capable of 1.3 W of heat lift at 80 K for 35 W of input power. It was also capable of 1.9 W of heat lift at 105 K for 30 W of input power. Finally, the helium leak rate from the microcooler did not change as a result of the thermal cycling.

![Figure 4](image)

**Figure 4.** Isotherms at 80 K and 105 K measured at different times throughout the test campaign with a heat rejection temperature of 220 K and drive frequency of 122 Hz.

3. Microphonics

3.1. Test setup and procedure

Figure 5 shows photographs of the high-power microcooler mounted on a Kistler dynamometer at JPL. This setup was very similar to that previously used in Ref. [8] and described in detail in Refs. [9, 10]. The microcooler was operated near room temperature and the cold tip was held under vacuum. Steady-state microphonics measurements were made for input power varying from 10 W to 60 W and frequency varying from 135 Hz to 145 Hz. For all of the data presented in the following section, the cooler mounting block was bolted directly to the dynamometer such that the cold finger was aligned with the gravity vector and pointed downwards. This configuration corresponds to the left photograph in Figure 5. The axes were defined such that the compressor axis was along the direction of piston motion, the pulse tube axis was along the length of the cold finger, and the transfer line axis was orthogonal to the others and along the transfer line where it connected to the compressor and expander. The microcooler was driven with both the Iris Technologies LCCE-2 and a HP-LCCE that was modified to accept a voltage signal for vibration feedback. The voltage output from a Kistler charge amplifier that was connected to the dynamometer was used as feedback to the HP-LCCE.
3.2. Results

Figure 6 shows the 0-peak exported forces from the microcooler in all three axes as a function of harmonic and input power for the cooler driven at 140 Hz. It is evident that the largest forces were in the pulse tube axis. The small forces in the compressor axis indicate that the pistons were well balanced. Figure 7 shows the compressor axis force as a function of harmonic for various input powers with the cooler driven at 140 Hz (a) without and (b) with vibration feedback control from the HP-LCCE acting on the drive frequency and the first four harmonics. Vibration feedback control reduced the forces in the compressor axis for the controlled harmonics to below 15 mN 0-peak for input power up to 40 W. Moreover, the microphonics were also measured in the configuration shown in the right photograph of Figure 5 to ensure that the large measured forces in the pulse tube axis were not caused by gravity. Indeed, the forces in each axis were independent of the mounting configuration. Finally, for a given input power, changing the drive frequency did not have a significant effect on the measured forces in any axis.

Figure 5. Photographs of the microcooler mounted to dynamometer in different configurations.

Figure 6. Exported forces measured 0-peak in all axes from the high-power microcooler driven at 140 Hz for various input powers and harmonics without vibration feedback control.
Figure 7. Compressor axis force vs. harmonic for various input powers with the compressor driven at
140 Hz (a) without and (b) with vibration feedback control.

4. Electron radiation

4.1. Test setup and procedure

Figure 8 shows a photograph of the high-power microcooler in a vacuum chamber at the National
Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. It also shows a rendering
of the test setup. The microcooler was dosed with 500 krad from a 25 MeV electron beam with a flux of
0.065 nA/cm² for a total of 12 hours in two six-hour doses. The cooler was operating in vacuum with
29 W input at 122 Hz and a controlled expander temperature of 222 K throughout the dose. The first
stage of a CTI 350 coldhead was used as the cooling source and Dale resistors were used as heaters.
The voltage, current, and power into each compressor motor were measured using Yokogawa WT310
meters. The cold tip was controlled to 80 K and the cooling load applied was continuously measured.
The electron beam passed through the 1 mm wall of the vacuum chamber directly onto the compressor
of the microcooler. A shield was implemented that blocked everything but the compressor in order to
protect against charge build-up in the wiring. The shield also covered the expander which was not a
concern to fail from radiation because it has no moving parts and is fabricated entirely from metal. The
cables leaving the compressor motors were wrapped with copper tape to dissipate any charge build-up
in the dielectric insulation.

Figure 8. Photograph and rendering of electron radiation test setup.
4.2. Results

The cooler operated successfully for the duration of the radiation dose. The expander temperature and compressor temperature were 222 K and 235.5 K, respectively. The cold tip was controlled to 80 K and the average cooling load over the 12 hour dose was 1.0034 W with a standard deviation of 0.0037 W. This indicated that the cooler was not degrading during the radiation dose. Note that during this test, aluminized mylar insulation was not used around the cold tip in order to mitigate discharge events. Two discharge events were observed in the voltage of one of the motors. The voltage spiked briefly from 13.72 Vrms to 13.75 Vrms. In addition, the data acquisition rate was 10 seconds and there could have been more discharge events that were not captured by this relatively slow data rate. After the microcooler returned to JPL, isotherms at 80 K and 105 K were measured for a rejection temperature of 220 K and a drive frequency of 122 Hz. Multiple layers of aluminized mylar were placed around the cold tip for these measurements. Figure 4 shows isotherms measured both before and after the compressor was exposed to 500 krad. It is evident that, for a given input power, the cooling capability of the cooler changed by less than 6.5% as a result of this radiation dose. Finally, the helium leak rate from the microcooler did not change as a result of the radiation dose.

5. Electromagnetic interference

5.1. DC measurements

The DC magnetic fields around the compressor were measured with the cooler not operating. Figure 9a shows the magnitude of the magnetic field at various distances as a function of angular position. The compressor was rotated about its center in three axes while the DC field was measured. An angular position of zero corresponded to the magnetometer sensor being perpendicular to the compressor axis. The magnitude of the magnetic field was roughly symmetric about 180° indicating that the magnets in each motor were approximately the same strength. In addition, magnetic mapping measurements yielded a maximum radial zero-to-peak field strength of 10.41 nT at one meter. Nearfield analysis was also performed where measurements were taken close to the compressor and the dipole moment was extracted from spherical harmonic analysis. It yielded an overall dipole moment of approximately 10.33 mA·m² and the calculated magnetic field was 4.13 nT zero-to-peak at a distance of one meter.

![Figure 9](image_url)

**Figure 9.** (a) DC magnetic field magnitude as a function of angular position at various distances from the cooler compressor and (b) AC magnetic field measured along the compressor axis at 7 cm from the compressor end for the cooler at high operating power at 140 Hz as well as the RE101 requirements per MIL-STD-461G [12] as a function of frequency.
5.2. AC measurements
The radial and axial AC magnetic fields of the microcooler compressor were measured from 30 Hz to
50 kHz at distances of 7 cm, 15 cm, 25 cm, and 50 cm. The test setup was similar to that explained in
detail in Ref. [8]. Figure 9b shows that the measured AC field versus frequency for a drive frequency
of 140 Hz. The field was measured along the compressor axis at distance of 7 cm from the compressor
derm with the cooler operating around 50 W. The microcooler exhibited a peak field of 139 dBpT rms at
140 Hz (\(\mu T = 10^{13.9}\mu T\)). The harmonic peaks extended up to approximately 1.8 kHz. It is evident that
the microcooler meets the magnetic field radiated emissions limit for Army but not Navy applications
as specified in MIL-STD-461G [12]. In addition, the peak at 140 Hz decreased with decreasing input
power for a given location and direction. For input power decreasing from 60 W to 10 W, the peak at
140 Hz measured 7 cm from the center of the compressor in the radial direction decreased from 138
dBpT to 132 dBpT slightly below the Navy limit of 133 dBpT.

6. Conclusion
The Lockheed Martin high-power microcooler successfully passed thermal cycling and radiation testing
indicating that it is acceptable for use in the Europa environment. The cooler was able to operate at 185
K reject temperature, survived a minimum non-operating temperature of 125 K, and did not degrade
after a 500 krad radiation dose. The optimal drive frequency of the cooler was highly dependent on the
heat rejection temperature. The forces generated by the cooler in the compressor axis can be reduced
using vibration feedback. The AC magnetic field radiated emissions met the Army but not Navy
requirement. Overall, this cooler remains the baseline for the MISE instrument aboard the planned
Europa Clipper mission.

7. References
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Characteristics of Subsystems and Equipment

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