Characterization Testing of Lockheed Martin Micro1-2 Cryocoolers Optimized for 220 K Environment

I.M. McKinley, M.A. Mok, D.L. Johnson, and J.I. Rodriguez

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

ABSTRACT

The Mapping Imaging Spectrometer for Europa (MISE) Instrument on the Europa Clipper mission has baselined a Lockheed Martin high-power Micro1-2 pulse tube cryocooler operating at 135 Hz with a 220 K heat rejection temperature. This paper describes the testing and results of two Lockheed Martin Micro1-2 coolers optimized for these conditions. The thermal performance of the microcoolers was measured in vacuum for heat reject temperatures between 220 and 230 K. The coolers were operated with input powers ranging from 5 W to 40 W and drive frequency between 125 Hz and 145 Hz. The optimal drive frequency was strongly dependent on heat reject temperature. In addition, the exported forces and torques of the coolers were measured at 300 K heat rejection for input powers ranging from 5 W to 60 W and drive frequency between 120 Hz and 160 Hz. The exported forces were dependent on both piston amplitude and drive frequency. Moreover, the following were measured on one of the coolers: DC and AC magnetic fields at various locations, the off-state conductance of the pulse tube, and the effect of inclination angle of the pulse tube relative to gravity on the performance of the cooler. Finally, one of the coolers was subjected to random vibration testing.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) has chosen the Lockheed Martin Micro1-2 cryocooler to provide active cooling on the Mapping Imaging Spectrometer for Europa (MISE) Instrument on NASA's Europa Clipper spacecraft. The Micro1-2 coaxial pulse tube microcryocooler weighs 450 g including the compressor pedestal mount and is slightly larger than the 350 gram, 25 W standard version (Micro1-1) that has been thoroughly characterized previously [1-5]. The Micro1-2 cooler can be driven with up to 60 W at 140 Hz at 300 K heat rejection and is optimized to provide 2 W of cooling at 105 K cold tip [6]. Its performance at various heat rejection temperatures was measured and was previously reported [6-9]. 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 g mass on the cold tip and thermal vacuum (TVAC) cycling [6]. In addition, the same Micro1-2 unit was qualified to TRL 6 for the harsher Europa environment at JPL by undergoing electron radiation testing to 500 krad and thermal cycling at operational heat reject temperatures as low as 185 K [9]. The same unit has been under life-test at JPL operating at 220 K heat rejection temperature since October 2017 without any degradation in performance or increase helium leak rate. It also had previously accumulated 7,700 hours of operation at Lockheed Martin at 300 K heat rejection temperature [7].

Cryocoolers 20, edited by S.D. Miller, R.G. Ross, Jr. and J.R. Raab

MISE intends to limit power consumption by taking advantage of this cooler's functionality at much lower heat rejection temperature than that for which it was optimized. As a result, a Micro1-2 MISE prototype cooler was developed that was optimized for 220 K heat rejection temperature to provide 0.75 W of cooling at 80 K while operating at 135 Hz. The left photograph of Figure 1 shows one of the Micro1-2 MISE coolers as it was delivered to JPL. This work reports on the characterization testing performed on two Micro1-2 MISE prototype units. It discusses performance, exported forces, off-state conductance, random vibration, and magnetics testing.

THERMAL PERFORMANCE TESTS

Test Setup and Procedure

The right photograph of Figure 1 shows one of the Micro1-2 MISE coolers in a TVAC chamber at JPL. This test setup was very similar to that previously used and described in Ref. [5]. In this case, the cooler was mounted to a square aluminum plate that was connected to a CTI 1050 coldhead by means of a copper bar. All of the cold surfaces including the microcooler cold finger were wrapped in multiple layers of aluminized mylar (MLI) for insulation. The cold tip temperature was measured by a Lakeshore DT-670 diode and controlled by a Lakeshore 340 temperature controller powering a resistive element. Both the heater and sensor were attached to a copper block that was clamped to the cold tip and made use of four-wire measurements. The microcooler was powered using a Chroma 61602 AC source supplying between 5 and 40 W at frequencies between 125 and 145 Hz. The heat rejection temperature was defined as that of the expander mounting flange of the microcooler. It varied from 220 to 230 K while the cold tip temperature was fixed at 80 K. Furthermore, the square plate was rotated 90° and 180° in order to measure the performance of the cooler for various pulse tube inclination angles relative to gravity. Finally, Lockheed Martin provided a recommended maximum drive voltage based on the drive frequency, compressor temperature, and motor current. This maximum recommended voltage was not exceeded during testing.

Nominal Performance

Figure 2 shows (a) the specific power of the Micro1-2 MISE coolers and (b) the motor efficiency vs. drive frequency for 15 W input power and 80 K cold tip for different expander temperatures. The specific power was defined as the compressor input power divided by the cooling power. The motor efficiency was defined as the quantity of the losses due to joule heating (I^2R) in the coils subtracted

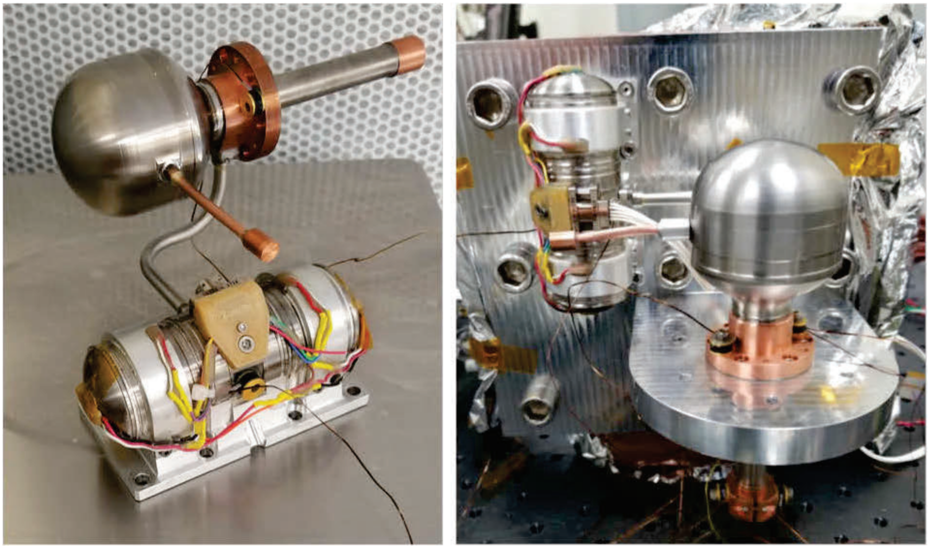


Figure 1. Micro1-2 MISE cooler as-delivered (left) and in TVAC test configuration (right).

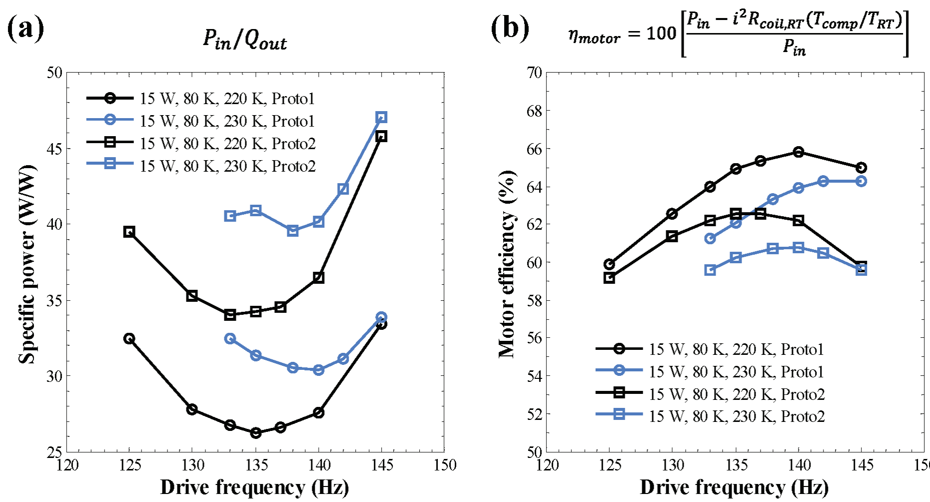


Figure 2. (a) Specific power and (b) motor efficiency vs. drive frequency for different heat rejection temperatures with the compressor input power at 15 W and the cold tip at 80 K.

from the compressor input power divided by the compressor input power [10]. In this case, the coil resistance was taken to be 5.4 ohms corresponding that at room temperature (RT) obtained with a 4-wire measurement. It is evident that the minimum specific power and the maximum motor efficiency both depend on heat reject temperature. However, for a given heat reject temperature, the minimum specific power for both coolers fell on the same drive frequency. This indicates that Lockheed Martin successfully optimized the drive frequency of the cooler to 135 Hz at 220 K. In addition, the performance of the first prototype cooler (Proto1) was better than that of the second (Proto2) over all drive frequencies and heat rejection temperatures.

Figure 3 shows the compressor input power vs. cooling load for both prototype coolers at 80 K cold tip for 220 and 230 K heat rejection temperatures when driven at the optimal drive frequencies determined from the minimum specific power shown in Figure 2a. Again, it is evident that Proto1 had better performance than Proto2 for all conditions measured. In addition, the optimization point of 80 K cold tip, 220 K heat rejection, and 0.75 W of cooling corresponded to a specific power of 25 and 30 W/W for

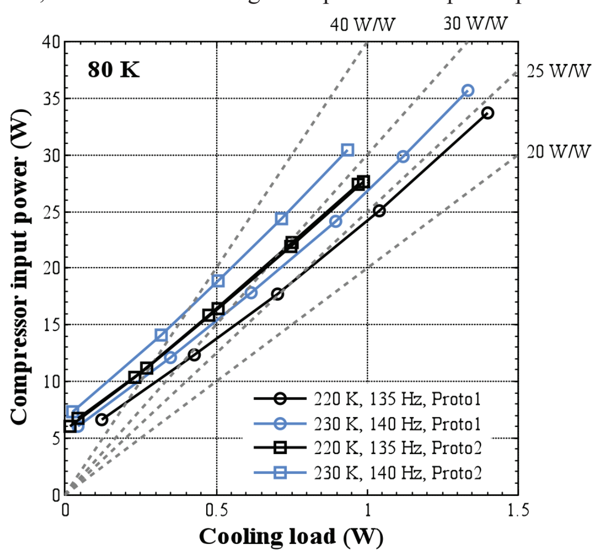


Figure 3. Compressor input power vs. cooling load for the two prototype coolers at 80 K cold tip with expander temperatures of 220 K and 230 K.

Proto1 and Proto2, respectively. Furthermore, for 220 K heat rejection and 80 K cold tip, the Micro1-2 MISE coolers had a difference in input power ranging from 20 and 17% for cooling loads ranging from 0.3 to 1 W. Finally, varying the compressor temperature from 210 to 230 K while fixing the expander at 220 K did not affect the performance of the cooler.

Effect of Pulse Tube Inclination Angle

Figure 4 shows compressor input power vs. cooling load for Proto2 driven at 135 Hz with an 80 K cold tip and 220 K expander temperature for different pulse tube inclination angles. An inclination angle of 0° corresponded to the cold tip pointed down as in the right photograph of Figure 1. It is evident that, for pulse tube inclination angles greater than 0°, the input power for a given cooling load increased. For large input power, the performance at 90° and 180° inclination angles was similar. In addition, the effect of inclination angle at 300 K reject was measured in finer angle increments. These measurements showed that an inclination angle of 120° corresponded to the worst performance for a given input power and cold tip temperature.

OFF-STATE CONDUCTANCE

One of the changes made to optimize the Micro1-2 cooler for 220 K heat rejection was to change the regenerator tube material from Inconel 718 to a titanium alloy in order to reduce the heat conduction along the regenerator tube. The off-state conductance was measured to assess the heat conduction on the modified design. The photograph on the left of Figure 5 shows the test configuration used to measure the off-state conductance of the cold finger of Proto1. A heater in a copper block on the cold tip was used to apply a constant heat load to the cold tip and the expander temperature was controlled to a colder temperature by closed loop control. The cooler was mounted with a 180° inclination angle relative to gravity to minimize natural convection in the pulse tube. In addition, a radiation shield was implemented around the cold finger to minimize radiative heat leak from the surroundings. The shield was approximately the same temperature as the expander.

The plot on the right in Figure 5 shows the measured total conductance vs. mean temperature of the cold tip and expander. The data includes measurements made with fixed heat loads of 18 mW and 37 mW as well as with a fixed cold tip temperature of 208 K. It is evident that the conductance increased with increasing temperature. This plot also shows the computed conductance of the combination of the titanium alloy pulse tube and regenerator tube based on their geometries, the measured cold tip and expander temperatures, and the temperature dependent thermal conductivity of titanium 6Al-4V [11].

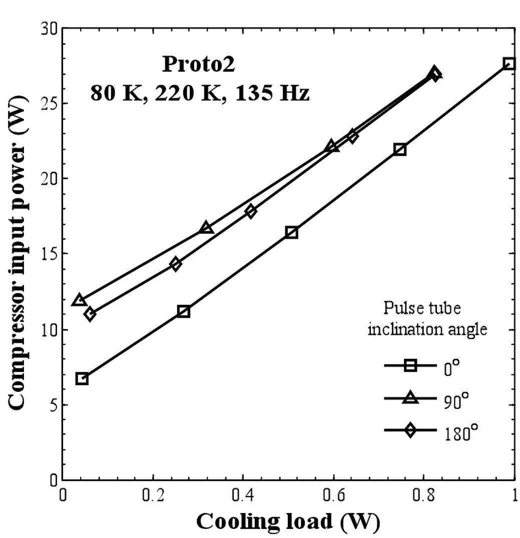


Figure 4. Compressor input power vs. cooling load for the second prototype cooler at 80 K cold tip, 220 K expander, and 135 Hz drive frequency for different pulse tube inclination angles relative to gravity.

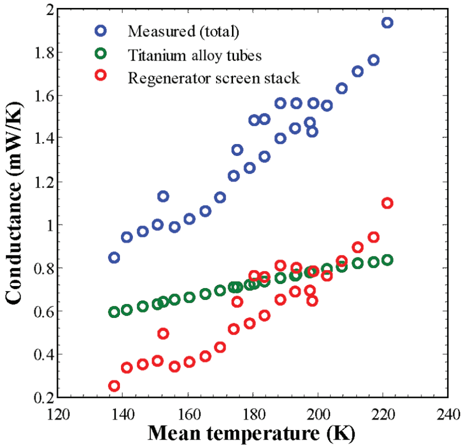


Figure 5. Photograph showing the configuration used to measure off-state conductance (left). MLI not shown. Measured total conductance vs. mean temperature of the expander and cold tip for the cooler in its off-state (right). The calculated conductance of the titanium alloy tubes and the stainless steel regenerator screens is also shown.

In addition, the contribution of the stainless steel regenerator screens was computed by subtracting the contribution of the titanium alloy tubes from the measured conductance. Note that the thermal conductivity of stainless steel follows the same trend and increases nearly linearly with increasing temperature in this range [11]. Finally, the gas contribution of the conduction of the helium in the pulse tube was negligible and calculated to be between 0.05 mW/K and 0.07 mW/K in this temperature range.

EXPORTED FORCES AND TORQUES

Test setup and Procedure

Figure 6 shows a photograph of one of the prototype coolers mounted on a Kistler dynamometer at JPL. This setup was very similar to that previously used in Ref. [5][9] and described in detail in Refs. [12][13]. The coolers were operated near room temperature and the cold tip was held under vacuum. Steady-state force and torque measurements were made for input power varying from 10 to 60 W and frequency varying from 120 to 160 Hz. The axes were defined such that the compressor axis was along

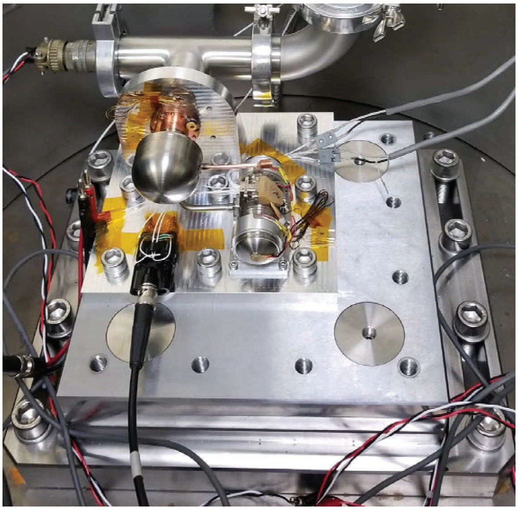


Figure 6. Photograph of one of the prototype coolers mounted on the Kistler dynamometer.

the direction of piston motion, the radial vertical axis was aligned with the gravity vector, and the radial horizontal axis was orthogonal to the others. The coolers were driven with a Chroma 61602 AC source.

Effect of Drive Frequency

Figure 7a-c shows the 0-peak exported forces from Proto1 in all three axes as a function of drive frequency with a 1 mm piston amplitude. Figure 7b and Figure 7c indicate that the largest forces were in the compressor radial axes and occurred at 480 Hz. This frequency corresponded to the second harmonic of 160 Hz and the third harmonic of 120 Hz. Indeed Lockheed Martin structural analysis predicted a radial first mode around 480 Hz for a piston stroke around 2 mm (1 mm amplitude). Note that these large radial forces cannot be reduced by active vibration control, but can be reduced by lower piston amplitude. On the other hand, Figure 7a shows the forces in the compressor axis that can be reduced with active vibration control. The forces in this axis are concentrated at the drive frequency and first harmonic. In addition, vibration feedback control was successfully demonstrated on the prototype coolers using an Iris LCCE-2 drive electronics with a test configuration similar to that used previously [9]. Finally, the second prototype cooler exhibited similar behavior to Proto1.

Effect of Piston Amplitude

Figure 7d-f shows the 0-peak exported force at each harmonic from the first prototype cooler in all three axes as a function of piston amplitude for the cooler driven at 135 Hz. It is evident that the total force in the compressor axis increases incrementally with increasing piston amplitude. However Figure 7f shows that the second and third harmonics in the vertical axis increase non-linearly with piston amplitude for amplitudes above 0.75 mm. This indicates that the moving mass of the piston is exciting a radial mode of the compressor. In addition, the first harmonic increases linearly with increasing piston amplitude. This could be indicative of a slight misalignment of the pistons in the vertical direction leading to an induced moment about the center of the compressor. Such a moment would cause a vertical force when the pistons change direction twice per stroke. Note that this feature did not appear as prominently in the second prototype cooler whereas the non-linear increase of the second and third harmonics did. Furthermore, Proto2 exhibited a non-linear increase in the third harmonic of the radial horizontal axis that Proto1 did not. Finally, Proto2 had a force greater than 1 N at the drive frequency in the compressor axis for piston amplitudes above 0.6 mm indicating that the motor modules were not as well balanced as the first prototype cooler. Overall, the exported forces from the Micro1-2 MISE coolers were on the same order of magnitude as the Micro1-2 cooler [9].

RANDOM VIBRATION

Random vibration testing was required to confirm the structural integrity of the regenerator tube on the Micro1-2 MISE cooler after the material change to a titanium alloy from Inconel 718 on the Micro1-2 cooler. The photograph on the left in Figure 8 shows the Proto1 cooler in the random vibration test configuration at Experior Laboratories in Oxnard, CA. The cooler was subjected to 14.1 grms in three axes for one minute each. The profile corresponded to the protoflight levels specified in the Goddard Space Flight Center (GSFC) General Environmental Verification Standard (GEVS) [14] shown in the plot on the right of Figure 8. For the full random vibration levels, there was no added mass on the cold tip and the input was force limited to reduce the response of the cooler and fixture at their resonances in order to replicate the response at the combined system resonances in the flight mounting configuration [15]. In addition, for the full input levels, the accelerometer on the cold tip was response limited due to the fact that the MISE Instrument intends to use a bumper on the cold tip to limit deflection during launch. Moreover, the motor coils were shorted during full levels as the MISE Instrument intend to have them during launch. Finally, the cooler was subjected to low-level inputs with a 22 gram mass on the cold tip as well as with the motor coils unshorted.

The Micro1-2 MISE Proto1 cooler successfully survived the random vibration testing. The cooler performance and helium leak rate measured before and after the test were similar. The cold

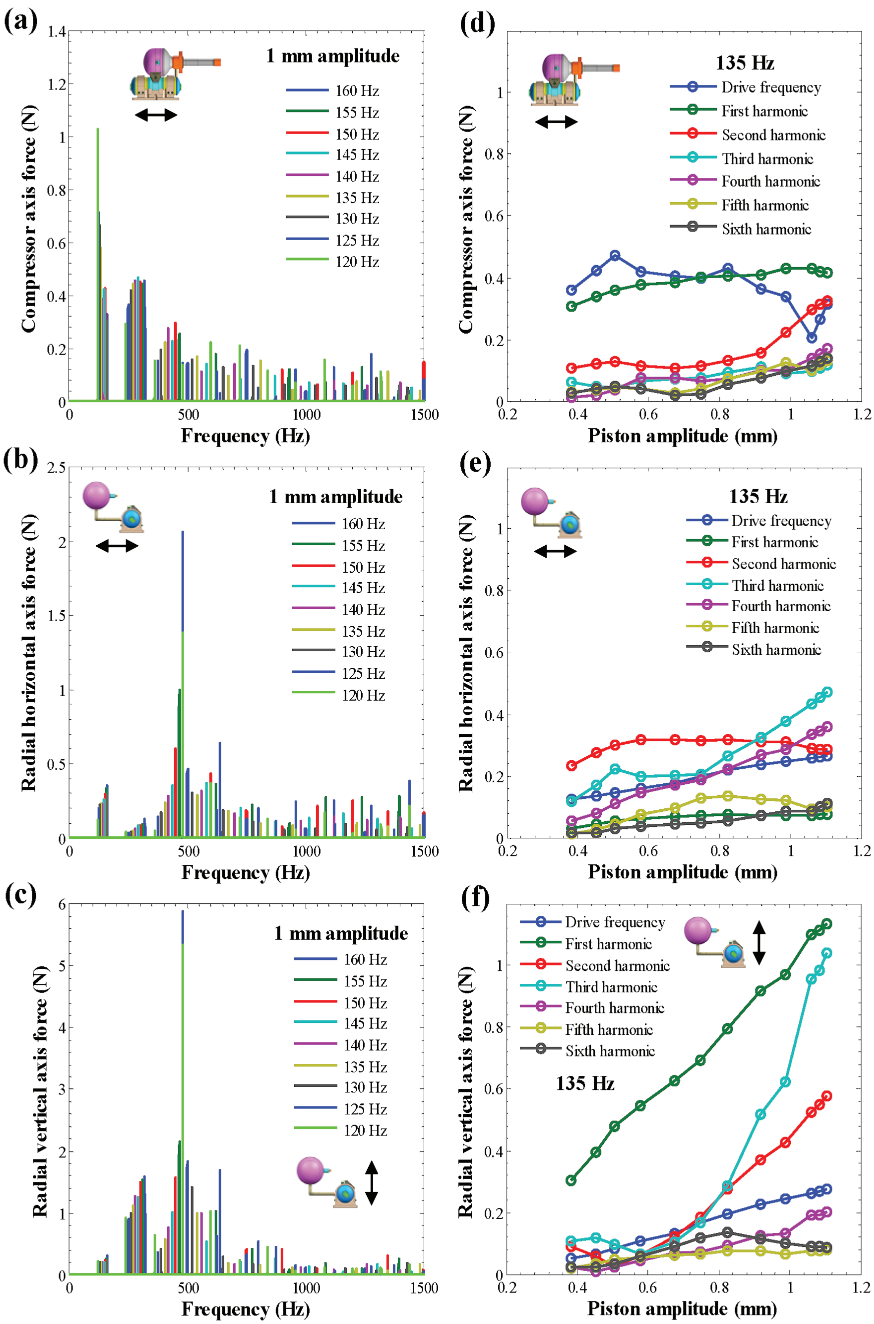
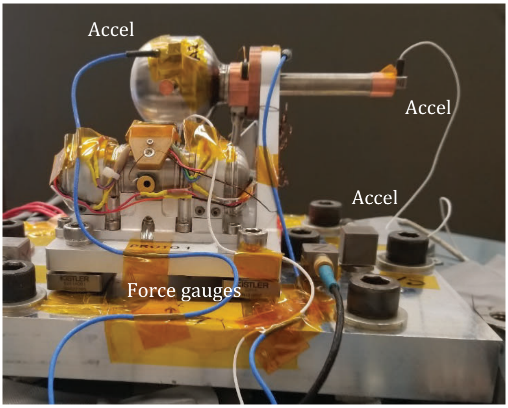


Figure 7. Exported forces measured 0-peak in all axes from the first prototype cooler driven (a-c) at 1 mm piston amplitude for various drive frequencies and (d-f) at 135 Hz for various piston amplitudes.



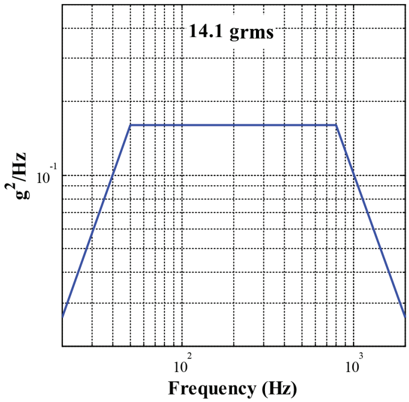
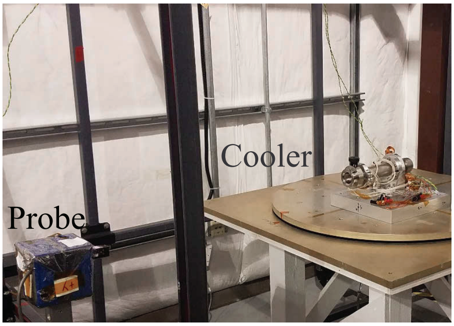


Figure 8. Micro1-2 MISE cooler in the random vibration test configuration (left) and the GEVS protoflight random vibration input levels (right).

tip mode of around 500 Hz was response limited and the fixture modes around 750 Hz were force limited. The cold tip bending mode shifted from 500 Hz to 300 Hz with the addition of a 22 gram mass to the end of the cold tip. In addition, the motor slosh mode of the pistons appeared around 50 Hz when the coils were unshorted. Scaling the output of the piston position sensors indicated that, if the motor coils were unshorted during full input level in the compressor axis, the pistons would have contacted the end-stops in the compressor.

ELECTROMAGETIC INTERFERENCE

The AC and DC magnetic characteristics of the Micro1-2 MISE Proto2 cooler were measured at a distance of one meter with the cooler operating with 55 W input power near room temperature at 157 Hz. The cooler was powered with an Iris LCCE-2 electronics. Figure 9 shows the test setup for the DC test (left) and AC test (right). These test setups and procedures were similar to those used previously to measure the magnetic characteristics of the Micro1-2 cooler [9]. The DC magnetic nearfield measurements showed that the Micro1-2 MISE cooler had a total magnetic dipole of 14.38 and 14.68 mA-m^2 when operating at 55 W and not operating, respectively. This indicates that operating the cooler did not affect the DC magnetic characteristics at a distance of one meter. In addition, the dipole zero to peak magnetic field was calculated from the moment results to be 2.88 and 2.94 nT at a distance of one meter while operating at 55 W and not operating, respectively. The dipole moment was larger than the 10.33 mA-m^2 measured on the Micro1-2 cooler at a distance of one meter [9]. This can be attributed to the fact that the Micro1-2 MISE cooler had upgraded motor ironworks from those of the Micro1-2 cooler. On the other hand, the AC magnetic fields measured from the Micro1-2 MISE and Micro1-2 cooler were nearly identical. The Micro1-2 cooler had an AC field of 139 dBpT rms



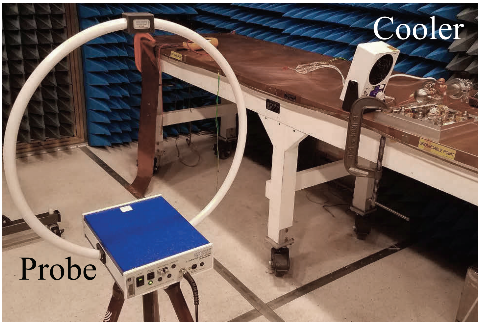


Figure 9. Photographs of the test setup for DC (left) and AC (right) magnetic field measurements

measured at a distance of 7 cm at the drive frequency of 140 Hz with 50 W of input power [9]. This scales to 69 dBpT rms at a distance of one meter. The Micro1-2 MISE cooler exhibited a peak of 68 dBpT rms at the drive frequency of 157 Hz with 55 W of input power measured at a distance of one meter.

CONCLUSION

This paper described the thermal performance, off-state conductance, exported vibration, random vibration, and magnetics testing and results of two Lockheed Martin Micro1-2 pulse tube cryocoolers optimized for operation at 220 K heat rejection. This cooler will be used on the MISE Instrument on the planned Europa Clipper mission. The thermal performance of the microcoolers was measured in vacuum for heat reject temperatures between 220 and 230 K. The coolers were operated at input powers ranging from 5 to 40 W and drive frequency between 125 and 145 Hz. The optimal drive frequency was dependent on heat reject temperature. In addition, the exported forces and torques of the coolers were measured at 300 K heat rejection for input powers ranging from 5 to 60 W and drive frequency between 120 and 160 Hz. The exported forces were dependent on both piston amplitude and drive frequency. The AC and DC magnetics testing showed that this cooler had similar magnetic characteristics as a Micro1-2 cooler previously tested. Finally, this cooler survived GEVS protoflight random vibration levels with no mass on the cold tip and the motor coils shorted. Overall, this cooler remains the baseline for the MISE Instrument.

ACKNOWLEDGMENT

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration. In addition, the authors would like to thank Jeff Olson and Mike Jacoby of Lockheed Martin, Experior Laboratories, as well as Tim McCann, Chris Hummel, Katherine Dang, Manny Soriano, Kevin Pham, Roderick McIntosh, Bill Hatch, Pablo Narvaez, Ryan Sorenson, Will Krieger, Tim Neville, Gary Wang, Ali Kolaini, Kirsten Maynard, Rick Redick, Carl Bruce, and Diana Blayney of JPL for their contributions to this work.

REFERENCES

1. T. Nast, E. Roth, J. Olson, P. Champagne and D. Frank, "Qualification of Lockheed Martin micro pulse tube cryocooler to TRL6," *Cryocoolers 18,* ICC Press, Boulder, CO (2014), pp. 45-50.
2. J. Olson, G. Kaldas, P. Champagne, E. Roth and T. Nast, "MatISSE Microcryocooler," *IOP Conf. Series: Materials Science and Engineering,* 101 (2015).
3. J. Olson, P. Champagne, E. Roth, G. Kaldas, T. Nast, E. Saito, V. Loung, B. McCay, A. Kenton and C. Dobbins, "Coaxial Pulse Tube Microcryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO (2014), pp. 51-57.
4. J. Olson, P. Champagne, E. Roth, T. Nast, E. Saito, V. Loung, A. Kenton and C. Dobbins, "Microcryocooler for tactical and space applications," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014).
5. I. McKinley, D. Johnson and J. Rodriguez, "Characterization Testing of Lockheed Martin Standard Micro Pulse Tube Cryocooler," *Cryocoolers 19*, ICC Press, Boulder, CO (2016), pp. 75-84.
6. D. Frank, P. Champagne, E. Will, G. Kaldas, L. Sanders, E. Roth and J. Olson, "Extended range of the Lockheed Martin coax Micro cyrocooler," *Cryogenics*, Vol. 74 (2016), pp. 55-58.
7. T. Nast, J. Olson, P. Champagne, E. Roth, E. Saito, V. Loung, B. McCay, A. Kenton and C. Dobbins, "Development of Microcryocoolers for Space and Avionics Applications," *Cryocoolers 19*, ICC Press, Boulder, CO (2016), pp. 65-74.
8. J. Olson, E. Roth, L.-S. Sanders, E. Will and D. Frank, "Lockheed Martin Microcryocoolers," in *Proceedings SPIE 10180, Tri-Technology Device Refrigeration*, (2017).
9. I. McKinley, C. Hummel, D. Johnson and J. Rodriguez, "Characterization testing of Lockheed Martin high-power micro pulse tube cryocooler," *IOP Conf. Ser.: Mater. Sci. Eng.* 278 (2017).

10. A. Orlowska and G. Davey, “Measurement of losses in a Stirling cycle cooler,” *Cryogenics,* Vol. 27 (1987), pp. 645-651.

11. E. Marquardt, J. Le and R. Radebaugh, “Cryogenic Material Properties Database,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 681-687.

12. D. L. Johnson, I. M. McKinley and J. I. Rodriguez, “Flight Qualification Testing of the Thales LPT9510 Pulse Tube Cryocooler,” *Cryocoolers 18*, ICC Press, Boulder, CO (2014), pp. 115-124.

13. D. Johnson, I. McKinley, J. Rodriguez, B. Carroll and H. Tseng, “Characterization testing of the Thales LPT9310 pulse tube cryocooler,” *Cryocoolers 18*, ICC Press, Boulder, CO (2014), pp. 125-133.

14. GSFC-STD-7000, “General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects,” *NASA Goddard Space Flight Center*, Greenbelt, MD (2005).

15. T. Scharton, “Force Limited Vibration Testing Monograph,” *NASA*, Pasadena, CA (1997).