Overview and analysis of laboratory life tests and field data for RICOR's high reliable Cryocoolers

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ABSTRACT

The growing demand for Electro Optic (EO) applications that work around the clock 24hr/7days a week, such as in border surveillance systems, emphasizes the need for a highly reliable Cryocooler having increased operational availability and decreased integrated system Life Cycle (ILS) cost. In order to meet this need, RICOR has developed Integral Rotary and Split Linear Cryocoolers technologies which meet this challenge.

RICOR's Cryocoolers reliability characteristics are assessed by analytical reliability models, demonstrated by normal and accelerated life tests and finally verified by field data.

The paper will focus on the reliability evaluation models for different technologies, report and analyze life demonstration test data at different mission profiles and verify the results by fielded Cryocoolers operating as a feedback to approve the theoretical assumptions and calculation models. In addition, it will review the system's end user needs and expectations from advanced high reliable Cryocoolers.

Keywords: Cryocooler, Integral Rotary, Split Linear, Stirling, Weibull distribution, MTTF, RICOR

1. INTRODUCTION

RICOR fielded during recent years thousands of Integral Rotary and Split Linear Cryocoolers for space, military & defense and homeland security applications. During definition of such applications the Cryocooler's reliability becomes an important parameter for maintenance considerations and Life Cycle Cost calculations. As an outcome the Cryocooler Mean Time to Failure (MTTF) design goal became > 20,000 hr. In compliance with that requirement, RICOR has made several technical improvements, which increased Cryocooler reliability significantly achieving higher Mean Time to Failure (MTTF). This article will present the methodology used, updated MTTF and the new life test approach.

The Cryocooler's MTTF can vary from thousands of hours to tens of thousands of hours according to the Cryocooler type and operating conditions. Each Cryocooler model has its own span of MTTF. The span is a product of parameters that impact on Cryocooler reliability. For example for the Integral Rotary Cryocoolers' parameters namely; bearings dynamic capacity, special lubrication environmental conditions etc. Whereas for the Split Linear Cryocooler parameters will be different namely; contamination, degradation of dynamic contact clearance seals, leaks etc.

As a means of motivation to find common ground for different operational profiles transformation RICOR uses a common reliability approach.

2. RICOR'S METHODOLOGY FOR MTTF ESTIMATION

2.1 Methodology Overview

The approach for MTTF estimations is shown in the following figure. The estimation is made for a specific program and mission profile.

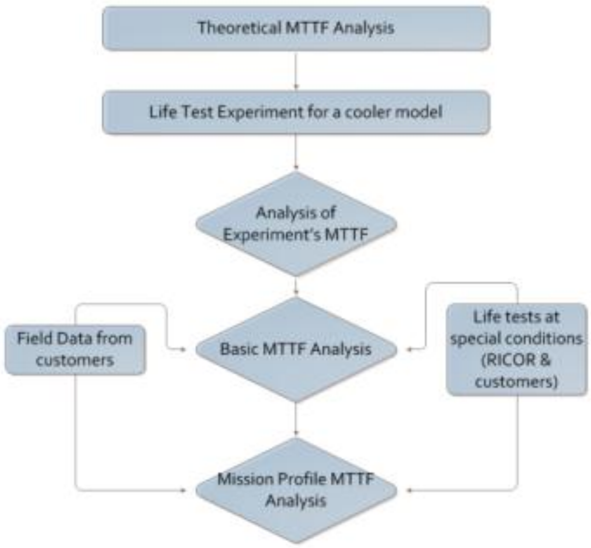


Figure 1 - RICOR`s Methodology for MTTF estimations

In this figure it is shown that the initial stage for MTTF estimations is RICOR's Cryocoolers life test data. This life test is performed in some accelerated method that provides us with the ability to gain as much engineering knowledge in the shortest time possible. When the experiment analysis is completed, we approach the MTTF standard mission profile estimation which is called "Basic MTTF". This standard mission profile is a pre-defined profile at nominal conditions.

From the "Basic MTTF" one can derive the mission profile MTTF that should be stated in terms of amount of operating hours on each ambient and mechanical environment. The transformation from the basic MTTF to the mission profile MTTF is related with many coefficients that were found as a result of a special experiment on different Cryocoolers and a collection of relevant field data. This part of the analysis is performed continuously in close loop as more information is accumulated, so the exact values of these coefficients may vary from time to time

3. MTTF PREDICTION MODEL

3.1 General approach

RICOR's general approach towards MTTF prediction was first introduced in [Ref. 1].

From the presented equation for prediction model for Integral Rotary Cryocoolers [Ref. 1]. We applied the following model which defined basic MTTF as an outcome of life experiments:

$$\text{(Eq. 1)} \quad \theta_b = \theta_{EX} \pi_{ctt} \pi_E \pi_{Tl} \pi_T$$

Where:

θ_b	Basic MTTF
θ_{EX}	Experiment MTTF
π_{ctt}	Cold tip correction factor
π_E	Environmental factor
π_{Tl}	Thermal load correction factor
π_T	Ambient temperature correction factor

3.2 RICOR's prediction model for Split Linear Cryocoolers is defined as follows

$$\text{(Eq. 2) } Q_b=\left[\frac{1}{Q_{EX}\pi_E\pi_T}+\frac{1}{[(W_{MAX}-W_0)/S]\pi_E}\right]^{-1}$$

Where:

π_E Environmental factor

S Slope of the input power curve [W /Hr]

W_{MAX} Maximum allowable input power [W]

W_0 Initial input power (At the beginning of Cryocooler life) [W]

As additional results accumulate from the life experiment for the K570 Split Linear Cryocooler we will adjust the model above and may combine it with the Watt-Hour model (Eq. 4) to obtain a more accurate life prediction.

3.3 Split Linear life test study

Recently we started a study (related to Split Linear Cryocoolers) aiming to gain more information about life parameters and life predication models utilizing the Watt-Hour approach which has been developed by Miskimins and later suggested an integral method, by Yuan et al. (Ref. 5), which improves the accuracy of the watt-hour approach. In order to predict life, a large database is required and for that purpose we have several Split Linear Cryocoolers running in our laboratory. The method assumes that running the Cryocooler at low power will extend its life and vice versa. As regards to that assumption 6 groups running at different % input power of their maximum power (over-stroking is a limit), other parameters are the same for all groups including: Ambient temp, FPA temp, closed loop mode. Failure criteria will be evaluated in terms of max power, current, temperature variation, etc. We believe that within the next year we will have tangible result.

The method assumes that input power and Cryocooler life is constant. The main goal is to get the Cryocooler life curves and the slope of the life test data (W/Hour) in order to apply the formula:

$$\text{(Eq. 3) } Cooler\ Life\ (W-Hr) = ((\boldsymbol{P_f}+W_0)/2)\cdot(\boldsymbol{P_f}+W_0))/S$$

Where:

$\boldsymbol{P_f}$ Failure criterion [W]

W_0 Initial input power (At beginning of Cryocooler life) [W]

S Slope of the input power curve [$\boldsymbol{W^2/Hr}$]

4. LIFE TEST OVERVIEW

4.1 General

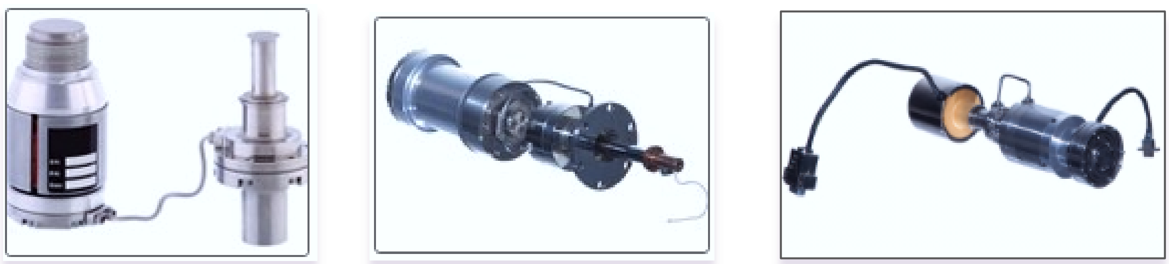
During the recent years RICOR has conducted an extensive laboratory life test; dozens of Cryocoolers have been subject to and are still undergoing life tests, as part of RICOR approach for continuous improvement. The life tests are performed under the careful supervision of a technician from the development laboratory, and the Cryocooler's operation data are monitored throughout the experiment. Figure 2 shows one of many test arrays at RICOR's laboratory comprising 3 K570 type Split Linear Cryocooler groups at different input power of 75%, 50% and 25% of its maximum.

Figure 2 - Life test– Split Linear Cryocoolers

As shown in figure 3 and 4 RICOR's Integral Rotary and Split Linear Cryocoolers respectively, models which are continuously undergoing life experiment

K508 K548 K561

Figure 3 - RICOR`s Integral Rotary models - in routine production



K527 K529N K570

Figure 4 - RICOR`s Split Linear models

4.2 Life tests status

Presented in Table 1 & Table 2, a partial list of life test status for ongoing & ended tests.

Table 1 - Life test status example for Integral Rotary Cryocoolers

Cooler Model	Accelerated Parameters	Test Profile and Type	Running hours	Basic MTTF equivalent	Status and Failure Mode	Result Evaluation
K508 Integral Rotary	Temp. & Frequency	80°C@60Hz@35 bar	8,193 5,126 5,037	20,876	Failed -Bearing end of life	More than expected
		45°C@35Hz@40 bar*	11,500 11,120 9,500	20,737	Failed -Bearing end of life	More than expected
	Temp.	45°C@25Hz@35 bar	3,746 3,670 3,337	Still running		
K508N Integral Rotary	Temp. & Frequency	80°C@65Hz@40 bar	1,200 1,110 1,100 7,44 7,40 7,29	Still running		
		60°C@45Hz@40 bar	2,110 2.100 1,980 7,50 7,31 7,25	Still running		
K548 Integral Rotary	Temp, Frequency, Pressure	80°C@67Hz@45 bar	5,300 4600 4450	26,442	Failed –Bearing end of life	As expected
K560/ 1 Integral Rotary	Temp, Frequency	40°C@38Hz@20 bar*	6,030 5,690 4,700	15,947	Failed –Bearing end of life	As expected
	Temp, Frequency	60°C@38Hz@18 bar**	1,752 1,744 1,740	Still running		
K562S-Integral Rotary	Frequency	23°C@33Hz@20 bar	15,044 14,232 10,355	15,725	Failed – Bearing end of life	More than expected
	Temp.	76°C@33Hz@20 bar	10,749 8,536 6,764	16,016	Failed – Bearing end of life	More than expected

* Equivalent to test profile with few ambient temperatures segments

** Improved model – expected increased reliability

Table 2 - Life test status example for Split Linear Cryocoolers

Cooler Model	Accelerated Parameters	Test Profile and Type	Running hours	Basic MTTF equivalent	Status and Failure Mode	Result Evaluation
K535 Split Linear	Medium Load	23°C@ med load	24,800	57,433	Proactive stop	More than expected
			23,871		Failed -Performance degradation	
			20,249		Proactive stop	
K529N-Split Linear	Temp, load	70°C@ med load	27,500	TBD Based on Linear Watt-Hour life test	Failed –Motor, current short	More than expected
K527 Split Linear	None	20°C@ low load	4112	Still running		
			4110			
			4100			
	Medium Load	20°C@ med load	4270			
			4266			
			4225			
	High Load	20°C@ high load	3300			
			3280			
			3100			
K570 Split Linear	None	20°C@ low load	4524	Still running		
			4505			
			4504			
			4424			
			4418			
	Medium Load	20°C@ med load	4558			
			4551			
			4455			
			4451			
			4450			
	High Load	20°C@ high load	4450			
			4449			
			4448			
			4448			
			4440			

4.3 Coolers statistical life distribution

Laboratory life tests conducted at RICOR's facilities with various types of RICOR's Cryocoolers have indicated that the Cryocooler's life follows the Weibull distribution. The assumption is that the Cryocooler's field life distribution would also according to Weibull.

Weibull life density distribution function $\boldsymbol{f_{T(t)}}$:

$$\text{(Eq.4) } \boldsymbol{f_{T(t)}} = \frac{\boldsymbol{\beta}}{\boldsymbol{\alpha}}\left(\frac{\boldsymbol{t}}{\boldsymbol{\alpha}}\right)^{\boldsymbol{\beta-1}} \boldsymbol{e}^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Weibull life cumulative distribution function $\boldsymbol{F_{T(t)}}$:

$$\text{(Eq. 5) } \boldsymbol{F_{T(t)}} = \boldsymbol{1 - e}^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

Weibull MTTF:

$$\text{(Eq. 6) } E(T) = MTTF = \alpha\,\Gamma(1 + 1/\beta)$$

Where β is the shape parameter and α is the scale parameter. β can indicate for instance if the failure of a component is due to infant mortality, wear out, or a random cause. The Weibull distribution is based on the analysis of a population of Cryocoolers, and their failure as a function of time.

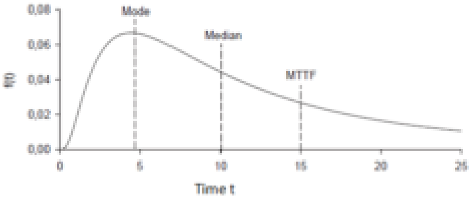


Figure 5 – Typical Weibull's distribution

4.4 Reliability assessment

Cryocooler K548 – Integral Rotary

Basic MTTF conditions are defined as: GF, 20°C, thermal load of 350mW@23°C, nominal fill pressure of 30 Bar, cold tip temperature of 80K.

In order to calculate the basic MTTF some coefficients are needed. The correction is performed on cold tip temperature, thermal load and ambient temperature.

These are the correction factors:

π_{ctt} Cold tip correction factor

π_{Tl} Thermal load correction factor

π_{T} Ambient temperature correction factor from 80°C to 20°C

These correction factors were valued based on MIL-HDBK- 217F, based on RICOR's engineering experience with similar cooling systems, filed data analysis and life reliability tests.

(Eq. 1) yields: $\theta_{EX}\ \pi_{ctt}\ \pi_{Tl}\ \pi_{T} > 25{,}000$ hours

A similar calculation was done to the rest of Cryocoolers and summarized as follow:

Table 3 - Summarized Basic MTTF results

Cooler Model	Basic MTTF Conditions	Basic MTTF Results
K508	GF, 20°C, thermal load of 200mW@80K	20,500
K548	GF, 20°C, thermal load of 350mW@80K	25,000
K560 /1	GF, 20°C, thermal load of 150mW@80K	16,000
K562S	GF, 20°C, thermal load of 150mW@110K	16,000
K543 / 4	GF, 20°C, thermal load of 450mW@80K	25,000
K508N	GF, 20°C, thermal load of 200mW@80K	28,500
K527	GF, 20°C, thermal load of 150mW@110K	*50,000
K529N	GF, 20°C, thermal load of 250mW@80K	*40,000
K570	GF, 20°C, thermal load of 450mW@80K	*60,000
K535	GF, 20°C, thermal load of 2W	*55,000
K549	GF, 20°C, thermal load of 350mW@80K	16,000

* Will be verified based on Watt-Hour life test results

5. FIELD DATA

5.1 Evaluation and Analysis

In addition to the laboratory life tests, filed data are being analyzed as well.

The analysis based on two different approaches; one approach refers to field data analysis reported by the customer, per serial number, including Cryocoolers' operation hours. The reported operation hours analyses and processes using reliability software "ReliaSoft Weibull++ 7". While assuming the distribution is "Weibull". The other approach based on the field Cryocooler failures population, as the analysis relies on total accumulated operating hours of all Cryocoolers served in the field. By dividing the total operating hours by the number of field Cryocooler failures we receive MTTF.

The second approach analysis is presented as follows:

The analysis presented here refers to several projects where a large number of Cryocoolers were supplied.

The data were collected and recorded by RICOR's quality assurance department during the years 2004 – 2013.

The following assumptions were taken in this analysis:

a) On the average, the Cryocoolers are assumed to be actually fielded 3-6 months from the time they leave RICOR's facilities.
b) Returns due to failures in a period shorter than 3-6 month from delivery are not counted and considered as infant mortality failures.
c) The average time from Cryocooler failure in the field to arrival at RICOR's dock is assumed to be 3 months.
d) Spare parts - 30% of the Cryocoolers are assumed to be kept unused.

These assumptions are based and supported by customers and military expert commander's estimates. Table 4 shows the models and quantities of Cryocoolers

Table 4 - Field data summary 2004-2013

Cooler Model	Profile #	Application Profile	Application	No. of fielded Cryocoolers
K508	1	GF, 25°C, thermal load of 200mW @78K	Long range thermal Imager	7312
	2	GF, 55°C, thermal load of 220mW @78K	Border surveillance cameras	1743
K548	3	GF & AUC, 60°C, thermal load of 550mW @77K	Gimbals and P&T	301 (Since 2007)
K561	4	AUC, 50°C, thermal load of 200mW @78K	Miniature gimbal	599
	5	GM, 35°C, thermal load of 185mW @78K	Hand held google	5528
K562S	6	GM, 40°C, thermal load of 200mW @95K	Miniature gimbal	72 (Since 2011)

5.2 K548 Field Data Analysis Results

The K548 Cryocoolers integrated in ground fixed payloads on the Mediterranean shore for observation and operated 75% of the year hence about 6,500hr/year.

The K548 Cryocoolers integrated in Airborne Uninhabited Cargo operated 25% of the year hence 2260/year. From the data of repairs, only Cryocoolers that classified as End Of Life were taken into account in our calculating and data analysis. The total accumulated operating hours of all coolers served in field was 724,120 hours for GF & AUC applications .

As a result the calculated field MTTF is 16,840.

By converting the field MTTF to basic MTTF we get MTTF = 24,583

A similar analysis was done to the other Cryocoolers presented in table 4, and summarized as follow:

Table 5 - Field data converting to basic MTTF summary for applications profile presented in table 4:

Cooler Model	Profile #	Field MTTF	Basic MTTF
K508	1	19,288	20,993
	2	15,409	22,013
K548	3	16,840	24,583
K560/1	4	14,558	16,542
	5	12,030	18,045
K562S	6	13,279	19,198

Each application was analyzed according to the evaluation above, field MTTF was calculated and afterwards was converted to Basic MTTF respectively.

6. WHAT NEXT

RICOR intends to extend reliability activities for other Cryocoolers models, including Split Linear Cryocoolers. Significantly increasing capabilities for reliability predictions, by further life tests, more field data, and with RICOR's upgraded extensive reliability lab. We have ongoing life tests yet to be completed as shown in table 6. As more life tests for the K570 accumulate we will be able to verify the Watt-Hour method

Table 6 - Life test undergoing summary

Cooler model	Accelerated Parameters	Number of Cryocoolers under test	Test Profile and Type
K508 Integral Rotary	Temp	3	45°C@25Hz@35 bar
K508N Integral Rotary	Temp, Frequency	6	80°C@65Hz@40 bar
		6	60°C@45Hz@40 bar
K561 / 3 Integral Rotary	Temp	3	60°C@38Hz@18 bar
K527 Split Linear	None	3	20°C@ low/ med/high load
	Medium Load	3	
	High Load	3	
K570 Split Linear	None	5	20°C@ low/ med/high load
	Medium Load	5	
	High Load	5	

7. CONCLUSIONS & SUMMARY

As one can see RICOR puts a lot of resources in validating and enhancing its Cryocoolers reliability performance. We believe in continuing improvements, as motivation to be more accurate in life predications. We combine new and innovative methods, statistical tools, and literature surveys, with field data, life tests, and engineer knowledge. Consequently we have more reliable Cryocoolers with higher demonstrated MTTF. Watt- hour approach was presented and as life tests conclusions will be drawn we look forward further studies.

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