How to manage MTTF larger than 30,000hr on rotary cryocoolers

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ABSTRACT

The cooled IR detectors are used in a wide range of applications. Most of the time, the cryocoolers are one of the components dimensioning the lifetime of the system. Indeed, Stirling coolers are mechanical systems where wear occurs on millimetric mechanisms. The exponential law classically used in electronics for Mean Time to Failure (MTTF) calculation cannot be directly used for mechanical devices. With new applications for thermal sensors like border surveillance, an increasing reliability has become mandatory for rotary cooler. The current needs are above several tens of thousands of continuous hour of cooling. Thales Cryogenics made specific development on that topic, for both linear and rotary applications. The time needed for validating changes in processes through suited experimental design is hardly affordable by following a robust and rigorous standard scientific approach. The targeted Mean Time to Failure (MTTF) led us to adopt an innovative approach to keep development phases in line with expected time to market. This innovative approach is today widespread on all of Thales Cryogenics rotary products and results in a proven increase of MTTF for RM2, RM3 and recently RM1. This paper will then focused on the current MTTF figures measured on RM1, RM2 and RM3. After explaining the limit of a conventional approach, the paper will then describe the current method. At last, the authors will explain how these principles are taken into account for the new SWaP rotary cooler of Thales Cryogénie SAS.

Keywords: Cryogenics, MTTF, Reliability, Accelerated ageing, Stirling, Cooler, IR detector, RM2

1. INTRODUCTION

IR detectors are used within various military applications for years. Depending on the key driver needs, either linear or rotary Stirling cooler can be used to cool down these detectors. In the past, one of the main advantages of the linear cooler was the reliability, with a MTTF which can be more than four times higher than an equivalent rotary. On the other hand, rotary were preferred when compactness or price were favored. In the recent years, improvements implemented by Thales on design and processes of its rotary coolers have led to a continuous increase of rotary cooler Mean Time to Failure (MTTF). In parallel, new market has grown like border surveillance, where competitive cooled IR detectors can place themselves since cooled solutions can endure several thousands of hours before failure. As a consequence, there is a growing market where cool IR detector equipped with rotary coolers can be used if the failure rate after two or three years of continuous operation remains under control and economically viable. Consequently, rotary coolers MTTF shall be typically higher than 30,000 hrs to become competitive.

Unlike electronics, the failure rate of a mechanical system does not remain constant during the whole life of the system, mainly because of friction and other wear mechanisms. The evaluation of MTTF is therefore usually carried out using ageing tests.

The rotary cooler category with a 30,000 hrs MTTF requires a particular approach to drive the MTTF increase. This approach may remain compatible with an economically relevant development time and cost. Thales Cryogénie SAS (TCsas) has then developed an innovative method in order to reduce that cycle.

After a description of the usual tools used by TCsas to determine the reliability of coolers (tests profile, type of coolers tested, calculation law, and classical method of reliability growth), the paper will then explain an innovative method to grow the reliability and to verify in a short period of time that the targeted 30,000 hours are reached. This method will be illustrated by the RM2 example.
2. METHODOLOGY FOR RELIABILITY EVALUATION

2.1 Test profiles
Since the end of 1990s, TCsas has chosen a unique reliability development strategy for all of its coolers. In order to have strong data, several test profiles have been set-up and compared initially before choosing the final experimental specific profiles used in our reliability measurements. This allows TCsas:

- to present MTTF results based on reliable figures,
- to correlate the failure analysis and eventual root causes (physics of failure),
- thus to identify the relevant eventual corrective actions needed.

Among the various profiles, this paper presents 2 main profiles used by TCsas.

2.2 STP profile
The STP profile is the reference profile of TCsas in which the cooler performances are specified. It corresponds to a profile approaching a typical operational use.

![STP profile](image)

Figure 1: STP profile used for specification. This profile is close to typical operational use.

Different coolers were tested with STP profile during 2000s to assess various types of RMX (RM2, RM3 and RM4) reliability [2]. Nonetheless, the increasing life expectancy of the coolers has strongly extended the test duration. It reaches several years when the coolers reliability exceeds 10,000 hours. As a result, no coolers are anymore tested according to this profile for MTTF calculation.

2.3 A20 profile
Establishing accelerated ageing became therefore more and more necessary. The use of acceleration factors leads to an optimization of the test duration. In the absence of accelerated standard test for the coolers, TCsas has developed its own profile of accelerated test which is called A20 profile. This profile has been closely described in [7]. It has been designed to accelerate the ageing of the cooler, without introducing alternative failure modes. The actual failure modes were compared to those of the field returns.

Basically, the cooler is run at room temperature in speed regulation. This speed has been chosen to simulate a cold temperature well below the operational one (acceleration), with an upper limit which is the maximum rotation speed endured during the cool down phase. Thus, the rotation speed is tuned to accelerate the tests without introducing undesired mechanical conditions that could induce other failure modes.

The second acceleration factor is based on the time of operation. The A20 profile is a continuous operation profile. This profile probes the failure mode linked to operational use only. The impact of storage has been evaluated from a previous internal study based on analysis and experiments. The MTTF in storage is several times higher than the one in operation, and can then be dissociated.
Performances are checked every 500 hrs of operations. The cooler is declared in default as soon as performances (cool down time or power consumption) are no longer in line with the technical specification.

This profile of A20 test has become the standard profile to TCsas.

2.4 Sample Size for lifetime tests

The sample size is one of the most dimensioning parameters for a characterization campaign. Too low sampling may lead to uncertainties and unusable test results. Conversely, over-sampling is expensive and lead to a loss of efficiency.

Depending on the development phase, the needs of evaluation of the cooler reliability can be different:
- Evaluation of new coolers (new development),
- Evaluation of new concepts,
- Evaluation of new suppliers,
- Continuous evaluation of the reliability for the delivered products.

To evaluate a new cooler or a new concept, generally the size of the sample is from 3 to 5 coolers. This number of coolers is generally a trade-off made between non-recurring costs and confidence on a first estimation of the reliability. When the cooler is in mass production, the reliability evaluation will be done by tests made with coolers from mass production: Coolers are tested regularly (around one each month) in A20 test. This method allows:
- To increase the number of units dedicated for reliability evaluation (40 RM2 todays) in order to improve the confidence interval around the refined mean value.
- To have a continuous evaluation of the reliability of the cooler and monitor potential drifts. One can then introduce quickly, if necessary, a corrective action before detection by the return from the field.

Another use of the reliability test can be done to evaluate a new supplier (bearings or piston/liner for example). In this case the size of the sample will be a compromise between the time required to obtain the results and the costs of the test. The sample is never below 3 coolers, and reaches generally, from 5 to 7 coolers.

For each need, an adapted profile could be necessary. To reduce de number of test and simplify the use of results, we have considered that all the coolers must be assessed in A20 profile.

TCsas has developed a method of calculation allowing converting the reliability obtained from A20 profile into any other profile [7].

The evaluation of the reliability for A20 test, for all the coolers, gives an additional robustness to the calculations of reliability. Indeed, all the configurations are assessed without risk of biased results linked to different protocol of tests. Moreover, the A20 profile has not evolved since the beginning of its use: we can thus assess on the same scale of stress all the configurations of coolers, all type of coolers for twenty years.

Today, approximately 100 units, concerning 5 types of coolers (RM1, RM2, RM3, RM4 and RMS1) are running in parallel in A20 test.
This long term strategy on reliability assessment has allowed us to constitute a huge database of more than 500 coolers, giving us a lot of information on the typologies of the most likely failures, the rare typologies or non-existing breakdowns.

2.5 MTTF Calculations

In order to evaluate a robust and reliable MTTF, it requires a resilient database on one hand, but also on the other hand an efficient modeling for calculation. In the toolkit of the reliability expert, numerous methods are available. They have to be chosen according to the system to be studied. For example, reliability assessment by using the exponential law is applicable to electronic equipment, but must be banned for mechanical devices most of time, which cannot have a constant rate of breakdown. Nevertheless this exponential law is sometimes inappropriately used by manufacturers of mechanical devices, included coolers manufacturers [5]. This misuse is probably linked to its simplicity of implementation: the MTTF is basically the ratio of operating hours on the number of failures. But this type of results, besides it leads to inaccurate MTTF values, brings increasing errors on the real failure rate according to time.

TCsas has thus opted, since the early 2000s, for an analysis based on the Weibull’s law [1]. This law is typically adapted to reliability assessment for mechanical devices subjected to wear [8]. This approach is used to evaluate the MTTF and the failure rate, but also other information such as the number of failure modes.

At last, a third approach derived from the Weibull’s law is currently used by TCsas. Indeed, the shape parameter of the Weibull’s law has been determined on previous test campaigns. To use this approach, we make the assumption than this parameter sparsely varies as long as failure modes do not change. This allows us to use a particular case of Weibull (Weibayes) to estimate the reliability, even with a few number of operation hours. The advantage of Weibayes appears when the percentage of failed coolers is low or zero [3].

Last advantage but not the least, the Weibull’s law is recognized and very used all around the world [8]. Thus the understanding and the robustness of the results obtained by Weibull are reinforced.

3. TRANSFER FUNCTION FROM A20 TO ANY OTHER PROFILE

The evaluation of the reliability requires to be indicated according to the user profiles. Thus the choice of TCsas to establish the standard test A20 can be satisfactory for an internal development and can be suited for customer needs if one has the capacity to evaluate the equivalent MTTF in customer’s profiles. Thus, TCsas has developed a method allowing to transfer the reliability obtain for A20 test to any other operational profile [4]. Below is the synoptic of the procedure followed to establish the transfer function.
Both methods (rotary and linear coolers) use Weibull’s law and lead to similar MTTF principle evaluation. Actions are currently undertaken to standardize the MTTF results and analysis for linear and rotary coolers.

4. HOW TO DEAL WITH MTTF LARGER THAN 30,000 HOURS

4.1 Standard method

The classical method for growth of reliability is based on extensive lifetime tests and failure analysis. If the tests are based on an accelerated ageing, one has to validate the failure mode are the same as the ones occurring during operational uses.

The main milestones therefore are:
- Search for the root cause (failure analysis, experimental design, physics of failure)
- Determination of the corrective action (process improvement, new component design)
- Validation of the corrective action (pilot batch, non-regression and performances evaluations, lifetime tests)
- Application in mass production

This method has been used successfully up to 2012 [4]. Its application allowed us to increase significantly the reliability of the coolers by:
- Removing the bearing failures since 2006 (not the first failure mode anymore)
- Adopting a particularly well adapted lubrication to the coolers (performances and outgassing).

Indeed, the low ageing of the lubrication confers a big longevity to the cooler. Besides, the good behavior of these lubrications allowed first to reduce the ageing of devices and also to improve the behavior in acoustic noise of the coolers during their life: the increase of the acoustic noise, during the life of the coolers is nil. The graphs below gives the acoustic behavior for 40 RM2 tested in A20 test.
A few units show an evolution of their acoustic level during their life. Most of the cases, this rise occurs during the last hours of operation, as illustrated below.

Two coolers have shown a significant increase in noise during operation from a definite event. Particular failure analyses are done on these specimens. For most of the coolers, the variations of noise between the beginning and the end of life (see table 1 for associated hours of operation) remains quite limited, and is of the same order than the standard deviations. That very stable behavior of emitted noise is the results of the works done on lubrication and bearing designs.

But, although efficient, the duration of the cycle of this method is now inadequate with the requirements of the market, especially as the reliabilities objectives of coolers are now at 30 000 hours.

Typically, to prove a reliability of 30,000 hours, for 10 coolers tested, around 2 years of test are necessary to obtain the first results, and 3 or 4 years are necessary to confirm the results.

4.2 Innovative method

The previous section illustrates how the conventional approach – based on failure analysis and on additional lifetime test to prove the impact on MTTF of any change on the cooler – leads to inappropriate duration for qualification. Any process modification which may have an impact on the MTTF shall be subjected to an accelerated ageing of several month, nay several years.
A faster method for driving the growth of reliability has then been elaborated by TCsas. This method is directly linked to the initial discrepancy on MTTF obtained on initial designs. The analysis of the results of lifetime tests showed that the reliability of coolers is scattered per batches. In particular we notice that certain batches have an important lifetime which approaches the objective of reliability at 30,000 hours.

The following procedure has been applied:

1- One can infer from the “golden” batches that the design and the manufacturing process may be compatible with the objective (MTTF ≥ 30,000hr). If TCsas can avoid coolers with poor MTTF, the discrepancy may be reduced, close to the objective.

2- To preserve a “short” duration of this new method cycle, this reduction of the dispersal of mass production must be realized without a new qualification. Thus, this reduction of dispersal of mass production has to be established by a limitation of the existing tolerances. So, the coolers built with this restriction do not need a new qualification. This approach involve one can analyze which parts and tolerances impact the MTTF and its discrepancy.

3- With these conditions, the modification can be applied in production and all the coolers including this modification can be delivered as standard units. In parallel, several coolers are sampled for A20 test. With this method, the implementation of the modification in mass production (and delivery) is concomitant with coolers used for the evaluation:

- If the modification is ineffective: none negative effects on the delivered coolers are expected.
- If the modification is efficient: all the coolers delivered since the modification benefit from this gain.

The cornerstone of such an approach lies in the ability to isolate influential factors. Two points are followed at the same time. Based on cooler physics and on the understanding of failure mechanisms, a list of preferential parameters assumed to influence the reliability is built. This analysis is mandatory to determine optimum for each key parameter. In parallel, an audit of the production line is carried out to monitor the variability of the input parameters.

From the cross breeding of these data, several actions are undertaken:

- Reducing the variation around the optimum value, and with respect of cost,
- Adding the measurements of parameters of interest not yet registered (ie. Parameters assumed to influence the MTTF),
- Strengthening the cooperation with our suppliers by heightening awareness them on the key parameters.

4.3 **RM2 current status**

This method has been applied on RM2 since 2013. A few months after the implementation of this approach, we started to notice an extension of the life of RM2. Today, the results obtained in A20 test confirm the MTTF improvement for the RM2. Below are the results for 40 coolers RM2, sampled from production since 2013, and tested by A20 test. This table is an update of the figures shown last year [6].

<table>
<thead>
<tr>
<th>Rank</th>
<th>number of hours</th>
<th>Status</th>
<th>Rank</th>
<th>number of hours</th>
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<td>18867</td>
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<td>15</td>
<td>11468</td>
<td>still running</td>
<td>29</td>
<td>5850</td>
<td>still running</td>
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<td>16</td>
<td>11364</td>
<td>still running</td>
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<td>17</td>
<td>10104</td>
<td>still running</td>
<td>31</td>
<td>5850</td>
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<td>still running</td>
<td>18</td>
<td>9280</td>
<td>failed</td>
<td>32</td>
<td>5850</td>
<td>still running</td>
<td></td>
<td></td>
<td></td>
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<td>19</td>
<td>9152</td>
<td>still running</td>
<td>33</td>
<td>5400</td>
<td>failed</td>
<td></td>
<td></td>
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<tr>
<td>6</td>
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<td>20</td>
<td>8100</td>
<td>still running</td>
<td>34</td>
<td>4500</td>
<td>failed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>14665</td>
<td>still running</td>
<td>21</td>
<td>7876</td>
<td>failed</td>
<td>35</td>
<td>3600</td>
<td>still running</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>8</td>
<td>13242</td>
<td>still running</td>
<td>22</td>
<td>7264</td>
<td>failed</td>
<td>36</td>
<td>3600</td>
<td>still running</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9</td>
<td>12738</td>
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<td>still running</td>
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<td></td>
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<tr>
<td>13</td>
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<td>failed</td>
<td>27</td>
<td>6300</td>
<td>still running</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>still running</td>
<td>28</td>
<td>5850</td>
<td>still running</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 1. Number of hours of RM2 used for A20 analysis. When the status is “failed”, the number of hours corresponds to the last time the cooler had properties meeting all specifications.
The experimental distribution can be approached with the following parameters of the Weibull’s law:

- Shape factor: $\beta = 1.5$
- Scale factor: $\eta = 35,000\text{hr}$ (median)
- $80\%$ confidence on scale factor: $18,900 < \eta < 64,900\text{hr}$

The corresponding distribution is shown on Figure 7.

The confidence interval remains quite large insofar as there are a very limited number of failures up to now.

For such cases, one can use the Weibayes analysis (see section 2.5). This kind of approach is used when only a very limited number of samples have failed, and when the shape parameter can be approximated otherwise.

$$\eta = \left[ \sum_{i=1}^{n} \frac{t_i^{1/\beta}}{r} \right]$$

Where $r$ is the number of failed units, $t_i$ is the operation time on each unit.

If considering a shape parameter $\beta = 1.5$, we can then estimate a resulting scale factor $\eta = 34,200\text{hrs}$ for the RM2 dataset.

Even if the definitive MTTF cannot be well estimated, several conclusions can be done anyway:

- the reliability in A20 profile is higher than 15,000hr. The equivalent MTTF in a Standard Temperature Profile (STP) could be $> 40,000\text{hr}$.
- the expected reliability for A20 test could be higher than 20,000hrs: 35,000 hours is the median value obtained by calculation for a rate of failure at 63%
- the reliability expectation of RM2 cooler has increased by more than 33% since 2016.

Nonetheless, these projections should still be considered with cautious, insofar as no cooler has worked longer than 36,000hr in A20 up to now. A specific failure mode could occur at higher operation time, with a higher shape factor. Moreover, the conversion in STP which is based on a comparison of results between accelerated ageing and STP was not done for such high value and the transfer function may become less accurate at such values.
The example of the RM2 shows the benefit of this method. First, the improvement for the MTTF is continuous and rise significantly. The objective of reliability at 30,000 hours is widely exceeded. The efficiency of this approach seems to be proven on RM2. Second, the process was relatively quick if we consider the time of delivery of improved RM2, even if the knowledge on the reliability improvement has taken several years. So all the coolers delivered since 2013 could be considered as having a potential lifetime of several tens thousands of hours. Third, the significant quantity of coolers sampled for accelerate ageing (around 10 coolers a year in 2016) lead to a robust evaluation of the MTTF based on 40 RM2.

This approach is currently being used on other coolers like RM3. Even if we are still at the preliminary results, returns from the field are attractive, and are updated from last year too [7]. For 200 coolers well known (serial number, operating hours, failure description), the reliability has not reached the results obtained for the RM2; but the figures show that the reliability in operational arrives at 22,000 hours< rate of return: 63% < 31,000 hours (interval confident: 80%).

4.4 **RMs1 - Limitation on new developments**

That approach has been designed for products already in mass production. It is based on a sampling and on the analysis of variability.

When working on new products, that procedure needs to be adapted. For the new SWaP rotary cooler dedicated to HOT application (RMs1 cooler), only a few number of prototypes is available right now. The qualification includes a certain amount of coolers put in A20 tests for an initial lifetime evaluation. While the product is not in mass production, variability analysis will not be feasible.

Nonetheless, the lifetime expectations are based on design comparison with legacy RMx, especially RM2. The improvements successfully implemented on RM2 are reused and directly taken into account into the RMs1 design. Other dimensioning parameters like internal pressure and rotation speed are also taken into account. From now, the MTTF of the RMs1 is then expected to be more than 15,000hr, with a target to reach also 30,000hr with the current design. The time needed to confirm these figures is directly linked to the amount of product manufactured in the coming years.

Once this first database consolidated (it will take 3 or 4 years), the approach described in this paper should be use. Especially, small amount of coolers will be enough to test if a process adaptation or other improvement will have an impact or not on the reliability.

5. **CONCLUSION**

During the past ten years, the rotary coolers MTTF has increased. That trend is an answer to address new markets like border surveillance, where a large number of detectors are needed for continuous applications. The failure rate after two or three years of continuous application must remain under control in order to have a relevant economic model.
Rotary coolers are mechanical systems with friction and wear. As a result, the failure rate increases with time of operation. That statement leads us to perform extensive accelerated ageing on a significant sampling of coolers productions to provide accurate and robust MTTF figures to our customers. The counterpart is the time needed to prove an MTTF higher than 30,000 hr which is hardly affordable for an industrial like Thales Cryogénie SAS.

That is why an innovative approach is proposed, based on variability analysis and comparison with a reference database built over the years. Even if that approach doesn’t focus on root causes identification, it can allow us to:

- deliver coolers with a potential increase of MTTF as soon as the improvement are implemented,
- reduce the non-recurring costs (no qualification required),
- by using the important number of coolers tested from the mass production in life time test, obtain a high level of robustness on figures, nearly unfeasible with a conventional approach.

The RM2 cooler has been the first cooler subjected to that approach. The current figures tend to show that the MTTF is currently above 40,000 hr in Standard Test Profile. Other legacy coolers (RM3, RM4, RM1) are currently analyzed and improved following the same methodology. Preliminary field returns on RM3 tend to show that its reliability is higher than 10,000 hrs in STP.

On new developments like the RM31, the initial database still needs to be built. Nonetheless, the feedback from legacy coolers has been taken into account early in the design phases. The comparison between RM31 and RM2, both from a design point of view and conditions of use, let us assume that the MTTF of this new product will be higher than 15,000 hr. 30,000 hr is also the target for this new product.

REFERENCES