Lifetime validation of high-reliability (>30,000hr) rotary cryocoolers for specific customer profiles

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ABSTRACT

The cooler reliability is a major performance requested by the customers, especially for 24h/24h applications, which are a growing market. Thales has built a reliability policy based on accelerate ageing and tests to establish a robust knowledge on acceleration factors. The current trend seems to prove that the RM2 mean time to failure is now higher than 30,000hr. Even with accelerate ageing; the reliability growth becomes hardly manageable for such large figures. The paper focuses on these figures and comments the robustness of such a method when projections over 30,000hr of MTTF are needed.

Keywords: Cryogenics, MTTF, reliability, Weibull, Weibayes, Stirling, Cooler, IR detector.

1. INTRODUCTION

Thales LAS France, formerly known as Thales Cryogenie SAS, designs and provides rotary Stirling coolers for twenty years. These products constitute the part of the rotary coolers offered by Thales Cryogenics, while linear coolers come from Thales Cryogenics BV, Holland.

The reliability is a key performance of the cryocooler market. Rotary Stirling coolers were especially known to have a limited reliability compared to electronics components. The cooler reliability has sized the reliability at system level for several years. However, over the last 15 years, rotary coolers reliability has hugely increased from a few thousands of hours [1] up to several tens of thousands proved nowadays [2]. The current good MTTF figures allow the use of rotary coolers within new applications highly demanding about reliability, like 24/7 applications. Required reliabilities are upper than 20,000 hours in that kind of applications.

With a focus made on reliability enhancement of the rotary coolers, the products of Thales LAS France are compatible with these applications. Indeed, reliabilities ranging from 20,000 hours till 30,000 hours are already demonstrated for RM2 and RM3 products. Both coolers are actually implanted on successful continuous applications (24/7).

However, for some cases, the requirements of reliabilities are upper than 30,000 hours. In those case, the challenge becomes how to manage at the best, the reliability knowledge (databases, methods of calculations), how to be able to answer quickly at these requests, without increasing the costs linked to extensive experimental plan and production control, and by preserving estimation as accurate as possible.

This paper will describe the current approach developed at Thales LAS France and will comment on the way to constitute the dataset exploited up to now. In a second part, based on test results, conversion of reliability figures from life time test to reliability for operational profile will be analyzed in order to evaluate the high values of reliability. A statement will then be proposed about the relevancy of extrapolation where reliabilities higher than 30,000hr are announced on rotary.

2. DATA AND METHODS

2.1 Experimental setup

Thales LAS France has used during several years various test profiles of life time tests in order to determine the behavior of cryocoolers, according to various profile missions. These test profiles have assessed:

- The thermal regulation mode (i.e. intermediate rotation speed regulation to insure a constant focal plan working temperature),
- The functioning in hot ambience,
- The impact of the storage at 20° or at hot ambience,
- The functioning at 80 % of the maximal power of the cryocooler.

Henceforth, this knowledge allows us to build a specific modeling of rotary coolers which take into account the known failure modes. Bolstered up by this experiment, Thales Cryogenics has been able to based MTTF prediction on only one accelerated ageing called the A20 test [3].

The cycle A20 is illustrated in Figure 1.

- The rotation speed (3,000rpm) of the cryocooler is approximately twice the rotation speed obtained for an usual application.
- The ambient temperature is 20°C.
- The performances, according to the acceptance test procedure (ATP), are checked every 450 hours.

The A20 test increases the stress applied at the cryocooler, because it is more severe than most of the real applications. Thus, the reliability obtained by an operational profile is larger than the reliability obtained for the A20 test. Nonetheless, a conversion of the reliability figures, obtained in A20 test, towards the reliability figures for an operational profile, has to be made. Depending on the operational profile, the acceleration factors has then to be known.

Henceforth, the A20 test is an internal standard life time test for Thales LAS France: all the configurations and all kinds of coolers are assessed on this A20 test. A room dedicated to these A20 tests is shown in Figure 2.

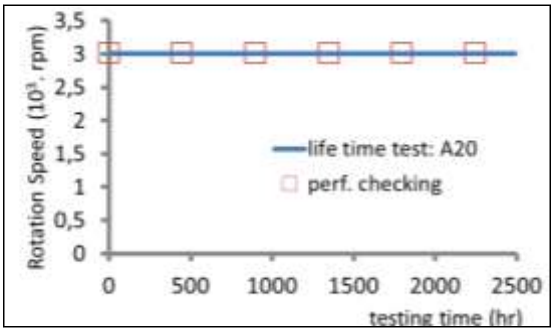

Figure 1: A20 profile used for MTTF estimation

Figure 2: benches for A20 test profile.

Currently, the life time test bench can assess more than 100 simultaneous operational coolers. In the years to come, it is scheduled to increase the number of channels to fit with the increasing production capacity and the longer MTTF of each cooler.

2.2 Databases

2.2.1 Internal database

Thales LAS France has started the cooler evaluations of reliability 20 years ago. Today, more than 500 coolers have been tested according to the same A20 profile.

Below are provided the quantities tested in A20 test per coolers:

- RM1: 70
- RM2: 232
- RM3: 91
- RM4: 121
- RMs1: 4

The reliability evaluation is organized as continuous production supervision. The coolers quantities are fitted annually to the production rates. The objectives of these tests are:

- For production:
  - Constant reliability evaluation for mass production.
  - Evaluation of new suppliers.
  - Evaluation of new manufacturing process.
- For development:
  - Reliability evaluation for new coolers (mainly qualification test).
  - Reliability evaluation of new concepts.

These tests constitute a highly valuable database, insofar as:

- The profile applied at the coolers and the environmental conditions used for reliability evaluation are well known and reproducible.
- The behavior can be monitored during all the life of the coolers:
  - Evolution of the power consumption.
  - Evolution of the cool down time.
  - Evolution of the acoustic noise.
  - Events, incidents…
- One can proceed to an expertise and identify root causes of the failures.
- The sensitivity of the coolers performances and MTTF towards internal defects or external incidents can then be assessed.

The most relevant points resulting from these analyses have already been published [2] and no significant change has been observed during 2017 supervision. All the coolers performances are constant (no variation) during all the life of the cooler, including the acoustic noise.

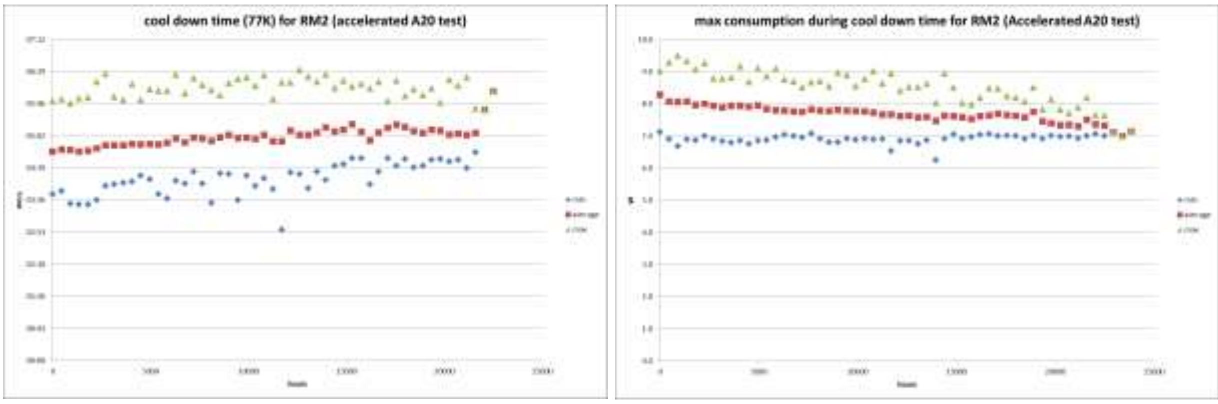

Figure 3: cool down time in A20 test (left) and max consumption during cool down phase (check point during A20 test) (right).

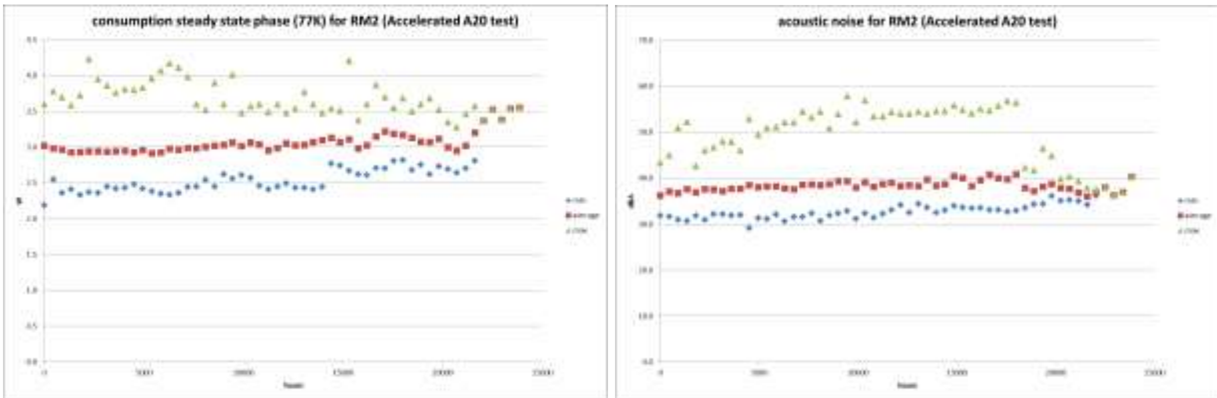

Figure 4: consumption at 77K (regulation).(Check point during A20 test) (left) and acoustic noise. (Check point during A20 test) (right)

That quality seems to be the results of two factors:

- The minimization of awkward stresses due to a relatively good quality of internal alignment.
- The bearings which have been specifically designed for our coolers applications.

In addition, the coolers behaviors during the life and their drift over time are explained by several root causes which have been analyzed from expertize over the years. At last, the corrective actions undertaken for the last years have proved effective are efficient to cancel these failure modes.

2.2.2 External database

In parallel to that internal database built on life time tests, gathered information about coolers on the field could be an alternative. Indeed, using direct operational data seems less expensive at first sight.

Unfortunately, these databases are generally incomplete (many figures are missing) and sometimes, the integrity and the normality of the population cannot be insured at our level. The databases are indeed already post-processed by end-users or even our customers before we have access to the data.

Moreover, the environmental conditions and the actual profile missions are hardly monitored for every cooler, and the data has then larger dispersion related to these hazards of use.

So, at the end, to fill the hole and try to rely on these external databases, a model is built with assumptions like the following:

- The cooler is used XX hours a month,
- Its starting date will come into effect YY months after our delivery,

- As long as machines did not return in repair, they do not break down.

As a result, the constitution of these data introduces a bias which may strongly impact the robustness of the reliability results.

That's why Thales LAS France has decided to use this type of database from the field at the conditions the following data are available:

- The hours number of all the failed coolers.
- The hours number of all the operational coolers.
- The operating profile, at least an average profile per batch.

As a consequence, Thales LAS France has used only one database from the field up to now, concerning a batch of 250 RM3, working 24/7 [4].

2.2.3 Database conclusion

The data used for reliability calculation must be as close as possible to the reality. Thales LAS France has chosen to use a database make by life time test results on its own premises to obtain a strong and robust database. Data gathered on the field can also be used at the condition specific information is available. Nonetheless, these data are only used to strengthen the figures obtained from internal life time tests.

2.3 The data processing

2.3.1 How to calculate the reliability

The knowledge of the reliability is used to determine the failure likelihood as a function of time. The reliability is materialized by a mathematical law which approach at the best, the real distribution of the breakdowns. Among the various laws used in reliability, the law of Weibull is very well adapted to the mechanical devices with wear issues:

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

With η= scale parameter and β = shape parameter. Please note the scale parameter η is equivalent to the following three points:

- The failure rate at 63 %.
- The MTTF when random occurrence of the breakdowns (i.e. β=1), generally used for the component electronics MTTF.
- The cooler reliability figure indicated by Thales LAS France for the coolers.

At the beginning of the life time test on a new configuration, the breakdown coolers are rare. In this case, if the shape parameter β is known, a variant of the Weibull law (Weibayes) can be used to realize first reliability estimations. The robustness of this method is very strong especially when coolers architectures remain close to previous one [5].

The very well-known exponential law is well suited to assess the electronic reliability sets, but it supposes a random failure rate. Random failures mean the same probability to have a failure between 0/1,000 hours or between 9,000h / 10,000 hours. Insofar as wear occurs during the use of a rotary coolers (moveable part with contacts like bearings or piston/liner systems), rotary Stirling coolers cannot be modelized with such a law.

Thus the exponential law cannot be applied for the coolers.

2.3.2 Conversion of the reliabilities

To avoid to do tests for each profiles, which should increase the cost and introduce delay, Thales LAS France has developed a method of calculation to convert the A20 test reliability results to the reliability for any profile [3]. This method has been applied by Thales LAS France for 15 years. It has been recently confronted with a reliability figure obtained by calculation from an operational data with a quite good overlapping of the prediction from A20 profile and actual reliability [4].The actual MTTF in this operational profile was around 25,000hrs.

3. EVALUATION FOR RELIABILITIES HIGHER THAN 30,000 HOURS

3.1 Reliability of the RM2

3.1.1 RM2 A20 test reliability

Since 2013, 48 RM2 have been tested in A20 test. The first cooler started in 2013, the last in 2018. All the coolers are sampled from the mass production. The results are given in Table 1:

Table 1: state of RM2 coolers in A20 test. For Status column-“rk” stands for rank, “hrs” for hours, “st” for status, “rc” for root cause, “s” for “still running” “f” for “failed”.

rk	hrs	St	rc	rk	hrs	St	rc	rk	hrs	St	rc	rk	hrs	St	rc
1	24291	s		13	16764	s		25	11250	s		37	5850	s	
2	22514	s		14	15068	s		26	10800	s		38	5850	s	
3	20544	s		15	14002	s		27	10180	f	process	39	5400	f	bearing
4	20403	s		16	12738	f	process	28	9900	s		40	5400	s	
5	20401	s		17	12600	s		29	9000	s		41	4950	s	
6	20165	s		18	12182	f	bearing	30	7876	s		42	4950	s	
7	19355	f	bearing	19	11904	f	coating	31	7650	s		43	4950	s	
8	18642	s		20	11700	s		32	7650	s		44	4050	s	
9	18320	s		21	11250	f	process	33	7264	f	bearing	45	2700	s	
10	17638	s		22	11250	f	process	34	6750	f	coating	46	2250	s	
11	17174	s		23	11250	s		35	6410	s		47	1002	f	process
12	17058	s		24	11250	s		36	6300	s		48	900	s	

Here are some first comments on these results:

- The size of the sample is important: 48 coolers tested. So the reliability results obtained are robust.
- The 48 coolers tested add up more than half of million operating hours.
- The tested coolers have been sampled from batches produced during 5 years (from 2013 till 2018).

Up to now, these figures let us consider the 5 years production as a homogeneus batch from a MTTF point of view. Despite several improvement implemented on processes, the number of failures of units under A20 tests are not large enough. The MTTF is expected to progress but cannot be quantified for now.

The reliability of 48 RM2 tested with the standard A20 life time test is established with Weibull law. The graph of this reliability is given in figure 5.

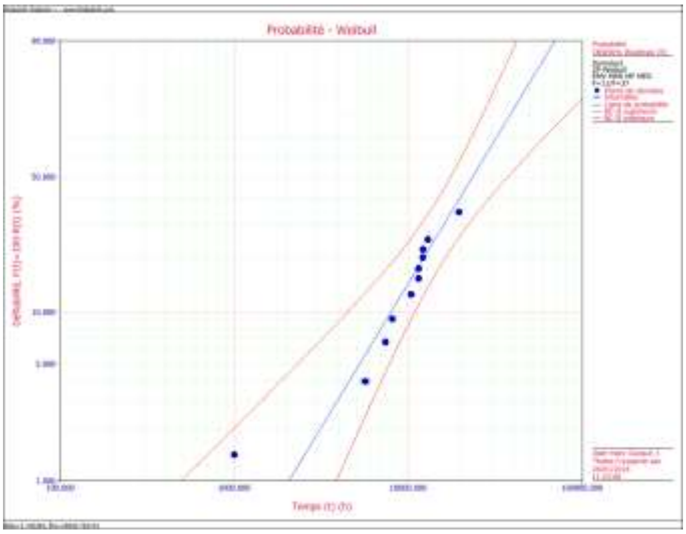

Figure 5: graph of Weibull law for the batch of RM2 in A20 test.

The shape parameter β_{RM2} obtained, for the RM2, according to the accelerated test A20, is 1.7.

The scale parameter η_{RM2} obtained, for the RM2, according to the accelerated test A20, is 29,000 hours.

So the reliability of the RM2 in A20 test is evaluated at 29,000 hours and the reliability of the RM2 for an usual operational profile is largely higher 29,000 hours.

3.1.2 RM2 reliability for an operational profile

The reliability of the RM2 in A20 test is 29,000 hours, and the majority of the fields applications are less stressful than A20 test so the RM2 reliability in field applications is higher than 29,000 hours.

Considering the acceleration factors which has been established several years ago (cf. section 2), such a high figure could lead to operational reliability between 50,000 hours and 100,000 hours for some field applications.

Insofar as the acceleration factors have been determined on much smaller MTTF, one may question the validity of the reliability estimation for such high MTTF. Indeed, if specific failure modes occurring only after ten thousands of hours were not activated during the establishment of the acceleration factors, the current extrapolation from A20 profile could be blind to failure rate rise occurring at large operating hours. The extrapolation would lead to an overestimated MTTF.

3.2 Robustness of the reliability evaluation for high reliability values

3.2.1 Inventory of failure modes

The A20 test presented above actuates several failure modes. By analyze, from the definition, other potential failure modes have been identified. There is then a risk than the effects of these failure modes, not detected today, introduces an error into the conversion calculation and falsify the reliability estimation in operational profile.

To evaluate the risk, all the failure modes are listed below. The failure modes actuated by the current A20 test are underlined:

- <u>Bearing</u>
- Electrical
- <u>piston/liner coating</u>
- internal defect of part
- leak
- <u>process defect</u>
- outgassing

The following sections focus on the physics of failure linked to these failure modes.

3.2.2 Failure mode: bearings damage

Using the results of 48 RM2 tested, the bearings reliability can be calculated by the Weibull law:

Four failed coolers for a bearing defect have been detected. It is low, so, it is more clever to realize the reliability calculation by Weibayes. The shape parameter β corresponding to the usual bearing value is $\beta_{bearing}$= 2 [6]. The associated graph is shown in Figure 6.

For the bearings failure mode in A20, the corresponding scale factor is $\eta_{Bearing}$ = 44,000 hours.

3.2.3 Failure mode: electrical defect

The random occurrence of electrical breakdown is well established [7]. Thus the corresponding Weibull shape parameter is taken as β_{random}=1.

By a Weibayes approach, coming from the Weibull law, we calculate the scale parameter $\eta_{electrical\ defect}$. Because no breakdowns have been detected, we can determine, with a confident interval of 80 %, the minimum value for $\eta_{electrical\ defect}$:

$$\eta_{electrical\ defect} > 337{,}000 \text{ hours.}$$

Thus the MTTF electrical failure for the RM2, in A20 profile, is upper than 337,000 hours.

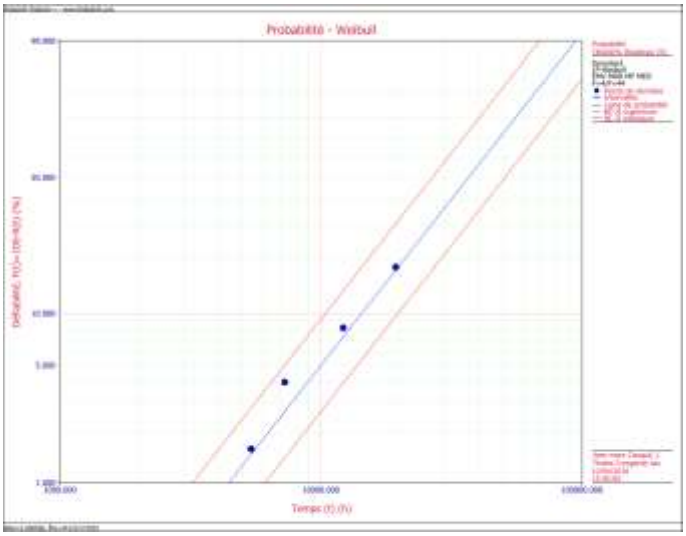

Figure 6: graph of Weibull law for the failure mode: bearing damage in A20 test.

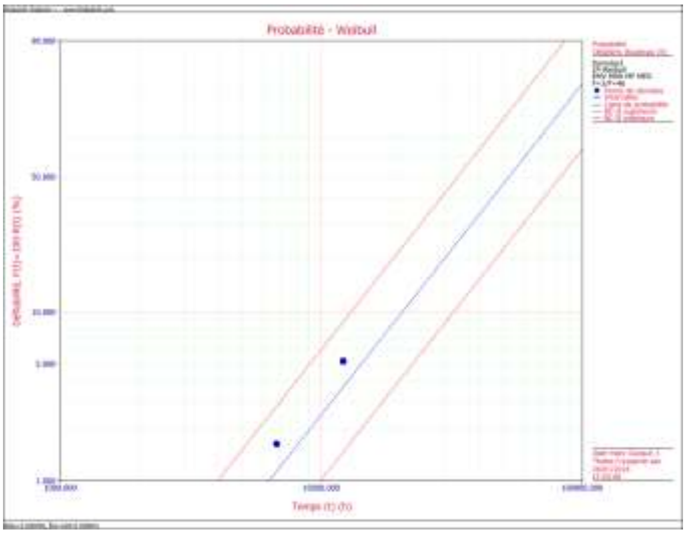

Figure 7: graph of Weibull law for the failure mode: coating piston/liner defect in A20 test.

3.2.4 Failure mode: coating piston/liner defect

Using the results of 48 RM2 tested, the piston/liner reliability for the RM2 can be calculated by the Weibull law. The number of coating defect remains low (2 defects), so it is more relevant to make the reliability calculation with Weibayes. To determine the shape parameter $\beta_{coating\ piston\ /\ liner}$, we use the data of 500 machines tested in A20 for 20 years. The shape parameter β for the piston/liner failure is estimated to be close to 2. $\beta_{coating\ piston\ /\ liner}=2$.

The figure 7 is the plot of the law for the piston/liner coating in A20 test:

We obtain, for A20 test, the scale parameter for the failure mode “coating pistons/liner”:

$$\eta_{coating\ piston\ /\ liner} = 63{,}000 \text{ hours.}$$

3.2.5 Failure mode: failure for the mechanical parts

The RM2 parts have been calculated, tested, qualified to resist to the forces applied by the device to the internal parts (bearings, crankshaft,…). The parts are strong enough to support the force, no failure were detected during the qualification test. The mechanical fatigue on nominal parts is then considered as negligible. However, the production is submitted to hazards defects which can generate unpredictable breakdowns after a certain amount of hours. The burn-in phase removes the largest number of defective products. For the few remaining units with internal defects, we can then assume that the shape parameter is: β_{random}=1.

As for the failures of electrical type, no breakdown of parts was declared on the 48 machines in A20 test. So the MTTF for the breakdown of parts is at least higher 337,000 hours.

3.2.6 Failure mode: leak

The tightness is obtained by metallic seals. The principle is based on a spring which is pressed on the surface to be sealed. Its efficiency is increased by a ductile cover which is interposed between the spring and the part to be sealed. This is a static device, using the materials characteristics (stiffness and ductility). When the device is tight, it must be definitive.

The sensitivity of the leak detection applied in production line is efficient enough to ensure the use of coolers during several years without refilling operations. The product has been qualified for that. So when the cooler are delivered, the risk to have a leak is close to 0. After the delivery, the occurrence of a leak, based on the wear is excluded. So the possibility to have a leak after delivery is only possible if we consider a defect of the process leading to a leak occurring over time after mechanical or thermal fatigue. Consequently, like the previous failure mode, the leak failure mode is characterized by the random occurrence, so by β_{random}=1.

For the 48 RM2 cooler in test, no leak has been detected. So, we can determine, with a confident interval of 80 %, the minimum value for η_{leak}:

$$\eta_{leak} > 337\ 000 \text{ hours.}$$

Thus the MTTF of leak of the RM2 is at least higher than 337,000 hours.

3.2.7 Failure mode: process defect

The manufacturing instructions are present in every step of the production, those procedures include check points and the presence of quality team inside the Thales production line as supplier production line reduce the risk of mistake. Nevertheless, the complexity of the devices can not cancel all the risk like the human error. Random failure can appear. Thus, the reliability for this failure mode is established with the Weibull law by choosing the shape parameter β_{random}=1. The burn-in phase removes the largest number of defective units.

Figure 8 gives the graph of the Weibull law for the failure mode: process defect.

For the failure mode process defect in A20, the current scale parameter is $\eta_{defect\ process}$ = 108,000 hours.

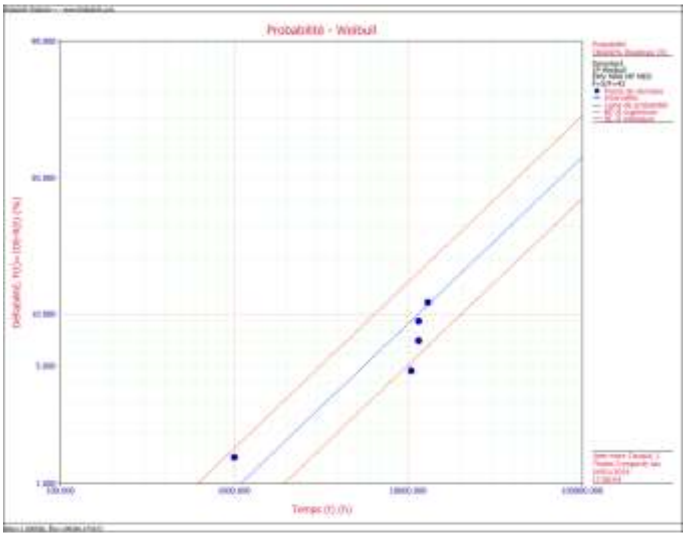

Figure 8: graph of Weibull law for the failure mode : process defect in A20 test.

3.2.8 Failure mode: outgassing

This failure mode is provoked by a continuous emanation of gas susceptible to cause, by their accumulation, a modification of the cooler performances without mechanical damage. This type of failure is reversible: a replacement of the helium deletes the outgassing effect (pollution = 0 after refilling) and the performances come back to the original values (if the cooler is not damaged by an other way).

To calculate the reliability of this failure mode by the Weibull law and in the absence of failure, we have to determine the shape parameter $\beta_{outgasing}$. This one is unknown, but by using the database of the 500 coolers tested in A20, we consider that the $\beta_{outgasing}$ value may be between 1 and 3.

As the outgassing is a continuous phenomen (it exists even when the cooler is OFF), the reliability calculation is made using the sum of hours cooler ON and hours cooler OFF. The table 2 gives the hours of the 48 coolers since the end of the cycle production

Table 2: hours (ON/OFF) for the batch of RM2 in A20 test. Legend for Status column:"rk" stands for rank, "hrs" for hours

rk	hrs	rk	hrs	rk	hrs	rk	hrs
1	39480	13	27768	25	19008	37	9528
2	37172	14	28512	26	19008	38	9528
3	33648	15	26304	27	21192	39	10248
4	35064	16	21216	28	16800	40	9504
5	35064	17	21216	29	16104	41	744
6	35064	18	18984	30	16056	42	9504
7	33600	19	21168	31	22680	43	9504
8	30720	20	19752	32	22680	44	744
9	29976	21	21960	33	10944	45	5136
10	29976	22	20472	34	21216	46	5136
11	29976	23	20472	35	11640	47	4392
12	29232	24	19008	36	13176	48	2208

None outgassing case are declared for these 48 machines.

The reliability results of the outgassing are established for the values of the shape parameters $\beta_{outgassing}$ and are given in Table 3:

Table 3 : summary of values for scale parameter η function of shape parameter β for failure mode: outgassing

$\beta_{outgasing}$	$\eta_{outgasing}$
1	>592,000 hours*
3	>75,000 hours*

*: The absence of failure allows us to determine the minimum value of $\eta_{outgassing}$ with a confident interval of 80% confidence.

We consider for the current paper the most unfavorable case for the outgassing reliability, that is to say a scale parameter at least higher than 75,000 hours.

This value characterizes the reliability for a park of coolers when no filling maintenance is made. But, the RM2 maintenance recommendations are to refill the coolers every 4 years. Thus, every four years, after maintenance action, the rate of gas pollution accumulated in the cooler drops to 0. Thus, the rate of this failure mode doesn't follow the Weibull law with parameters (β=3, η=75,000 hours) for all the life of the coolers. The failure distribution for the outgassing is calculated by this way:

- The most unfavorable distribution of outgassing occurrence is obtained for the Weibull law like the parameters are:
  - $\beta_{outgassing}$ =3,
  - $\eta_{outgassing}$ > 75,000 hours.

- The period application of this law is:
  - T0= the delivery time of the coolers.
  - The maximal duration between 2 fillings is 4 years (35,040 hours).Thus the failure distribution follow the Weibull law (β=3, η=75,000 hours) betweenT0 and T0+ 4 years(35 040 hours). The maximum failure rate at 35,040 hour is 9.8%.
  - At T0+ 4 years, after refilling, for the next 4 years period, the failure distribution of outgassing is equivalent to the 1st period. So at T0+8 years, it reach the maximum rate of failure. 4 years after the refilling, and 8 years (70,080 hours) after T0:
    - At 70 080 hours the rate of failure is 9.8% since the refilling.
    - At 70 080 hours the rate of failure is 2x9.8% since T0.
  - It is the same for the next 4 years.
  - And so on…

By convention, Thales LAS France indicates the coolers reliability at the rate of failure: 63% (like for electronic components). Thus, for outgassing defect, 63%/9.8% = 6.42 periods of 4 years are necessary to reach the rate of defect 63%. It corresponds to 25.68 years which correspond to 225,000 hours.

Thus the reliability for the failure mode of outgassing is considered to be higher than 225,000 hours.

3.2.9 Summary

The table 4 summarizes, for every failure mode, the reliabilities values for a rate of failure: 63 %.

Table 4: summary of value for scale parameter η for RM2 in A20 test

Failure mode	Failure rate @ 63%		Failure mode	Failure rate @ 63%
Bearing	44,000 hours		Leak	>337,000 hours
Electrical	>337,000 hours		Process	108,000 hours
Coating	63,000 hours		outgassing	>225,000 hours
rupture	>337,000 hours			

We notice:

- Like expected, the failures modes detected on the sample of 48 RM2 are the failure mode with the lower reliability.
- The other failure modes (no detected today) have a reliability > 225,000 hours. With this high value, it is estimated, very improbable that the failure modes, none detected by test today, change the reliability estimation.

4. CONCLUSION

The policy reliability applied at Thales LAS France for almost 20 years, has built a robust predictive method of reliability. It allows to gives in a very short time, an accurate estimation of the reliability of the coolers for any operational application, even if the reliabilities are very important: several tens of thousands of operating hours.

Thales LAS France has undergone several works, leading to a strong increase in the rotary cooler reliability during the last five years. The current Mean Time To Failure of a RM2 may be greater than 40,000hr in operation. With such high figures, one have to question the validity of hypothesis done to make extrapolation from accelerated ageing where the longest product has reached less than 30,000hr up to now. First, one has to consider dataset with the more accurate figures, in order to reduce biases that introduce increasing errors with extrapolation as far away. We then recommend using data on the field only when specific conditions are well known. Otherwise, lifetime test like the A20 profile defined by Thales Cryogenics seems to constitute the most robust approach to MTTF evaluation.

The continuous samples of coolers from mass production assure the durability of this method. By considering since 2013 the production as a homogenous production from a MTTF point of view, the RM2 reliability assessment relies on 48 coolers put on A20 profile. This paper focuses on the analysis of scale and shape factors of every failure mode which could have an impact on large MTTF rotary coolers. The large amount of units available brings a better confidence in that elementary mode approach. A gap appears between known failure mode of mechanical parts which sustained wear, and other functions. That gap is mainly due to the fact that current failure units do not show any defect linked to these predicted failure mode. The third failure mode after the bearing and piston-cylinder wear out seems to be defects linked to process defects. Such a failure mode is sensitive enough to batch effect or drift in Supply Chain manufacturing. Based on that analysis, Thales LAS France has launched an internal program to reinforce the mastery of its manufacturing processes.

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