Cryocoolers developments at Thales Cryogenics enabling compact remote sensing
A. Benschop, W. van de Groep, J. Mullié, D. Willems, O. Clesca
THALES Cryogenics BV, Eindhoven, the Netherlands

R. Griot, J-Y. Martin
THALES Cryogénie SAS, Blagnac, France.

ABSTRACT
Thales Cryogenics (TCBV) has an extensive background in developing and delivering long-life cryogenic coolers for military, civil and space programs. This cooler range is based on three main compressor concepts: rotary compressors (RM), linear close tolerance contact seals (UP), and linear flexure bearing (LSF/LPT) compressors. The main differences – next to the different conceptual designs - between these products are their masses and Mean Time To Failure (MTTF) and the availability prediction of a single unit.

New developments at Thales Cryogenics enabling compact long lifetime coolers – with an MTTF up to 50,000 hrs - will be outlined. In addition new developments for miniature cooler drive electronics with high temperature stability and power density will be described. These new cooler developments could be of particular interest for space missions where lower costs and mass are identified as important selection criteria. The developed compressors are originally connected to Stirling cold fingers that can directly be interfaced to different sizes of available dewars.

Next to linear coolers, Thales Cryogenics has compact rotary coolers in its product portfolio. Though having a higher exported vibration level and a more limited MTTF of around 8,000 to 10,000 hours, their compactness and high efficiency could provide a good alternative for compact cooling of sensors in specific space missions.

INTRODUCTION
Many of today’s applications require cryogenic temperatures of 80 K – 120 K with heat loads of typically less than 400 mW. These applications are often limited in terms of volume and mass available for the cryocooler. Therefore rotary monobloc Stirling coolers are often used in these applications. The main reason for this is that rotary coolers offer a very high efficiency in a limited volume and low mass. The Carnot efficiency of coolers is expressed as

$$n_{\text{Carnot}} = \frac{T_{\text{low}}}{T_{\text{High}} - T_{\text{low}}}$$

being the theoretically absolute maximum efficiency. Cooler efficiency is often expressed as a percentage of this maximum.

The relative efficiency of rotary coolers between 77 K and 296 K can be as high as 17 % of Carnot, whereas higher power linear coolers can reach 10 %-15 % of Carnot efficiency with lower efficiencies for linear coolers with a cooling power comparable with rotary coolers. However, disadvantages of high efficiency rotary coolers in comparison to linear Stirling coolers are the lower lifetime expectancy, higher acoustic noise, and higher induced vibrations. Therefore a program was initiated at Thales Cryogenics to develop, next to their extensive rotary portfolio, a miniature linear Stirling cooler that can offer an alternative for those applications where lifetime, vibration levels, and acoustic noise are the main drivers but still a compact lightweight cooler is required.

LIFETIME DETERMINING DESIGN CHOICES
Cryocoolers are mechanical systems and thus their lifetime and related reliability are directly linked to the design choices made in the definition phase of the coolers. For tactical cooler we categorize three kinds of compressor designs and two kind of cold finger principles. The compressor designs are rotary compressors, linear
compressor with contact between piston and cylinder, and linear compressors without contact between piston and cylinder. The cold finger principles are Stirling type cold fingers and pulse-tube cold fingers.

For small and compact systems the use of Stirling cold fingers above pulse-tube cold fingers is advised due to their higher efficiency [1] and compact size. Examples of pulse-tube coolers using Thales linear compressors developed dedicated for these space applications are discussed at past conferences [2] [3]. These products known as MPTC and LPTC are being commercially handled by Air Liquide France. In the sections below the most important design aspects of rotary and linear compressors will be addressed.

**Rotary compressors**

Rotary compressors convert the rotary motion of the DC brushless motor to the linear motion of the compressor piston by using a crankshaft and multiple ball bearings. In monobloc coolers both the compressor and cold finger are mechanically driven by the cooler main shaft enabling an optimal phase control between the two reciprocating movements. This compact concept guarantees a high efficiency of the cooling process (cycle?). Due to the high efficiency of this cooler concept the requirements for adequate heat dissipation are limited. Due to the geometrical constraint the coolers are able to withstand harsh mechanical environmental conditions such as vibration, shock, or temperature.

The piston and cylinder materials are chosen such that they can easily withstand the side loads on the surfaces in the applicable dry - not lubricated - conditions. Typically a hard coating on a hard metal surface is used with a very tight gap of only a few microns between piston and cylinder. The lifetime of the rotary coolers is, above all other criteria, determined by the negative effect of increased friction inside the ball bearings and/or the friction between the piston and cylinder.

The bearings used for these coolers are miniature bearings using a minimum amount of lubrication. Therefore these bearings have to be designed correctly and allow only a small margin of safety. For these specific miniature bearings only limited information is available with respect to the reliability prediction under the applicable lubrication, load conditions, and operating conditions as used in rotary cryocoolers. Thales Cryogenics has a long-term experience in designing these mechanical systems leading to a MTTF of more than 10.000 hrs.

The problem with respect to the interpretation of MTTF to reliability for space applications is the fact that for space missions the availability of the cooling performance during the time of the mission should be extremely high while normally the MTTF is evaluated based on a large quantity of coolers. This makes rotary coolers, although specifically prepared and screened for space missions, only suitable for mission where the cooling performance is required during a limited operational running periods, for example less than 2000 hrs. In such missions (applications?), the advantage of the rotary monobloc cooler is their high efficiency, robustness, and high cooling power to weight ratio [6].

Rotary monobloc coolers are available with a weight below 250 g within a space envelop of 89 x 42 x 74 mm. Thales Cryogenics rotary monobloc range is based on four main references: RM1, RM2, RM3, and RM4, covering an extended cooling power range and mostly dedicated for cooling IR sensors. The RM1 is a small size, low power cooler especially adapted for applications requiring intermediate cold temperature around 110 K. The RM2, RM3 & RM4 are designed to provide 77 K cooling for different cooler powers up to 750 mW. The RM3 is equipped with integrated digital driver electronics for accurate temperature regulation. Today, these devices are widely used in military tactical applications and may be suitable for space when reduced cooling powers are required.

**Contact seal linear compressor**

In low-vibration linear compressors the two opposed pistons are driven by linear motors. In these compressors the side forces on the pistons are generally lower compared to rotary coolers. A difference between rotary coolers and linear compressors is that rotary coolers use a fixed stroke and a variable frequency, while linear coolers are operated at a fixed frequency with variable stroke. In general the stroke of linear compressors is approximately a factor 4 larger compared to rotary coolers. This higher stroke leads to a much higher velocity between piston and cylinder. The relatively high velocity between the two surfaces defines the possible coating combinations which can be used in linear compressors. Thales uses in its linear coolers a coating that leads to (has proven?) operating lifetimes of more than 20.000 hrs for coolers generating 1 watt cooling power at 77 K.
To further improve the reliability performance of these linear coolers contact between piston and cylinder should be eliminated. In the design of these non-contact linear compressors other risks such as out-gassing of components or the use of flexible wires should be mitigated.

**Linear compressors non-contact seal**

A non-contact seal compressor could use magnetic, gas (rotating / linear), or flexure bearing support of (for?) the pistons. Thales Cryogenics has chosen 10 years ago for the use of flexure-bearing support of the pistons to avoid the contact between the piston and cylinder [5]. Flexure-bearing compressors are mechanically less complex compared to magnetic and rotating gas bearings. With respect to static, linear, gas bearings flexure compressors are less susceptible to contamination of the gas bearing orifices and valves and create no extra flow loss due to the DC flow required to generate the gas bearing effect.

Thales Cryogenics uses flexure bearings in its LSF Stirling and LPT pulse-tube cooler range. With the correct material selection and definition of the flexure bearings as well as using a dedicated mounting procedure compressors can be built with a very high reliability leading to reliability figures in excess of 50.000 hrs.

Design requirements needed for the correct definition of flexure bearing compressors have been highlighted in several publications [6], [8].

**Reliability definition**

Typically the reliability figures of civil or military coolers are based on a large number of delivered or tested products. For mass production and mechanical systems the Weibull characteristics can be used, determining the number of rejects (63%) based on an average reliability (the scale parameter) and the distribution of the number of operating hours until the product fails (the shape factor) [6]. This Weibull characterization can be used to define optimal repair or overhaul procedures to improve system availability. For space coolers, where only the reliability of a single or low number of unique products is requested, the Weibull characterization can be used to select designs for which a high shape factor and high reliability can be provided.

Another method for predicting the reliability of for example cryocoolers has been presented by Ross [7]. This method determines the potential lifetime of a cooler by accumulating the different failure modes with their risk of occurrence. Problem is that for cryocoolers - in contrast to electrical components - the determination of the risk criteria is far from trivial and only limited data is readily available.

The mean reliability determination for cryocoolers should thus be done by design; a correct FMEA and the application of the correct MAIT (Manufacturing, Assembly, Integration and Testing) procedures. Extensive intermediate quality assurance testing is required to achieve the requested reliability for space applications. Thales Cryogenics has used this philosophy in the design and manufacturing of a large 6 W Stirling cooler [8] which is still operating correctly in an accelerated life time test set-up, now running for more than 6 years in continuous mode.

The high reliabilities as demonstrated with flexure bearing coolers could allow for future use of standard commercially available cryo coolers manufactured with an extended build standard in space missions.

**LINEAR COMPRESSOR DEVELOPMENTS**

The starting point for any linear compressor development and thus also for compact remote sensing is the targeted mechanical power the compressor should be able to deliver. The mechanical power is the output power (pneumatic work) from the compressor, available for the cooling cycle. In the case for compact remote sensing a target nominal cooling power of around 400-500 mW at 80 K had been defined. It was chosen to set the required compressor’s nominal mechanical power at around 16 W. Secondly it was decided to choose the commonly used dual piston split Stirling cooler approach because of the low induced vibrations that are inherent to this concept.

This baseline information has been used for the definition of both a contact seal and a non-contact seal compressor. Both coolers have been designed to operate in full resonance meaning that the motor force only has to overcome the internal damping due to friction, gas flow, and of course the thermodynamic cooling cycle. Running the compressor in resonance condition maximizes the cooler efficiency and minimizes the phase shift between drive voltage and current. Using the resonance conditions as a starting point, the first design parameters such as piston diameter, piston amplitude, axial stiffness, system damping, and required motor force were established.

Under funding of the NSO¹ (PEP projects 2008-2009), two different types of linear compressors have been developed: a close tolerance contact seal compressor (UP8497) and a full flexure bearing supported non contact compressor (LSF9997). The outline dimensions of the resulting compressors are shown in the Figure 2.

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¹ Netherlands Space Office
Both compressors have been designed to match a ¼” IDCA cold finger. In Figure 2 a photograph is shown of the different types of compressors. The top compressor is the standard LSF95xx compressor with a diameter of 60 mm and a length of 122 mm. Below the LSF95xx the LSF99xx compressor is shown. The UP84xx compressor is shown at the bottom. The masses of the coolers have been measured at 855 grams for the LSF9997 and 580 grams for the UP8497.

**COOLER PERFORMANCES AND EFFICIENCY**

**Measured cooler performance**

After building and characterizing of the first compressors, both systems have been optimized in combination with a ¼” IDCA cold finger for maximum coefficient of performance (COP) and input power. The combination of maximum COP and maximum input power maximizes the produced cooling power. In order to increase the maximum input power of the cooler several options are available such as: 1) increase the internal system damping by changes in the cold finger design, 2) increase the compressor piston diameter, 3) increase the charge pressure and consequently operating frequency. The first two options can decrease the COP of the cooler and were already optimized during the design phase. Experimental work has lead to a drive frequency of 60 Hz, leading to an optimum in both cooler efficiency and maximum input power. The measured cooling performances are given in Figure 3 and Figure 4.

From these figures several observations can be made. Main difference in compressor efficiency is visible in the measured COP of the coolers. As both compressors are measured against a similar cold finger the difference in cooling power is caused by the slight difference in efficiency of the compressors.

**Cooler efficiency**

The cooler efficiency can be directly calculated from the measured performance. In Figure 5 the cooler efficiency is represented as a specific power (required input power in watts per watt of generated cooling power). A lower specific power means a higher efficiency. As comparison some average efficiencies of other tactical coolers available today are given. For reference, lines of constant relative Carnot efficiency are also shown. From this figure it can be seen that both miniature linear coolers offer a good COP that in the higher power cooling range can match the COP of a rotary cooler in the lower cooling power range. Moreover it is demonstrated that these new coolers also match linear Stirling cooler efficiencies that previously were limited to the higher power Stirling coolers such as SADAII coolers. This COP will result in steady state input powers of around 7-8 W in a typical ¼” IDCA dewar of around 200 mW which is typically sufficient for the cooling of small IR Focal Plane Arrays.
LIFETIME PREDICTION OF MINIATURE COOLERS

To investigate the reliability of the two miniature linear coolers several aspects need to be taken into consideration. First is the lifetime test data acquired on similar coolers. Design similarities enable the comparison with the newly developed miniature Stirling coolers. Second consideration is the progress made in the improved operating conditions of the coating materials used, both for the compressor pistons and Stirling expander. Final aspect to be considered for the lifetime prediction is the difference in the designs that can have an impact on lifetime.

The LSF9997 has a high similarity with the LSF91xx, LSF93xx and LSF95xx cooler families. These flexure bearing compressors have demonstrated lifetimes well over 70,000 hours under continuous or on/off operation and environmental thermal cycling. From the flexure-bearing cooler lifetime data it is demonstrated that the Stirling cold finger has become the limiting factor concerning lifetime as the moving expanders in the tested design still rely on contact bearings. The main difference of the expander contact bearings with contact bearings of a linear compressor is the bearing pressure. Typically the mass of a Stirling expander is a factor 10-20 less than that of the moving mass of a linear compressor resulting in much lower contact pressure and consequently less wear. Apart from the bearing pressure also the stroke of the displacer bearing is significantly lower.

During the last years Thales Cryogenics has been working on the implementation of improved bearing materials in both compressors and Stirling expanders. In addition to this new bearing material, improvements have

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2 It should be noted that for some applications flexure bearing suspended expanders can be used[8].
been defined to reduce the wear rate of this new material even more. Pin on disk tribological tests have been performed to quantify the improvement in wear rate possible and differences in coating hardness. The wear rate \( k \) (in \( \text{m}^2/\text{N} \)) has been measured with the existing coating material including the scratch depth caused by the pin on the moving metal disk. After that the improved coating material was measured under exactly the same conditions. It was found that the improved coating material has a 30% lower wear rate than the baseline material. Moreover the scratch depth caused by the coating material on the counter plate was found to be 20% deeper than the baseline test, clearly demonstrating an increased hardness of the bearing material resulting in significantly lower wear.

In order to assess the potential for lifetime of the UP8497 cooler the piston wear can be reviewed in more detail. Piston wear of a contact compressor is determined by the relation

\[
h = k_i p_n s,
\]

with \( h \) representing the coating wear, \( k_i \), the specific wear rate coefficient, \( p_n \) the normal contact pressure and \( s \) the sliding distance of the piston. The contact pressure is mainly caused by gravity acting on the moving mass and the piston surface area. In an attempt to translate the lifetime data of the existing UP7080 cooler to the new UP8497, both moving masses and contact surface areas can be compared. For this the pressure ratio and consequently coating wear ratio can be determined. This results in

\[
h_{\text{ratio}} = \frac{F_1}{A_1} \frac{A_2}{F_2} \approx 2
\]

This ratio indicates that with the newly developed miniature compressor in the expected worst-case position, which is compressor mounted horizontally, wear is expected to be a factor of 2 lower than the existing UP7080 compressor. The lifetime and wear characteristics of the UP8497 will of course be finally verified with lifetime tests. These tests will be initiated middle of 2010 with the first test data becoming available end of 2010.

Using the lifetime test data and the intermediate cooling performance data measured on these coolers, the average performance evolution over time of the different types of coolers can be plotted, as has been done in Figure 6. From this figure a gradual degradation of cooling power can be observed. For the flexure bearing coolers this degradation is of course much more gradual because of the absence of wear in the compressor. For the UP series of coolers the potential reliability improvement is plotted by using the improved Stirling expander coating material. This will not only lead to less degradation but also to a longer lifetime and most likely less variance in wear behavior. The same applies for the Stirling flexure bearing systems. Here the projected lifetime is much longer because the failure chance for the compressor is much lower than that of a close tolerance contact seal compressor.

Finally the projected curve for the miniature UP8497 cooler is given. This cooler will not only benefit from the coating improvements, but also from the lower coating pressure as outlined earlier. For the LSF9997 the same lifetime is expected as the existing flexure bearing Stirling coolers.

**COOLER DRIVE ELECTRONICS**

For the power input and temperature control of TCBV’s linear cryocoolers high-efficiency DC/AC converters are available. With this electronics, power conversion from a DC power source to a pure sine wave output for the cryocooler is obtained with an efficiency of more than 92%. Short-term temperature stability of less than 0.02 mV has been obtained with these converters. In the photograph below two of the new TCBV tactical converters are depicted. The footprint of this converter is 60x55x20 mm capable of delivering 100 Watt regulated output power.
Under an ESA TRP (contract number 16130/02/NL/JA) TCBV demonstrated its capability - using in-house knowledge - to develop cooler drive electronics that decreases the vibration output of the cooler. This electronics has been under production for application in a civil application based on DSP technology and analogue amplifiers. An important feature of this technology is that it is fully adaptive. This means that any change in system parameters that might increase vibration levels will automatically be compensated. If required the system transfer function will be adjusted by recalibrating without any manual manipulation or interference. This feature is called adaptive vibration control.

More recently developments have been initiated to investigate the possibility of cooler drive electronics that uses fully digital power amplifiers instead of analogue amplifiers. This development would enable adaptive vibration control electronics in a very limited volume operating at a high efficiency. These developments include developments regarding the control algorithm and its implementation on new hardware. Both electronics power stages use the HPCDE miniature tactical controller electronic power bridge. One of the boards acts as master and drives the power stage of the second board. Tests have been concluded successfully enabling adaptive vibration control with very compact hardware.

**COOLER DIAGNOSTIC TOOLS**

For space programs it is essential that during manufacturing adequate testing is performed to guarantee the correct assembly of the cooler. Next to the verification of specific processes such as laser welding the testing of the cooler will require special utilities to test for example piston leakage or piston alignment. Some of this specific tooling is manufactured at TCBV enabling the required quality assurance testing of space coolers. An example of this equipment is described below.
Flexure-bearing compressor diagnostics tool

In 2008 and 2009 TCBV has developed an innovative flexure bearing compressor diagnostics tool which enables the measurement and analysis of the alignment quality of the pistons of a linear compressor without using an additional internal piston position sensor. Advantage of this approach is that this eliminates the need of an internal position sensor inside the compressor which is often implemented in space qualified compressors. This reduces complexity and eliminates a failure mode and allows the setup to be used for (semi) commercially off the shelf systems possibly to be used for space missions. This tool not only allows for verification of initial alignment quality but also for monitoring of the compressor’s health over time. In Figure 9 a photograph of the test bench is given. On the right hand of this figure an example of the output of the test bench is shown.

FUTURE PROGRAMS

Thales Cryogenics is involved in the execution of the following programs. These programs have direct relations to the reliability of the coolers or the way how the coolers can be operated to fulfill demanding system requirement.

Tribology measurement

In June 2010 Thales Cryogenics was awarded a PEP-funding project named 'Miniature Linear Space Coolers Lifetime Qualification and Methods'. This project aims at the development of a test bench specifically designed to test and qualify liner/coating materials for linear Stirling type compressors and Stirling expanders. A schematic representation of a possible setup is shown in Figure 10. This test bench will allow for much more detailed tribological research of different liner materials including different treatments. Also much more repetitive tests are possible with such a set-up enabling more statistical data to be gathered. Performing such repetitive tests outside Thales Cryogenics is not feasible because of the specific testing conditions.

Figure 9: Compressor diagnostics test bench (left) and output example (right).

Figure 10: Schematics linear tribological setup under helium conditions.
The above test set-up could be used for the qualification of the basic material choice for contact seal bearings or being implemented in the quality control of new batches of materials.

**ESA Small Scale Cooler:**

Above discussed coolers 8497 and 9997 developed under the NSO contract can be used in the frame of a TRP for designing, producing and testing a small scale cooler that shall be able to provide a cooling power of more than 0.75 W at 77 K, for a mass of less than 1 kg, an input power lower than 25 W, and a lifetime exceeding 50,000 hours. This project will last 24 months and is aimed at providing a proof of concept for applications such as planetary and interplanetary probes carrying multiple instruments. This project also involves work around the fully digital vibration control board described above.

This TRP has been launched begin 2010 and TCBV has answered in line with the technical information provided in this paper.

**CONCLUSIONS**

With the UP8497 and LSF9997 miniature coolers a new range of high efficient long life coolers has been added to the product portfolio of Thales Cryogenics. With cooling powers of well over 800 mW at 80 K and efficiencies of around 10 % of Carnot these miniature coolers will enable the use of long life linear coolers in applications that could previously only be addressed by the use of rotary coolers. Especially those applications that require longer lifetimes and low induced vibrations such as surveillance cameras will benefit from these developments.

In application where space or weight restrictions are leading the choice of the required cooler technology, Thales Cryogenics also has a complete line of rotary coolers in its portfolio that can be evaluated or adapted for specific space missions enabling compact remote sensing.

**ACKNOWLEDGMENT**

The authors would like to thank the Netherlands Space Office (NSO) for their support of this development program for the initial development of the 8497 and 9997 cooler as well as the tribology set-up.

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