Overview of RICOR's Reliability Theoretical Analysis, Accelerated Life Demonstration Test Results and Verification by Field Data

Igor Vainshtein, Shlomi Baruch, Itai Regev, Victor Segal, Avishai Filis, Sergey Riabzev
RICOR Cryogenic & Vacuum Systems, En Harod Ihud 18960, Israel

ABSTRACT

The growing demand for 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 optimized system's Integrated Logistic Support (ILS). In order to meet this need, RICOR developed linear and rotary cryocoolers which achieved successfully this goal.

Cryocoolers MTTF was analyzed by theoretical reliability evaluation methods, demonstrated by normal and accelerated life tests at Cryocooler level and finally verified by field data analysis derived from Cryocoolers operating at system level.

The following paper reviews theoretical reliability analysis methods together with analyzing reliability test results derived from standard and accelerated life demonstration tests performed at Ricor's advanced reliability laboratory. As a summary for the work process, reliability verification data will be presented as a feedback from fielded systems.

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

1. INTRODUCTION

During recent years RICOR has fielded thousands of Integral Rotary and Split Linear Cryocoolers for space, 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 reached > 20,000 hr. In compliance with that requirement, RICOR has made several technical improvements, which increased Cryocooler reliability significantly achieving a higher Mean Time to Failure. 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, the Integral Rotary Cryocoolers' parameters are: 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.

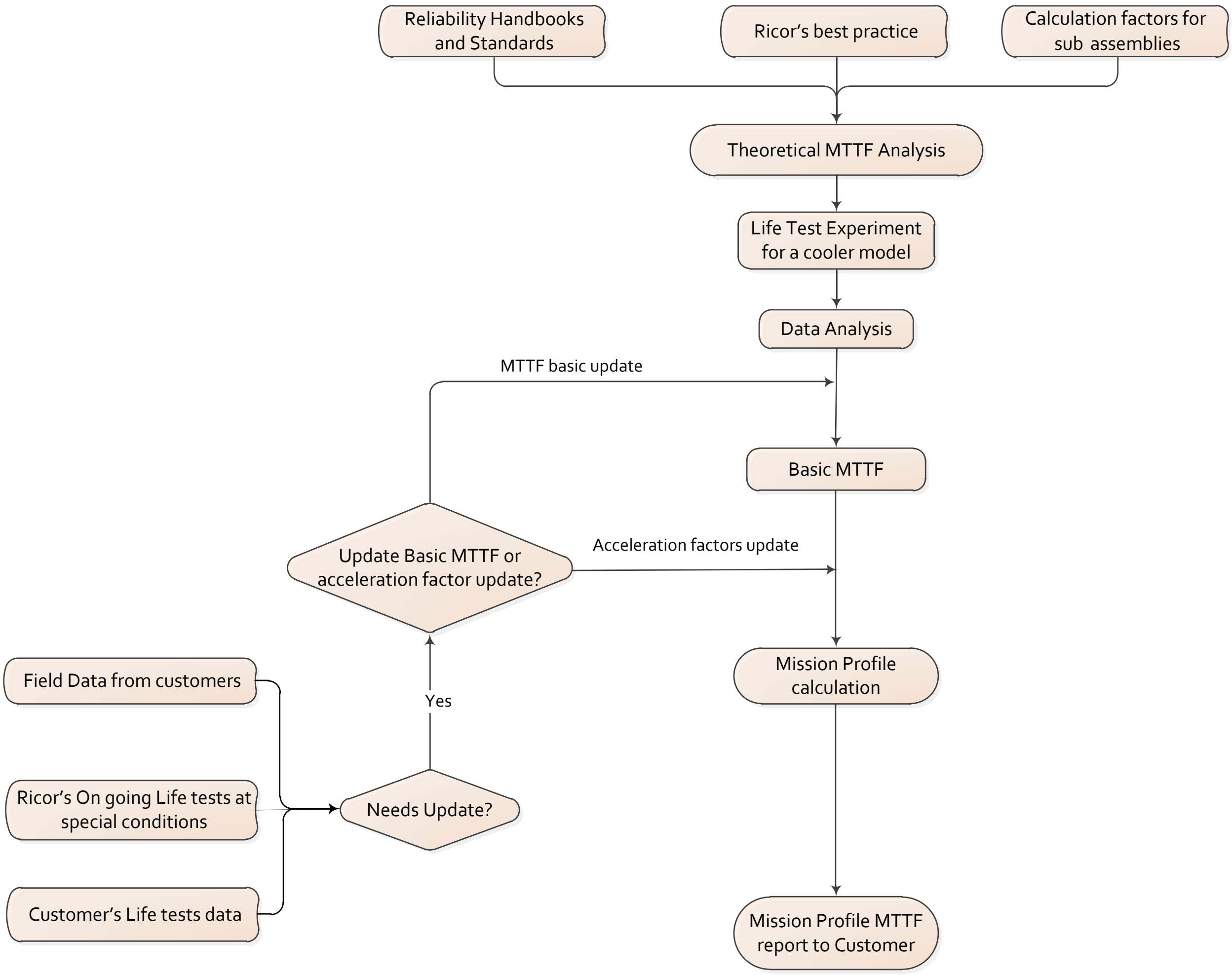


Figure 1 - RICOR`s Methodology for MTTF estimations

In Figure 1 the initial stage for MTTF estimations is RICOR's Cryocoolers life test data. This life test is performed in an 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 the amount of operating hours in 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 performed on different Cryocoolers and gathering 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 [1].

From the presented equation for a prediction model for Cryocoolers we applied the following model which defined customer profile MTTF as an outcome of the basic MTTF multiplied by a set of factors:

$$MTTF = \theta_b \pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode} \tag{1}$$

Where:

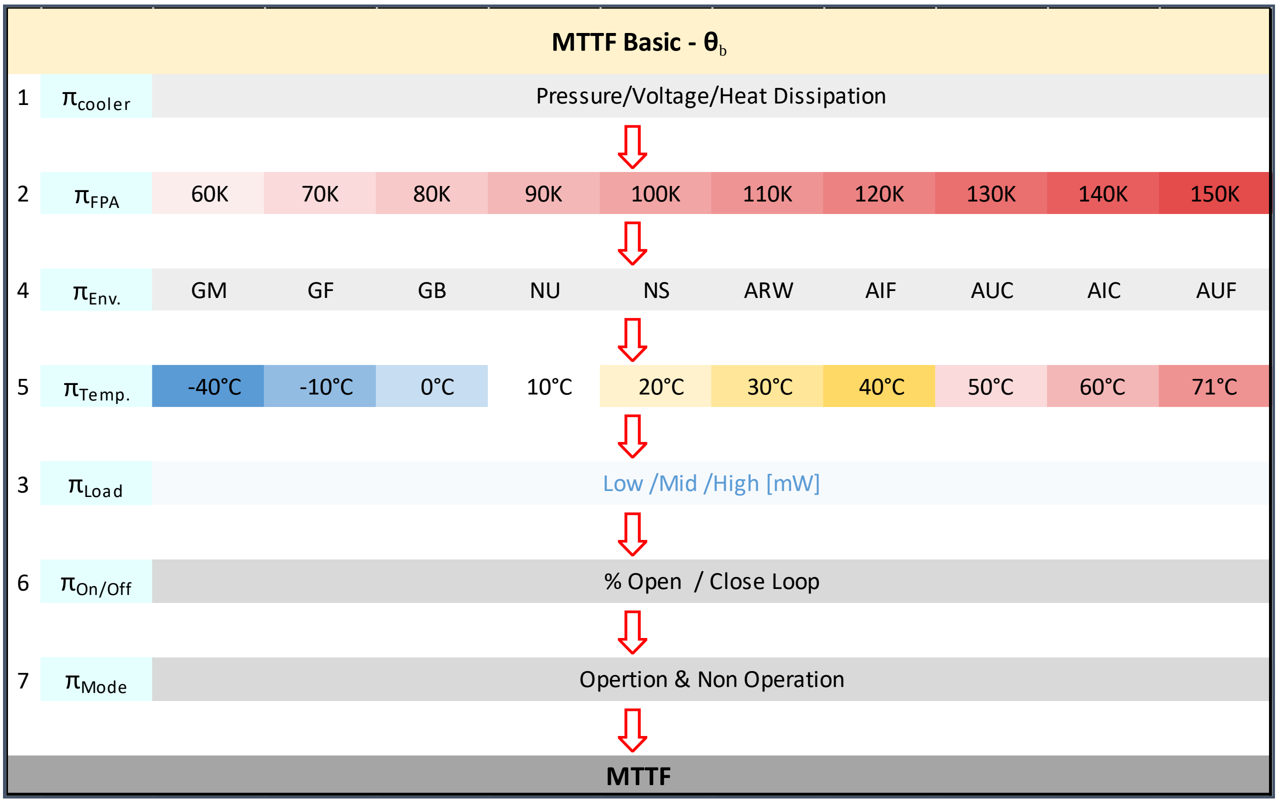


Figure 2 - Set Of Factors

4. LIFE TEST OVERVIEW

4.1 General

During recent years RICOR has conducted extensive laboratory life tests for new cooler models, an Ongoing Reliability Test (ORT) to ensure the quality and reliability of the coolers during mass production and an acceleration life test for definition and verification of conversion factors as part of RICOR's quest for continuous improvement.

Ricor’s life test laboratory facility can run 85 coolers at different acceleration conditions simultaneously, from -40°C to +100°C with a different thermal load or/and a different frequency Cryocooler operation mode (Figure 3 shows the laboratory facility at RICOR).

Cryocooler's operation data are monitored at a high sample rate and automatically saved in Ricor’s database storage server throughout the life test experiment.

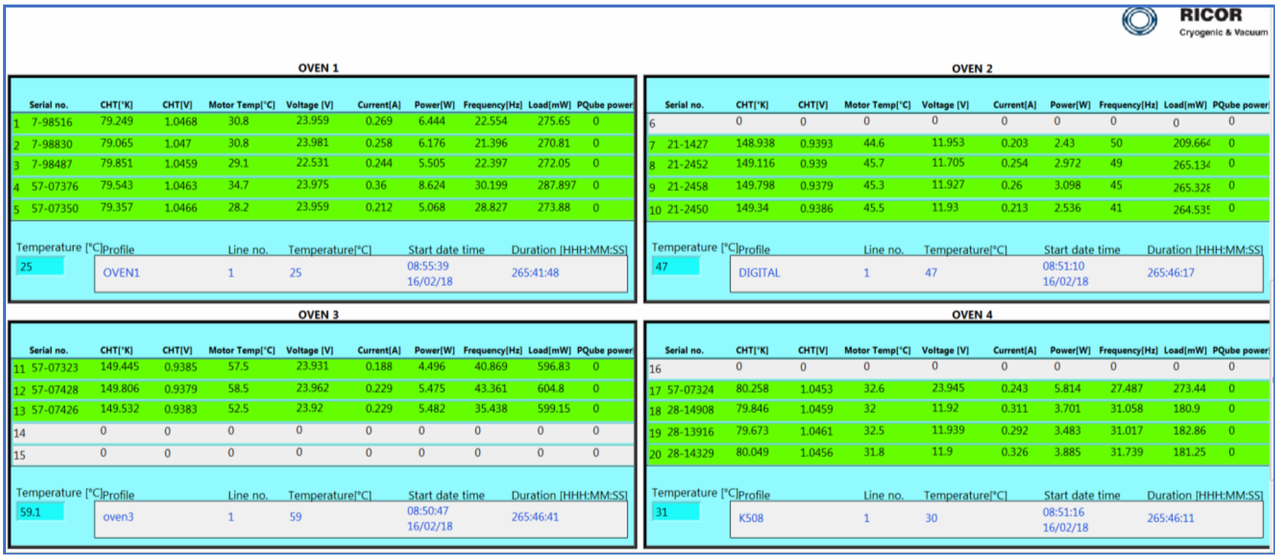
Measurement data that include the following parameters are continuously monitored during the life test:

- Current
- Voltage
- Operation Frequency
- Thermal Load
- Motor and Environmental Temperature
- Power Consumption
- Cold tip temperature
- Accumulated operating time

Figure 4 and 5 shows an example of measurement data.

The life tests are performed under the careful supervision of a technician who performs ongoing tests such as: acoustic noise, helium leakage, visual inspection and induced force tests for identification of degradation during the life test experiment.

Figure 3 - Life test Cryocoolers Laboratory



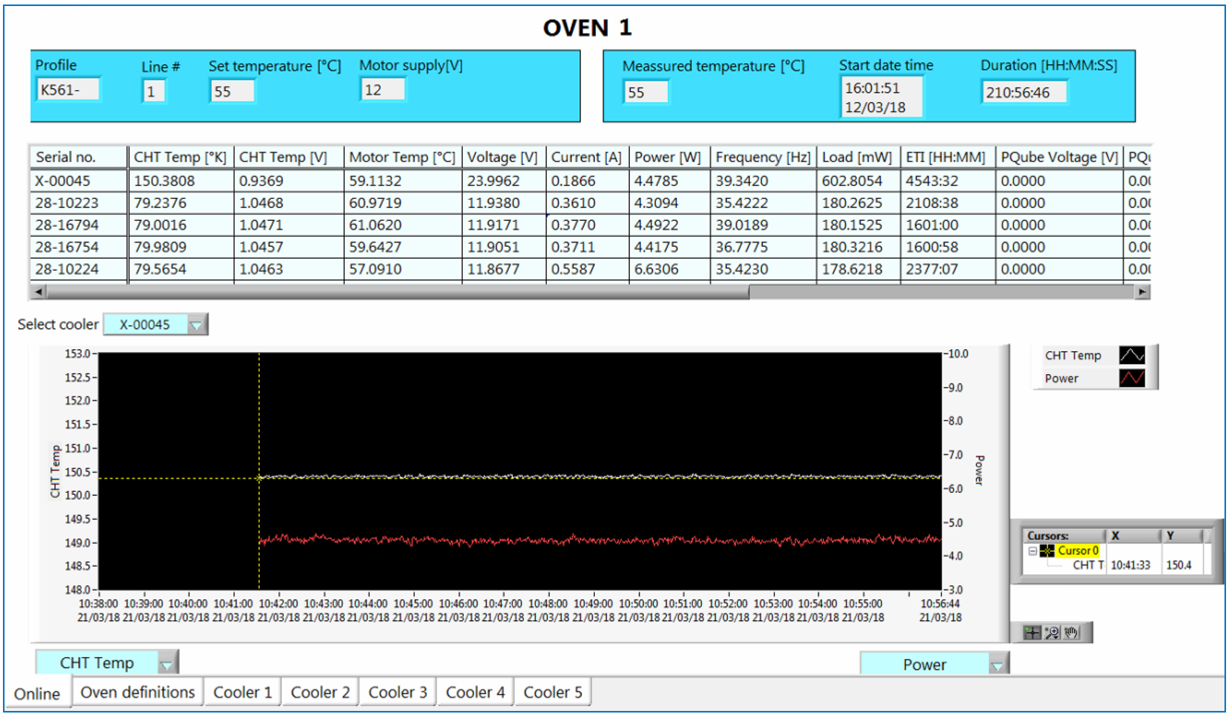


Figure 4 - Life test Cryocoolers Measurement

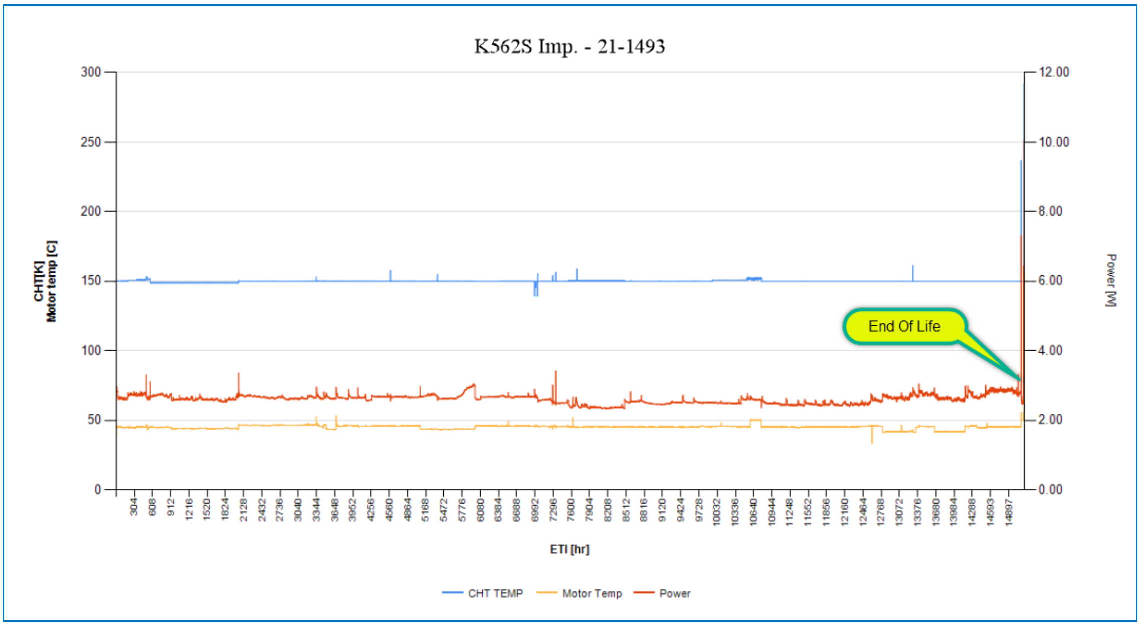


Figure 5 - Life test Cryocoolers graph

RICOR's Integral Rotary and Split Linear Cryocooler models that continuously undergo life experiment tests are shown in Figure 6.

Figure 6 – Several RICOR Integral Rotary and Linear models under production

5. LIFE TESTS RESULTS

5.1 Models for Hot Detectors:

5.1.1 The following is a K580 R&D Life Demonstration Test (Figure 7) result for 6 coolers running without acceleration at 23°C ambient temperature, 150K cold tip temperature and 230mW total heat load. The experiment is performed with two types of cold fingers.

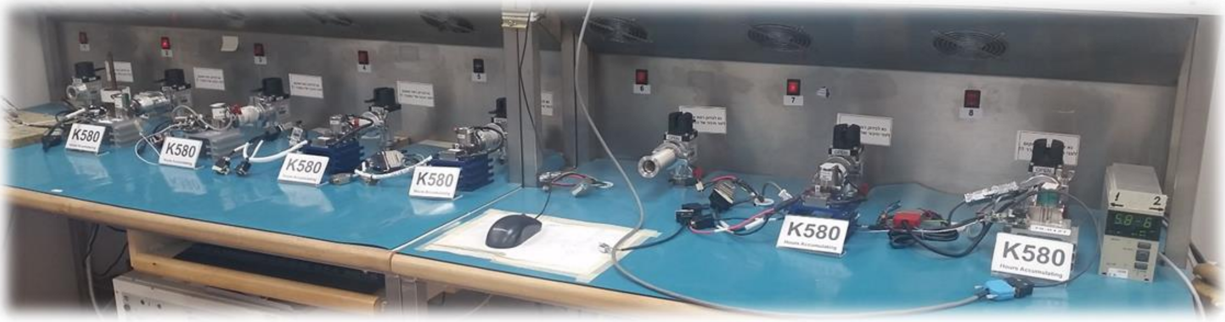


Figure 7 – K580 R&D life demonstration test

Table 1- Life test status for K580 Cryocooler model:

#	Cooler S/N	Cold Finger	Experiment hours	*Predicted basic MTTF	Status
1	78-0121	Standard	19,194	16,121	Still running
2	78-0129		16,619		End of Life
3	78-0134		16,981		End of Life
4	78-0135		15,459		Still running
5	78-0228	Generic	9,450		Still running
6	78-0230		9,823		Still running

*Basic MTTF conditions are defined as: GF, environment temperature 23°C, thermal load of 180mW@23°C, nominal fill pressure and cold tip temperature of 150K. Probability Density function and MTTF calculation for current stage of the experiment presented in figure 8.

Basic MTTF calculation according to paragraph 3.1 (only π_{Load} factor applied during the experiment):

$$MTTF = \theta_b \pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}$$

$$\Downarrow$$

$$\theta_b = \frac{MTTF}{\pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}} \Rightarrow \frac{14{,}670}{1*1*1*1*0.91*1*1} = 16{,}121 hr.$$

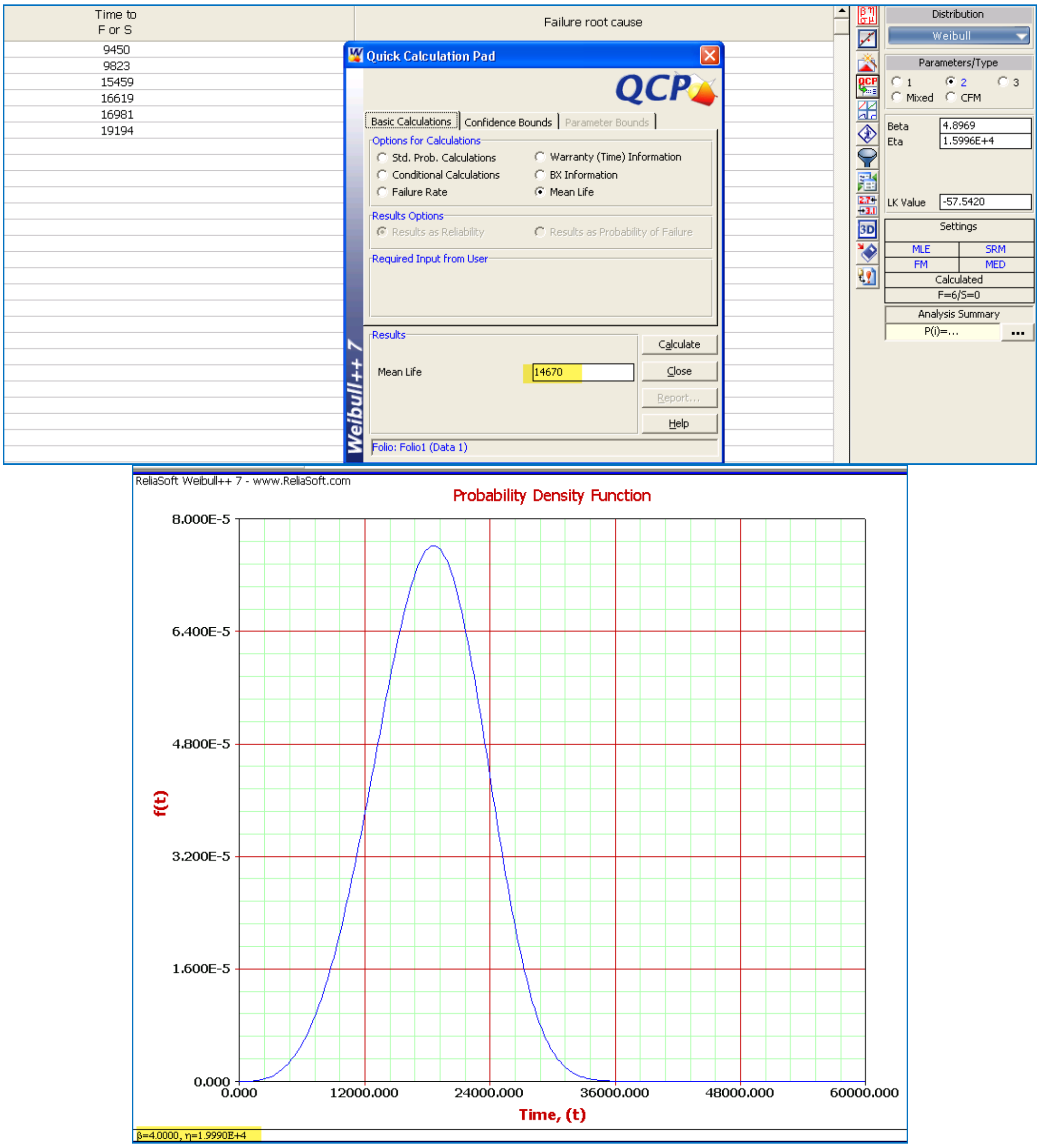


Figure 8 – K580 R&D Probability density function and MTTF calculation

5.1.2 The following is a K562Short Improved Accelerated Life Demonstration Test result of 3 coolers running at 40°C ambient temperature, 150K cold tip temperature and 210mW total heat load. Additional 3 coolers will begin the experiment during Q2 2018 at 55°C ambient temperature.

Table 2- Life test status for a K562S improved Cryocooler model

#	Cooler S/N	Experiment hours	MTTF experiment	*Basic MTTF	Status
1	21-1427	12,940	14,650	17,650	Still running
2	21-1493	15,282			End of Life
3	21-1404	14,226			End of Life

*Basic MTTF conditions are defined as: GF, 23°C, thermal load of 195mW@23°C, nominal fill pressure and cold tip temperature of 150K.

Basic MTTF calculation according to paragraph 3.1 (only π_{Temp} factor applied during the experiment):

$$MTTF = \theta_b \pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}$$

$$\Downarrow$$

$$\theta_b = \frac{MTTF}{\pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}} \Rightarrow \frac{14{,}650}{1*1*1*0.83*1*1*1} = 17{,}650 hr.$$

5.1.3 The following is a K508 Accelerated Life Demonstration Test result (Figure 9 present life demonstration facility) of 5 coolers running at 35°C ambient temperature, 105K cold tip temperature and 170mW total heat load.

Table 3- Life test status for K508 Cryocooler model:

#	Cooler S/N	Experiment hours	MTTF experiment	*Basic MTTF	Status
1	7-89213	30,656	24,150	15,406	End of Life
2	7-88469	19,973			End of Life
3	7-89357	27,036			End of Life
4	7-89407	26,983			End of Life
5	7-88308	15,500			End of Life

*Basic MTTF conditions are defined as: GF, 23°C, thermal load of 270mW@23°C, nominal fill pressure and cold tip temperature of 80K.

Basic MTTF calculation according to paragraph 3.1 (π_{Temp} and π_{FPA} factors applied during the experiment):

$$MTTF = \theta_b \pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}$$

$$\Downarrow$$

$$\theta_b = \frac{MTTF}{\pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}} \Rightarrow \frac{24{,}150}{1*1.65*1*0.95*1*1*1} = 15{,}406 hr.$$

Figure 9 - Life test Cryocoolers Laboratory

5.2 Split Linear cooler:

5.2.1 The following is a K527 Life Demonstration Test result of 7 coolers running without acceleration at 23°C ambient temperature, 80K cold tip temperature and two groups of total heat load (170mW/ 290mW).

Table 4 - Life test status for K527 Cryocooler model:

#	Cooler S/N	Heat Load	Experiment hours	*Predicted basic MTTF	Status
1	46-0461	170mW	34,005	38,410	Still running
2	46-0404		33,630		Still running
3	46-0463		32,786		Still running
4	46-0400		33,421		Still running
5	46-0397	290mW	29,187		Still running
6	46-0538		20,734		Still running
7	46-0408		29,259		Still running

*Basic MTTF conditions are defined as: GF, 23°C, thermal load of 170mW@23°C, nominal fill pressure and cold tip temperature of 110K.

*Assuming Betta=4 by similarity to other rotary cooler models and confidence level=90% for Weibull distribution.

Experiment hours of coolers from a group with 290mW heat load multiplied by a thermal load factor of (π_{Load}) to convert to the same conditions as in group one with a heat load of 170mW.

6. METHODOLOGY IMPLEMENTATION EXAMPLE

This section presents an example of Ricor's MTTF estimations methodology mentioned in paragraph 2.1 on K508N Cryocooler model.

6.1 Theoretical analysis:

Performed reliability assessment on K508N Cryocooler model according to the FMEA (Failure Mode Effects Analysis), Ricor's historical data from the field and experiments, reliability handbooks and calculation factors for sub-assemblies and parts, leads us to the theoretical MTTF base equivalent to 28,490 hours at GF, 20°C environmental temperature and a thermal load of 200mW@80K.

The following are details of methods used for reliability assessment:

6.1.1 FMEA:

The FMEA employs the hardware FMEA approach, i.e. the failure modes are specified according to the product tree assemblies and components.

The FMEA worksheet is presented in Table 5 and consists of ten columns as follows:

1. #: FM identification number.
2. ITEM: provide the component name.
3. FUNCTION DESCRIPTION: describes the component function.
4. FM DESCRIPTION: details the ways in which the component fails.
5. FM CAUSES: specifies the physical/chemical etc. mechanisms which generate the FM mode.
6. LOCAL EFFECT: details the failure mode effects on the cooler.
7. END EFFECT: details the failure mode effects on the system incorporating the cooler.
8. COMPENSATION PROVISION: lists the measures taken to minimize or eliminate the FM likelihood.
9. FAILURE SEVERITY CLASS: details the END EFFECT severity class.
10. FM PROBABILITY: qualitative assessment of the relative probability of the FMs.

Table 5 – FMEA table

#	ITEM	FUNCTION DESCRIPTION	FAILURE MODE DESCRIPTION	FAILURE CAUSES	FAILURE EFFECTS	COMPENSATION PROVISION	FAILURE SEVERITY CLASS	FAILURE PROB. CLASS
					LOCAL EFFECT	END EFFECT		
1. **Sub. assembly**								
1.1								

6.1.2 Reliability Block Diagram

The reliability block diagram for K508N is displayed in Figure 10. The cooler reliability configuration is serial, i.e. the success of all the components is required for the successful cooler operation.

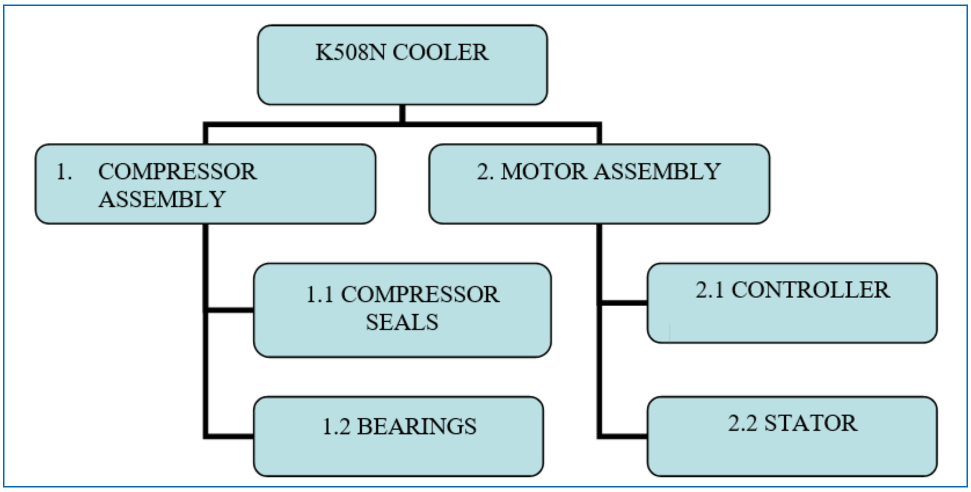


Figure 10 - Reliability block diagram - Serial model

6.1.3 Methodology

The cooler reliability model is provided in equations 2, and the MTTF model in expression 3.

The assessment methodology is the Bayesian one and it has been applied on the cooler level; rather than bottom-up from the component to the cooler level by using equations 2-3.

(2)

$$R_{K508N}(t) = \prod_{j=1}^{2} R_{1,j}(t) \cdot \prod_{j=1}^{2} R_{2,j}(t)$$

(3)

$$MTTF = \int_0^\infty t \cdot f_T(t)dt = \int_0^\infty R(t)dt$$

In theoretical analysis we assume constant failure rate to the main parts, therefore time to failure (t) is distributed exponentially:

(4)

$$R(t)=\exp(-\lambda * t)$$

λ - The failure coefficient rate in: $\frac{failure}{10^6\,hour} = fpMh$

(5)

$$\text{MTBF} = \lambda^{-1} \times 10^6 \text{ hours}$$

According to the expression 2 and 4 the cooler failure rate is calculated according to the following expression (6):

(6)

$$\lambda_{cooler} = \lambda_{Bearing} + \lambda_{Compressorseals} + \lambda_{Controller} + \lambda_{Stator}$$

Component failure rate is calculated according to Ricor's historical data for the same components in other models, Reliability handbooks and standards, the result of the calculation is as follows:

1. $\lambda_{Bearing} = 31*10^{-6}$ - Based on a bearing calculation according to Ricor's data and international standards such as ISO 281. Ricor's modified L10 equation presented in equation 7 based on (Ref. 7)..

(7)

$$L_{10} = \frac{10^6}{60 \times n} \times \left(\frac{C_r}{P_r} \right)^3 \times f_C \times f_T \times f_L$$

L_{10} : Hours (h)
n : Speed (rpm)
C_r : Basic dynamic radial load rating (N)
P_r : Dynamic equivalent radial load (N)
f_C : Cleanliness factor (N)
f_T : Temperature factor (N)
f_L : Lubrication factor (N)

2. $\lambda_{Controller} = 5*10^{-8}$ - The reliability prediction was performed on two electrical boards in accordance with the MIL-HDBK-217F Notice 2 method, System Reliability Toolkit (RiAC ,2006), RAM Commander software and thermal analysis .The method of prediction: Part Stress Analysis.

3. $\lambda_{Compressorseals} = 3*10^{-8}$, $\lambda_{Stator} = 2*10^{-8}$ - Derived from Ricor's experience based on filed data in other models of returned coolers with controller and helium leak failures.

Based on all the above data the failure rate is calculated in expression 8 and MTTF in expression 9.

(8)

$$\lambda_{cooler} = \lambda_{Bearing} + \lambda_{Compressorseals} + \lambda_{Controller} + \lambda_{Stator} = 31*10^{-6} + 3*10^{-8} + 5*10^{-8} + 2*10^{-8} = 31.1*10^{-6}$$

(9)

$$\text{MTTF} = \lambda^{-1} \times 10^6 \text{ hours} = 1/(31.1*10^{-6}) = 32{,}154 \text{ hours}$$

6.2 Cooler life distribution

In reality, the life distribution of the coolers is a mixed one and has the general form of expression 10:

(10)

$$f_T(t) = p f_{1,T}(t) + (1-p) f_{2,T}(t)$$

It arises from the fact that the coolers population usually consists of two subpopulations:

1) Weak coolers with a life distribution f1, T(t). The proportion of this subpopulation is p. Coolers belonging to this group will fail in a relatively short time after shipment, mainly because of poor installation or integration into the system, mishandling, poor workmanship and QA inspection deficiencies.

2) A fraction 1-p of mature coolers with life distribution f2, T(t).

6.3 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 be according to Weibull.

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

(11)

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

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

(12)

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

Weibull MTTF:

(13)

$$E(T) = MTTF = \alpha\, \Gamma(1 + 1/\beta)$$

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.

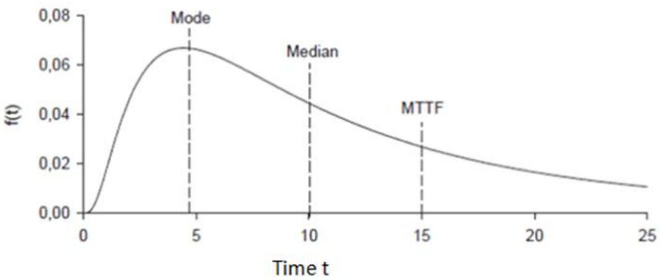


Figure 11 - Typical Weibull's distribution

6.4 Experiment analysis:

The following is a K508N Accelerated Life Demonstration Test result of 9 coolers running at 60°C ambient temperature, 150K cold tip temperature and 610mW total heat load.

Table 6 - Life test status for K508N Cryocooler model:

#	Cooler S/N	Experiment hours	MTTF Experiment	*Basic MTTF	Status
1	57-1222.1	25,480	18,790	28,255	End of Life
2	57-01628	24,000			End of Life
3	57-01633	9,550			End of Life
4	57-01753	16,135			End of Life
5	57-02018	9,400			End of Life
6	57-01883	21,140			End of Life
7	57-01772	14,950			End of Life
8	57-01913	24,040			End of Life

*Basic MTTF conditions are defined as: GF, 23°C, thermal load of 270mW@23°C, nominal fill pressure and cold tip temperature of 80K.

Basic MTTF calculation according to paragraph 3.1 (π_{Temp} , π_{Load} and π_{FPA} factors applied during the experiment):

$$MTTF = \theta_b \pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}$$

$$\Downarrow$$

$$\theta_b = \frac{MTTF}{\pi_{Cooler} \pi_{FPA} \pi_{Env} \pi_{Temp} \pi_{Load} \pi_{On/Off} \pi_{Mode}} \Rightarrow \frac{18{,}790}{1*1.9*1*0.5*0.7*1*1} = 28{,}255 hr.$$

6.5 Field Data analysis:

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

The analysis is based on field data reported by the customer. The reported operation hours analyses and processes using reliability software "ReliaSoft Weibull++ 7". While assuming the distribution is "Weibull". The approach based on the field Cryocooler failures population, as the analysis relies on total accumulated operating hours of all Cryocoolers served in project. By dividing the total operating hours by the number of field Cryocooler failures we receive MTBF.

Because Cryocoolers are replaced in the field and not repaired the MTBF is identical to the MTTF.

Table 7 shows the different K508N projects, application profile, field MTTF and basic MTTF.

Table 7 - Field data summary 2014-2017

Project	Application	Qty. fielded coolers	Field MTTF	Application Profile						Basic MTTF
				FPA [K]	Env.	Env. Temp.[°C]	Load [mW]	On/Off	Mode	
A	Border surveillance	30	18,633	77	GF	43	330	100% On	Operational	27,844
B	Border surveillance	100	40,720	150	GF	50	270	100% On	Operational	30,616
C	Border surveillance	113	19,909	77	GF	50	270	100% On	Operational	30,256
D	Border surveillance	49	27,663	77	GF	50	220	100% On	Operational	38,219
E	Airport control	24	15,017	77	GF	42	270	100% On	Operational	19,870
Summary		**316**	**27,204**							**30,587**

6.6 Summary of K508N MTTF estimations methodology:

Following table 8 present summary analysis of MTTF for K508N cryocoolers based on flow mentioned in paragraph 2.1.

Table 8 - summary analysis for K508N

#	Methodology	Basic MTTF
1	Theoretical analysis	32,154
2	Life Experiment	28,255
3	Field Data	30,587

Based on worst case data in table 8, the MTTF for K508N is **28,255** hours.

7. RELIABILITY ASSESSMENT FOR OTHER CRYOCOOLERS

A similar analysis mentioned on section 6 was done to the other Cryocoolers, the result summarized and presented in table 9 as follow:

Table 9 - Summarized Basic MTTF results:

Cooler Model	Basic MTTF Conditions						2018 Updated MTTF
	FPA[K]	Env.	Env. Temp.[°C]	Load [mW]	ON/OFF	Mode	
K508	80	GF	23	270	100% On	Operational	15,000
K548	80	GF	23	500	100% On	Operational	17,000
K561	80	GF	23	190	100% On	Operational	10,000
K563	80	GF	23	210	100% On	Operational	9,000
K562S	110	GF	23	190	100% On	Operational	12,000
K562S-short	150	GF	23	190	100% On	Operational	17,000
K543 / 4	80	GF	23	650	100% On	Operational	12,000
K508N	80	GF	23	270	100% On	Operational	28,000
K527	110	GF	23	170	100% On	Operational	35,000
K549	80	GF	23	500	100% On	Operational	10,000
K562Short imp.	150	GF	23	190	100% On	Operational	17,000
K580	150	GF	23	180	100% On	Operational	16,000

8. WHAT IS NEXT

RICOR is intending to extend reliability activities for other Cryocooler models, including Split Linear Cryocoolers and new cooler models. Significant increasing capabilities of reliability predictions is planned, by further life tests, more field data, and with upgraded RICOR's extensive reliability lab.

We have ORT (Ongoing Reliability Tests) on the following models – K508N, K508, K561, K563, K544, K543, K562Short imp., K580, K527.

In additional special environmental tests will be performed for definition more accurate correction factors.

Also On/Off tests on controllers and coolers will be performed in some Cryocooler models.

9. CONCLUSIONS & SUMMARY

It's clearly evident that RICOR has invested considerable resources in validating and enhancing Cryocooler reliability performance. We believe in continuous improvements motivating greater accuracy in life predictability. We combine innovative methods, statistical tools, and literature surveys, with field data, life experiments, and engineering knowledge.

An analysis of the results shows a distinct and unequivocal correlation between theoretical analysis, laboratory testing and field results. Part of the activity in this work includes updating the MTTF base in accordance with the experiments conducted and the field results received from customers (See Table 9).

As a standard work method Ricor conducts continuous tests on all active models, gathers field data and analyses it for the purpose of improving predictability, product reliability control and continuous improvement.

Consequently we can provide more reliable Cryocoolers with higher demonstrated MTTF.

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