Development of Cost Effective Cryocoolers for Space

R. Arts[1], T. Benschop[1], P. Bruins[1], T. Rijks[1], G. de Jonge[1], T. Trollier[2]

[1]Thales Cryogenics BV, Hooge Zijde 14, 5626 DC, Eindhoven, NL
[2]Absolut System SAS, 5 bis rue du Champlars, 38240 Meylan, FR

ABSTRACT

In the past two decades, flexure-bearing technology has gained a firm footing in the tactical cryocooler market. This has dramatically increased the reliability of COTS (commercial off-the-shelf) systems, making them a viable choice as cost-effective cryocoolers for space missions.

Thales Cryogenics is currently involved in several projects to develop cryocoolers suitable for space applications based on its tactical heritage. An overview is presented of COTS activities for space applications now running such as the use of flexure bearing Stirling and pulse tube coolers. In the presentation, design concepts and choices will be discussed. Furthermore, performance graphs of the optimized cryogenic cooler performance as well as an assessment of the product robustness will be presented.

INTRODUCTION

In the past, there was a seemingly insurmountable gap between the level of manufacturing control of a space cryocooler and a cryocooler for the tactical or commercial market. The high reliability and traceability requirements of a space application have driven these controls and the cost. However, cryocoolers produced for tactical applications have reached a level of process control and reproducibility that opens up the debate: how insurmountable and wide is the gap, between “space” level process controls and normal off-the-shelf production?

For space applications, cryocooler replacement is, for obvious reasons, not an option, which is why the space cryocooler has been designed and produced to reach an extremely high probability of survival. Various strategies and paradigms exist to increase the cooler survival probability in a given mission, such as the use of dual redundant cryocoolers [1]. However, due to the added mass and cost of a second cryocooler, adding a second cooler is not always practical.

Therefore, controlling failure mechanisms is of paramount importance. Much of this can be achieved by making the correct design choices and by sufficient verification of manufacturing and assembly steps.

One example of designing to eliminate failure mechanisms is the pulse-tube cold finger. The absence of moving components inside these cold heads effectively removes failure mechanisms related to mechanical wear.

Cryocoolers 18, edited by S.D. Miller and R.G. Ross, Jr.

For components where eliminating moving parts from the design is not possible or not practical, the use of flexure bearings has resulted in significant advances. The linear flexure bearing compressor where pistons are suspended in flexure bearings is preferred by many, as this design results in essentially wear-free operation.

Around the turn of the century, flexure bearings started to become viable for use in tactical cryocoolers as well [2], leading to a steady increase in design lifetime and proven reliability [3]. Furthermore, series production of flexure-bearing compressors for tactical cryocoolers has resulted in a rapid increase in control over the tactical-grade production processes and designs, increasing the reliability of standard commercial-off-the-shelf tactical cryocoolers to a level where they become a viable option for space missions.

This was recognized by several major players over the past decade (see e.g. [4]). In this paper, we present past and present highlights in the development of space cryocoolers based on tactical cryocoolers at Thales Cryogenics. We start by exploring the differences in technical requirements, followed by a number of examples.

REQUIREMENTS

Many different cryocooler aspects can be compared between space applications and tactical applications, but we will restrict the discussion below to two key differences: reliability and heat lift.

Reliability

In the introduction, we already explored a key requirement for both space and tactical cryocoolers: reliability. The figure of merit quoted for tactical cryocoolers is MTTF (mean time to failure). This figure signifies the number of hours until 63% of a cryocooler population will have failed. For the tactical cryocooler, this is a useful figure of merit, as a relatively large failure rate can be accepted as cryocooler replacements can be performed. For a space cryocooler, a much smaller failure probability over the mission life is required.

This means that, while the same MTTF figure can be stated as a requirement for a space cryocooler, the failure probability that is acceptable for a space cryocooler is much lower. This means that a higher MTTF is required, to ensure a low failure probability during mission life.

A high MTTF is accomplished by process control, part inspections, inline inspections and tests. All these aspects have matured significantly over the past decade for tactical cryocoolers.

Heat lift

In the tactical market, power density (heat lift versus mass or volume) is a key driver. For a traditional tactical infrared application, a sensor needs to be cooled down to operating temperature as fast as possible with a cryocooler fitting into a space envelope or mass constraint [5].

In contrast, for a space cryocooler there is usually a challenging power budget. This means that for a space cryocooler the specific power (W of electricity per W of cooling) is a much more important requirement.

In recent years there has also been a drive to decrease the specific power of tactical cryocoolers to a point where they now are coming close in efficiency to their space counterparts. Simple changes in materials (Titanium on Inconel) could be applied to tactical cryocoolers to increase efficiency.

ADAPTING A COMMERCIAL DESIGN TO SPACE: THE LSF9330

For Thales Cryogenics, a significant milestone in adapting off-the-shelf technology to the requirements of a space program was the LSF9330 cryocooler. This cryocooler, developed for the ESA CRYOSYSTEM vial freezers on board the International Space Station [6], was based on the LSF9320 Commercial Off-the-Shelf cryocooler. This resulted in a relatively

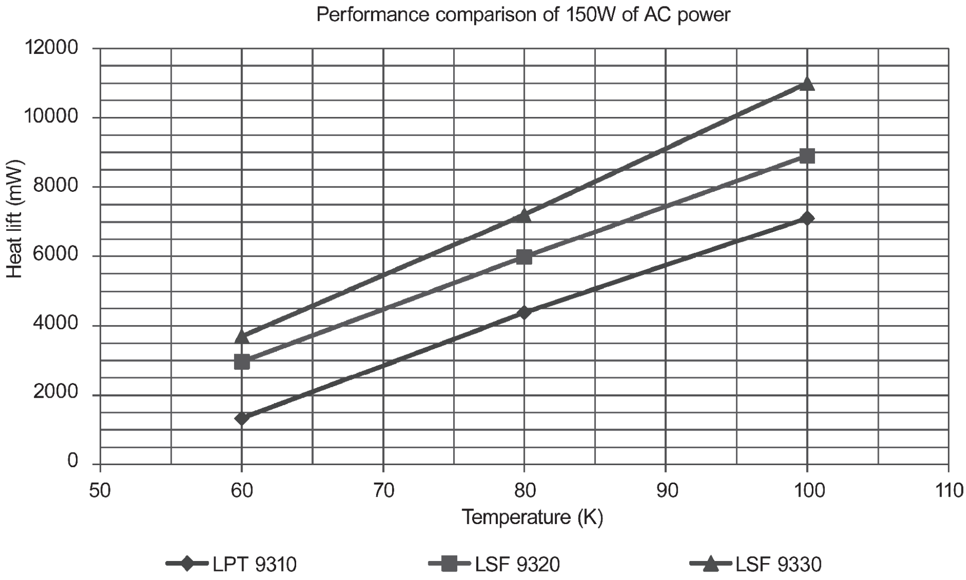

Figure 1. Load curves of LPT9310, LSF9320, LSF9330

straightforward development strategy. A number of design, qualification and manufacturing changes compared to the LSF9320 are listed below:

- The displacer was mounted on flexure bearings to achieve no-wear operation
- All flexures were subjected to over-stroke tests to verify robustness
- The NASA MAPTIS system was used to reevaluate all materials used in the cryocooler
- To improve the specific power, the displacer was changed to a pneumatically-driven design. The effect can be seen in Figure 1.
- To reduce parasitic losses, the cold finger was changed to Ti6AlV4
- Internal heat sinking structures were implemented, enabling liquid cooling or direct heat pipe cooling.
- The compressor was built from Inconel 718 rather than stainless steel to increase all safety margins of the pressure containment vessel as required by, for instance, ESA ECSS standards

Furthermore, rigorous structural and thermal analyses were performed to ensure design compliance to the margins of safety required by ESA. While this cryocooler was never put into flight, four units were put into life testing at an operating profile significantly more severe than would be encountered in practice. All units are still running today, with over 9 years of operation accumulated per cryocooler and operating well beyond the required cooling performance [3].

For Thales, the LSF9330 provided a valuable exercise in mapping out the differences between normal production and space (ECSS) production. This experience was applied as well in the design and production of the MPTC and LPTC compressors, developed under ESA funding.

Reducing the cost and complexity of a space cryocooler design by making use of existing cryocooler concepts is therefore very viable. However, this still leaves the cost and complexity of qualifying all materials and processes according to a strict set of product assurance requirements, such as those put forward by ESA in the ECSS standards.

The next step in paving the way for a cost effective space cryocooler is therefore to find a suitable middle ground between fully qualifying all parts, materials and processes (PMP) in line with ECSS on the one hand, and applying previously qualified and practice-proven series production processes of the non-space cryocooler on the other hand.

The strategy we propose for cost-effective cryocoolers is to apply FMECA techniques to identify critical processes. By making a selection of processes to apply a full PMP qualification to, the cost and complexity of space cryocooler production is greatly reduced while still adhering to the spirit of low-risk high-reliability cryocooler production. This paradigm has been applied in the next example.

BUILDING A SPACE CRYOCOOLER FOR IDCA

The drive for lower-cost systems and the use of off-the-shelf products and heritage is present beyond just the cryocooler. In 2013, development was started at Thales Cryogenics supported by infrared detector manufacturer Sofradir [7]. A large part of Sofradir's business consists of the development and manufacture of Integrated Detector Cooler Assemblies (IDCAs) delivered to infrared system integrators. Sofradir identified a new need for space-compatible IDCAs, resulting in the development of a Thales space-compatible cryocooler based on existing proven off-the-shelf modules.

A number of key requirements for this cryocooler are highlighted below:

- The cryocooler should be suitable for cooling various large-format focal plane arrays, ranging from very long wave (VLWIR) detectors, typically operated at temperatures below 55 K, to short wave (SWIR) detectors, typically operated at temperatures above 140 K.
- The cryocooler should have a very high coefficient of performance
- The cryocooler should have a very high survival probability for multi-year missions
- The cryocooler should be based as much as possible on existing modules and proven design concepts

The Thales LSF9199 series was identified as a suitable baseline for this cryocooler. A key point in this choice is that this cryocooler is based on a ½" SADA-II compatible displacer design suitable for cooling large-format infrared detectors, greatly reducing the required design effort for the infrared Dewar. As life time and coefficient of performance are key requirements for this cryocooler, the displacer was changed to a pneumatically-driven flexure-bearing design, as was previously done with the LSF9330 cryocooler, taking advantage of the proven excellent reliability and performance heritage of the LSF9330.

While the cryogenic requirement for this cryocooler is not the 77 K or 80 K typical of a tactical infrared cryocooler, we present a comparison at 80 K nonetheless to show the impact of the pneumatically-driven flexure-bearing cold finger. Figure 2 shows measurements performed with

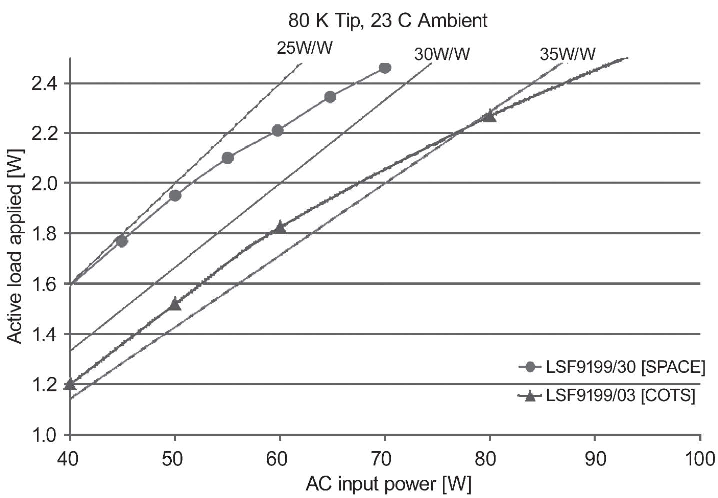

Figure 2. LSF9199/30 versus LSF9199/03. Specific power lines are also indicated in the graph.

a standard factory test Dewar. The quoted applied heat load is excluding the Dewar parasitics, active (resistor) load only. A drastic improvement was measured over the standard LSF9199.

The heavier pneumatic displacer does result in a larger net exported force. Various options can be considered for balancing the cold finger. One such option is using an active balancer driven from a control loop, regulating the vibration force along the axial direction of the cold finger. Though a Thales space-qualified cryocooler drive electronic solution is presently not available, vibration suppression results using Thales Cryogenics off-the-shelf electronics are presented in [8].

While the qualification effort for the LSF9199/30 cryocooler is still ongoing, results up to now indicate that performance requirements have been exceeded. Performances of the cryocooler excluding measurement dome parasitic leaks are shown in Figure 3.

The experiments and FMECA / reliability analyses performed so far show that the LSF9199/30 is a suitable candidate for cost-effective space cooling. The cryocooler stands its ground even in a trade-off against a cryocooler with a true space-grade compressor, such as the MPTC compressor developed under ESA TRP [9]. Even though the MPTC compressor has a higher electromechanical efficiency and was designed specifically to meet ESA ECSS requirements, the more cost-effective LSF91xx compressor is shown to exceed performance requirements, to have a comparable reliability and to be fully compatible with the launch- and space environment.

USING A TACTICAL CRYOCOOLER IN SPACE

While taking advantage of a tactical cryocooler design and production heritage for a space application can give a significant advantage, it is also possible to go one step further in what is sometimes called the “black box approach”.

This approach typically consists of the following strategy:

- A paper analysis is done on the compliance of an off-the-shelf cryocooler to a space requirement
- A risk analysis is performed and documented
- Three units are procured: one is subjected to stringent qualification level tests, while the other two are subjected to screening/acceptance level testing.
- Of the two units not subjected to qualification levels, one is kept as a spare and one is used as a flight cryocooler

While no details have been published on programs where this strategy has been used as many of them are US DoD sponsored, an example of this strategy is the TacSat-3 [10] satellite launched in 2009.

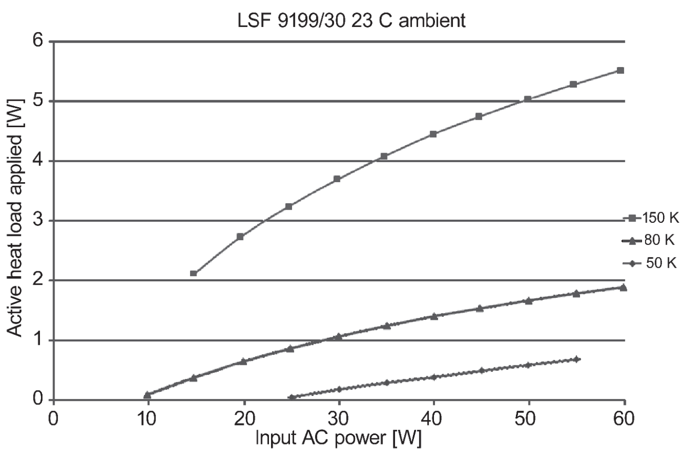

Figure 3. LSF9199/30 heat lift for various tip temperatures.

This paradigm is being expanded on further by, for instance, JPL [11] who are currently testing off-the-shelf pulse-tube cryocoolers for space use. A similar development can be applied to pulse-tube cryocoolers as with the free-displacer Stirling cryocoolers presented in previous sections. However, in the case of a Thales LPT-series pulse-tube cryocooler, an upgrade of design life is not required, as the design is already based on wear-free operation. The key area in which improvement is sought is therefore the cryocooler's efficiency. As presented earlier (see Figure 1), pulse-tube efficiency is still significantly below that of a comparable-sized Stirling cryocooler.

Thales has therefore started development on a high-efficiency pulse-tube cryocooler for space applications with a size comparable to the LPT9510 cryocooler but with a far superior efficiency, to be presented at a later date.

CONCLUSION

By taking advantage of existing building blocks and the maturity of tactical-grade cryocooler production, cryocoolers suitable for a wide variety of space missions can be produced at a fraction of the cost traditionally associated with space cryocoolers, provided close attention is paid to selecting the correct technology building blocks to fit a given mission profile.

REFERENCES

1. Ross Jr., R.G., “Cryocooler Reliability and Redundancy Considerations for Long-Life Space Missions,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 637-648.
2. Meijers, M., Benschop, A.A.J., Mullié, J.C., “High Reliability Coolers under Development at Signaal-USFA,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 111-118.
3. Van de Groep, W., "Update on MTTF figures for linear and rotary coolers of Thales Cryogenics," *Proceedings of SPIE* Vol. 8353 (2012), SPIE, Bellingham, WA.
4. Kirkconnell, C.S., and Ross, B.A., “Raytheon Dual-Use Long Life Cryocooler,” *Proceedings of SPIE,* Vol. 5783 (2005) , SPIE, Bellingham, WA, pp. 169-177.
5. Arts, R., "Deployment of tactical-grade COTS cryocoolers for space applications," *5th European Space Cryogenics Workshop,* Noordwijk, 2013.
6. Trollier, T. et al, "High Capacity Flexure Bearing Stirling Cryocooler On-Board the ISS," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 31-36.
7. http://www.sofradir.com .
8. Willems, D., “Developments in Advanced Cooler Drive Electronics,” *Cryocoolers 18*, ICC Press, Boulder, CO (2015), (this proceedings).
9. Trollier, T., “Miniature 50 to 80 K pulse tube cooler for space applications,” *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 165-171.
10. Silny, J., “Responsive Space Design Decisions on ARTEMIS,” *8th Responsive Space® Conference,* Los Angeles, CA, March 8- 11, 2010.
11. Johnson, D., et. al.,“Integrated Testing of the Thales LPT9510 Pulse Tube Cooler and the Iris LCCE Electronics," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), pp. 1806-1813.