UPDATE ON MTTF FIGURES FOR LINEAR AND ROTARY COOLERS OF THALES CRYOGENICS

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ABSTRACT

Thales Cryogenics has an extensive background in delivering linear and rotary coolers for military, civil and space programs. During the last years several technical improvements have increased the lifetime of all Thales coolers resulting in significantly higher Mean Time To Failure (MTTF) figures. In this paper not only updated MTTF values for most of the products in our portfolio will be presented but also the methodology used to come to these reliability figures will be explained. The differences between rotary and linear coolers will be highlighted including the different failure modes influencing the lifetime under operational conditions. These updated reliability figures are based on extensive test results for both rotary and linear coolers as well as Weibull analysis, failure mode identifications, various types of lifetime testing and field results of operational coolers. The impact of the cooler selection for typical applications will be outlined.

This updated reliability approach will enable an improved tradeoff for cooler selection in applications where MTTF and a correct reliability assessment is key. Improving on cooler selection and an increased insight in cooler reliability will result in a higher uptime and operability of equipment, less risk on unexpected failures and lower costs of ownership.

Keywords: Stirling, Pulse tube, Cooler, reliability, MTTF, Linear, Rotary

1. INTRODUCTION – LACK OF A MTTF STANDARD

MTTF figures as presented by the manufactures of cryogenic coolers are often difficult to compare because no internationally agreed standard exists today. Different test and analysis methods are used meaning that no clear comparison can be made between the different MTTF figures. But even with a standardization to present these values the transformation to different operational profiles is not always clear for users of cryogenic coolers.

In this paper an approach towards cooler reliability is presented which is valid for different cooler types. Although these cooler types have different failure mechanisms a common approach can still be used.

Figure 1: Thales rotary monobloc coolers (RM, left) and contact bearing linear cooler (UP, right)

Figure 2: Thales long life pulse tube coolers (LPT, left) and long life flexure bearing coolers (LSF, right)

The portfolio of Thales Cryogenics consists of a wide variety of Cryogenic coolers. The rotary monobloc coolers (RM) are being developed and manufactured at Thales Cryogenics France (TCSAS). The development and manufacturing of all linear coolers being the standard close tolerance contact seal linear coolers (UP series), long life flexure bearing coolers (LSF) and long life linear pulse tube coolers (LPT) takes place at Thales Cryogenics in the Netherlands (TCBV). These different cooler types are all depicted in the two figures above.

2. LIFE TIME TESTING HERITAGE

At the test facilities of both TCBV and TCSAS a substantial amount of life tests on several hundreds of coolers have been performed and are still ongoing in order to enable continuous improvement of our products. Figure 3 shows one of the test setups at TCBV at which linear coolers are operated continuously at input powers of around 70% of its maximum until failure.

Figure 3: Lifetime test setup linear coolers

Below an overview of recent life test results of both TCBV and TCSAS are presented.

Table 1: Recent lifetime test results summary with rotary coolers (left) and linear cooler (right)

Cooler type	Description cooler	Running hours	Status
RM1	A20 accelerated test	4.192	Failed
		6.059	Failed
		6.843	Failed
		5.587	Failed
RM2	New configuration, A20 accelerated test	574	Still running
		574	Still running
		1.100	Still running
		1.582	Still running
		1.586	Still running
		2.181	Still running
		2.192	Still running
		2.197	Still running
		2.479	Still running
		2.578	Still running
RM3	A20 accelerated test	1.324	Failed
		2.875	Failed
		5.166	Failed
RM4	New configuration, A20 accelerated test	9.041	Failed
		9.545	Still running
		9.560	Still running
		11.300	Still running
		11.341	Still running

Cooler type	Description cooler	Running hours	Status
Flexure Bearing coolers			
LSF9088	Moving coil	81.669	Still running
LSF9188	10 mm Stirling coldfinger	89.840	Still running. Worn out displacer replaced at 69.000 hours.
LSF9188		48.741	Stopped. Displacer worn out around 30.000 hours: restarted new cold finger
LSF9188		30.150	Stopped, displacer wear
LSF9188		47.328	Stopped, displacer wear
LSF9180	5 mm Stirling	44.325	Stopped, displacer wear
LPT9110	500 mW Pulse tube	85.222	Still running
LSF9320	20 mm Stirling cold finger	50.113 (70.478[1])	Still running. New displacer bearing material after 20.000 hours
LSF9320		49.478 (65.082[1])	Still running. New displacer bearing material after 15.000 hours
LSF9330	20 mm Stirling cold finger with flex bearings	68.909	Still running
LSF9330		70.098	Still running
LSF9330		54.062	Still running[2]
LSF9330		54.270	
LSF9597	¼" IDCA	19.196	Still running
LSF9597		19.225	Still running
LSF9597		11.939	Still running
LSF9597		22.951	Still running
LSF9997		2.518	Still running
LSF9997		10.425	Still running
Close tolerance contact seals			
UP 7080	Moving coil 5 mm Stirling cold finger	12.955	Stopped, worn out
UP 7080		40.322	Stopped. At 29.000 at 50% of initial performance.
UP 7080		35.229	Stopped, worn out
UP 7080		32.738	Stopped, worn out
UP 7080		14.346	Stopped early for research project, still within spec.
UP 7080		28.353	Stopped, worn out
UP 7080		32.131	Stopped early for research project, cooler within spec
UP8497		2.466	Still running

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[1] Total operational hours of the compressor against two cold fingers

[2] Test setup temporarily stopped for maintenance

For rotary coolers life tests are often performed under accelerated test conditions. As will be described later, all test results presented will be used as input for the calculation of the cooler reliability. New RM3 coolers being manufactured incorporate all lessons learned from the RM2 and RM4. New life tests on the most updated configuration of RM3 will be initiated in the beginning of 2012. Because of the similarities between the cooler types it is expected that the reliability of the latest RM3 configuration will be equal to at least that of the RM2 and probably equal to that of the RM4 cooler.

3. WEAR MECHANISMES AND DEFINITION OF A FAILED COOLER

Wear of a cryogenic cooler depends on the cooler type with its characteristic failure mechanisms and operational conditions. Two fundamentally different failure types can be identified. The first is the occurrence of a mechanical or electrical failure resulting in an immediate loss of functionality of the cooler. Such a failure is for instance failure of a bearing, spring or coil wire. The second failure type is the cooler not being able anymore of producing the required heat lift leading to a gradual increase of the temperature set point. In that case the moment of declaring the cooler as being failed depends on application specific considerations such as cool down time or image quality.

Linear and rotary monobloc coolers behave quite differently over time with respect to the different types of failure modes. Rotary monobloc (RM) coolers show a very constant cooling power and consequently input power to the cooler over time. Indications of wear of this cooler type are a gradual increase in acoustic noise and vibration levels until the cooler eventually completely fails. Thales' linear Stirling coolers on the other hand show a very gradual and controlled reduction in cooling power over time. The slope of this reduction depends on the linear cooler type. Standard linear coolers have contact bearings in both the compressor and cold finger. In the LSF long life coolers piston wear in the compressor has been completely eliminated using flexure bearings which suspend the compression pistons. The positive effect of this on the cooling power degradation is clearly visible in the next figure.

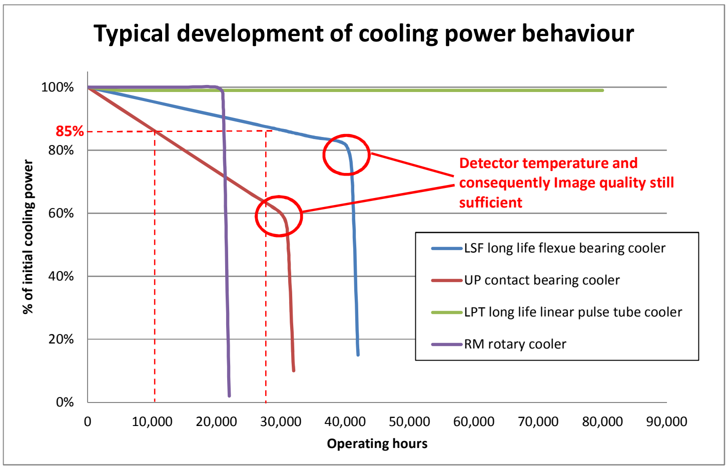

Figure 4: Typical behaviour of cooling power over time of Thales' coolers

Figure 4 shows the typical development of cooling power behavior for the different Thales' cooler families. The cooling power slopes for the UP and LSF cooler families have been based on actual life test results and can be regarded as representative. The impact of the flexure bearing compressor on both the gradual decrease of cooling power and the end of life moment of the cooler is clearly shown when comparing the LSF line with that of the UP cooler. Both the RM cooler and the pulse tube cooler (LPT) show no or very limited degradation of cooling power over time. Ideally from a reliability standpoint of view the cooler and application should be matched in such a way that at the end of life of the cooler the required heat lift for the maximum allowed detector temperature can still generated.

4. APPROACH TOWARDS MTTF

4.1 Overall approach

The approach towards determining the reliability of a cooler is shown in the next figure. All manufacturing and test processes at Thales Cryogenics are aimed at reducing the probability of infant failures by performing of various intermediate production tests and by implementation of correct burn-in procedures of all coolers. With these controlled manufacturing processes this means the reliability analysis can focus on the operational life of the coolers.

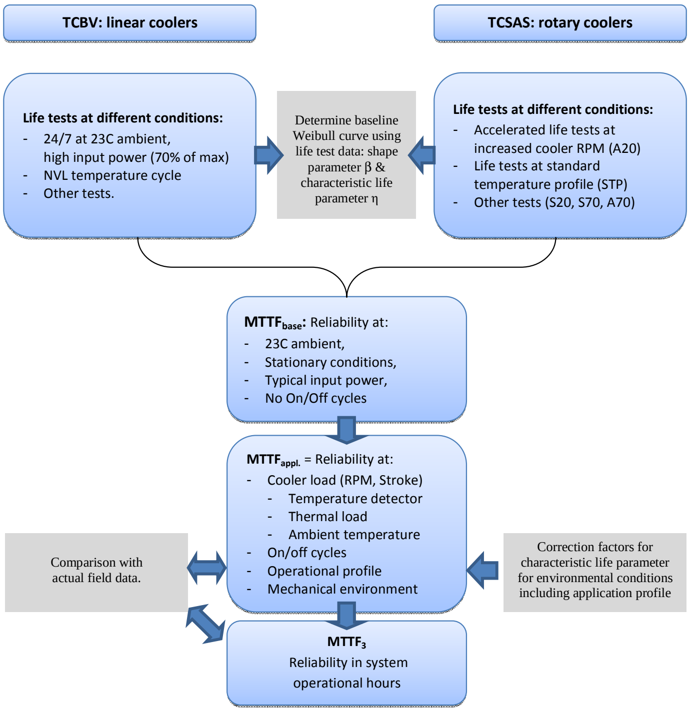

Figure 5: Thales approach cooler reliability

In this figure it is shown that for determining the reliability of all Thales' coolers life test data is being used. With these data the reliability of the cooler, which is called the baseline reliability or $\mathrm{MTTF}_{\mathrm{base}}$, is then determined for continuous operation under typical 23 °C ambient conditions. Here it is assumed that the cooler and application are matched in such a way that there is sufficient margin between required and produced heat lift. Typically a maximum of 70% of the cooler maximum input power under worst case condition, mostly 71 °C ambient, is used as a guideline. With this baseline figure the reliability or $\mathrm{MTTF}_{\mathrm{app}}$ of the cooler can now be determined for a specific operation profile which includes operating temperature, mechanical environment, number of cool down cycles and specific operational and non-operational hours of the cooler. Finally, the reliability of the cooler can be expressed in the number of operational hours of the application itself. This is called the MTTF_3. Dedicated calculation models are available at Thales Cryogenics in order to assess the reliability of all coolers under several possible operational profiles. Clearly, determining the reliability of a cryogenic cooler needs to be tailored to its application.

4.2 Baseline MTTF

For all coolers life test results are used in order to determine the baseline MTTF or $\mathrm{MTTF}_{\mathrm{base}}$. Using life test data as input a Weibull plot can be constructed using the following equation that describes the probability density:

$$f(x,\beta,\eta)=\frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} e^{-(x/\eta)^{\beta}} \qquad (1)$$

In this equation β is the shape factor and η is called the scale factor or characteristic life. The shape factor determines the failure evolution. If $\beta<1$, then the failure probability reduces with time, for instance when there is a high rate of "infant mortality". If $\beta>1$, then the failure rate increases with time, for instance due to an aging process. If $\beta=1$, the failure probability is constant, which means that failures occur purely random. Typically, Stirling coolers have a $\beta > 1$ as they contain components that are subjected to slow wear. However, pulse tube coolers and flexure bearing Stirling coolers with flexure support on both compressor and cold finger are subjected to random failures only and are treated consequently as having a $\beta = 1$ within a reasonable life interval of the cooler.

With life test as shown in tables 1 and 2 and commercially available statistical software Weibull plots for different types of coolers can be constructed. Software tools used by Thales for this analysis are Wes Fultons SuperSmith© and a specialized software suit 'La boite à outil du fiabiliste'. The resulting characteristic life or η from these Weibull plots represent the amount of hours at which 63% of the population has failed. In the analysis as shown in this paper the nominal value for η is always given. However in all calculations a confidence interval of 80% is typically used. For simplicity reasons the upper and lower levels are not presented in this paper. When performing specific customer application reliability calculations, the confidence interval can always be taken into account depending on the required calculation accuracy.

The characteristic life or η determined using this method is now defined as the MTTF of the cooler and is the reliability of the cooler as being operated during the life test. For linear coolers this reliability number is subsequently used as the baseline reliability despite the fact that the life test coolers are being operated at a steady state input power of 70% of its maximum. Thus well beyond the steady state input power at 23°C which is typically between 30 and 40% of the maximum. This is however done to simplify later calculations when tailoring the wear-out slope of linear coolers to a specific application. In order to determine the baseline MTTF for RM coolers the MTTF resulting from the life test data analysis is corrected for differences in motor speed between the accelerated life tests (such as A20 test) and the typical baseline conditions being a standard operating temperature of 77K and an ambient temperature of 20 °C.

4.3 $\mathrm{MTTF_{app}}$

The operating conditions of almost every application will differ from both the life test conditions and the baseline MTTF. This means that the MTTFbase will need to be translated into a MTTF of the final application with a specific operating profile. This specific MTTFapp can be determined using the following relation:

$$\mathrm{MTTF_{app}} = \frac{\gamma}{\frac{\alpha_1}{\mathrm{MTTF}_{\alpha 1}} + \frac{\alpha_2}{\mathrm{MTTF}_{\alpha 2}} + \dots \frac{\alpha_n}{\mathrm{MTTF}_{\alpha n}}}, \tag{2}$$

with γ being the amount of hours in a profile (8.760 hours in 1 year), αn = amount of hours for a specific part of the profile and the $\mathrm{MTTF}_{\alpha n}$ is the base MTTF including correction for the specific profile environment. The different segments of the profile include both operating and non-operating parts. The calculation of the MTTF assumes the shape parameter to remain the same. The correction therefore applies only to the characteristic life parameter resulting from the life tests. The $\mathrm{MTTF_{app}}$ indicates the cooler reliability expressed in calendar time expired. Non-operating conditions are regarded as standard storage (warehouse) conditions which are corrected for the environment for that specific storage. For the uncorrected storage conditions for linear coolers an average calculation of the allowed pressure loss over time has been made. In these calculations a maximum helium leak rate of 6*10-9 Pam3/s is used and an allowed pressure loss of 1 bar over time. Depending on the cooler type and gas volume of these cooler types this then results in an allowed uncorrected minimum storage period between 30 and 60 years. In reality however the leak rate is much lower than 6*10-9 Pam3/s so the leak rate does not limit the reliability of the cooler.

For the rotary coolers a storage period of minimum 30 years is used which is based on analysis of actual coolers being stored.

4.4 $\mathrm{MTTF_3}$

The MTTF3 is a slightly different way of expressing the cooler reliability than the $\mathrm{MTTF_{app}}$. Whereas the $\mathrm{MTTF_{app}}$ expresses the reliability in calendar time expired, the MTTF3 expresses the reliability in operating hours of the system the cooler is integrated into. This reliability is calculated according to:

$$MTTF_3 = \frac{1}{\frac{\alpha_1}{\alpha_{CON} MTTF_{\alpha 1}} + \frac{\alpha_2}{\alpha_{CON} MTTF_{\alpha 2}} + \cdots \frac{\alpha_{sn}}{\alpha_{CON} MTTF_{sn}}} \quad (3)$$

Here αn = the amount of hours for a specific part of the profile, αCON = total amount of hours the application will be operated over the period Σαi. As many systems are not operational continuously this will always result in the $MTTF_3 < MTTF_{app}$. For an end user of a cooled system the $MTTF_3$ provides a good figure concerning the cooler reliability over the operational life (being the amount of years the system can be used considering the expected average operating hours per year) of the total system.

5. MTTF CALCULATION FOR ROTARY COOLERS

5.1 Determining $MTTF_{base}$ for RM coolers

In order to determine the baseline MTTF of a rotary monobloc cooler, two steps need to be performed:

1) Analysis of accelerated life test data.
2) Translation of this life test data into a baseline MTTF.

New or modified definitions of rotary monobloc coolers are always put into life test. In order to accelerate these tests several coolers are being operated at a higher motor speeds than the cooler will typically be operated at. This accelerated test, which is called the A20 test, runs at a motor speed of 3.000 RPM which is well over typical motor speeds and consequently overstresses critical components such as bearings and piston coatings.

In the figure below the performance of a RM4 cooler at different motor speeds is shown as an example.

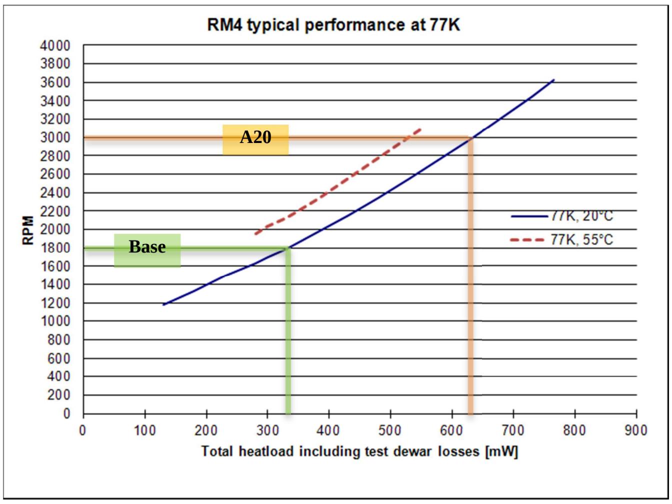

Figure 6: Typical performance RM4 cooler

It can be seen that at the accelerated motor speed of 3000 RPM the total heat lift of the cooler with a tip temperature 77K and an ambient temperature of 20°C is 630 mW. A typical ¼" bore infrared dewar typically requires a much lower heat lift of approximately 200 to 325 mW at 23°C depending on the design of the cryostat. Using the upper value worst case heat load will then result in a motor speed of around 1800 RPM which is significantly lower than the motor speed used during the A20 accelerated life test. For an ambient temperature of 55°C the expected cooler motor speed is 2.300 RPM with a total heat load of 375 mW at 77K.

Thales Cryogenics has performed extensive life tests in order to correlate the A20 accelerated life tests to continuous typical operation in a 20°C environment. Some of those results have been presented in [3].
These studies have resulted in the following relation:

$$MTTF_{base\_RM} = \left(\frac{RPM_{A20}}{RPM_{20°\mathrm{C}}}\right)^{1,5} MTTF_{A20\ test\ Weibull} \tag{4}$$

In case cooler life tests have been finalized, meaning that all coolers put in test have failed, a standard 2-parameter Weibull analysis is performed in order to determine the shape factor (β) and characteristic life (η). Life test results from the last years have shown a β of around 1,5 and 1,8 for rotary cooler types with η varying per cooler type. In case life tests results are still running a Weibayes analysis is performed. Weibayes is a Weibull analysis with a given β. The characteristic life parameter η can then be calculated according to:

$$\eta = \left(\sum_{i=1}^{N} \frac{h_i^{\beta}}{r}\right)^{1/\beta} \tag{5}$$

The Weibayes analysis can be used in case the shape factors of the failure mechanisms is expected to remain unchanged. The updated results of the still running RM4 lifetime test (see table 1) show that the value for β of the cooler is most likely increased due to the implemented design improvements. It is estimated that the actual β resulting from the current life test results will be in the order of magnitude of β ~ 3,5. From a reliability standpoint of view an increase of the shape factor is a positive development as long as this is accompanied by an increase in the value for the characteristic life. An increase of β means failures of various coolers will occur in a more limited timespan enabling a more accurate prediction of the cooler reliability and a lower quantity of early failures in the operational life.

5.2 Determining $\mathrm{MTTF}_{\mathrm{app}}$ for RM coolers

Before the $\mathrm{MTTF}_{\mathrm{app}}$ according to equation 2 can be calculated, the different values for MTTFαn of the various parts of the profile and the accompanying profile times need to be determined. The MTTFαn is calculated by correcting the $\mathrm{MTTF}_{\mathrm{base}}$ for the impact that the ambient temperature has on the internal mechanics of the cooler and for any increased levels of mechanical environment the cooler is subjected to:

$$MTTF_{\alpha n} = \left(\frac{RPM_{A20}}{RPM_{T\alpha n}}\right)^{1,5} MTTF_{A20\ test\ Weibull}\ C_{1\alpha n} \tag{5}$$

In this equation $\mathrm{RPM}_{\mathrm{T\alpha n}}$ is the motor speed at the ambient temperature of the specific profile part n. $\mathrm{C}_{1\alpha n}$ is a correction factor for the impact of the temperature on the internal cooler components that are not directly related to the wear mechanism of the moving parts such as metallic seals, Hall sensors motor coils and glass feedthroughs.

C1αn is calculated according to:

$$C_{1\alpha n} = 1{,}02^{k}, \tag{6}$$

with k = 1, 2….n for each 5 degrees of temperature rise with respect to the standard 20 °C ambient temperature. The amount of hours αn for each part of the profile are corrected for the time required for cooling down the detector and for the temperature under which the cooler is not operating. For each cool downtime that is being performed, the time required for reaching set point temperature is translated into the operating time for that specific part of the profile according to:

$$\alpha_{\mathrm{n}} = \left(\alpha_{\mathrm{on(n)}} - \alpha_{\mathrm{CDT(n)}}\right) + \left(\alpha_{\mathrm{CDT}} \frac{\mathrm{RPM}_{\mathrm{A20}}}{\mathrm{RPM}_{\mathrm{n}}}\right) \tag{7}$$

For rotary coolers no correction for the mechanical environment is applied. Because of the design of rotary coolers only very low induced forces are exerted internally as a result of for instance random vibrations resulting in very little impact on the reliability.

6. MTTF CALCULATION FOR LINEAR COOLERS

6.1 Determining $\mathrm{MTTF}_{\mathrm{base}}$ for linear coolers

As outlined before the $\mathrm{MTTF}_{\mathrm{base}}$ for linear coolers is determined using life test data to construct a Weibull curve. In many applications in which the available cooling power has sufficient margin to accommodate performance degradation the life test results as shown in table 2 are used to determine the characteristic life of a linear cooler family. These hours represent the end of life moment of the test coolers at which the cooling power shows a relative rapid nonlinear degradation. This is the moment at which the required set point temperature no longer can be maintained and marks the beginning of image quality deteriorating. This point in time is encircled in Figure 4. There are however applications in which less margin is available meaning that the cooler is no longer able to maintain the required heat lift in combination with necessary detector temperature before the actual end of life moment of the cooler has been reached. This then marks an early end of life moment of the cooler despite the fact that the cooler is still operational and producing heat lift. This is also shown in Figure 4 in which an example is shown where only 15% of cooling power degradation is allowed. In this case a lower value for the $MTTF_{base}$ is calculated. This correction for the baseline MTTF is done by calculating for each of the life test coolers the amount of degradation and accompanying life test hours that would be allowed for the specific application being analyzed. These reduced end of life hours of the test coolers are then used as input for the Weibull analysis. Next the revised baseline MTTF is determined resulting in a characteristic life and shape factor that is tailored to a specific application.

6.2 Determining $MTTF_{app}$ for linear coolers

With the $MTTF_{base}$ number known, the translation to an actual application can be made. For this the reliability for each part of the profile MTTFαn needs to be calculated. For this the following correlation is used:

$$\mathrm{MTTF}_{\alpha n} = \frac{\mathrm{MTTF}_{\mathrm{base}}}{\pi_1 \pi_2 \pi_3 \pi_4} \tag{8}$$

π_1 is a factor to correct for differences in ambient temperature with respect to the baseline ambient temperature of 20 °C. π_2 corrects for the amount of cool down cycles the cooler is subjected to: standard life test coolers are often being operated continuously without on/off cycles. π_3 corrects for the mechanical environment such as random vibrations the cooler is subjected to during operation. Finally, π_4 is a correction for differences in cold tip temperature with respect to the baseline cold tip temperature of 77K in case no cold tip temperature corrections have already been assumed in determining the $MTTF_{base}$.

The different correction factors have been determined quantitatively and qualitatively using assessments of input power versus piston wear and results from random vibration and life test results. Furthermore data from the installed base have been used in order to correlate the correction factors to actual coolers used in applications. The various factors used are summarized in the table below.

Table 2: Correction factors linear coolers

<table>
<tr><th></th><th>UP cooler family</th><th>LSF cooler family</th></tr>
<tr><td rowspan="2">π_1 ($T_{ambient}$)</td><td><i>(Operating)</i>
$1+(0,01*(T_{amb\_op}-20))$</td><td><i>(Operating)</i>
$1+(0,005*(T_{amb\_op}-20))$</td></tr>
<tr><td colspan="2"><i>Non operating:</i> $1+(2.5E-4*(T_{amb\_op}-20))$</td></tr>
<tr><td>π_2 (# cycles)</td><td colspan="2"><i>Operating:</i> $1.01^{N/100}$
<i>Non-operating,</i> no correction: $\pi_2 = 1$</td></tr>
<tr><td>π_3 (mech)</td><td><i>Operating & non-operating:</i> 1 (none), 1,2 (medium), 1,4 (severe)</td><td><i>Operating & non-operating</i>: 1 (none), 1,1 (medium), 1,2 (severe)</td></tr>
<tr><td rowspan="2">π_4 (T_e)</td><td>$1/((T_{set}-77)*0,02+1)$</td><td>$1/((T_{set}-77)*0,01+1)$</td></tr>
<tr><td colspan="2"><i>Non-operating,</i> no correction: $\pi_4 = 1$</td></tr>
</table>

For the correction factor used at π_2, N represents the number of cool down cycles in one year. For the mechanical environment a differentiation is made between ground fixed ($\pi_3 = 1$), medium environments ($\pi_3 = 1,2$ for UP and 1,1 for LSF coolers) and severe environments ($\pi_3 = 1,4$ for UP and 1,2 for LSF coolers). LSF coolers are less affected by the mechanical environment as the flexure bearings provide additional radial support for the moving parts inside the compressor. Next, knowing the reliability for the different parts of an operating profile the application reliability or $MTTF_{app}$ can be calculated according to equation 8.

6.3 Estimation of pulse tube cooler reliability

Ross et al. has presented a method for determining the reliability of a flexure bearing space Stirling cycle linear coolers [1]. This method makes use of the identification of the different failure modes in a linear cooler and has been used before by Thales [4]. By determining the failure probability for each of the failure modes, the overall cooler MTTF can be determined. This is achieved by the correlation of MTTF = 1/λ, with λ being the summation of the failure rate of all failure mechanisms. As this methods uses a summation of different types of random failures, this approach is only valid in case all failure mechanisms are considered as random failures and the overall Weibull shows a shape factor of $\beta = 1$.

In order to assess the reliability of a pulse tube cooler consisting of a flexure bearing compressor and a pulse tube an overview of the various possible failure modes has been created using the initial list as presented by Ross as guideline.

Table 3: Failure mechanisms according to Ross

FAILURE MECHANISM	***MTTF***	**λ= 1/MTTF**
Structural seal/weld connection failure	578.051	1,73E-06
Compressor flexure breakage	578.051	1,73E-06
Coil wiring isolation breakdown	578.051	1,73E-06
Compressor piston alignment failure / piston seal failure	578.051	1,73E-06
PT cold finger brazing / welding failure	-	1,73E-06
Loss of inertance connection	-	2,70E-07
Cold finger - compressor connection failure	578.051	1,73E-06
Overall MTTF	**93.899**	

In table 3 for each of the possible failure mechanisms the total amount of accumulated hours in life test without observing such a failure have been summated. For compressor related hours corrections have been added for those cases where coolers with worn out Stirling cold fingers were restarted with the same compressor. Two pulse tube cold finger failure modes that have been identified are a failure of a brazed or welded connection of the pulse tube and a failure of the inertance[3] connection. For both failure modes the failure probability has been estimated. The resulting overall MTTF of 93.899 hours is then used as the characteristic life or η of a Weibull distribution with an assumed $\beta = 1$. In case future cooler returns would reveal wear related failures after all, the hypothesis of $\beta = 1$ might need adjustment. However because of the already large amount of accumulated hours of the current installed base this would then always result in a high value of β of possibly > 10.

Next step is to use the accumulated hours of the installed base of Thales Cryogenics' linear pulse tube coolers as input for the same analysis. In total several hundred of coolers are currently operational with an estimated total of 23.200.000 hours accumulated with almost no failures reported. The only failures reported have been a loss of the inertance connection in two instances. These failures were found to be process errors and can therefore be regarded as infant failures and not as random failures during life of the coolers. Nevertheless these failures have been taken into account as random failures. The resulting value for η now becomes 1.855.087 hours, also with a value of $\beta = 1$. It should be emphasized that this is not the actual expected average life of a pulse tube cooler but is used a statistical parameter to calculate probability of a cooler failure during operation.

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[3] The inertence in a pulse tube cooler is a phase shifting device consisting of a long tube

7. MTTF BASELINE RESULTS

Using the test results as presented in tables 1 and 2 several Weibull curves for the baseline reliability can be constructed as shown in the next figure.

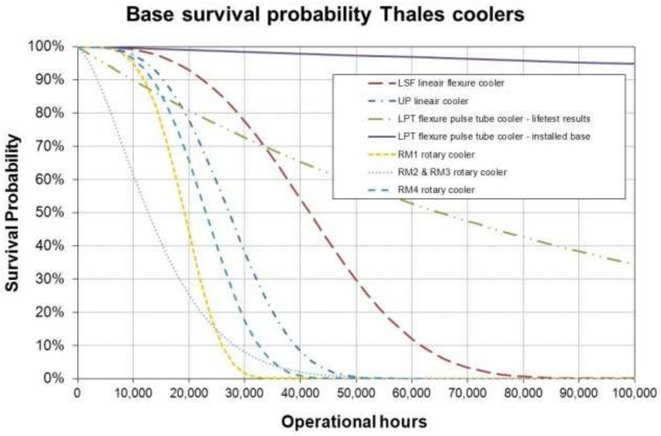

Figure 7: Baseline Weibull curves Thales coolers

This figure shows the expected survival probability for the different cooler types when operated continuously at 23 °C at a typical input power. For the rotary coolers in this figure the numbers resulting from the accelerated life test are already corrected according to equation 4. As an example, after operating a linear flexure bearing Stirling cooler for 20.000 hours, there is a 93% chance that the cooler is still operational. The differences in shape parameters between the different cooler types is clearly visible.

For the pulse tube coolers the calculated results using the method of Ross [1] have been used to plot two lines, both with $\beta = 1$. First the reliability is shown using the results from the current life test coolers with $\eta = 93.899$. Second the probability line is plotted when using the amount of hours resulting from the installed base of pulse tube coolers with a value of $\eta = 1.855.087$. Because of the shape factor $\beta = 1$ the failure probability slowly decreases over time. With a presented failure chance of only 5% after 100.000 hours of operation the pulse tube cooler shows the best reliability of all cooler types. It should be noted that these numbers are supported not only by the large installed base of coolers with almost no returned failures, but is also confirmed by pulse tube cooler analysis. Life tests of flexure bearing compressors still running today have demonstrated uptimes of well over 90.000 hours can be met. Moreover, performance analysis on several pulse tube coolers being operated in an actual application have shown no performance degradation could be measured after 15.000 and 25.000 hours of operation.

8. MTTF APPLICATION RESULTS

8.1 Application profile

Using the baseline MTTF numbers for the various coolers as shown in Figure 7 the translation towards an actual application can be made. For this purpose an operational profile needs to be chosen. As an example a standard temperature profile has been chosen as shown in the next figure:

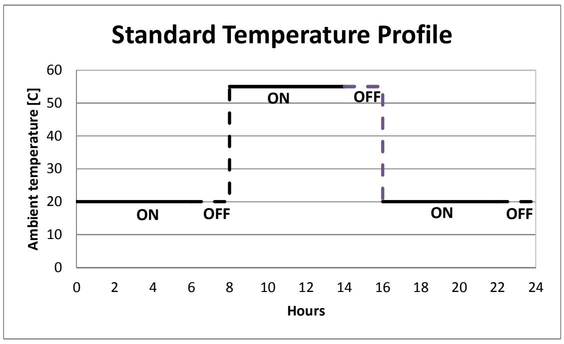

Figure 8: Standard Temperature Profile (STP)

In this profile the cooler is being operated in both on and off conditions at ambient temperatures of 20 °C and 55 °C. For the example calculations used in this paper no mechanical environment is used so a ground fixed application is assumed. For the two different temperatures the following required cooler heat lifts are assumed. These required heat lifts are based on assumed worst case heat loads of infrared dewar at a focal plane array temperature of 77K and are shown in the table below.

Table 4: Assumed heatloads for STP

Ambient temperature	**20 °C**	**55 °C**
Cold finger losses	175 mW	210 mW
Other conductive and radiation losses	50 mW	65 mW
FPA dissipation	100 mW	100 mW
Total heatload estimated	**325 mW**	**375 mW**

For infrared dewars with a ¼” dewar bore lower heat loads will typically be encountered. The required heat lifts as presented here are therefore considered as worst case.

8.2 MTTF_{app} and MTTF_3 results for linear and rotary coolers

By applying the environmental correction factors for rotary and linear coolers to the base reliability figures as given in Figure 7 and combining the different parts of the application profile, a new reliability graph for the different cooler types when subjected to a standard temperature profile can be constructed:

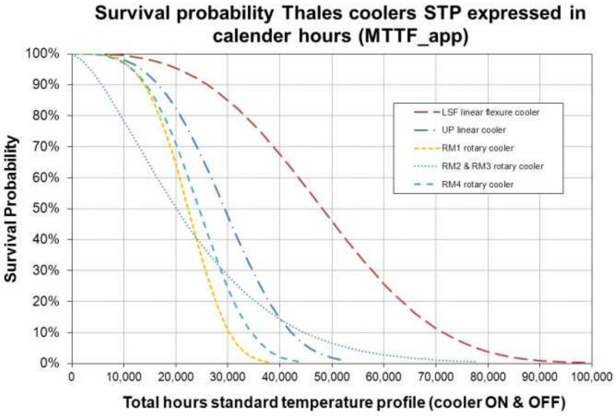

Figure 9: Weibull curves Thales Coolers based on Standard Temperature Profile expressed in total calendar hours

This graph shows an increase of the MTTF of all cooler types. On one side the reliability is reduced because of the higher ambient temperature condition of 55 °C that is part of the profile. On the other side the reliability is increased because the coolers are not in operation continuously resulting in an increase in the overall MTTF. It should be noted that in this graph the amount of hours are total hours so include the hours that the cooler is turned off. In many applications cryogenic coolers are operated significantly less than the 18 hours as being used in the standard temperature profile. In those applications the overall MTTFapp of the coolers will become substantially higher than those shown in Figure 9.

Next, using equation (3) the reliability of the various coolers can be plotted not expressed in calendar hours expired but in operational hours of the application itself. This then results in the following plot:

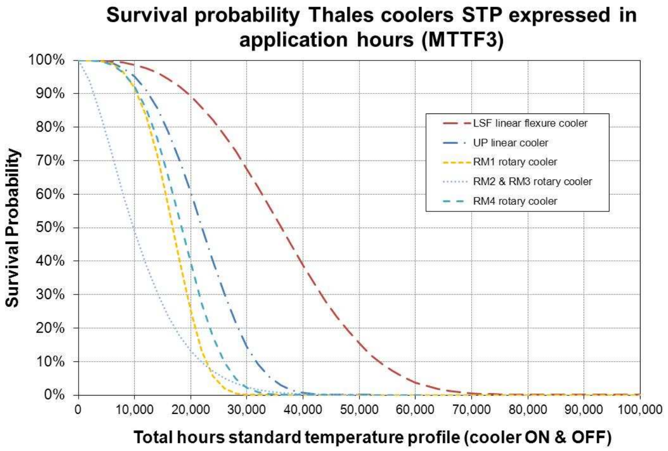

Figure 10: Weibull curves Thales Coolers based on Standard Temperature Profile expressed in total application hours

In this plot the reliability has been expressed into operating hours of the system itself in which the cooler has been integrated into instead of calendar hours. Clearly the reliability curves have changed as a result of this different representation. Of course the reliability of the various coolers is identical to that as depicted in Figure 9.

Both representations provide interesting information to be used in for instance in the assessment of service intervals or the identification of critical components in the system.

9. MATCHING LINEAR STIRLING COOLER – APPLICATION

For matching the cooler reliability with the required reliability of an application a detailed analysis of the main reliability parameters of both is required. In Figure 11 a schematic overview is shown.

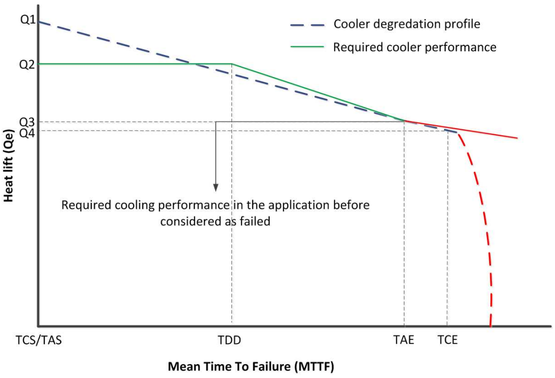

Figure 11: Matching of linear cooler with an application

This figure shows two performance lines. The dotted line represents the decrease in cooling power of a linear Stirling cooler over time. The solid line depicts the total heat lift that the detector/dewar assembly requires. For this example this means it is assumed that the detector/dewar assembly is able to accommodate a certain increase in detector temperature before being declared as failed. This means that over time a reduction in total heat lift is allowed. The moment as of which this increase in detector temperature is allowed is indicated by TDD or Time Detector Degradation. In relation to the degradation over time Sofradir has presented [2] that with the use of HgCdTe based focal plane arrays an increase in detector temperature from 80K to 110K with a perfect NETD lead to 0.5 % of defects being observed which is regarded as still acceptable. This means that the cooler detector assembly is declared as failed when the cooler is no longer able to sustain 110K instead of the initial 80K. This is different for other materials such as for instance InSb detectors which are typically less able to operate at temperatures higher than 80K. Nevertheless this demonstrates the impact this parameter can have on the definition of end of life of the detector cooler assembly and consequently reliability of the system.

In Figure 11 the difference between points Q1 and Q2 is the performance margin determined by the cooler selection at the start of the lifetime. This moment is marked by TCS / TAS meaning Time Cooler Start / Time Application Start. After a certain amount of operating hours the heat lift of the cooler has degraded to such a point (TDD) that the detector temperature starts to increase but still with acceptable impact on detector noise. At Q3 however the detector temperature has increased to such a point that the detector cooler assembly is eventually considered as failed. This is marked as TAE or Time Application End. At Q4 the cooler actually reaches its final end of life which is marked by a rapid decrease in cooling power. This moment is marked as TCE or Time Cooler End. In order to maximize the operation time of the detector-cooler assembly this moment should always be later in time than TAE.

From the exercise as shown it can be concluded that several parameters of both the cooler and focal plane array need to be considered and matched closely in order to fully utilize the lifetime of the cooler:

- Definition of margin on cooling power Q1-Q2 at the beginning of operation.
- Quantification of the acceptable cooler performance loss over time.
- Specification of the operation profile.

10. INSTALLED COOLER BASE AND SERVICE RETURNS LINEAR COOLERS

Recently a study has been performed into approximately 6.000 linear coolers being fielded from different types. Any cooler that is returned to Thales Cryogenics for service has been categorized with respect to the type of failure and reason for return. The most recent analysis has been focusing on differentiating between normal expected wear (above or equal to the specified MTTF) and early wear (failure due to unexpected wear leading to failed coolers early than predicted). Historically, for the standard contact seal UP coolers an average of around 4% has been returned for early wear. However, for the last 3 years it has been found only 0,5% of the population has been returned for reasons of early wear. This improvement is a direct result from implementing improved piston coatings and several process innovations.
Next, an assessment of the average amount of operating hours for each cooler has been made. Underlying assumptions have been that a cooler delivered is put on stock for 6 months before becoming operational and that the cooler is operational for 60% of its time. This analysis then leads to an average of 6.000 operational hours for each cooler. When investigating the STP profile Weibull plot of Figure 9 for the UP cooler it can be found that the reliability for 6.000 hours has been calculated for 99.6% which is very close to the amount of UP coolers being returned for service in the last three years.

With regard to systems based on flexure bearing compressors (LSF and LPT) no early wear returns have been reported. Based on the amounts of fielded coolers with this compressor type more than 1.500 systems have accumulated a total well over 25.000.000 running hours without any failures on wear. The first supplied pulse tube systems have passed the 60.000 running hours. These data also supports the high reliability of the coolers using flexure bearing technology in the compressor.

11. SUMMARY AND CONCLUSION

With respect to cooler reliability Thales has chosen an analysis method based on the Weibull distribution. Optimizing cooler reliability is embedded though all of the company processes by: reducing infant failures using cooler burn-in procedures, reduce the probability of random failures in all design processes, focus of design changes aimed at increasing of the characteristic life or η of the cooler and maximize the shape factor β in order to prevent early cooler failures. Moreover developments are aimed at efficiency improvements in order to reduce cooler stresses and increase margin on cooling power in the application.

The reliabilities of the different Thales' cooler types can be summarized as follows:

Table 5: Summary reliability figures Thales' coolers

Cooler type	**MTTF life test conditions (Weibull calculated)**	**Baseline MTTF (23 °C)**	**$MTTF_{ADD}$ STP**	**$MTTF_3$ STP**
RM1 rotary	6.154 (Accelerated, 3.000 RPM)	21.034 (1.800 RPM)	24.530	18.432
RM2 rotary	6.021 (Accelerated, 3000 RPM)	16.156 (1800 RPM)	25.651	12.508
RM3 upgraded rotary	TBC, expected 6.000 hours (Accelerated, 3.000 RPM)	TBC, expected 15.000 (1800 RPM)	TBC, expected 25.000 hours	TBC, expected 12.000 hours
RM4 rotary	11.905 (Accelerated, 3.000 RPM)	25.615 (1.800 RPM)	27.164	20.430
UP linear family	30.349		32.824	24.618
LSF flexure linear family	46.928		54.298	40.724
LPT flexure pulse tube family	92.940 (based on life test coolers)			

It is shown that design improvements as demonstrated in the RM4 cooler have resulted in an increase of the shape parameter β, increasing the cooler reliability significantly. During 2012 it is expected that the same improvement can and will be implemented in all rotary coolers.

Not only updated reliability figures but also an updated approach towards determining the reliability of Thales' coolers has been presented. Both offer detailed insight in the cooler reliability for continuous operation and use in actual applications offering integrators and end users valuable tools for improving equipment uptime and reducing total costs of ownership.

REFERENCES

[1] Ross et al., "Cryocooler reliability and Redundancy Considerations for Long-Life Space Missions", Cryocoolers 11, (2001).

[2] Breniere, Cauquil et al., "Reliability optimization for IR detectors with compact cryo-coolers", SPIE 5783-21, (2005).

[3] Cauquil et al., "Update on life time test results and analysis carried out on Thales cryogenics integral coolers (RM family)", SPIE , (2002).

[4] Mullié et al., "Development of the LSF95xx 2nd generation flexure bearing coolers", SPIE, (2005).