Qualification Testing of Northrop Grumman MiniCoolerPlus Thermal Mechanical Unit for a Space-Flight Mission

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ABSTRACT

Northrop Grumman Aerospace Systems (NGAS) introduced the Mini Cooler Plus (MCP) to their family of pulse tube cryocooler in 2019 [1]. This thermal mechanical unit (TMU) is an extension of their space-qualified pulse tube coolers, all of which are designed to provide a long-life (ten plus years) of delivering low-mass, high-cooling capacity for hyperspectral and infrared imaging payloads in tactical airborne and space applications. The cooler is of modular split configuration allowing flexibility in the compressor (wave generator) and cold head placements in order to meet the available envelope of packaging constraints. The cold head assembly can be oriented at any position relative to the compressor assembly, and the transfer line (length and shape) can be customized to individual applications. The TMU weighs less than 3 kg and can lift 1.5 W at 45K or 11 W at 110K with 150 W electrical input at a 300K reject temperature.

This paper reports on the qualification testing of a MCP unit to achieve a technology readiness level (TRL) of 6 for an upcoming spaceflight mission, and it presents the test data obtained in its flight configuration over a range of input powers and rejection temperatures. The cooler was subjected to launch vibration and thermal cycling conditions for the range of operating and standby conditions appropriate to its space application. The measured load lines and stable refrigeration performance of the cooler throughout the qualification program demonstrate the readiness of the design for flight. A functional testing of the unit was also performed with Northrop Grumman`s TRL9 CCE (Control Electronics) without active vibration control and a vibration signature of the TMU was characterized for all axes.

INTRODUCTION

In an earlier publication[1], Northrop Grumman Aerospace Systems now named Strategic Space Systems (NGSSS), introduced their new pulse tube cryocooler design, Mini Cooler Plus (MCP), and demonstrated its high cooling capacity in its laboratory configuration, *e.g.,* with bolted reservoir rather than welded reservoir. Northrop Grumman proceeded with the design maturation of the MCP and qualified a unit with a nominal set of requirements for an upcoming space flight mission, and a flight MCP unit has been delivered for payload integration and mission launch. The data presented in this paper is limited to the qualification tests. The acceptance test data and flight characterization

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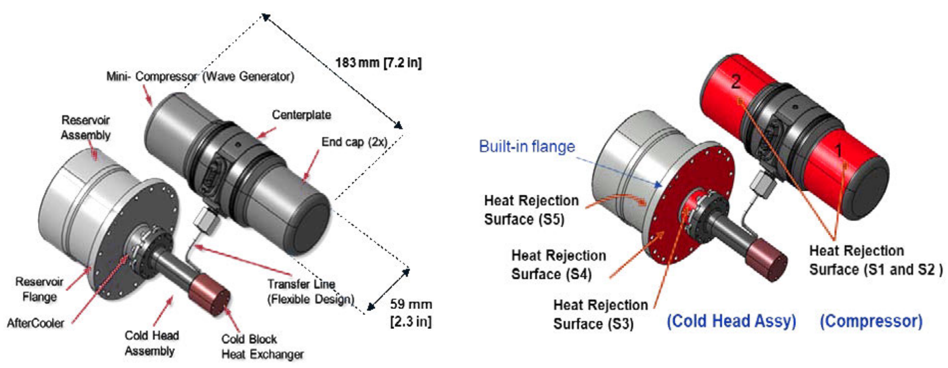
Table 1. Northrop MCP capability versus operating TRL6 test parameters

Parameter	**TRL 6 Qualification levels**	**MCP Capability**
Ambient Reject Temperature **(Operational)**	Low: -10°C (263K) High: +65°C (338K)	Low: -40°C (233K) High: +70°C (343K)
Parameter	**TRL 6 Qualification levels**	**MCP Capability**
Ambient Reject Temperature **(non-Operational)**	Low: -50°C (223K) High: +65°C (338K)	Low: -50°C (223K) High: +80°C (353K)
Cooling Performance	5.5 watts at 135K or less (278K-323K ambient reject range)	1.5W at 45 K[1] 6.5W at 77 K 11.0W at 110K 17.0W at 150 K (298 K ambient reject)
Output Frequency Range	Fixed frequency of 82 Hz (Provides maximum efficiency with 323K reject and 135 K cold tip temperature)	70 to 90 Hz (User Selectable)
Compressor Input Power	<=60 watt	150 watt

[1] Current MCP variant is built with a cold head design and fill pressure that are optimized for cooling a focal plane to 47 K with 1.5 W lift requirement.

tests will be made available in a later publication. This paper describes the system along with TRL6 qualification campaign as set by the nominal requirements of the upcoming spaceflight mission. Table 1 compares the MCP capability with the levels that were assumed during the TRL6 testing. Qualification testing of the cooler to higher levels remains to be done.

MCP Thermal Mechanical Unit Description: Figure 1 shows the MCP`s TMU, which is a split configuration thermal mechanical pulse tube cooler, with a remote coaxial cold head connected through a transfer line to the MCP Compressor. The modular split configuration allows flexibility in the compressor and cold head placements to meet various configuration needs. The cold head assembly can be oriented at any position relative to the compressor assembly and the transfer line (length and shape) can be customized to individual applications. The TMU can also be readily re-configured for an integral cold head. The mass of the mechanical cooler is about 2.7 kg (less than 3 kg) without the mounting provisions and/or the drive electronics.



(a) (b)

Figure 1. (a) MCP`s Thermal Mechanical Unit and (b) available thermal interface surfaces.

The cold head assembly is equipped with a built-in flange to provide structural support, easy integration with the payload, and additional heat rejection interfaces, if desired. The available heat rejection interfaces at both compressor and cold head assembly are indicated in Figure 1b. The heat rejection surface (S5) was used here to dissipate the rejected heat from the warm end of the cold head assembly. The compressor's mechanical and thermal interfaces (S1 and S2) are assumed to be around the circumference of the end caps for the existing MCP variation.

The compressor is scaled down from the space qualified High Efficiency Cryocooler (HEC) compressor, with special considerations given to the choice of materials, design tolerances, and fabrication processes in order to reduce the manufacturing cost while utilizing the same flight proven technology (second-generation flexure bearings) [2-3]. The MCP compressor is designed for both space and airborne applications, with the latter driving its design. It must operate at reject temperatures up to 70°C and be sufficiently compact to fit in small volumes generally required by tactical airborne applications. The compressor`s end caps are welded to the center plate to provide a hermetic seal and a good thermal contact between the end caps and the center plate.

TEST SET-UP

Figure 2 shows the TMU in the thermal-vacuum test configuration designed to support a full range of thermal-vacuum operational conditions, and Figure 3 shows the TMU in its random vibration test configuration. The laboratory Ground Support Equipment (GSE) drives the TMU during thermal vacuum testing. Testing in thermal vacuum chamber is performed with the TMU cold head oriented in the downward vertical position as shown in Figure 2. A copper block instrumented with cartridge heaters and two temperature sensors was attached to the tip of the cold head (see Figure 4). Six additional temperature sensors monitored the temperature of the system at various locations.

Figure 2. MCP mounted in the test fixture, instrumented for thermal performance test

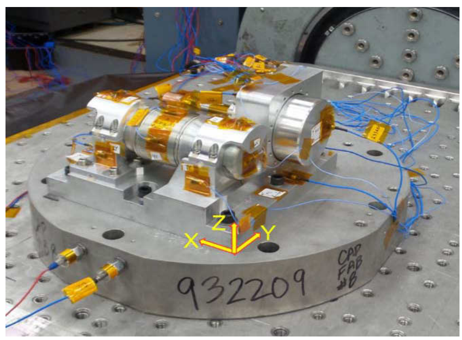


Figure 3. Dynamics test setup with the cooler shown mounted on the shaker to perform the random vibration tests along the Y-axis

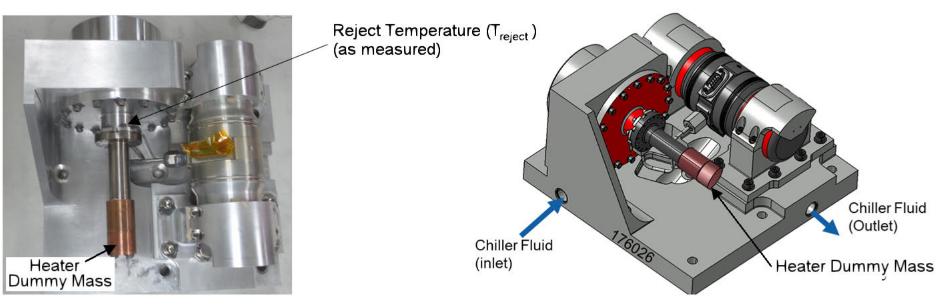


Figure 4. The MCP mounted in the non-flight test fixture (176026) showing the heat rejection arrangement and the location of the controlled reject temperature (T_{reject}). A dummy mass of 85 grams is affixed to the cold tip for launch-vibration testing.

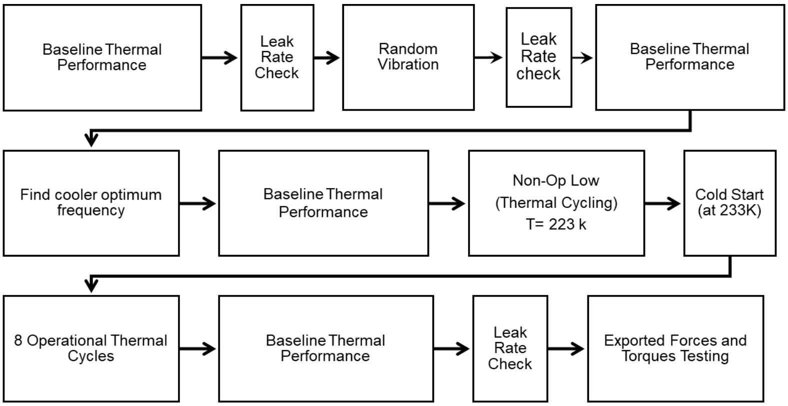


Figure 5. TMU Qualification Test Sequence

The heat rejection temperature (T_{reject}) was controlled by circulating a thermally controlled fluid through the heat exchanger plate, as shown in Figure 4, while removing the rejected heat at the cold head flange and the compressor. The compressor temperature was therefore allowed to float based on the thermodynamic operating conditions and the thermal control arrangement set by T_{reject}. The TMU power (P_{TMU}) refers to the electric input power to the compressor where the cable`s resistive losses are reduced.

ENVIRONMENTAL TESTS

The sequence of operations throughout the TRL6 qualification testing is illustrated in Figure 5.

Thermal Performance Tests: A cooling performance benchmark was established prior to the launch-vibration-conditions (pre-vibe) in order to set an assessment standard for any observed changes in the cooling capability after vibration testing (post-vibe). After vibration testing, the cooler returned for a second round of thermal vacuum performance tests followed by thermal cycling tests. The performance load line data was collected and shown to replicate the pre-vibe operating conditions, *i.e.,* a constant power load line at a constant operating frequency. The pre- and post-random vibration load lines are compared in Figure 6 indicating effectively no change in performance after exposure to the TRL6 qualification levels of launch vibration.

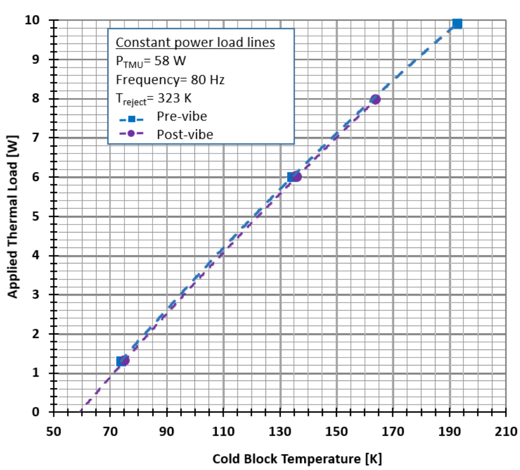


Figure 6. Pre- and Post- Random Vibration, Comparison of Load lines, Reject Temperature = 323K, Compressor Input Power= 58W, operating frequency = 80Hz)

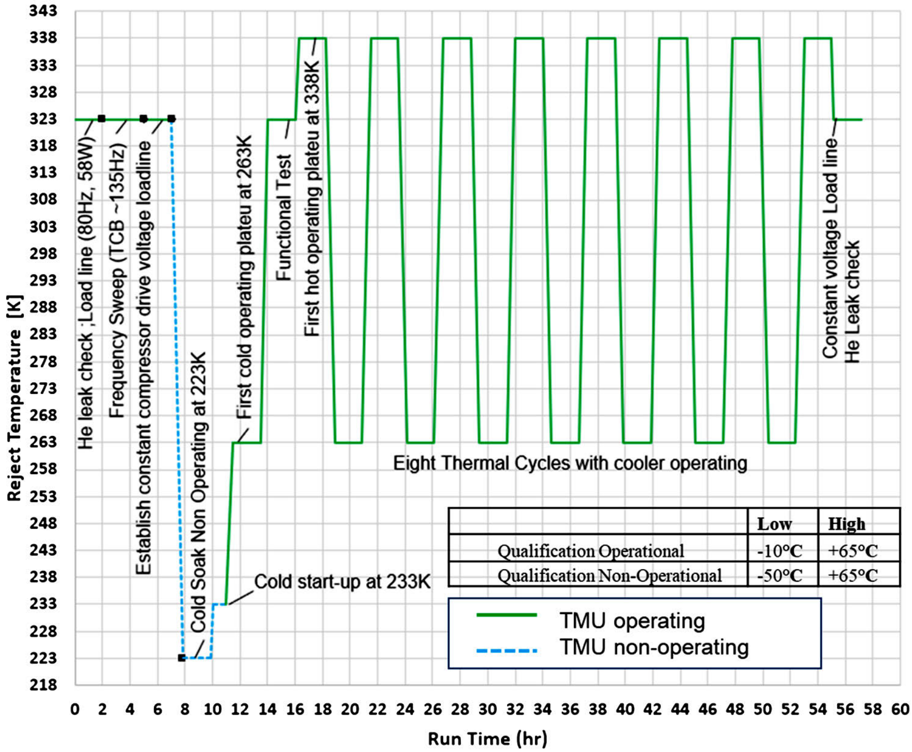


Figure 7. MCP TMU post-random vibration thermal qualification test

The optimum drive frequency of the TMU was found, during the frequency sweep, to be 82 Hz when the heat rejection temperature (T_{reject}) was set to 50 ºC (323K) and the cold tip temperature approximately 135K(nominal operating conditions for the tests). The operating frequency was hereon set to 82 Hz.

While holding the drive frequency at 82 Hz and maintaining the reject temperature at 50 ºC (323 K), a base load line was established using a constant compressor drive voltage. The pre-test load line level would be compared to cooler performance under the same condition after the cold start and thermal cycling tests. The consistency of the load line measurements serves as the measure of the cooler`s design adequacy.

The details of this qual-level thermal cycling tests are illustrated in Figure 7. Thermal vacuum qualification consisted of one non-operational (unpowered) qualification (with a 223Klower limit and 338K upper limit) and eight powered qualification cycles (with a 263K lower limit and 338K upper limit) as specified in Figure 7. The unit was held for a minimum of 2 hour soaks at each plateau. During the operational thermal cycling, the cold tip temperature was kept at approximately 135K with an applied load of approximately 6 W load with no more than 60 W of power into the TMU. The TMU cold start capability at -40 ºC (233 K) was demonstrated at the start of the thermal cycling. Helium leak rate was measured at ambient temperatures at the start and end of the test. The measurements remained consistent in the order of 10^{-9} mbar-liter/s, which is two orders of magnitude better than what is required for a 15-year mission.

Figure 8 compares the pre-thermal and post-thermal cycling performance load lines. No change in performance was observed after exposure to the TRL6 thermal qualification levels documented in Figure 7.

The cooler performance was tested with other various reject temperatures: 283K, 300K, 313K, and 323K specifically. The operating frequency and the compressor drive voltage were fixed

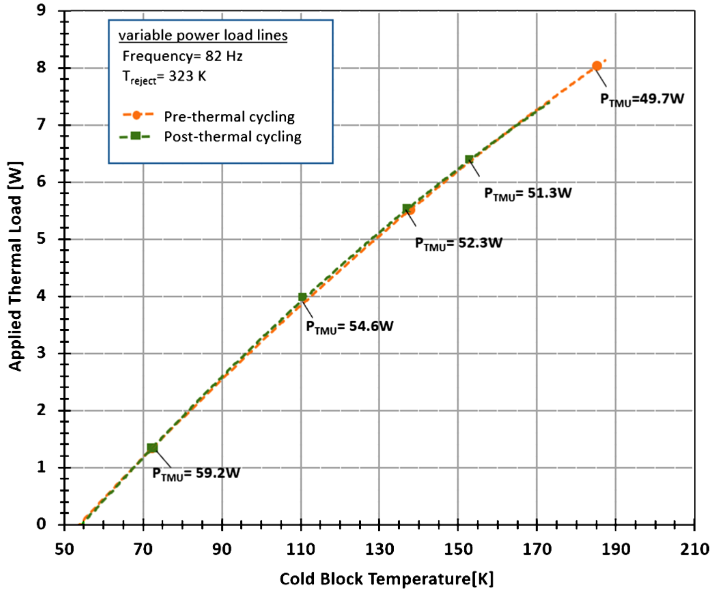


Figure 8. Variable power load-lines obtained at Reject Temperature = 323 K and operating frequency = 82 Hz

across all tests. The constant voltage load lines are of a generally nonlinear performance, as seen in Figure 8. However, the assumption of linearity is valid in the investigated operating range of 100K-180K. Inspecting the data in Figure 9, one should note that the cooler is only run at about 35% of its power capacity (150 W). All load lines shown in Figure 9, with the exception of the 323K load line, reflect the performances below capacity, due to the fact that operating at the fixed drive frequency of 82 Hz, the resonant frequency at the hottest reject value of 50 °C (323K), places the other load lines at their off-resonance performance. Characterization of the cooler for a range of reject temperature reflecting MCP`s capability will be subject of future publications.

Random Vibration Testing: The MCP (unpowered) unit was subjected to random vibration qualification testing in three orthogonal axes. Testing was performed at the vibration test facility within Northrop Grumman, Space Systems using a T1000 head unit and associated oil bed slip table. A dummy mass of 85 gram was affixed to the cold tip.

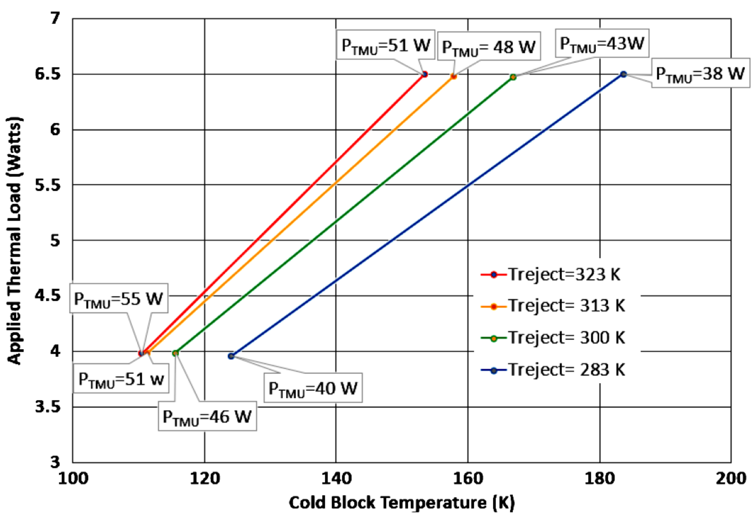


Figure 9. MCP Load Lines for constant compressor drive voltage, 82 Hz (i.e., optimum frequency for 323K reject/135K cold block condition).

The vibration levels are displayed in Figure 10. Overall test levels were 12.4 GRMS, and the test ran for two minutes duration in each axis and covered 20-2000 Hz frequency band. Low level (-9 dB) system response was captured prior to, in between, and after the full level exposures of all three axes. A comparison of those low-level responses from the pre-, intermediate, and post-test stages show no shifts in the resonant frequencies of the system, which indicates no structural degradation occurred during the TRL6 test procedure. In addition, a visual inspection was performed after test completion. No structural degradation was found through this inspection method either. The Y-axis response (to a Y-axis excitation) as measured at the cold tip of the cold head (the location of most interest) is shown in Figure 11. The response shows a cold head natural frequency of 255 Hz. The fatigue margin of safety based on 4 lifetimes is 18.

Exported Force Vibration: The exported vibration of the Northrop MCP was measured at Northrop Grumman's Cryocooler Dynamic Test Facility. The system was mounted on a fixture attached to a Kistler 9257B Dynamometer and the forces and torques were measured in 3 directions with background noise force magnitudes below a few mN. The mechanical cooler and dynamometer fixture are mounted on a 2-inch-thick steel plate which is bolted to a 70-ton seismic mass beneath and decoupled from the floor. The test apparatus design assures that a stable and rigid base is used

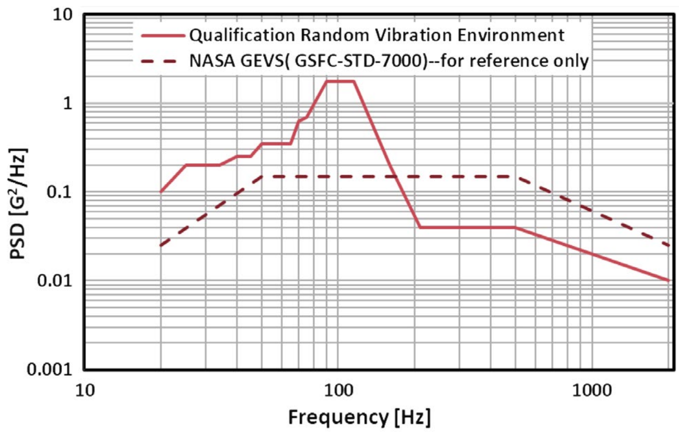


Figure 10. The TRL6 random vibration qualification test level in support of a nominal mission requirements

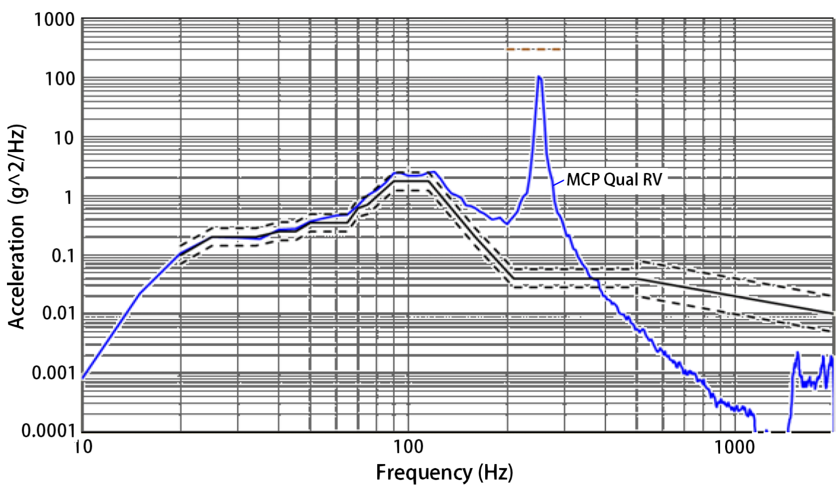


Figure 11. Y-axis vibration response of the cold tip to the Y-axis excitation at qualification (-3dB) level

in the calibrated force measurements. This gives a direct measure of the force and torque output. However, since the cooler is rigidly mounted to the massive fixture, the accelerometer output is too small to produce an error signal output at these very low vibration levels. Therefore, the loop is closed around one of the Kistler force transducers parallel to the cooler drive axis. In this test mode, the well understood rigid boundary condition provides the data that an analyst can use to determine the effect on a more complex spacecraft structure. The dynamic data are analyzed and processed with a Data Physics' SignalCalc Dynamic Signal Analyzer. The SignalCalc Analyzer provides highly accurate measurements in the time and frequency domains with the capability of synchronous data averaging increase the signal to noise ratio. The cooler was operated with a purge gas rather than in vacuum to remove the additional fixture modes associated with the vacuum hardware.

For this testing, the cooler was driven by heritage NG Cryocooler Control Electronics without using the active vibration control. Operating conditions were 58W of input power, 140K cold head temperature, and 290K reject temperature. The cold head EFT test temperature is higher than usual space flight temperatures because the gas purge (rather than vacuum) creates much higher parasitic heat loads. Prior testing indicates cold head temperature is not a driver of EFT magnitudes.

Exported Force Vibration is at low levels in all 3 axes as indicated in Figure 13-15. All Drive axes forces for the first 10 harmonics are below 30 mN. The largest force over the range of drive frequencies was less than 170 mN in the Cross Axis.

CONCLUSION AND FUTURE WORK

The Mini Cooler Plus unit successfully completed all random vibration and thermal cycling performance testing to a space mission specified qualification program. The unit demonstrated its

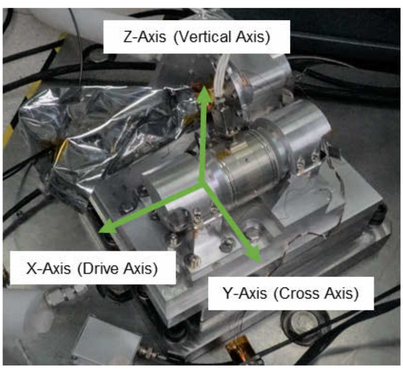


Figure 12. TMU rigidly mounted on force table

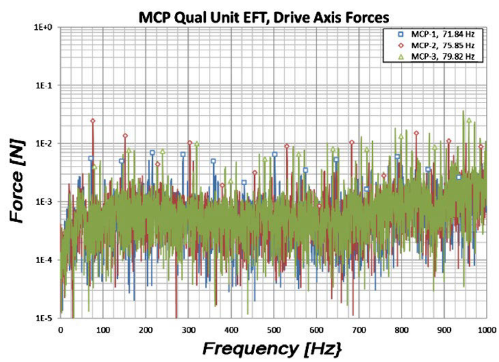


Figure 13. X-Axis (Drive Axis) Forces

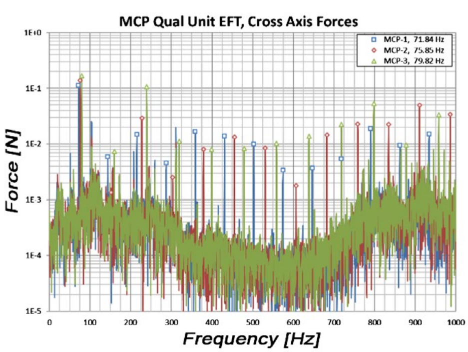


Figure 14. Y-Axis (Cross Axis) Forces

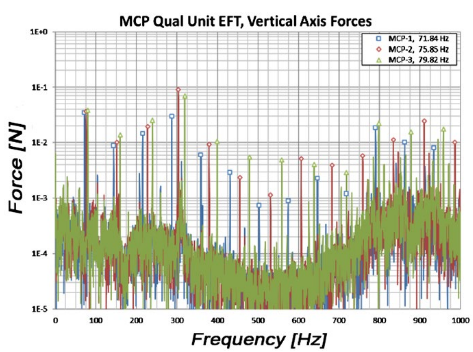


Figure 15. Z-Axis (Vertical Axis) Forces

Test Readiness Level (TRL) 6 as a viable candidate for a space flight. The TMU proved a cold start capability at -40C (233K) and Exported Force measurements were made. The MCP's higher design capability, over these qualification levels, were addressed here. Near term future work entails testing the MCP unit to higher levels and characterizing the cooling capacity at different powers (up to 150 W to the TMU) across variety of reject temperatures.

ACKNOWLEDGMENTS

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