Robust Stirling coolers for sensing in extreme environmental conditions

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ABSTRACT

With the achievements made in the last decade with respect to reliability and cryogenic performance, the use of Stirling and Pulse Tube cryocoolers for new application areas has become viable. Thales Cryogenics has been challenged by its customers to deliver robust and compact solutions for a variety of applications.

The test approaches within the Thales Environmental Test Lab – a centre of excellence within the Netherlands – have been refined significantly, departing from the classical robustness testing principles, which typically consist of submitting the product to an environment with a compressed energy allocation - shorter time duration and higher PSD levels.

An overview is given of recent activities at Thales Cryogenics regarding the development and testing of linear Stirling cryocoolers for extreme environmental conditions. A novel cooler will be presented that has been developed specifically for operation in high ambient temperature conditions. In addition, an overview will be given of ongoing test & development activities regarding coolers for operation under severe mechanical loads. Design aspects, margin philosophy, test plans (including robustness testing) and test results will be presented.

Keywords: stirling, linear, cryocooler, robustness, temperature, shock, vibration,

1. INTRODUCTION

In this paper, we will examine two specific cryocooler cases, in which the cryocooler is expected to operate far beyond the typical operating conditions.

The first case that will be presented is a Stirling cooler developed for the petrochemical industry, for operation at high ambient- and tip temperatures.

The second case that will be presented is a development and test philosophy for cryocoolers for extreme mechanical conditions, such as in a next-generation fighter aircraft, UAV, or tracked vehicles with hard-mounted sensors.

2. CRYOCOOLERS FOR EXTREME THERMAL CONDITIONS

2.1 Introduction

In this section, we will examine a Stirling cooler that has been developed for use in ambient temperatures of 150℃ for a down-well application in the petrochemical industry. While the thermodynamic considerations and trade-offs made will be presented at the ICC conference [2], we will examine the impact of environmental temperature on design and processes, and will discuss qualification method and test results. We will start by briefly describing the cooler, after which material strength considerations will be discussed. Subsequently, material performance aspects will be described. Finally, process- and product qualification testing will be discussed.

2.2 Overall design description

During initial trade-off studies and thermodynamic modeling, the LSF9340 Pneumatic cold finger was identified as a suitable starting point for development. A new moving-magnet, close contact seal compressor was developed for this application. As only a limited amount of running hours is required in the final application, a flexure bearing compressor is not needed.

The cooler can be seen in Figure 1.

Figure 1. Photograph of two coolers

2.3 Strength considerations

A typical Thales linear cryocooler design consists mainly of austenitic stainless steel outer parts, welded together using either laser or EB welding. At elevated temperatures, the ultimate strength of the base materials will be reduced compared to room temperate values (see Figure 2.). This therefore needs to be taken into account in designing all pressure components. Furthermore, as Thales has limited heritage with designing or qualifying for these conditions, process qualifications were performed for critical welds.

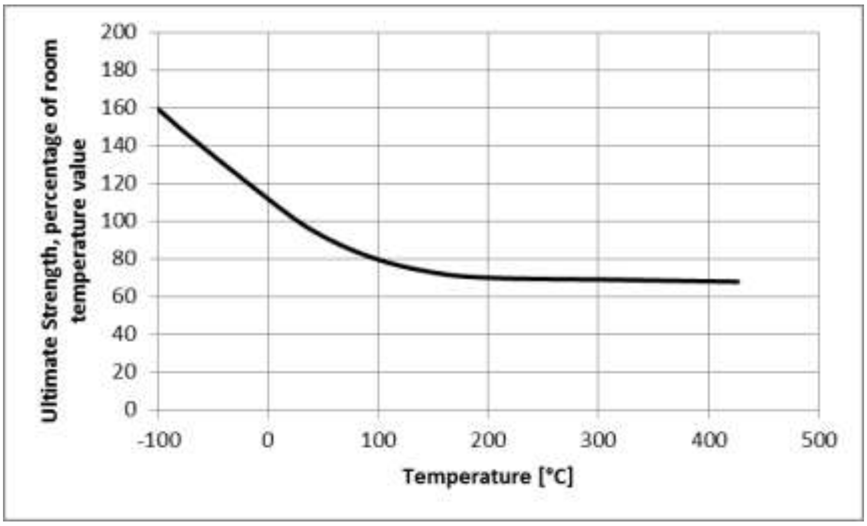


Figure 2. Ultimate strength vs temperature.

2.4 Performance considerations

The high ambient temperature restricts the permanent magnet materials that can be used. A permanent magnet material will be demagnetized above a certain temperature (Curie temperature). Care must therefore be taken to select a magnet that will retain its permanent magnetization under the conditions (working point and temperature) with sufficient margin.

Further impacting this effect is the electrical resistivity of compressor coil wires. With compressor coils made from copper wire, a typical temperature coefficient of $4 \cdot 10^{-3}$ K^{-1} can be assumed. This means that a temperature increase of 150 K (assumed difference in coil temperature versus room temperature) will result in a 60% increase of Joule losses – and therefore the dissipation inside the coils.

Apart from having a detrimental effect on compressor efficiency, this also means that careful consideration needs to be placed on thermal management of the coils, to prevent thermal runaways and overheating of the compressor and magnets.

2.5 Process- and material qualification testing

As previously indicated in paragraph 2.3, several of the materials and components can be assumed to have reduced strengths as well as fatigue limits.

To verify that the design margins that were used to accommodate this effect were incorporated in the correct way, tensile strength tests were performed on weld qualification samples for welds that showed the lowest margin of safety, at an elevated temperature of 200℃.

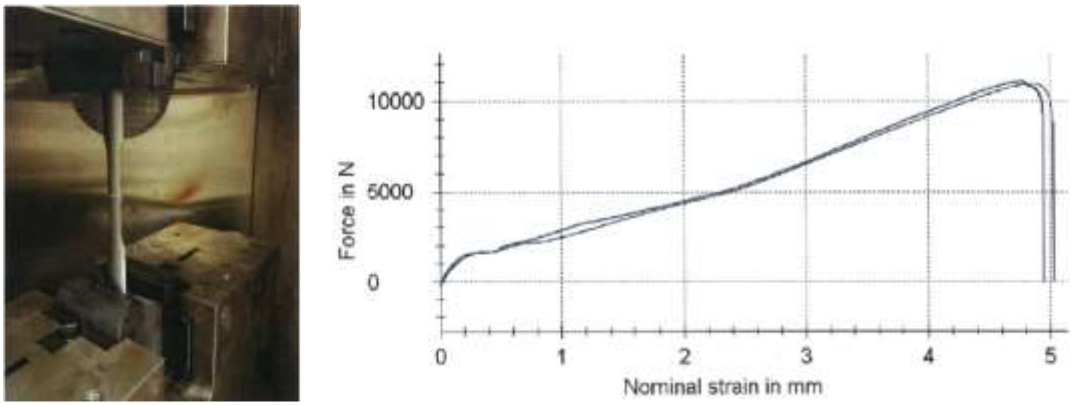


Figure 3. Tensile testing at 200 C

Test results correspond well to the design calculations, providing early validation for the design margins.

In a similar manner, the fatigue limit for compressor piston springs was tested. Compressor piston springs were tested at $>2*10^7$ cycles, at elevated temperature, for a fixed amplitude, starting at low amplitude. After each test run, the amplitude is increased step-wise and the test is repeated. After spring failure, a new spring is mounted.

The number of cycles can be assumed to be beyond "infinite life" in fatigue testing – the test is therefore suitable for determining the amplitude at which material stresses result in failure for the spring under test.

Two different spring batches were tested, one batch that had been subjected to a thermal treatment to further increase the material strength.

A Weibull statistical analysis was performed on both spring batches. As can be seen in Figure 4, the Weibull fit shows a high shape factor, which is to be expected with fatigue as the failure mechanism. With the heat treated springs, the design will have a sufficiently low failure probability over its useful life.

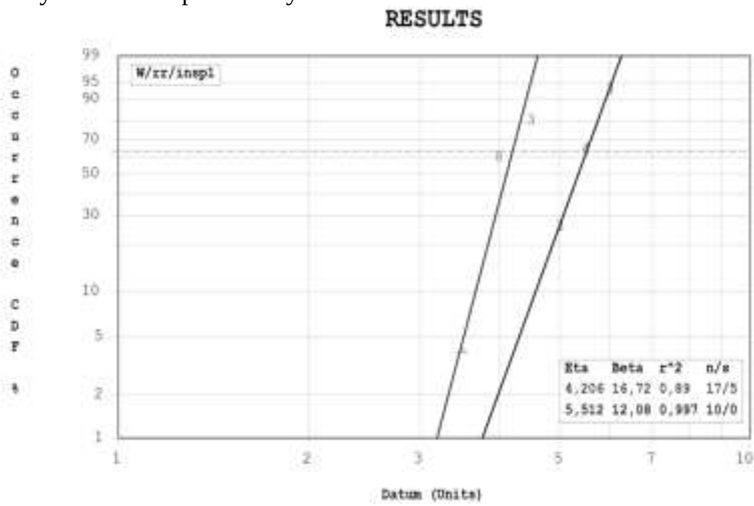
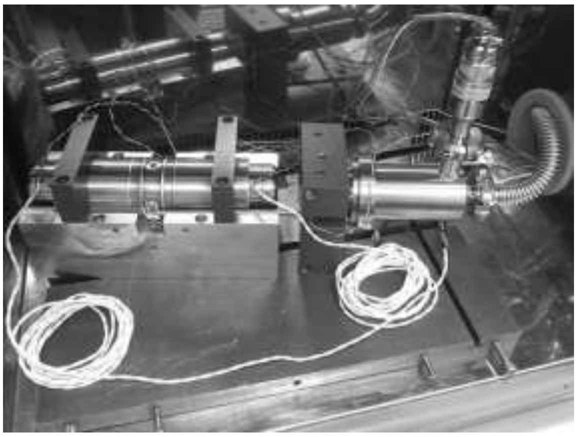


Figure 4. Weibull fit of fatigue failure amplitude for untreated (left-hand curve) and treated (right-hand curve) springs. Datum axis indicates stroke [mm].

2.6 Performance testing

Performance mapping as part of the qualification was done on two qualification models. The coolers were placed in a temperature chamber with the correct ambient temperature (Figure 5). Additional temperature sensors were placed near the cooler skin and in the compressor coils to monitor thermal management in the cooler



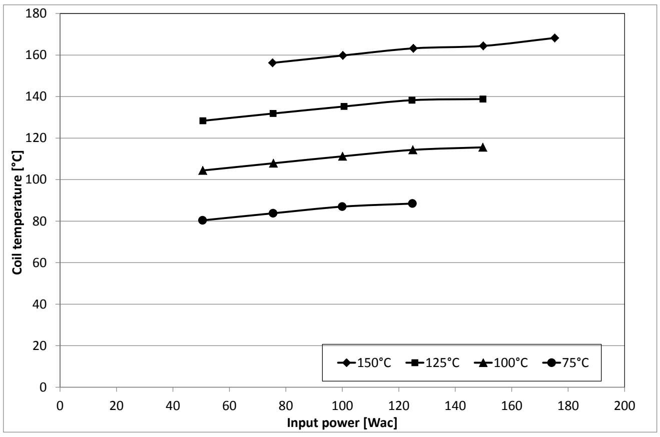


Figure 5. Qualification model in climate chamber (left), coil temperature measurement (right).

Further performance details are presented at the ICC conference[2].

3. CRYOCOOLERS FOR EXTREME MECHANICAL CONDITIONS

3.1 Introduction

A variety of mechanical conditions can be envisioned that could potentially damage a mechanical cryocooler. These cases can differ in terms of shock and vibrational signature as well as duration and variation.

For example, a typical space application will have severe vibrations applied to the cryocooler during launch (cooler non-operating), with conditions smooth after that.

On the other hand, for a typical military aircraft application, there will be a continuous background level of sine- and random vibrations, with occasional static loads (g-loads) superimposed in the case of a fighter aircraft application and with excursions to more severe levels. As the cooler will be operating during the exposure to vibrational loads, failure mechanisms can no longer be viewed separately – apart from damage resulting purely from vibration, the wear-based failure mechanisms typically present in a mechanical cryocooler will be impacted by the applied mechanical loads.

For the sake of discussion, in subsequent paragraphs we will examine the use case of a next-generation fighter aircraft application, in which the cooler is subjected to moderate as well as severe loads during its operating life.

3.2 Overall approach

An overall approach is proposed for combined development, robustness and lifetime testing of cryocoolers designed for extreme environmental conditions. The proposed process combines analyzing the impact of the conditions on cooler behavior, finding failure mechanisms, providing input to design iterations and testing for product life under the actual application conditions.

To clarify the overall approach, with individual steps described in the following paragraphs, a schematic overview is given in Figure 6.

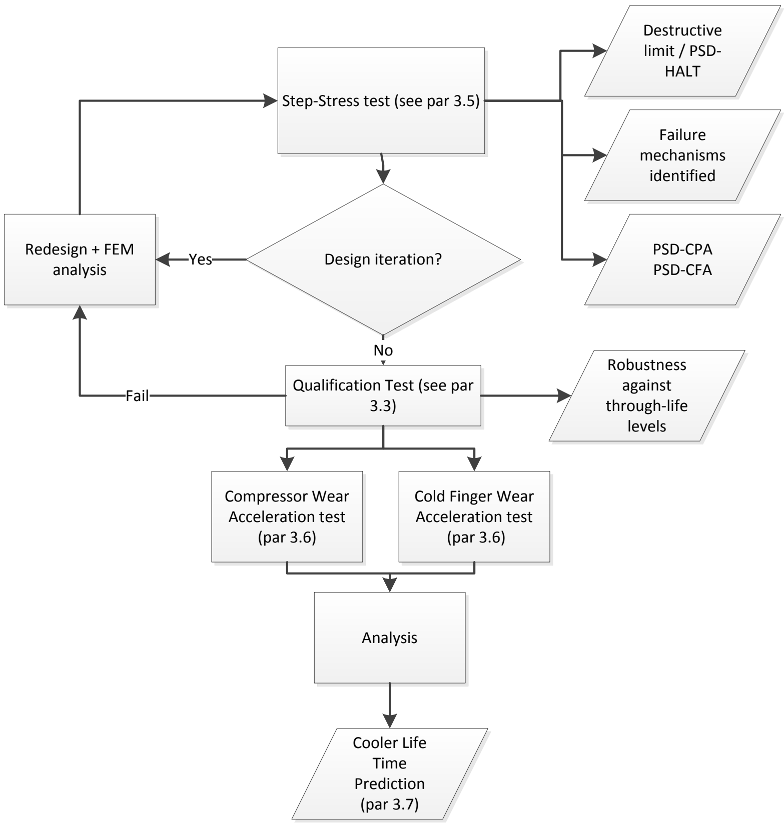


Figure 6. Overall test logic

We will start by examining the classical testing methods for robustness against mechanical loads, describing the limitations of these methods. Furthermore, we will present a method for experimentally verifying the lifetime of cryocoolers exposed to severe mechanical loads over a significant portion of their operating life time (continuous vibration background rather than peak loads). Finally, we will link this information to the previously-presented general approach for calculating cryocooler MTTF in a specific application profile [1].

3.3 Classical approach: Qualification-level mechanical robustness testing

The classical approach for (qualification) testing of a product consists of subjecting the product to an energy-condensed version of the through-life applied loads. Dependent on the type of application, this can either serve to:

- Prove that the product will survive the total vibrational energy exposure over the useful life of the product
- Prove that the product will survive the worst-case short duration vibrational exposure with margin

The advantage of this approach is that it allows verification of robustness in a limited time span.

For a specification where the product is not allowed to show any signs of damage (such as testing the effects of launch loads in a space application), a low-level sine sweep (resonance scan) before and after heavy vibration test combined with a before/after functional check may suffice to show robustness against the applied level.

However, in the case where the qualification level is intended to represent through-life exposure with potential degradation, this type of test will need to be combined with a life time test to verify the effect of vibrational exposure on either inducing latent failure mechanisms or aggravating other failure mechanisms.

Furthermore, the justification of time-compressed testing (using an “exaggeration factor”) requires an understanding of impact of test level on the amount of time-compression, and therefore of the physics of failure.

In order to obtain an answer to the question: “when will it fail” in an acceptable period of time, it is therefore first required to answer the question: “where and how will it fail”, “why did it fail during the test”, and “is the test representative for the intended use of the product”.

3.4 HALT testing

At the other end of robustness testing, there is the Highly Accelerated Life Test, or HALT. This test method makes no attempt to answer the question “when will it fail”, but rather provides information on “what could fail first”.

A typical HALT chamber setup is equipped to provide simultaneous stresses – both vibrational stresses and thermal stresses. In such a setup, vibrational loads are applied using pneumatic hammers to provide simultaneous six-axis excitation, and thermal stresses are induced by rapid cycling using cold nitrogen and high-power resistive heaters.

The advantage of such a setup is that potential weak points in the equipment under test can be rapidly identified – by applying extreme thermal and mechanical stresses, potential failure mechanisms are exposed. It is therefore a process suited to an iterative development process in which multiple intermediate prototypes are manufactured. As such, it is eminently suited to a development process where prototypes can be manufactured rapidly and cost-effectively. It is therefore not an obvious choice for cryocooler developments, as a mechanical cryocooler prototype where parts need to be manufactured or procured typically has a lead time of several months.

An important fundamental disadvantage of the HALT test is that there is no longer a clear link between the test performed and the actual operating conditions for which the product is designed. For example, the white spectrum applied using the pneumatic hammers in a typical HALT chamber have no relation to either the expected spectral exposure in the actual application, or to the levels used in qualification testing. Therefore, an alternative approach is proposed in the next paragraph.

3.5 Step-Stress Testing

A dual approach is needed to both verify “what will fail” and “when will it fail”. A proposed overall approach is shown in Figure 7. For the hypothetical case of a next-gen fighter aircraft application, the levels depicted are as follows:

- PSD-HALT: Level of vibration at which the cryocooler shows malfunction after a short duration of exposure (several minutes)
- PSD-Qual: Level of vibration test during qualification testing

- PSD-3: Upper (extreme) level of operating conditions, expected to occur only a small fraction of the time during real-life operation
- PSD-2: Nominal operating conditions during flight
- PSD-1: Conditions on ground (negligible vibration levels)

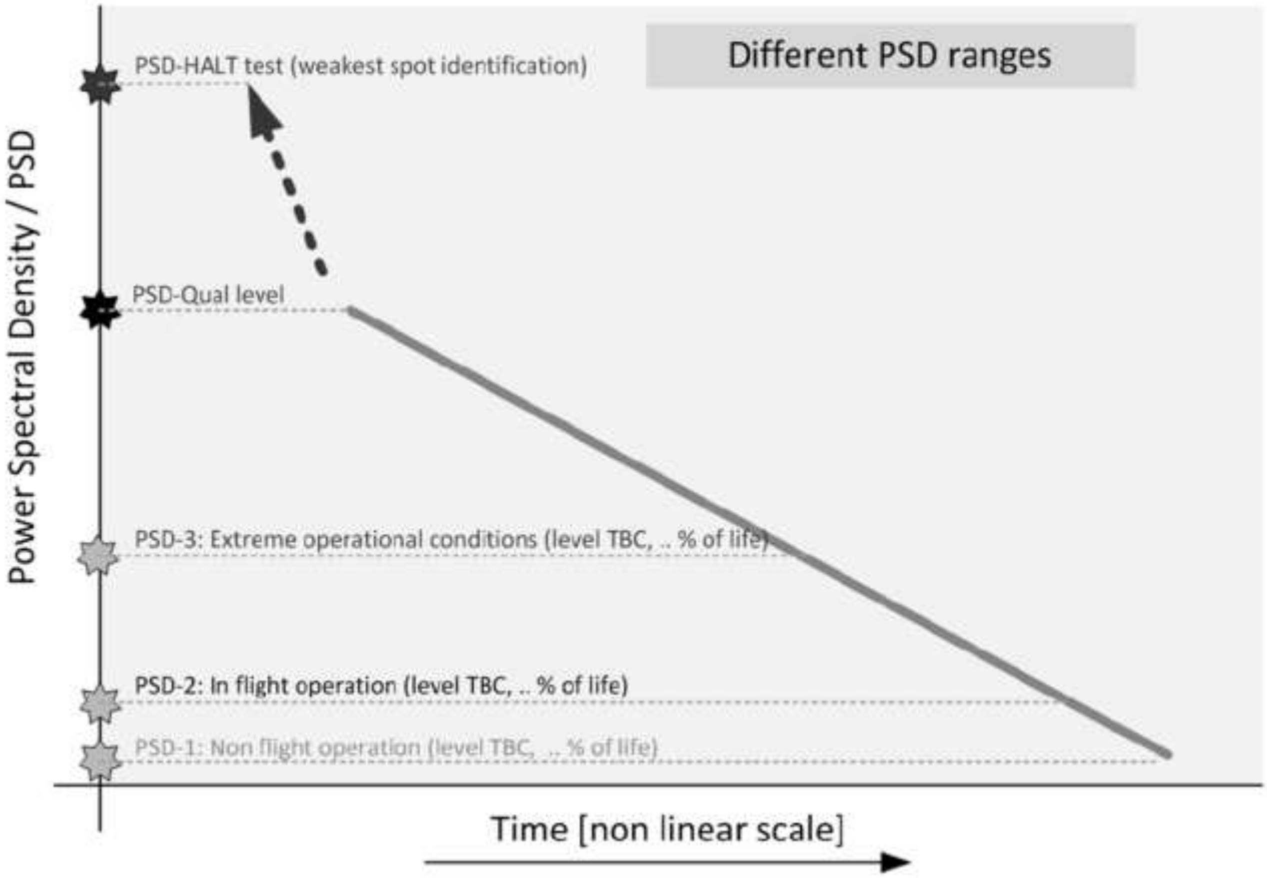


Figure 7. PSD levels for testing

For this method to be usable, there needs to be some relation between the exposures at the various levels. In other words, there needs to be some form of equivalence between exposures to different levels, differing only by the exposure time after which a defect occurs.

The basis for testing should be a FEM analysis, determining the limit level as well as predicted failure mechanism. Test results can then be compared to the FEM results and the model can be refined where needed.

The first step will be to determine the relation between PSD-HALT and PSD-Qual, by a method called step stress testing. Testing is started at a predetermined attenuated level, based on the qualification power spectral density. This could be for example PSD -12 dB.

We will describe a general case, in which vibrations are applied sequentially at three axes on an electrodynamic shaker for vibration testing with a spectrum similar to what is expected in the actual application.
For a linear cryocooler, there is a cylindrical symmetry and the test could be limited to two axes.

The test progression for each PSD level would then be as follows:

- Test at PSD-Qual -12 dB, three axes, 15 minutes per axis
- Monitor functionality during and after each axis.
- Perform low-level sine sweep after test, compare to initial sine sweep results. A shift in resonance could indicate that the destructive limit is being approached.

These PSD levels can then be used as input for a design iteration – by modifying the design to increase PSD-CPA and PSD-CFA, the cryocooler design can be optimized for life time in the actual application.

This test progression should then be applied at increasing PSD levels, in steps of 3 dB.
By performing this test, both the operational limit (level at which the cryocooler no longer operates correctly – performance is recovered after end of vibration) and destructive limit (level at which the cryocooler is damaged) can be experimentally determined.

In addition, during testing, the steady-state power at a fixed dewar temperature should be monitored, together with the cryocooler electrical data. This information can be used as input for the life time test approach as outlined in section 3.6 – it can be assumed that PSD levels which show no significant influence on cryocooler performance, also will not significantly impact the wear mechanisms in the cryocooler. In other words: two additional PSD levels will be defined after testing:

- PSD-CPA: Level above which the compressor performance is significantly impacted
- PSD-CFA: Level above which the cold finger performance is significantly impacted

Distinguishing between PSD-CPA and PSD-CFA should be done by placing the compressor and cold finger axes in an orthogonal configuration, as well as careful analysis of the electrical behavior of the cryocooler during testing. A cross-test could be performed during which the compressor is tested independently (pressure wave test), to validate the PSD-CPA level.

After the destructive limit is reached, the cooler is subjected to destructive analysis.

The failure mechanism as well as the destructive limit should be compared to FEM results, to validate the understanding of the product.

After the Step Stress test the following will be known:

- Validation of FEM predicted failure mechanism and destructive limit
- Cooler design improvements identified (increase of PSD-CPA and PSD-CFA)

In case no further product design iterations are needed, the next step could be to perform a PSD-Qual level test on a new unit with the same configuration.

This test is, essentially, the same as the classical approach described in paragraph 3.3 – a test intended to deliver a representative spectral content with a representative energy content to in a limited amount of time.

After the PSD-Qual test the following will be known:

- The cryocooler is capable of withstanding the through-life vibrational exposure of the application

By testing at the PSD-Qual level until the destructive limit is reached, information could potentially be obtained on the viability of performing an accelerated life time test with combined effects of cooler operation (normal wear) and additional stresses due to vibration exposure.

3.6 Life time testing approach – Subsystem Wear Acceleration

Defining a relation between mechanical loads and life time (or MTTF) is not trivial. In the past, simplified wear acceleration factors have been proposed for this [1], but especially in the case of longer duration severe mechanical load conditions, this approach is an oversimplification that will not give meaningful results.

Let us examine the viability of using an increased power spectral density to perform an accelerated life time test (time compression), with the eventual goal to provide input for a life time or MTTF estimate.

We will assume a cryocooler design that has been verified to be robust against the stresses induced at the PSD-Qual level. The question now is, can the effect of the vibrational load assumed to be to aggravate (accelerate) normal dominant failure mechanisms.

As an example case, we will examine a Thales LSF series cryocooler, schematically depicted in Figure 8.

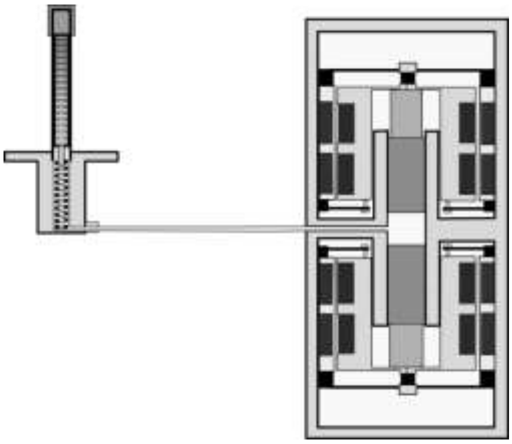


Figure 8. Schematic overview of Thales LSF cooler

This figure immediately makes it apparent why life time and reliability cannot be viewed independently from the exposure to mechanical loads, in the case of our example fighter aircraft application.

In a normal ground-based application, the dominant failure mechanism for such a cryocooler can be assumed to be wear of the displacer sealing, as this is a contact surface for motion of the displacer. Nominally, no contact pressure is applied on the compressor piston-cylinder contact, as these are supported by flexure bearings with a high radial stiffness – the compressor is essentially wear-free when operated under low external mechanical load, and has a negligible influence on cryocooler life time and reliability.

In the case of exposure to significant random vibrational loads, these can be assumed to influence the bearing surface contact of the displacer, as well as inducing a more or less random force on the compressor piston-cylinder surface – in other words, even though the radial stiffness of the flexure bearings will limit the wear of the pistons, this wear can no longer be assumed negligible under conditions above PSD-CPA as determined during step stress testing (section 3.5).

This poses an additional challenge – the failure mechanisms of the compressor and the cold finger cannot be reasonably expected to scale the same way as they would in a ground-based application.

One approach to get around this limitation would be to perform more fundamental research into the various failure mechanisms (physics of failure), and thereby perform a bottom-up analysis. For example, by performing tribological testing such as a pin-on-disc test of the wear of contact surfaces, information could potentially be obtained that could be translated by analysis to the conditions inside a cryocooler. The many limitations of such a test, however, reduce the representativeness of such a test. For example:

- The motion of contact surfaces is linear, instead of the rotating pin-on-disc configuration
- Conditions inside a cryocooler (high-purity, high pressure helium) cannot be approximated sufficiently by a tribo test
- Cryocooler-specific effects such as thermal gradients and cold trapping of pollutants

The proposed approach is therefore to perform the combined life time and robustness test, and to evaluate the influence of the vibration exposure at subsystem level. For the flexure-bearing compressor – assuming robustness actions have been taken and the design is robust against qualification-level testing as described in paragraph 3.3 – the pressure wave produced by the compressor can be measured, and used as a figure of merit to determine the wear rate. The limiting value for this performance parameter is well understood, and can be budgeted. In other words, by applying different levels of random vibration during an operational test of the compressor and evaluating the degradation of the pressure wave, the scaling of compressor wear rate to PSD level can be approximated, as sketched in Figure 9. As also shown in this figure, for levels at or below PSD-CPA as determined in the step-stress test (paragraph 3.5), the flexure bearing compressor is assumed to be wear-free.

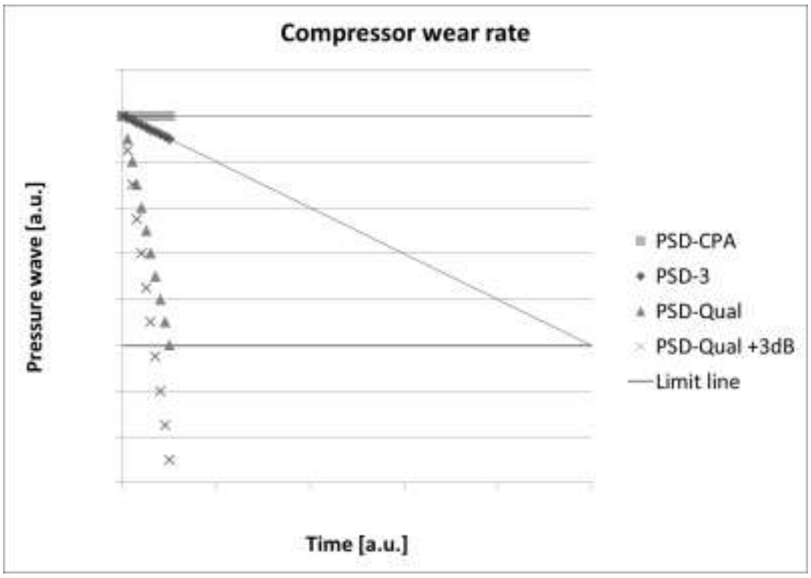


Figure 9. Determining the scaling of compressor wear rate

A similar analysis may be chosen for the cold finger, with heat lift (cooling power) at a predetermined pressure wave value as the figure of merit to determine the speed of degradation.

As it is desirable to obtain measurements at PSD levels that are close to the actual levels in the application, other acceleration mechanisms may be combined in this test.
For example, the cryocooler can be tested at an increased input power, with a high heat load test dewar - resulting in a larger travel distance for both the compressor pistons and the displacer, resulting in an additional wear acceleration factor. While other methods can be envisioned to further time-condense testing, such as modifying cryocooler parameters to increase the drive frequency and thereby the traveled distance of all wearing parts, these will reduce the validity of the test conditions when compared to the actual operating conditions.

While the wear mechanisms should be evaluated on subsystem-level, a representative test can only be performed on a complete cryocooler, for many of the same reasons why a fundamental tribological test will not suffice.

This is, however, in line with the method at Thales Cryogenics for testing the life time of linear cryocoolers- results are evaluated on subsystem (compressor or cold finger) level, and a life time test may be restarted with one of the two replaced. This same principle may be applied to accelerated lifetime-robustness testing, as outlined in Figure 10.

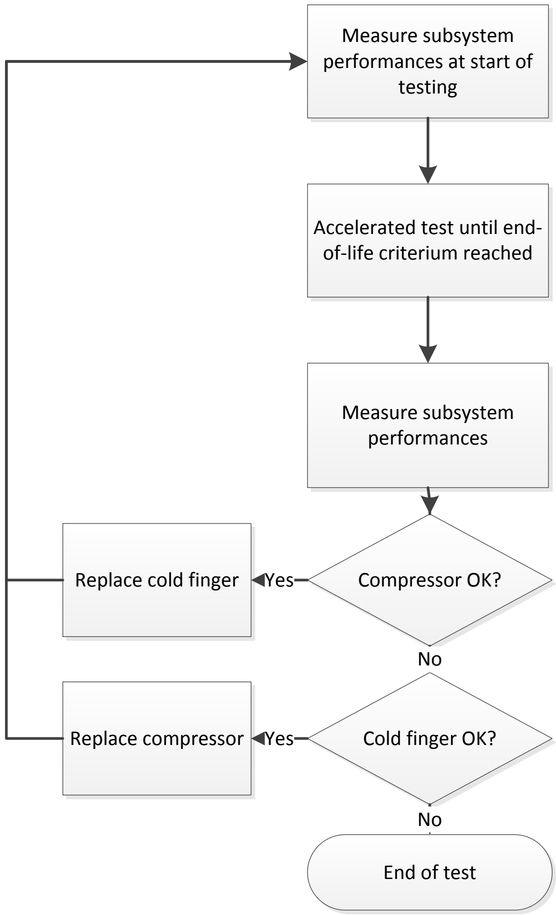


Figure 10. Test progression for accelerated testing with subsystem-level results evaluation.

3.7 Conclusion

Previously, an approach for reliability predictions was presented that made use of correction factors for environmental conditions, such as the mechanical environment [1]. By linking this approach to the previously-presented method for, a more accurate estimate could be given for the life time.
Thales Cryogenics is currently proposing this approach to select customers where it is expected that the PSD spectrum under normal use could have an influence on the cooler lifetime expectations and verifications.

4. CONCLUSION

Developing a cryocooler for high ambient temperatures requires a vastly different approach than developing for extreme mechanical conditions. When developing for high ambient temperature, the main challenge is in materials and process selection and qualification, while developing for extreme mechanical conditions requires not just controlling the design process, but also providing a clear link between product robustness testing and expected influence on life time.

A novel cooler has been presented that was developed for high ambient temperature conditions. In addition, a novel approach has been outlined for combined life time and mechanical robustness testing.

Thales welcomes discussion on potential applications of both.

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