ABSTRACT:

Thales Cryogenics (TCBV) has an extensive background in delivering long life cryogenic coolers for military, civil and space programs. This cooler range is based on two main compressor concepts: close tolerance contact seals (UP) and flexure bearing (LSF/LPT) coolers. Main difference between these products is the Mean Time To Failure (MTTF). In this paper an overview of lifetime parameters will be listed versus the impact in the different cooler types. Also test results from both the installed base and the Thales Cryogenics test lab will be presented.

New developments at Thales Cryogenics regarding compact long lifetime coolers will be outlined. In addition new developments for miniature linear cooler drive electronics with high temperature stability and power density will be described.

Keywords: Cryocoolers, Reliability, cooler degradation, miniature coolers, high performance cooler drive electronics, DSP technology, temperature stability, cooler efficiency.

1. RELIABILITY OF LINEAR CRYOCOOLERS

1.1 Introduction

The lifetime and reliability of mechanical cryocoolers is of continuous interest throughout the entire industry. The reliability of standard coolers at Thales Cryogenics has been improved to such an extend that the lifetime of these commercially affordable coolers is now within the domain of what was previously only feasible for high-end cryocoolers for space applications.

Two types of categories can be defined that have an impact on the lifetime of mechanical cryocoolers. The first types are random failures caused by for instance gas leaks, wire failure etc. as previously reported and analyzed in [1] and [2]. Earlier piston gas blow by was considered as a random failure. Advances in liner materials have replaced this random failure mechanism in a slow gradual wear out causing the cooler to degrade on cryogenic performances such as cooling power and cooldown time.

This can be considered as the second failure type as soon as the required cryogenic performance cannot be met anymore of if for instance the steady state input power passes a maximum threshold. With increasing operational hours of cryocoolers in for instance surveillance applications, performance cooler wear out and performance degradation becomes increasingly important in the assessment of cooler lifetime.
1.2 Lifetime test results at Thales Cryogenics

Below some of the lifetime test results of Thales Cryogenics are summarized:

<table>
<thead>
<tr>
<th>Cooler type</th>
<th>Description cooler</th>
<th>Running hours</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexure Bearing coolers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSF908 8 Moving coil</td>
<td>65.940</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>LSF918 8 10 mm Stirling coldfinger</td>
<td>74.090</td>
<td>Still running, Worn out displacer replaced at 69.000 hours.</td>
<td></td>
</tr>
<tr>
<td>LSF918 8 5 mm Stirling</td>
<td>48.741</td>
<td>Stopped. Displacer worn out around 30.000 hours: restarted new cold finger</td>
<td></td>
</tr>
<tr>
<td>LSF918 8 5 mm Stirling</td>
<td>30.150</td>
<td>Stopped, displacer wear</td>
<td></td>
</tr>
<tr>
<td>LSF918 8 10 mm Stirling</td>
<td>47.328</td>
<td>Stopped, displacer wear</td>
<td></td>
</tr>
<tr>
<td>LSF918 8 Stirling coldfinger</td>
<td>44.325</td>
<td>Stopped, displacer wear</td>
<td></td>
</tr>
<tr>
<td>LPT911 0 500 mW Pulse tube</td>
<td>69.450</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>LSF932 0 20 mm Stirling cold finger</td>
<td>56.620</td>
<td>Still running, New displacer bearing material after 20.000 hours</td>
<td></td>
</tr>
<tr>
<td>LSF932 0 20 mm Stirling cold finger</td>
<td>51.890</td>
<td>Still running, New displacer bearing material after 15.000 hours</td>
<td></td>
</tr>
<tr>
<td>LSF933 20 mm Stirling cold finger with flexure bearings</td>
<td>53.140</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>LSF933 20 mm Stirling cold finger with flexure bearings</td>
<td>54.330</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>LSF933 20 mm Stirling cold finger with flexure bearings</td>
<td>40.450</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>LSF933 20 mm Stirling cold finger with flexure bearings</td>
<td>40.700</td>
<td>Still running</td>
<td></td>
</tr>
<tr>
<td>Close tolerance contact seals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>12.955</td>
<td>Stopped, worn out</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>40.322</td>
<td>Stopped. At 29.000 at 50% of initial performance.</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>35.229</td>
<td>Stopped, worn out</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>32.738</td>
<td>Stopped, worn out</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>14.346</td>
<td>Stopped for research project, still within spec.</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>28.353</td>
<td>Stopped, worn out</td>
<td></td>
</tr>
<tr>
<td>UP 7080 Moving coil 5 mm Stirling cold finger</td>
<td>32.131</td>
<td>Stopped for research project, cooler within spec</td>
<td></td>
</tr>
</tbody>
</table>
All test coolers have been running at approximately 60-70% of the maximum allowed input power, which can be regarded as overstressed operation. Infant failures are not given in this table as the root causes of these failures have been eliminated by design iterations using the lifetime test failures.

The cooling power of the lifetime systems listed has been measured at regular intervals. This test data has been used to construct figure 1. In this figure the average cooling performances for standard contact coolers (UP series Stirling) and long life flexure bearing coolers (LSF Stirling and LPT pulse tube coolers) are given over time.

![Figure 1: Linear cooler degradation over time](image)

The following can be observed:

For UP contact systems the amount of degradation is on average the same: about 20% of reduction of cooling power over 10,000 hours of continuous operation.

For UP systems as of 10,000 hours the failure chance increases. For several systems running hours of over 25,000 hours have been demonstrated, however with significant loss in cooling power of almost 50% of the initial value. Clearly the failure point depends on the margin between available cooling power and heat load between begin – and end of life.
For LSF systems it is evident that the wear out factor of the compressor is largely eliminated - due to the used flexure bearing support of the pistons - resulting in much less cooling power degradation over time. The slow degradation in cooling power is mainly caused by slow wearing out of the Stirling expander.

Around 30,000 hours of operation the failure chance of a Stirling cold finger increases. This is indicated by the dashed line LSF high lifetime. In case of no failure the cooling power continuous to degrade slowly.

For pulse tube systems some minor initial cooling power degradation can occur as a result of initial none perfect compressor piston alignments. After stabilization no degradation will occur anymore. With respect to LPT systems, lifetimes up to 10 years of continuous operation are therefore very well feasible for standard available pulse tube systems.

### 1.3 Flexure bearing cooler heritage

Since the introduction of Linear Flexure Stirling (LSF) and Linear Pulse Tube (LPT) coolers significant numbers of high reliable systems have been delivered to customers. For different pulse tube systems the accumulated operational hours have been estimated and are listed in table 2. LSF (Stirling) systems are not considered as it is not possible to make any estimation regarding the amount of operational hours. LPT coolers are mainly for civil applications whereas LSF are also being used in military projects.

<table>
<thead>
<tr>
<th>Cooler type</th>
<th># of coolers</th>
<th>Estimated operational hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 mW PT cooler</td>
<td>~ 980</td>
<td>7,200,000 hours</td>
</tr>
<tr>
<td>1,3 and 5,6 W PT coolers</td>
<td></td>
<td>13,400,000 hours</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>20,600,000 hours</td>
</tr>
</tbody>
</table>

One of the systems is an integrated cooler system with additional complexity such as active heat sink components and a glass feed through. Of these systems put into operation around 25 systems have been returned for service. Main causes of these service returns were helium leakages, damaged compressors or cold fingers and damaged connection wires. No coolers with wear out have been reported so far.

The estimation of the MTTF for random failures then becomes approximately:
1.4 Lifetime and cooler applications

From the lifetime test and field results it is evident that modern linear split coolers offer excellent lifetime test results and consequently reliability. In table 3 a summary of the different linear cooler types is given with the approximated actual lifetimes expected.

Table 3: Lifetimes linear cooler variants

<table>
<thead>
<tr>
<th></th>
<th>Stirling cold finger</th>
<th>Stirling flex bearing cold finger</th>
<th>Pulse tube cold finger</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UP standard tactical</strong></td>
<td>10,000 hours</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Flexure bearing coolers</strong></td>
<td>30,000 hours</td>
<td>50,000+ hours</td>
<td>60,000+ hours</td>
</tr>
</tbody>
</table>

2. HIGH RELIABLE MINIATURE COOLERS

1.1 Introduction compact cryocoolers

Cryocooler applications clearly show an increased interest in reduced mass and volume of the cooler combined with an increased reliability. Typically rotary monobloc coolers are used in applications were a low mass and volume is required. Rotary monobloc coolers are based on mechanically coupled compression and expander pistons resulting in high efficient cryocoolers.

In Figure 2, two types of Thales' rotary monobloc coolers are shown. These coolers are being manufactured at Thales Cryogenics, Blagnac, France.

![Figure 2: Thales RM2 and RM4 rotary coolers](image)
The efficiency of a cryocooler can be expressed as a percentage of the theoretical Carnot efficiency. This Carnot efficiency is expressed as the maximum theoretical efficiency that can be reached when transferring energy between two temperatures:

\[
\eta_{\text{Carnot}} = \frac{T_{\text{low}}}{T_{\text{high}} - T_{\text{low}}}
\]  

(1)

The efficiency of rotary coolers between 77K and 296K can be as high as 17% of Carnot, whereas tactical linear coolers typically reach 13% of Carnot efficiency depending on size and type.

Main differences of rotary with linear cooler types are inherent higher induced vibration levels and a more limited lifetime of around 8,000 hours for the rotary coolers due to their operating principle.

2.1 Miniature linear coolers
In order to fill the gap between high reliable linear cryocoolers and compact, lightweight and efficient rotary coolers, Thales Cryogenics started a development for compact linear cryocoolers.

This development is driven by the increased need for coolers to be used in continuous operation applications for example surveillance IR-cameras. These cameras typically employ dewars with heatloads of only 100-300 mW at 80K or are operated at increased detector temperatures up to 110K. Required cooler lifetimes are around 15,000 – 25,000 hours which allows for 2-3 years of continuous operation.

These new developments have lead to two new cooler concepts currently under development. Both concepts are initially designed to be matched with the same ¼” IDCA dewar:

- The miniature UP8497 high reliable Stirling cooler.
- The miniature LSF9997 ultra high reliable Stirling cooler.

The compressors of both variants are dual piston systems in order to minimize induced vibrations inherent to single piston compressors. Both variants will offer the trade-off between cooler mass and volume with reliability. The UP8497 cooler is developed as a full miniature long life 15,000 hours cryocooler, whereas the LSF9997, being a medium compact cooler, is targeted for even higher lifetimes of up to 25,000 hours.

2.2 UP8497 moving coil compressor
The UP8497 compressor is a moving coil ‘close contact seal’ system. This means that the compression pistons are in direct contact with the cylinder wall. Compressor dimensions of the UP8497 are 35 mm diameter with a total length of 117 mm. The reliability of this compact close contact seal cooler is expected to be at 15,000 hours or better:
The UP8497 will benefit from developments in piston liner materials similar as used in the UP70xx systems as given in Table 1. As demonstrated via lifetime tests this liner material already enables lifetimes of 15,000 hours.

Thales Cryogenics has started a separate tribological program in order to increase the wear rate of the current liner material even more. Both the new UP8497 as well as existing UP coolers are expected to benefit from this development.

The very low moving mass of the small UP8497 compressor results in lower contact forces and consequently lower wear. This will be outlined more in the next paragraph.

In Figure 3 a photograph of the first UP8497 cooler prototype with a RM4 rotary cooler is shown.

![Figure 3: UP8497 cooler with an RM4 as reference](image)

Here the UP8497 with a long test transfer tube is shown and a transport cap over the displacer. For typical applications this transfer tube will be significantly shorter. The transfer tube offers the capability to orientate cold finger and compressor in optimal positions inside the camera.

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:

\[
\text{h} = k_l \cdot p_n \cdot s
\]

With \( h \) representing the liner wear, \( p_n \) the normal contact pressure and \( s \) being the sliding distance. The contact pressure is mainly caused by the gravity force acting on the moving mass and the piston surface area.

In an attempt to translate the lifetime data of the existing UP7080 to the new UP8497, of which the lifetime data is given in Table 1, both moving masses and contact surface areas need to be compared. For this the pressure ratio and consequently liner wear ratio can be determined. This results in:
This ratio means that with the new developed miniature compressor the expected worse case position, which is compressor mounted horizontally, wear is expected to be almost a factor of 2 lower than the existing UP7080 compressor which already has shown very good lifetime results. The lifetime and wear characteristics of the UP8497 however need to be finally verified with lifetime tests. These will be initiated in the beginning of 2010.

2.3 LSF9997 moving magnet flexure compressor

The LSF9997 is a moving magnet motor of which the moving mass is rigidly supported by flexure bearings in the radial direction. These flexures also allow for the correct required stiffness in axial direction. This means that with this compressor there is no contact between the piston and cylinder wall and consequently no piston wear will occur. The dimensions of this compressor are 44.4 mm diameter with a total length of 119 mm.

The diameter of this compressor type is driven by the design of the flexure bearings. With the requirements on both the axial and radial stiffness of the flexure bearings, a diameter of less than 44 mm is not feasible without comprising on performance or lifetime.

This compressor design benefits fully from the lifetime heritage of other flexure bearing coolers and is expected to have the same reliability. In Figure 4 a CAD model of this new compressor is shown.

![Figure 4: CAD model of the LSF9997 compressor](image)

For the first design a concept with integrated connectors on the endplates has been chosen. Without these integrated connectors the compressor length can be reduced with approximately 9 mm in total to a length of around 110 mm in case required for specific applications.
2.4 Performance UP8497 cooler

In 2009 performance tests with the UP8497 have been performed. In Figure 5 some of those test results are shown.

![UP 8497/xx preliminary test data](image)

Figure 5: Preliminary test results UP8497 cooler at 80K

In this figure several cold finger designs are presented. Cold finger option 1 is the current baseline design which clearly has the best coefficient of performance (COP). Other cold finger variants have also been tested. These cold fingers have proven to be efficient when tested against applied mechanical power only. What has been found is that the overall system damping of these alternative options is higher than the baseline cold finger. This damping causes the compressor efficiency to drop slightly, resulting in an overall reduction of cooler COP. Advantage of this damping is that the amount of input power before the compressor pistons start hitting the end stops increases. This then results in a higher amount of cooling power to be generated from the cold finger, with a penalty on efficiency.

Typically the baseline design will be chosen as this will result in the lowest steady state input power when the cooler is in regulation and thus a lower electrical input to the compressor that needs to be heatsinked in the application. However, for specific applications where for instance cool down time is more critical than steady state input power, design options 2 and 3 offer interesting alternatives.
2.5 Development status and next steps

The first prototype of the UP8497 has been build with good results. Compressor efficiency has been measured to be well over 70%. In the beginning of 2010 developments will focus on increasing the efficiency of the cold finger, especially in the range of lower input powers.

During the first quarter of 2010 the first prototypes of the LSF9997 compressor will be build and tested. In parallel tribological tests will be finalized in the beginning of 2010. Focus will be on improving wear characteristics of both the compressor piston liners and the Stirling expander liners. It is expected that for the Stirling expander another improvement in wear can be made. Eventually this could lead to less performance degradation of both the LSF and UP systems as shown in Figure 1 increasing the presented reliability even more.

During the first quarter of 2010 also tests will be performed with a UP8497 cooler integrated in a mid wave infrared Claire camera of Thales Land & Joint Systems Netherlands. The first integration of the UP8497 with the Claire ¼” IDCA dewar can be seen in Figure 6. The same dewar with a Thales RM4 rotary cooler integrated is shown in Figure 7.

![Figure 6: UP8497 cooler integrated in dewar](image1)

![Figure 7: RM4 cooler integrated in dewar](image2)

Initial performance tests with the UP8497 have shown a low steady state input power of approximately 5 Wac.

3. HIGH PERFORMANCE MINIATURE COOLER DRIVE ELECTRONICS

3.1 Introduction

Inline with market requirements for miniaturization of coolers a new family of cooler drive electronics has been developed. This family consists of two types of converters. Both converters are based on a Digital Signal Processor (DSP) that both processes the temperature signal and generates the output signal towards the cooler using the onboard Pulse Width Modulation (PWM) generator. The output signal to the cooler is generated by a PWM amplifier which is configured around four power MOSFETS in a typical H-bridge configuration.
This design has lead to a very compact single board converter that combines a very high power density at high ambient temperatures with flexible on board processing that allows for application specific adjustments and diagnostics.

### 3.2 Converter design choices and types

Two converter variants have been developed which are both based on the same architecture. During the design phase emphasis has been placed on robustness, volume and flexibility.

With respect to robustness an important consideration has been that the converter will be powering a linear cryocooler. These types of cooler behave as an inductance which means that a certain phase shift between voltage and current will always exist. Thales linear coolers typically have a power factor 0.98-0.99, which means that the voltage and currently are in-phase. However in case a cooler with a lower power factor has to be driven, this inductive load can cause harmful currents in the power bridge, especially at the moment that the power bridge changes direction. These currents can lead to irreparable damage of the converter. For the new series of converters the switching method has been designed in such a way that an inductive load is allowed to be driven without causing converter damage.

Difference between the two types of converters is the output current which are 5.0 Aac and 6.5 Aac for the MPCDE and HPCDE respectively. The footprint of both converters is with 67.4 x 56.5 mm the same, only difference is the height. For the HPCDE this is 24.4 mm and 19.4 mm for the MPCDE. The masses as measured of these two variants have been measured around 112 and 96 grams. In Figure 8 both converter types are shown.

![Figure 8: MPCDE (top) and HPCDE (bottom) miniature converters](image)

The converters are designed to operate on a single DC voltage supply between 18 Vdc and 32 Vdc. Already at 12 Vdc the converter will operate correctly, however with reduced output voltage. The maximum design output voltage with a 32 Vdc supply is 21 Vac.
3.3 Ambient temperatures and operation

Both converters have been tested for continuous output powers of well over 100 Wac. Limiting factor in the output of the converters are the ac output currents. The output filter coils have been designed for a continuous output current of 5.0 Aac and 6.5 Aac at a maximum operating temperature of 80 °C. Also the thermal management of the converters are aimed at operating at full output currents at 80 °C. All critical thermal components of the converter, such as the MOSFETS and the output filter coils, are thermally linked to the housing.

Both converters can be operated at either higher operating temperatures or higher output currents than specified. However in these cases maximum output power durations and ambient temperatures have to be reviewed carefully in order to prevent premature converter damage.

3.4 Temperature stability

Standard the MPCDE and HPCDE converters generate an accurate 1 mA current to bias the temperature diode attached. Variants that generate 100 µA of bias current also exist. The diode voltage generated by this bias current is measured by the converter using a 16 bit A/D converter which serves as input for the DSP processor.

The MPCDE and HPCDE have both been measured to have excellent temperature stability. In Figure 9 the measured short term stability is shown.

![Figure 9: Short stability measured on the HPCDE](image-url)
The temperature diode voltage in this figure is given in mV. The measured short-term stability is within an interval of 10 µV. For a typical temperature diode such as a 2N222 diode this would translate into a stability interval of 6 mK. These data have been measured using a HPCDE converter in combination with a LSF9597 cooler which is a ¼” IDCA flexure bearing cooler. It should be noted that the temperature stability is not only depended on the converter but also on the entire system response.

3.5 Converter efficiency

The efficiency depends on the power consumption of the electronics, such as the DSP processor, and losses in for instance the power MOSFETS and filter coils. For the two converter variants the efficiency has been measured, both with a resistive load and a cooler as load which is an inductive load. The results of these measurements are given in Figure 10 below.

![Figure 10: Measured converter efficiencies](image)

In this figure the impact of static power consumption of the active electronics on the efficiency is clearly visible at low input powers. Already at 9 Wac of output power the efficiency is at 80%. At higher output powers almost 95% of efficiency has been achieved.

3.6 Future work XPCDE tactical converters

Currently the MPCDE and HPCDE converters are fully qualified and in mass production. Future work will mainly focus on matching the MPCDE converter to the new compact linear coolers under development. Both coolers are expected to run in steady state conditions on a maximum AC input current of 2-3 A. For the MPCDE this means the design of the filter circuit can be re-optimised taking into account these lower
currents. With this it is expected that the current height of the MPCDE of 19.4 mm can be reduced to approximately 16 mm.

It is also envisaged to implement predictive maintenance functions inside the converter. These predictive maintenance functions could monitor cooler performance such as cool downtime over time and could be used to identify potential maintenance requirements at camera level. This could then be made visible via a software and/or hardware trigger.

4. CONCLUSIONS

All types of linear split crycoolers at Thales Cryogenics have demonstrated to have very good lifetimes. Sufficient data is available to support the implementation of the correct cooler type with optimum performance margin and lifetime.

In the very near future even more lifetime improvements of the UP and LSF cooler series are expected to be feasible.

With the UP8497 and LSF9997 miniature coolers and the new XPCDE miniature converter range, Thales Cryogenics has and will be extending its product portfolio. This extension provides new long life cooler and converter solutions, which could previously not be addressed correctly or could only be addressed using rotary coolers.

5. REFERENCES

1. Benschop A.A.J, Mullié J, Meijers M.

2. R.G. Ross, jr.,