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CubeSat-Sized Space Microcryocooler

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ABSTRACT

There is an increasing desire to perform Earth science and astrophysics missions with small satellite platforms. Among these missions, there are many instruments such as infrared imaging and spectroscopy and sensitive UV measurements which require cryogenic sensors. This paper describes the capabilities of several CubeSat-sized microcryocoolers developed by Lockheed Martin Space that are suitable for small satellite cryogenic sensor applications. These coolers are the only space-quality cryocoolers available that can be packaged within a single U of a CubeSat. They also share the long-life technology attributes used in larger space cryocoolers for missions which typically require 10 years of continuous operation on orbit without degradation. These Lockheed Martin microcryocoolers have been qualified to TRL 6. One cooler has been integrated into CubeSat, which will perform infrared imaging during a lunar flyby, and two others are planned for NASA deep space missions, each of which includes considerable environmental challenges.

INTRODUCTION

There is a growing desire to perform Earth science, astrophysics, and national security remote sensing missions from small satellites. SmallSats, and even CubeSats, are being proposed for performing missions previously conducted by billion-dollar satellites in geostationary orbit.

There are many different types of cryogenic instruments. Infrared cameras and spectrometers are perhaps the most familiar, but cryogenic X-ray detectors, gamma ray detectors, RF antennae, ultraviolet cameras, particle detectors, and superconducting devices have all flown on space missions. Each of these instruments requires the sensor to operate at cryogenic temperature to maximize sensitivity, or even to function at all in some cases. Although the space environment is generally envisioned as being "cold", it is challenging to radiatively cool devices to cryogenic temperature, and the pointing requirements of a cryogenic radiator can complicate mission operations considerably.

Long-life space cryocoolers have been available for large satellites since the mid-1990s [1], following breakthrough advancements at Oxford University in the configuration of Stirling cryocoolers using moving parts supported by spiral flexure bearings in a configuration which eliminated rubbing seals. This configuration was further simplified by TRW (now Northrop Grumman Aerospace Systems) by eliminating the solitary cold moving part (the displacer) in favor of the passive "pulse tube" cryocooler cold head configuration. According to a 2016 report [2] from the Jet Propulsion Laboratory (JPL), there has been no degradation in the measured performance of any of the 12 different pulse tube cryocoolers on orbit during more than 120 years of total operational lifetime, and pulse tube cryocoolers are now considered to be reliable space hardware. Pulse tube cryocoolers using "Oxford-style" compressors have a predicted reliability in excess of 0.98 at 10 years (excluding the electronic controller), allowing non-redundant cryocoolers to be used for Class B space missions.

The advent of smaller satellite platforms has led to a need for smaller cryocoolers. A typical space cryocooler has a mass of 4 kg or more. The mass and size limitations of even a 6U CubeSat require significantly smaller, lighter cryocoolers. There are many low-mass "tactical" Stirling cryocoolers available, developed to cool military infrared cameras, but these have lifetimes of less than 1 year and often have high exported vibration forces. Tactical coolers generally have a mean time to failure (MTTF) of 8,000–12,000 hours, whereas the space cryocooler reliability translates to a MTTF of several million hours.

Lockheed Martin (LM) began developing microcryocoolers in 2009 with funding from LM Santa Barbara Focal Plane (SBFP). The motivation was to develop cryocoolers with similar mass, size, and power to the smallest tactical Stirling coolers, but with cooler lifetimes typical for space cryocoolers, for applications where it is expensive or inconvenient to replace a tactical cryocooler. This paper will describe three different cryocooler models developed and tested at LM: the Micro1-1 (Standard Microcryocooler), Micro1-2 (High-Power Microcryocooler) and Micro1-3 (Fast-Cooldown Microcryocooler).

PULSE TUBE CRYOCOOLER DESCRIPTION

As mentioned above, the pulse tube cryocooler is a simplification of the Stirling cryocooler, utilizing the same thermodynamic cycle. Like a Stirling cryocooler, the pulse tube cryocooler is filled with high pressure helium gas (typically at 3-4 MPa mean pressure), and ac electrical power drives two moving pistons in the compressor, creating oscillating pressure and mass flow at the warm end of the cryocooler. The two pistons are driven by linear motors and move in opposed motion to minimize exported vibration. The compressor is shown at the top of the schematic in Figure 1. This input power is rejected at the primary heat exchanger at ambient temperature.

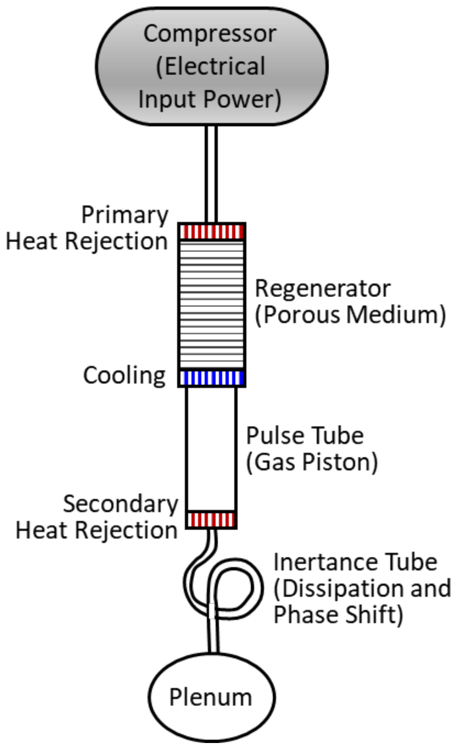

Figure 1: Schematic of pulse tube cryocooler configuration. The pulse tube is a simplification of the Stirling cryocooler

The gas oscillates through the regenerator, which consists of a porous medium (typically stacks of fine-mesh screens or metal felts) and acts as a passive thermal storage medium, absorbing heat as the gas moves from the hot to cold end, and releasing that same heat as the gas returns from cold to hot end. Minimizing flow friction while maximizing heat transfer between the gas and solid matrix is a critical step to maximizing cryocooler efficiency.

The oscillating column of gas within the pulse tube replaces the cold moving piston in a traditional Stirling cooler, and insulates the cold tip from the warm end of the pulse tube. In a Stirling cooler, work is extracted by the cold piston, and the phase of the cold piston motion is timed carefully with respect to the phase of the compressor piston in order to maximize the cooling power. In the pulse tube cooler, these are accomplished with the inertance tube, which is a long tube that dissipates the appropriate amount of work (which is rejected at a secondary heat exchanger) while the inertia of the oscillating gas provides the proper phase shift. The plenum volume helps tune the proper amplitude of gas motion.

The microcryocoolers described in the next sections use a more compact configuration than that shown in Figure 1. The regenerator and pulse tube are coaxial, and the inertance tube is packaged within the plenum volume.

MICRO1-1 CRYOCOOLER

The first version of microcryocooler developed at LM (Micro1-1) was designed for a high-operating temperature mid-wave infrared (MWIR) focal plane array (FPA) developed by LM SBFP. This FPA had an operating temperature of 150 K and a FPA heat load (including parasitics) of less than 1 W. The Micro1-1 cryocooler is shown in Figure 2. The mass of the compressor (on the left in the photo) is 200 grams and its length is 9 cm, while the mass of the cold head (on the right in the photo) is 150 grams and its length is 11.5 cm. The small copper piece on the end of the cold finger in the lower right is the cold tip, the portion of the cooler which gets cold, while the bulb on the upper right is the plenum volume, which also encloses the inertance tube.

Cooling load lines for the Micro1-1 are shown in Figure 3, which shows the cooling power (vertical axis) as a function of cold tip temperature (horizontal axis) at four different levels of ac electrical input power into the compressor. This cryocooler requires 15 W of electrical input power to drive the compressor in order to provide 1 W of net cooling at 150 K at the cold tip.

The SBFP FPA was bonded directly to this cold tip and integrated with a Dewar in the optical path, but most space instrument applications use a thermal strap from the cold tip to the cold region of the instrument.

Figure 2: Micro1-1 cryocooler. The compressor (left) includes two pistons which move in opposed motion to minimize vibration. The cold tip (lower right) is the portion that gets cold.

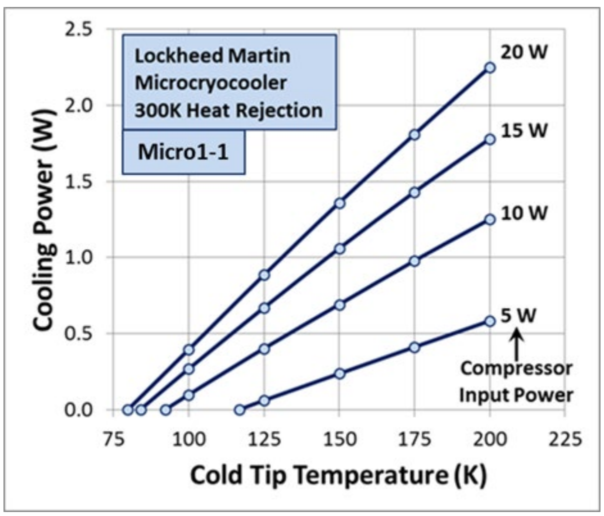

Figure 3: Cooling load lines for the Micro1-1 cryocooler. This cooler was designed for 1 W cooling at 150 K, which requires 15 W compressor electrical power.

The Micro1-1 cryocooler was qualified to TRL 6 in 2013. Launch vibration testing was performed at NASA GEVS protoqual levels for one minute in each axis with the cold tip supporting 15 grams of added mass. Thermal cycling included operation at -40°C and +65°C, and qualification testing was completed just in time to be included in three instrument proposals for the Mars2020 rover. Unfortunately, none of those three instruments were selected for the mission. A Micro1-1 demonstration model cryocooler was procured by JPL in 2015 with Maturation of Instruments for Solar System Exploration (MatISSE) funding and has been integrated with an infrared (IR) spectrometer designed for planetary lander missions [3].

Another Micro1-1 cryocooler was integrated into a technology demonstration CubeSat to provide cooling for a LM SBFP MWIR camera. This CubeSat will fly on EM1 along with the Orion module and will perform lunar imaging during a flyby. This launch is currently planned for 2021.

MICRO1-2 CRYOCOOLER

In response to a specific customer need for higher cooling power and lower cold tip temperature, a second version of microcryocooler (Micro1-2) was developed at LM. The customer required 2 W cooling at 105 K, which was expected to require more than 50 W of electrical power. The Micro1-1 cooler was designed for a maximum input power of around 25 W. Consequently, some modifications were made to the compressor to allow more than 60 W compressor electrical input power.

The pressure vessel structure of the compressor and the motor configuration were unchanged, but the piston diameters were increased to provide more swept volume and larger pressure amplitude. A larger compressor pedestal was designed for better heat rejection, and thermal heat straps were added to the motors to prevent overheating.

The cryocooler cold head was also reoptimized for the lower operating temperature and higher input power. The same general configuration and design features were unchanged, but the cold finger became slightly longer and larger diameter, the heat exchanger lengths grew to accommodate the greater power requirements, and the plenum volume grew. The Micro1-2 cryocooler mass is 475 grams, compared to 350 grams for the Micro1-1.

A Micro1-2 cryocooler is shown in Figure 4. This cooler includes a tab on the cold tip with a hole to facilitate integration with the customer's thermal strap. Cooling load lines for this cooler are shown in Figure 5. This cryocooler requires 55 W of electrical input power to drive the compressor, in order to provide 2 W of net cooling at 105 K at the cold tip.

The first Micro1-2 cooler was qualified to TRL 6 in 2015 with launch vibration and thermal cycle testing. Launch vibration testing was performed at GEVS acceptance levels for one minute in each axis with the cold tip supporting 50 grams of added mass. Thermal cycling included operation at -25°C and +60°C. This cooler was put on life test and ran continuously for 7700 hours with 60W input power before being delivered to JPL for Life Cycle testing related to JPL's Mapping Imaging Spectrometer for Europa (MISE) instrument for the Europa Clipper mission [4]. JPL performed AC and DC magnetic field characterization, measured exported forces and torques, exposed the cooler to 500 kRad of radiation dosage while operating with no change in cooler performance, subjected the ambient cooler hardware to non-operational thermal cycles as cold as 125 K and as hot as 340 K, measured operational performance at 185K, 220 K (nominal) and 250 K, and cold starts at temperatures as low as 140 K (simulating the cold quiescent periods and restarts between flybys of the Jovian moon Europa), and operated the cooler with 185-250 K ambient temperature for more than 500 days. Including operational hours at both LM and JPL, the cooler accumulated greater than three times the nominal MISE mission operational lifetime. This cooler was returned to LM and is available to send on loan to potential customers for integration and testing for maturation of space instruments.

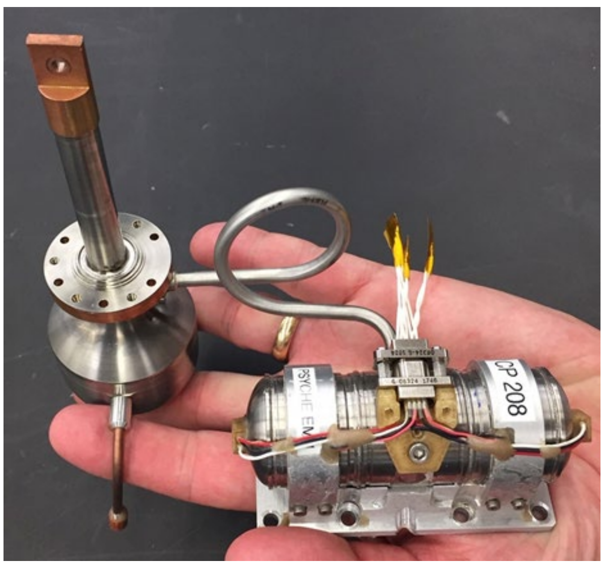

Figure 4: Micro1-2 cryocooler. The larger pedestal and added heat straps can be seen on the compressor on the right, and the tab/hole on the cold tip for integration can be seen on the upper left.

Two demonstration model coolers were subsequently manufactured and delivered to JPL for MISE in 2017, and these have been tested by JPL [5]. Flight cryocooler hardware is currently being built for MISE. The Europa Clipper is scheduled to launch in 2022.

A prototype Micro1-2 cooler was built and delivered to the Johns Hopkins University Applied Physics Laboratory (JHU/APL) in 2015 with MatISSE funding. This cooler was tested with JHU/APL's Gamma Ray Spectrometer instrument, similar to an instrument previously flown on the Mercury Messenger. This instrument was subsequently selected for the Psyche asteroid mission, and two engineering model cryocoolers were built for JHU/APL. One EM has been integrated with the GRS qualification model instrument and is undergoing instrument testing at JHU/APL and the second EM is undergoing Life Cycle testing at LM appropriate for the Psyche mission. Psyche is scheduled to launch in 2022. The flight contract is underway, with delivery of the flight cryocoolers planned for 2020.

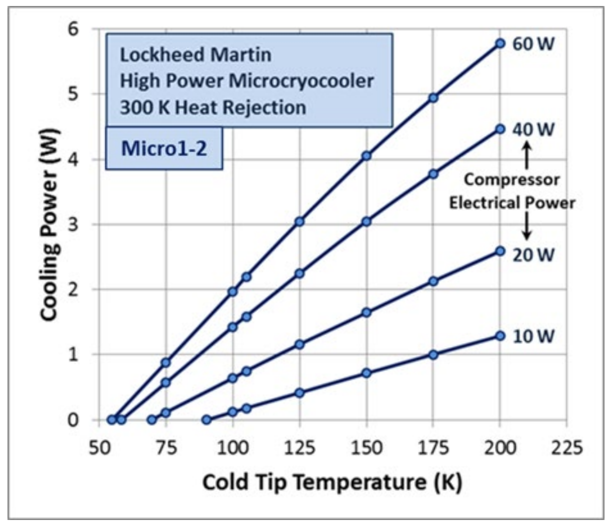

Figure 5: Cooling load lines for the Micro1-2 cryocooler. This cooler was designed for 2 W cooling at 150 K, which requires 55 W compressor electrical power.

Another prototype Micro1-2 cooler was built for a NASA Phase II SBIR program, called the Deep Space Cryocooler System (DSCS). The goal of this SBIR was to develop a low-mass cryocooler capable of cooling an instrument to 35 K while rejecting heat at 150 K. The SBIR small business lead, Iris Technology, developed a very low mass cryocooler electronic controller well-suited for use in CubeSat missions as part of the contract. The cryocooler system met the goals of the program and was delivered to NASA in April 2019.

MICRO1-3 CRYOCOOLER

The third microcryocooler model built and tested by LM was developed in response to a specific customer need for a cryocooler which could cool a MWIR focal plane to its 125 K operating temperature in less than three minutes. This program was initiated in 2014 and successfully demonstrated fast cooldown in 2016. Results of cooldown testing are shown in Figure 6, demonstrating that the cooler was capable of cooling a

4.1 gram copper mass (representative of the thermal mass of the FPA) to 125K in 2.5 minutes with 40 W electrical power. Although less than 7 W are required to maintain the focal plane at its operating temperature in equilibrium, as much as 50 W were available during cooldown. Cryocooler cooling load lines (in equilibrium) are shown in Figure 7.

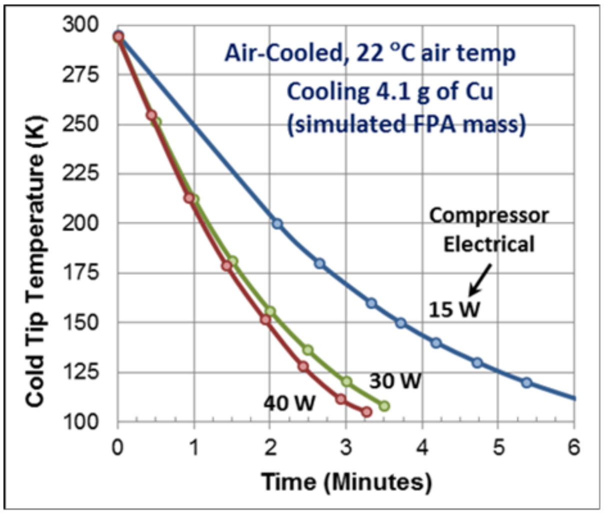

Figure 6: Measured cooldown of the Micro1-3 cryocooler for three different levels of compressor input power.

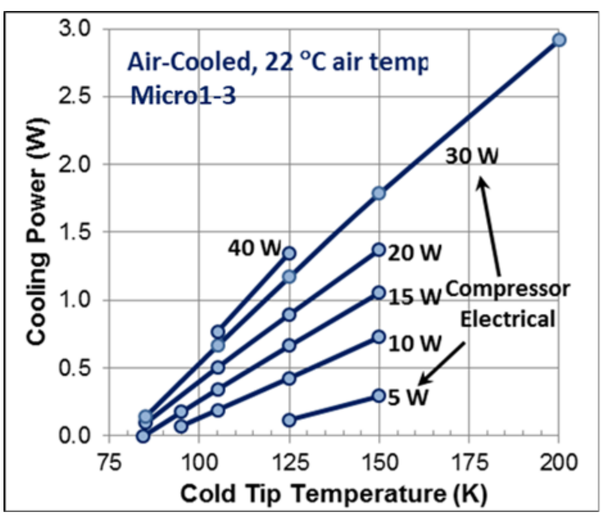

Figure 7: Cooling load lines for the Micro1-3 cryocooler. This cooler was designed for 0.3 W cooling at 125K, and requires 8 W electrical power.

Although this cooler was developed for a ground-based application, it incorporated a new, highly compact design which makes it ideal for use in small satellites. Specifically, the plenum volume was moved away from the end of the cold head and packaged in a toroidal volume around the cold finger, as seen in Figure 8. This packaging reduced the length of the cold finger from 12.5 cm to less than 6 cm. For IR camera applications, where the FPA is bonded directly to the cold tip, this reduction of more than 6 cm leads to in increase in allowed length of the optics of more than 6 cm, improving optical performance and leading to a better camera design. The same benefit can be achieved in small satellite instruments.

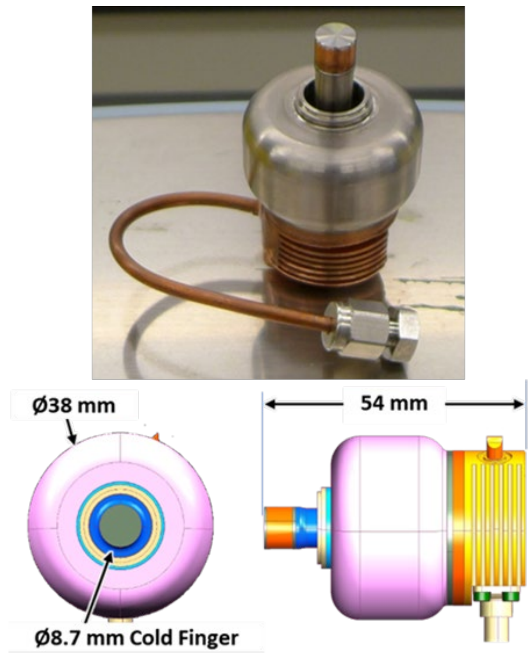

Figure 8: Micro1-3 cold head configuration, showing the highly compact packaging.

The Micro1-3 cryocooler has not yet found a space customer, has not undergone thermal cycling testing or launch vibration testing, and is currently at TRL 5.

COMMON ROBUST MICROCRYOCOOLER CHARACTERISTICS

All three models of microcryocooler have common characteristics that make them well-suited for small satellite applications requiring long lifetime and high reliability. The microcryocoolers use the same compressor, and more than 15 such compressors have been built and tested, leading to a proven and reliable assembly process. Similarly, the different cold heads use the same manufacturing techniques and have also been proven to be highly reliable.

Short lifetime missions such as student demonstration CubeSats and technology demonstration and maturation flight missions can reasonably use tactical Stirling cryocoolers to cool instruments for operational mission lifetimes of 6 months or possibly longer. Tactical coolers are cheaper and faster to procure. But real science missions almost always have operational lifetimes of several years or more, requiring a space cryocooler with high reliability. Furthermore, real science missions often have secondary environmental requirements which tactical coolers may be unable to meet.

Two examples of challenging environmental conditions are requirements from the MISE and Psyche cryocooler programs described above in the Micro1-2 section.

MISE Environmental Requirements

The MISE instrument being built by JPL for the Europa Clipper will perform IR imaging spectroscopy of the Jovian moon Europa, to perform chemical analysis of the surface during a series of dozens of flybys. The Jovian environment presents many challenges, including very high radiation levels, and the cryocooler must be located near the IR spectrometer in a lightly shielded portion of the spacecraft. Consequently, exposure to 500 kRad of radiation while operating was required (which includes a radiation design factor of two), and successfully tested by JPL, before allowing the cryocooler to be used for MISE. Furthermore, the ambient temperature at Jupiter is very cold (though not quite cold enough to allow passive cooling of the spectrometer to 85K), and the cryocooler must be able to survive operation at temperatures between 140K and 300K, and must also survive dozens of non-operational cold soaks to 140 K. The author is unaware of any cryocooler other than the LM microcryocoolers capable of such extreme ambient temperature survivability.

Psyche Environmental Requirements

The Gamma Ray Spectrometer being built by JHU/APL for the Psyche asteroid mission will perform gamma ray spectroscopy of the asteroid 16Psyche in order to measure what elements are present in the asteroid. The spectrometer uses a large single crystal of germanium, which has a measurable response to different gamma ray energies. However, sensitive measurements require high crystal quality, and the crystal is constantly being damaged by cosmic ray strikes. This requires the crystal to periodically undergo annealing at temperatures above 105°C. Stirling coolers, with moving parts at the "cold" end are much more prone to problems related to warming the cold end to elevated temperature, and this could prevent some types of Stirling coolers from being used at all for this instrument, while others may not be able to turn on, even at low power, with the cold tip at high temperature, requiring a long slow drift back to ambient temperature before being able to start the cryocooler. Since the pulse tube cooler has no moving parts in the cold head, it can easily survive elevated cold tip temperature and can be powered on even with the cold tip above 105°C.

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