Small Scale Cooler - Improvements

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ABSTRACT

The Rutherford Appleton Laboratory (RAL) has previously developed a small scale cooler targeted at providing low cost active cooling at 77 K for small missions. The particular focus of that initial development was to simplify and miniaturize heritage technology whilst maintaining life and reliability and reducing manufacturing costs. The production and extension of that cooler into adjacent markets by Honeywell-Hymatic was presented at the ICC19.

In the current paper we present recent developments focused on improving the thermal performance of the encapsulation and improving the accommodation and integration of the cooler into typical small mission instruments.

INTRODUCTION

The economics of space is changing rapidly; unprecedented access and exciting opportunities are arising from the availability of auxiliary launch opportunities, low cost commercial operational platforms and instrument components. However, conspicuously absent from the increased capabilities of small satellites, is the availability of reliable long-life, low cost, active cooling. Development of mechanical cryocoolers for space applications has been driven to underpin the requirements of high profile and increasingly complicated scientific missions, and as a result, they are generally prohibitively expensive for low cost missions. The objective of the Small Scale Cooler development is to address this by providing access to active cooling in the 77 K range for small low powered detectors at a price several orders of magnitude below the larger bespoke space cryocoolers, but whilst retaining their life and reliability.

An initial prototype, demonstrating miniaturization whilst retaining the heritage of life and reliability, was presented at the Space Cryogenics Workshop ESTEC in 2013.[1] The production and extension of that cooler into adjacent markets by Honeywell-Hymatic was also presented at the ICC in 2016.[2] Here we present the progression of the vision of a cheap product for space, by demonstrating a prototype in a relevant environment. The focus of this phase of the development is on an encapsulation appropriate to a space environment, with an emphasis to improve the accommodation of the cooler into typical instruments for small missions, and to address thermal and mechanical aspects not covered by the original development. Advantage has been taken of the modular nature of the SSC design by reusing motor mechanism modules that were used for the original development.

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RECOMMENDATIONS FOR ACCOMMODATION AND INTEGRATION

Key to this development is that the cooler must be as versatile as possible in order to be useful for a wide variety of missions and instruments without additional customization. Also, for low cost missions in particular, it is important that the cooler does not have a significant impact on either the instrument or the satellite at system level and as part of this, a review of previous missions utilizing small single-stage Stirling or Pulse Tube Coolers was undertaken.

Many of these civil missions feature 'tactical' cryocoolers that are known[1] to have flown in orbit for military applications. These single stage Stirling and Pulse Tube coolers are generally designed to be compatible with the Standard Advanced Dewar Assemblies (SADA's), developed and standardized by the US Department of Defence. Although there are mismatches in architecture and requirements that can require significant cooler customizations, an increase in their reliability in recent years, combined with cost and schedule constraints on space programs, have led to consideration of using the most suitable of these coolers for civil space missions and some effort is currently underway to adapt and qualify such coolers[4,5], in many cases making use of an Integrated Detector Cooler Assembly[6] (IDCA) as a variant adaptation of the SADA used for military applications.

Several tactical cooler manufacturers, notably AEG Infrared-Module (AIM) and Sumitomo Heavy Industries (SHI) have made recent adaptations of their linear-motor tactical coolers for space applications. AIM supplied the Infrared Imaging System instrument[5], with coolers, for the Korean KOMPSAT-3A Satellite in 2015 and also for the Hyperspectral Imaging Instrument[5] as part of the German EnMAP mini-satellite to be launched in 2020. SHI have supplied cryocoolers into the Japanese space program as part of the cooling chain for the X-Ray Spectrometer instrument[7,8] on the SUSAKU satellite in 2005, for the Gamma Ray Spectrometer[9] on the KAGUYA Lunar orbiter in 2007 and the Mid-Wave Infrared camera[10] of the AKATSUKI Venus orbiter in 2010.

Earlier, the US Ballistic Missile Defence Organization (BMDO) made use of Ricor rotary-motor tactical cryocoolers in space[11] , notably the Near Infrared CCD camera on the Clementine Lunar orbiter in 1994, the MSTI (Miniature Sensor technology Integration) series of satellites and also made use of the Texas Instruments tactical cooler as part of the STRV (space Technology Research Vehicle) series of satellites.[12,13] Other notable uses of the Ricor rotary tactical coolers in space[14] include the VIRTIS instrument[15] on ESA's Rosetta comet rendezvous spacecraft in 2004, the NASA gamma ray detector instrument[16] on the Messenger mission to mercury in 2004, the CRISM instrument[17,18] on NASA's Mars Reconnaissance Orbiter in 2005, the SPICAV imaging spectrometer[19] on ESA's Venus Express in 2005. In addition one was also used for the CheMin x-ray analyser[20] on the NASA Curiosity Mars Rover in 2011 and one is aboard the NOMAD spectrometer[21] on the Trace Gas Orbiter as part of the first ESA ExoMars program.

Examining the instruments referenced above in detail, several common approaches to accommodation and integration that meet the requirements of both the instrument and the coolers were evident. The majority of 'space cryocoolers' are of the split type, i.e. separate compressor and cold head units linked together with a gas transfer line. This works very well for larger coolers and provides a great deal of flexibility for accommodation in a large spacecraft or instrument where there may be some distance between cold and warm parts. However the benefits of this approach are not necessarily retained as the cooler size is decreased, primarily because of the mass penalty associated with each unit requiring its own interfaces and also since cold and warm parts are more likely to be in close proximity in small instrument architecture.

It is common for an instrument baseplate to also act as a radiator for heat rejection; and in these circumstances the cooler is usually mounted directly to the baseplate, frequently with the use of a dedicated bracket. In many cases extra thermal links between the cooler and the baseplate, with an associated mass penalty, are also needed to effectively remove the heat from the cooler. This is typically because the cooler body has been constructed from Titanium, which has a relatively poor thermal conductivity, or in the case of tactical coolers because convection cooling was envisioned for terrestrial applications. The use of a high conductivity material such as aluminium-alloy was recommended in order to render extra thermal links as unnecessary in those situations where the mounting bracket is not the limiting factor.

Some applications were identified where the cooler, or at least the cold head, is situated remotely from the radiator and linked to it via a heat pipe. Under these circumstances the mechanical interface is often an isolating thermal interface, such that the heat is not directed into the instrument bench. Separate thermal and mechanical interfaces are likely to be useful in this configuration, although it is conceivable that a bracket could be mounted under the heat pipe. A minimum of two interfaces was therefore recommended, and for maximum flexibility either of these interfaces should be able to act as a mechanical or a thermal interface or both simultaneously. These interfaces could be located on any convenient facet of the main body of the integral cooler.

For those instruments that have made use of an IDCA, the dewar is attached to a flange at the base of the cold finger to provide an evacuated enclosure around the detector. In addition several examples of an architecture in which the cold finger protrudes through the instrument bench or enclosure were identified. In this case a mechanical interface is required on the cold finger face of the cooler body, and this may also be required to double as a vacuum interface. For maximum flexibility this interface should also act as a thermal interface.

In general the detector is supported from the instrument bench separately from the cooler. This affords precise alignment when necessary, and also control of that alignment upon cooldown, but also because the cooler cold finger is extremely limited in its ability to support side loads. In the case of an IDCA the array is often bonded directly to the cold finger but the dewar and cold shield must be supported from the base. Flexible thermal links are therefore ubiquitously employed to thermally attach the cold finger to the detector whilst providing good mechanical isolation. The links are typically fastened at the interfaces; note that there can be significant thermal resistance at such an interface, which is largely dependent upon the force applied and the surface preparation, and therefore provision of a suitable area with sufficient fasteners to make a good thermal joint was recommended.

DESIGN DESCRIPTION

The prototype cooler is shown in Figures 1a and 1b, which highlight the main features. All of the recommendations described above for accommodation and integration were able to be implemented for this development of the encapsulation and in addition we were also able to incorporate a dedicated electrical connector for thermometry and housekeeping sensors which comprise a nominal and redundant PRT at the cold end, a survival thermistor on the body and a test heater at the cold end (these are removed, along with the launch tube, in Figure 1b for clarity).

The cooler comprises an opposed pair of moving magnet linear motor flexure bearing compressor mechanisms and a single moving magnet linear motor flexure bearing displacer mechanism, orthogonal to the compressor axis. The displacer can also be driven pneumatically without significant change in perfor-

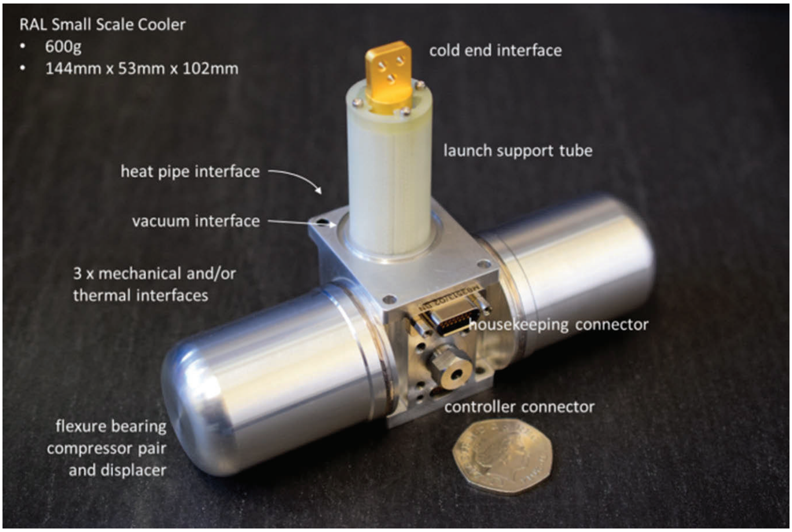

Figure 1a. RAL Small Scale Cooler

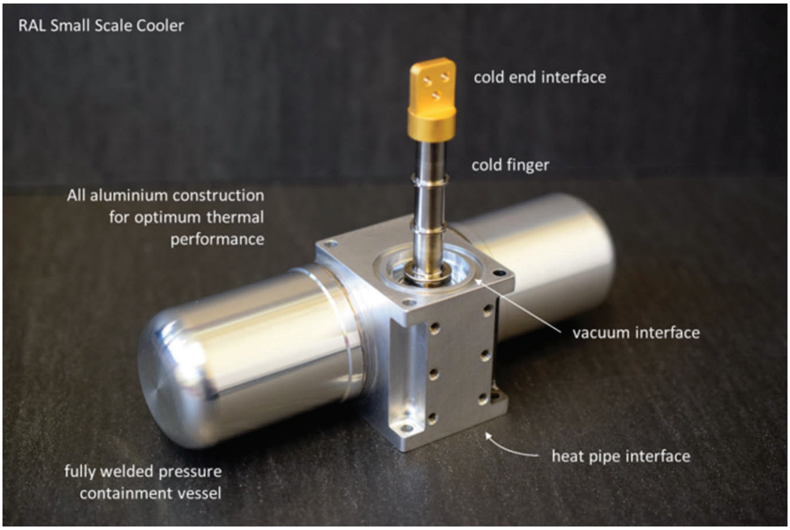

Figure 1b. RAL Small Scale Cooler without launch tube (for clarity).

mance. The body acts as a focal point for integrating these mechanisms with effective heat transfer to the rejection interfaces and an accurate register for alignment of the opposed compressor mechanisms. The pressure containment covers and all electrical connectors are of fully welded construction.

The cooler is fully modulating in that the input power may be adjusted by altering the compressor stroke amplitude at constant frequency, with a corresponding change in the cooling power. It is also possible to operate the mechanisms over a range of frequencies from 85 Hz to 95Hz without severely compromising the efficiency.

DESIGN AND ANALYSIS

Material Selection and Weld Development

Extraction of the electrical input power as heat requires a good thermal path through the cooler to the rejection interfaces. This becomes more difficult as the scale of the cooler is decreased and the cross sections of these thermal paths are reduced. Therefore the use of aluminium-alloy for the cooler body is attractive because of its low density as well as its high thermal conductivity.

In contrast, the cold finger is constructed from a low thermal conductivity material with as thin a cross-section as is practical to thermally isolate the heat rejection interface from the heat lift interface. Grade 5 titanium-alloy is a common choice of material for space coolers and one with which RAL has extensive heritage; for cheaper terrestrial coolers stainless steel is often employed.

Welds or braises are considered essential jointing methods for the small scale cooler because of the severe mass penalties associated with the use of bolted flanges using pressure sealing technologies. However welding and joining aluminium-alloys to titanium-alloys or stainless steels can be problematic and a significant part of this activity was to develop and verify all of the welds and brazes needed for the pressure containment components of the cooler encapsulation.

For the cold finger to body weld it is not possible to weld titanium to aluminium directly in situ, using conventional methods such as laser, e-beam, MIG/TIG etc. Instead, explosive welding and friction welding were both tried, with friction welding being preferred due to better control of the procedure and due to some previous flight heritage.

An additional consideration for the cold finger to body weld is alignment tolerance. The non-contacting clearance seals in the cooler are of order 10-15 μm and it is important that this alignment is achieved during assembly and is maintained during operation in order to achieve life and reliability of the cooler. As part of the weld development a procedure was developed and verified to ensure the correct tolerances could be achieved during the welding process.

All the welds were developed by extensive use of test pieces with sectioning and microscope analysis to determine penetration depths. Mechanical analysis, informed by pull and burst test results, was carried out for each weld using multiplicative safety factors in accordance with ECSS requirements, and a positive margin of safety (MOS) was demonstrated in each case. Subsequent weld verification was carried out by proof pressure and leak tests, thermal cycling and thermal shock tests.

Mechanical Analysis

A full FEM suite of mechanical analyses of the cooler was undertaken with the environmental requirements from standard ESA requirements for cryocooler mechanisms and with multiplicative safety factors applied in accordance with ECSS requirements. The MOS were again demonstrated to be positive in all cases. One of the main concerns was the survival of the cold finger; this very thin walled tube should not be expected to be capable of surviving a launch without additional support to limit the deflection of the cold finger under the mechanical loads and with an additional attached mass of a flexible thermal link.

The analysis included the following: a structural analysis evaluating the pressure containment components and welds, a quasi-static analysis evaluating the response to a 25 g load in all three coordinate directions, a modal analysis identifying the Eigen-frequencies up to 3000 Hz, a random vibration analysis under 13.1g rms acceleration in all three coordinate axes and a launch lock analysis evaluating the effectiveness of restraining the motor mechanisms by shorting their drive coils. For the compressors the displacement was shown to be constrained well within the maximum stroke capability. For the displacer the analysis indicated the possibility that the displacer may just make contact with its end stops; a metal-to-plastic interface designed to reduce the shock loading from such contact.

Thermal Analysis

A full thermal analysis was carried out as part of the original development[1] which highlighted concern at the hot end of the operating range (+50°C) due to the use of titanium for the body; the displacer motor shaft clearance seal begins to close as the temperature is increased due to CTE mismatches. This constrains the rejection interface to be close to the base of the cold finger, where the seal is located. However the use of aluminium-alloy for the new cooler encapsulation brought several clear benefits. In particular the reduction in thermal gradient across the body gave sufficient margin at the maximum operating temperature and gave freedom to locate the thermal rejection interface at any surface on the body.

TEST RESULTS

Characterization and acceptance tests were carried out as part of the build process. Performance tests were carried out in a dedicated test bench with the cooler under a vacuum environment and control of the rejection temperature.

Multi-layer-insulation (MLI) was added around the cooler cold finger under the launch support tube and also around the cold end interface to reduce radiative loads. All thermometry and housekeeping sensors are available from the test bench, as well as all mechanism drive waveforms. Laboratory dive electronics were used to control the cooler.

A reference point for the cooler performance was taken prior to and subsequent to mechanical environment tests to ensure no change had occurred.

Mechanical Environment Tests

The cooler was subjected to high-level sine and random vibration tests in all three axes according to typical ESA specifications given in Table 1. As is standard practice, a low-level resonance scan was performed between each high-sine/random run in order to detect changes in the structural integrity of the

Table 1. Mechanical environment test specification

Environment	Value
Quasi-static load	25g in 3 axes
Sine vibration	5-25Hz at +/-10mm; 25-100Hz at 25g in 3 axes
Random vibration	13.1g rms in 3 axes

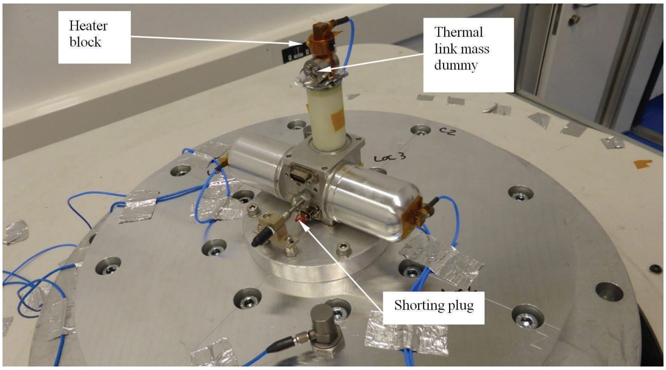

Figure 2. Vibration test set-up (z-axis, out of plane configuration is shown)

cooler. In addition short functional tests were performed to verify the cooler health between each vibration test.

Figure 2 shows the cooler mounted to the vibration table. An additional mass of 42 g was fitted to the cold tip to be representative of a typical thermal link that would be used with the cooler. Tri-axial accelerometers monitoring the cooler response are mounted on the compressor covers (#1, #2) and on top of the heater block (#3). The three motor coils are all shorted to limit motion of the mechanisms as for launch lock.

Lateral motion of the cold finger is the main concern in the x and y-axes. Modal analysis predicted the first lateral mode of the cold finger at 177 Hz and this was seen at 180 Hz on the resonance scans, see Figure 3a. A second resonance at ~1500 Hz that was not identified in the analysis was also evident in both x and y directions; this was suspected to be due to the interaction of the cold finger and launch support tube which could not be fully captured in the modelling.

In the z-direction, launch lock analysis predicted that the displacer would contact the end-stops, which are designed to reduce the shock loading from such contact, although due to uncertainty of the gas damping coefficient this was unclear. It was not possible to discern this from the accelerometer data, but during both the high-sine and random runs, a slight tapping noise could be heard suggesting this was indeed the case. The resonance seen in the cold finger at ~1500 Hz in Figure 3b is the result of a very small 'bellows' type movement permitted in the titanium-titanium weld preparation at the base of the cold finger.

Resonance scan responses were very stable between each high sine and random vibration test run indicating that there was no structural damage to the cooler. The short functional tests, operating the

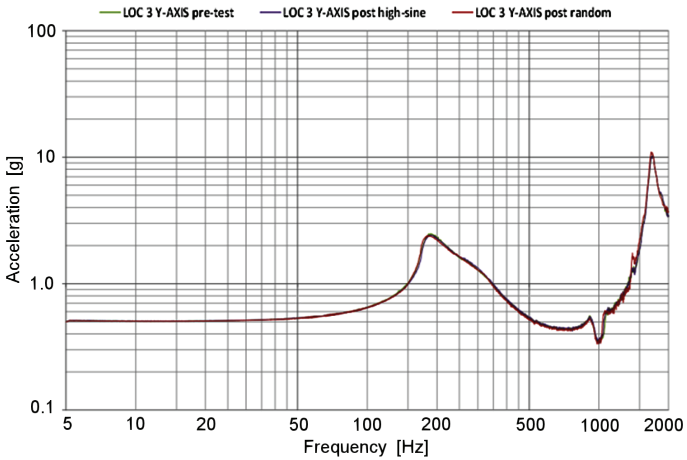

Figure 3a. Comparison of y-axis response of accelerometer #3 pre-test, post-high-sine and post-random response; there is no decernable difference.

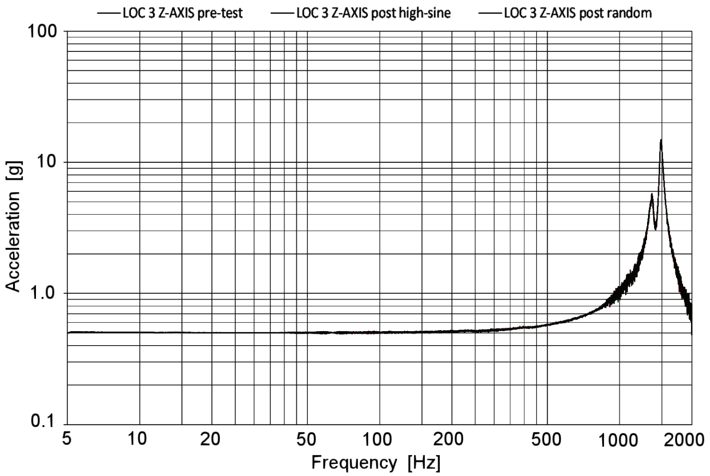

Figure 3b. Comparison of z-axis response of accelerometer #3 pre-test, post-high-sine and post-random response; there is no decernable difference.

cooler at nominal strokes to verify cooler health showed no differences between each of the vibration runs. Similarly the comparison between the pre- and post- vibration reference test showed no significant difference in the cooler performance.

Performance Tests

A load line and performance map of the cooler, taken after the vibration test campaign, are shown in Figure 4.

The new cooler has the same performance as for the previous development if a comparison is made with the base of the cold finger, at the joint with the body, at the same temperature. This is expected since the motor mechanisms were reused, but it is a final verification that the cooler has successfully passed mechanical environment tests and also that the launch support tube assembly has not compromised the thermal performance of the cooler.

However a benefit of using aluminium-alloy for the cooler body is the freedom to locate the rejection interface anywhere and this is demonstrated in Figure 5 which shows the performance of the previous cooler, SSC_004, and this current development, SSC-006, as a function of rejection temperature, with the rejection interface at the underside of the body. The input power is 22 W and a heat load of 500 mW

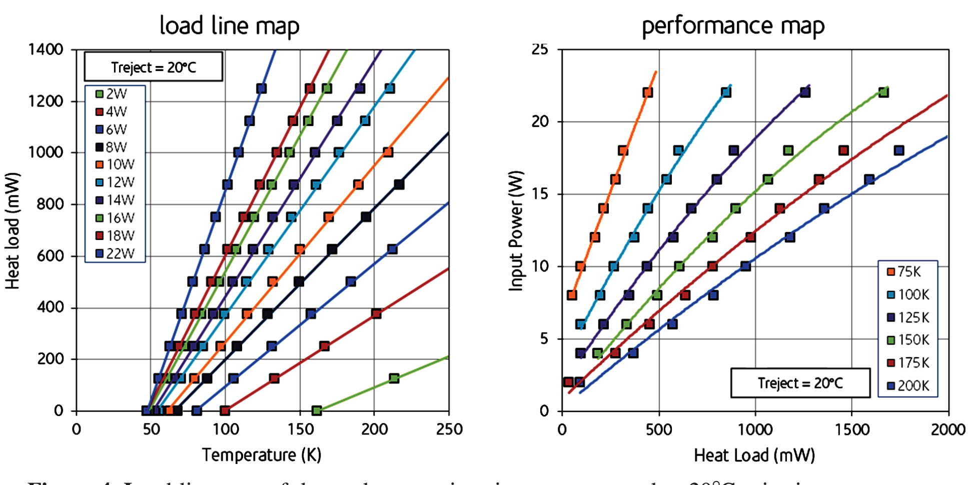

Figure 4. Load line map of the cooler at various input powers and at 20°C rejection temperature

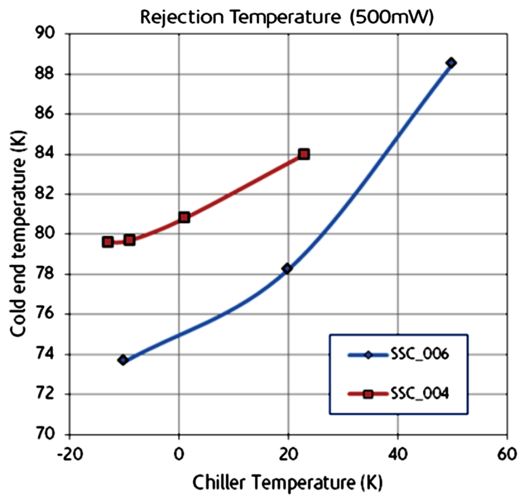

Figure 5. Comparison of performance using aluminium (SSC-006) and titanium (SSC-004) as the cooler body material

is applied at the cold end in each case. The improvement is obvious from the plot; the temperature gradient across the cooler body being significantly less and resulting in a cold end temperature approximately 6 K lower, corresponding to an equivalent improved heat load at 77 K of 100 mW.

A further improvement from using aluminum-alloy for the body material is that the hot operating range of the cooler is significantly extended. Ring-down tests were carried out for each of the mechanisms at 20°C, 50°C and 70°C, and no increase in friction was noted.

SUMMARY AND FURTHER WORK

Improvements have been made to the Small Scale Cooler focusing on providing an encapsulation which is appropriate for a space environment. The interfaces have been designed for accommodation and integration of the cooler into small instruments and to be as versatile as possible in order to offer flexibility for a wide variety of missions and instruments without customization and without impact at system level.

The cooler has successfully passed mechanical environment tests representative of a launch environment without any degradation of performance.

Some improvement in the cooler performance has been realized due to the use of aluminium alloy; the cold tip temperature is reduced for given operating conditions and the hot operating limit of the cooler has been extended.

At present the cooler is able to provide 500 mW of cooling power at 77 K with a total input power of 22 W, a future development will target 750 mW at 77 K. As part of that, a dedicated Small Scale Cooler drive electronics is currently under consideration to provide the power, drive, and control functions. This drive electronics will be appropriate for a space environment and will be commensurate with a low cost, low mass and high efficiency cooler.

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REFERENCES

1. 5th European Space Cryogenics Workshop, ESTEC 16th Dec 2013

2. Iredale et al., "Small Scale Cooler: Extending Space Developed Technology into Adjacent Markets," *Cryocoolers 19*, ICC Press, Boulder, CO (2016), p. 105.

3. Yi et al., “Tactical Cryocooler Vendor Survey:2015,” *Aerospace Report* No TOR-2015-02442.

4. Johnson, D.L et al., “Integrated testing of the Thales LPT9510 pulse tube cooler and the Iris LCEE electronics,” *Adv. in Cryogenic Engineering*, vol. 59A (2014), p. 1806.

5. Mai et al., “Status of AIM Space Cryocoolers,” *Cryocoolers 19*, ICC Press, Boulder, CO (2016), p. 161.

6. Raab et al., “Integrated Detector Cooler Assembly for Space Applications,” *Cryocoolers 17*, ICC Press, Boulder, CO (2012), p. 525.

7. Kelley et al., “The Suzaku High Resolution X-Ray Spectrometer,” *PASJ*, Vol 59, No.SP1 (2007), p.77.

8. Narasaki et al., “Development of Single Stage Stirling Cooler for Space Use,” *Adv. in Cryogenic Engineering,* Vol 51B (2006), p. 1505.

9. Kobayashi et al., “Germanium detector with Stirling cryocooler for lunar gamma-ray spectroscopy,” *Nucl. Instrum. Meth. A,* Vol 548 (2005), p. 401.

10. Satoh et al., “Development and in-flight calibration of IR2: 2-ìm camera onboard Japan’s Venus orbiter, Akatsuki,” *Earth, Planets and Space*, Vol 68 (2016), p. 74.

11. Moser et al., “The Qualification and Use of Miniature Tactical Cryocoolers for Space Applications,” *Cryocoolers 9*, Plenum Press, New York (1997), p. 905.

12. Glaser et al., “STRV Cryocooler Tip Motion Suppression,” *Cryocoolers 8*, Plenum Press, New York (1995), p. 455.

13. Cawley et al., “The Space Technology Research Vehicle 2 Medium Wave Infra Red Imager,” *Acta Astronautica* Vol 52 (2003), p. 717.

14. Riabzev et al., “Overview of RICOR tactical cryogenic refrigerators for space missions,” *SPIE 9821*, (2016) 98210Q-1.

15. Coradini et al., “VIRTIS: An Imaging Spectrometer for the Rosetta Mission,” *Space Science Reviews,* Vol 128 (2007), p. 529.

16. Goldsten et al., “The MESSENGER Gamma-Ray and Neutron Spectrometer,” *Space Sci Rev*, Vol 131 (2007), p. 339.

17. Murchie et al., “Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO),” *J Geophys Research,* Vol 112 (200&), E05S03.

18. Bugby et al., “Cryogenic diode heat pipe system for cryocooler redundancy,” SPIE 59040Z-1 (2005).

19. Nevejans et al., “Compact high-resolution spaceborne echelle grating spectrometer with acousto-optical tunable filter based order sorting for the infrared domain from 2.2 to 4.3µm,” *App Optics*, Vol 45 (2006), p. 5191.

20. Johnson et al., “The Ricor K508 Cryocooler operational Experience on Mars,” *Adv in Cryo Eng,* AIP 1573 (2014), p. 1792.

21. Neefs et al., “NOMAD spectrometer on the ExoMars trace gas orbiter mission: part 1—design, manufacturing and testing of the infrared channels,” *App Optics*, Vol 54 (2015), p. 8494.