RICOR's new development of a highly reliable integral rotary cooler - engineering and reliability aspects

Avishai Filis , Nachman Pundak, Moshe Barak, Ze'ev Porat , Mordechai Jaeger (RAFAEL)
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 decreased integrated system Life Cycle (ILS) cost. In order to meet this need RICOR has developed a new rotary Stirling cryocooler, model K508N, intended to double the K508's operating MTTF achieving 20,000 operating MTTF hours.

The K508N employs RICOR's latest mechanical design technologies such as optimized bearings and greases, bearings preloading, advanced seals, laser welded cold finger and robust design structure with increased natural frequency compared to the K508 model.

The cooler enhanced MTTF was demonstrated by a Validation and Verification (V&V) plan comprising analytical means and a comparative accelerated life test between the standard K508 and the K508N models. Particularly, point estimate and confidence interval for the MTTF improvement factor where calculated periodically during and after the test. The (V&V) effort revealed that the K508N meets its MTTF design goal. The paper will focus on the technical and engineering aspects of the new design. In addition it will discuss the market needs and expectations, investigate the reliability data of the present reference K508 model; and report the accelerate life test data and the statistical analysis methodology as well as its underlying assumptions and results.

Keywords: Cryocooler, Rotary integral, Stirling, Weibull distribution, MTTF, RICOR, K508N.

1. INTRODUCTION

Electro optical systems are based on various components such as optics, IR detectors, cryocoolers and electronic boards. During definition of such new EO systems the reliability evaluation of the system becomes an important parameter from system maintenance considerations and Life Cycle Cost calculations. In a few applications that work around the clock 24hr/7days a week, such as border surveillances, the cryocooler is defined as a critical component that limits system reliability, hence cryocooler reliability needs to be improved.

In the last 15 years, RICOR fielded more than 55,000 cryocoolers based on the K508 model for different types of applications. The K508 meets the MIL spec requirements of -40°C up to 71°C ambient while in a few applications the K508 served up to 85°C ambient.
The high cooling power of more than 1/2W at 71°C enables the K508 high redundancy relating to low & mid format arrays such as 320x256 and 480x384 pixels and advanced format arrays 640x512 pixels, 15µ pitch as well.
The K508 MTTF achieved during official life demonstration tests on three coolers >10,700 operating hours according to a specific mission profile. The K508 field MTTF is in the range of 8,000 ÷12,000 operating hours depending on the application type.

The combination between applications that call for a long life cryocooler and RICOR's strong and firmly established position in the field of rotary Stirling technology in the last three decades, led to the development of the new K508N model that is based on the interfaces of the standard K508 while including novel technologies. The main design goal of the K508N is to double the K508 MTTF and to achieve MTTF above 20,000 operating hours while ensuring interchangeability with the standard K508 for retrofit project scenario and including the latest technologies in the mechanical design and in the electronic controller design.

2. K508N DESIGN CONCEPT

The basis for K508N design derived from an analysis review of the weakest components dictates the K508 end of life. The bearing design and the internal mechanical parts of the K508 were analyzed in detail in order to implement the knowledge and advanced technologies developed at RICOR in the last 15 years since the K508 was initially designed.

It's well known that the classical end of life failure mode for a rotary cooler is bearing failure.
The mechanical design of the K508N model focused in optimization of the internal parts, especially the bearings, while the main challenge was to significantly improve the internal mechanical design without changing the K508 outer interfaces with the IR detector and the EO system.
The bearings optimized in accordance with a typical working point of the cooler while taking into consideration several design parameters such as the maximum internal bulk available without impact on outer interfaces, bearing maximum dynamic load, number of balls, cage construction, materials durability and other parameters.

As a rotary cooler includes reciprocating parts that apply forces on the crankshaft supported by two bearings, the mechanical optimization focused on the forces distribution between those two bearings from considerations of theoretical bearing life calculations.
A special design review was done for several grease types used in the bearing because of a direct impact between grease characteristics and bearing life span especially the viscosity sensitivity at high ambient temperatures.
The comparison between different greases analyzed in accordance with the following parameters:

Parameter type	Parameter name
General	Chemical compound
Grease basic characteristics	Viscosity @40°C [cst]
	Viscosity @100°C [cst]
	Freezing point [°C]
Physical characteristics	maximum temperature for usage [°C]
	Minimal temperature for usage [°C]
	Vapor pressure [torr]
	Dripping point [°C]
	Penetration [mm/10]
	Corrosion protection
	Density [g/ml]
	Volatility [wt% loss]
Load testing	Four balls test [N]
	Wear factor [mm]

Table 1 – Grease Parameters Analysis

At the final stage of the greases comparison, a grease type was chosen and a specific quantity for each bearing was precisely defined from life span considerations based on the typical working point of the cooler.

The internal mechanical design of the K508N has implemented novel technologies while keeping the external interfaces of the K508.
Preloading arrangement has been designed in order to damp vibration at bearing level and to achieve smooth operation with a low acoustic noise signature.

The crankcase structure was hardened and the clamping flanges thickened from 3mm to 5mm in order to increase the natural frequency of an IDDCA in case a reinforced Dewar for harsh environmental conditions is used.

The design of the metal seals used to seal the helium from the external environment is based on c-rings in order to minimize sensitivity of the seals to high ambient temperature and ensure stability of the seal for a long term of operation without helium leakage.
A new plating process was implemented for the external surfaces of the cooler from considerations of corrosion resistance, electrical continuity and manufacturing process simplification.

The three main outline dimensions of the K508N were kept the same as in the K508, the line of sight height relating to the mounting surface was kept the same and the positioning of the FPA relating to the mounting fixation was also kept the same as in the standard K508.

3. RELIABILITY EVALUATION

3.1. Observation of RICOR's Cryocoolers life distribution

Based on many samples, that have undergone life tests at RICOR's premises it was found that the two Weibull life distribution parameters would be appropriate to model the stochastic behavior of RICOR rotary cryocoolers' time to failure (T), namely:

(Eq. 1)
$$f_T(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \; t \geq 0, \alpha, \beta > 0$$
$$E(T) = MTTF = \alpha \cdot \Gamma\left(1 + 1/\beta\right)$$

Where:

- α – scale parameter
- β – Shape parameter
- Γ – Gamma function

As reported in [Ref. 5] β possesses higher values than 4, while some samples exhibited even much higher values than that. See β values in table 4 for the samples which are discussed later.
Regarding the Linear technology, lack of sufficient empirical data makes it premature to draw conclusions on the life distribution type.

3.2. RICOR's MTTF recent prediction practices

RICOR's general approach towards MTTF prediction was first introduced in [Ref. 4], since then it has not changed considerably.
The prediction model is a multiplication one, where the actual MTTF (θ_{PR}) of a given cooler type subjected to prescribed working conditions is computed by multiplying a basic MTTF value (θ_b) by a series of conversion factors (π). These factors quantify the sensitivity of the basic MTTF to the alteration in working conditions from the reference to the actual conditions.

<u>To a feasible extent, the basic values are derived from a life test or field data.</u>

The prediction model is:

$$\text{(Eq. 2)} \quad \theta_{PR} = \theta_b \pi_E \pi_T \pi_{S1} \pi_{S2} .....$$

Where:

θ_{PR} - Projected MTTF

θ_b - Basic MTTF

π_E - Environmental factor

π_T - Ambient temperature factor

π_{Si} - Stress i conversion factor

3.2.1. Rotary coolers

In addition to the environmental and ambient temperature common factors, typical working stresses that are accounted for in the case of rotary coolers are:

- Cooling gas pressure (P)
- Operating frequency (H), derived from parameters such as Thermal load and FPA temperature.

Thus:

$$\text{(Eq. 3)} \quad \theta_{PR} = \theta_b \pi_E \pi_T \pi_P \pi_H$$

- The factors π_P , π_H are computed according to the inverse power law as follows:

$$\text{(Eq. 4)} \quad \pi_P = \left(\frac{P_b}{P_{PR}} \right)^2, \ \pi_H = \left(\frac{H_b}{H_{PR}} \right)^2$$

Where b and PR stand for the working conditions at the reference and actual working points accordingly.

- MTTF Environmental Factor π_E

Traditionally the conversion factors presented in [Ref. 6] used by default. Based on RICOR engineering judgment the influence of the environmental conditions on the MTTF is much more moderate than that projected by the traditional factors. Consequently, a new system of MTTF environmental conversion factor will be used as in the following table.

From \ To	G_F	G_M	N_S	N_U	A_{IC}	A_{IF}	A_{UC}	A_{UF}	A_{RW}	S_F
G_B	1	0.75	0.85	0.55	0.75	0.50	0.40	0.20	0.30	2.2

Table 2: MTTF Environmental Conversion Factor π_E

Note: The symbols and definitions of environmental conditions are according to those used in various versions of MIL-HDBK-217.

- MTTF Ambient Temperature Conversion Factors π_T

The temperature conversion factors are presented in the table 3. They are based on [Ref. 6] and well fit our needs.

To [°C] / From	10	20	30	40	50	60	70	80	90	100
10°C	1	0.9	0.83	0.77	0.66	0.53	0.4	0.32	0.23	0.13

Table 3: MTTF Ambient Temperature Conversion Factor π_E

3.2.2. Linear coolers

RICOR prediction model for linear coolers is:

$$\theta_{PR} = \left[\frac{1}{\theta_b^* \pi_E \pi_T} + \frac{1}{[(W_{MAX} - W_0)/S]\pi_E} \right]^{-1} \quad \text{(Eq. 5)}$$

The first term calculates the failure rate of the hardware not including the compressor. The second term calculates the failure rate of the compressor and is based on [Ref. 1] where:

$$S = \frac{CPQT}{AT_C} \quad \text{(Eq. 6)}$$

Where:

A - Piston area in [cm2]
C - Constant
P - Fill pressure [Bar]
Q - Heat load [W]
S - Slope of the input power curve
T_C - Cold tip temperature in [K]
T - Ambient temperature in [°C]
θ^*_b - Basic MTTF of the hardware other than the compressor
W_{MAX} - Maximum allowable input power [W]
W_0 - Initial input power (At beginning of cooler life) [W]
π_E, π_T - according to tables 2 & 3

3.3. RICOR model for assessment of weighted MTTF over multi-phases mission profile

Often customers define a life profile comprising different phases while requesting estimates of the MTTF in the separate phases and over the entire life profile as well. This is trivial if the coolers' lifetime is exponentially distributed, but will become more complicated when the life distribution is other than exponential. Since we are assuming the Weibull life distribution, we propose here an approximate estimate to the life profile MTTF in this case.

3.3.1. Assumptions

3.3.1.1. Life profile

Let us assume that the life profile comprises cycles of mission profile as described in Figure 1.

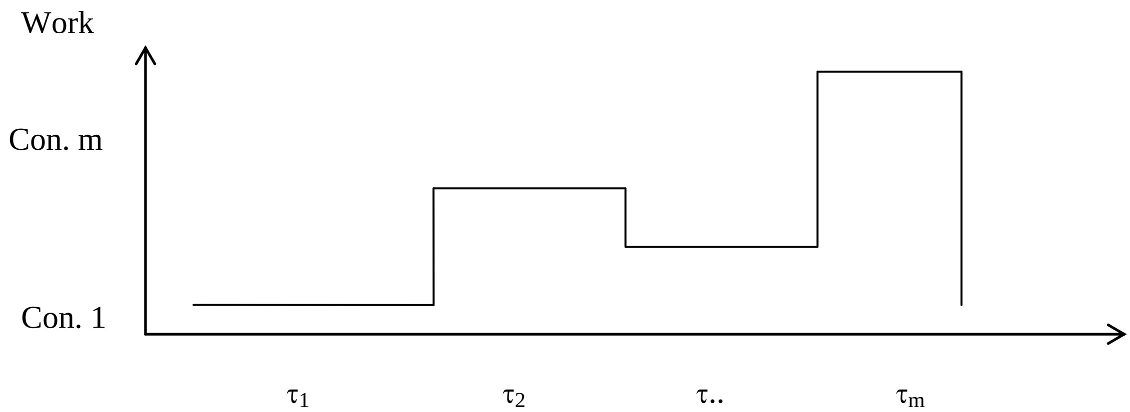

Figure 1: Illustration of single mission profile Cycle

Where:

Con. i - working and environmental conditions in the mission phase i

m - Number of mission phase

τ_i - time in phase i, i=1, m

T - $\sum_{i=1}^{m} \tau_i$, mission's cycle time

3.3.1.2. Phase's life distribution

It is assumed that the life distribution in each phase is Weibull with shape parameter β invariant from phase to phase and scale parameter α_i changing from phase to phase because of the changing working conditions.

3.3.1.3. Damage accumulation

The total damage to the component accumulated over time is calculated according to the Cumulative Exposure Model described in [Ref. 2] and [Ref. 3]. The model allowing computation of equivalent working time at the start of phase # i in terms of α_i is as follows.

(Eq. 7) $$e^{-\left(\frac{\tau^*_{i-1/\alpha_{i-1}}}{\alpha_{i-1}}\right)^{\beta}} = e^{-\left(\frac{\tau^*_{i-1/\alpha_{i}}}{\alpha_{i}}\right)^{\beta}}$$

Where:

$\tau^*_{i-1/\alpha_{i-1}}$ - Equivalent total time spent in the mission profile until the start of phase i, in terms of α_{i-1}

τ^*_{i-1/α_i} - Equivalent total time spent in the mission profile until the start of phase i, in terms of α_i

τ^*_{i/α_i} - Equivalent total time spent in the mission profile until the <u>end</u> of phase i, in terms of α_i

Yielding:

$$\tau^*_{i-1/\alpha_i} = \frac{\tau^*_{i-1/\alpha_{i-1}}}{\alpha_{i-1}} \alpha_i$$

(Eq. 8)

$$\tau^*_{i/\alpha_i} = \tau^*_{i-1/\alpha_i} + \tau_i$$

We now introduce the term α_{eq} being the approximated equivalent shape parameter over the mission profile. It is derived as follows:

(Eq. 9) $$e^{-\left(\frac{T}{\alpha_{eq}}\right)^{\beta}} = e^{-\left(\frac{\tau^*_{m/\alpha_m}}{\alpha_m}\right)^{\beta}} \Rightarrow \alpha_{eq} = \frac{T\alpha_m}{\tau^*_{m/\alpha_m}}$$

Applying expression (Eq. 8) recursively on

(Eq. 9) Yielding:

(Eq. 10) $$\alpha_{eq} = \frac{T}{\sum_{i=1}^{m} \frac{\tau_i}{\alpha_i}}$$

The probability of surviving n mission cycles (each at length T) and the approximated weighted life $MTTF_{eq}$ are as follows:

(Eq. 11) $$R(nT) = e^{-\left(\frac{nt}{\alpha_{eq}}\right)^{\beta}} \quad ; \quad MTTF_{eq} = \alpha_{eq}\Gamma(1 + 1/\beta)$$

Namely the Weibull formula holds for the end of each cycle (not for its middle point).

- The accuracy of the $MTTF_{eq}$ estimate is ± T. RICOR has separate full prove for the finding regarding $MTTF_{eq}$.

3.4. Estimation of K508N life improvement factor compared with standard K508

3.4.1. Accelerated Life Test comparison between K508 and K508N

In order to demonstrate K508N life's improvement, Ricor has performed a comparative accelerated life test between K508 and K508N, which are considered
as a practical evaluating tool in early stages of the development.
The accelerated test setup includes:

- Three standard K508 coolers from RICOR's production line compared with three K508N coolers.
- The coolers were integrated with standard K508 cold fingers.
- The coolers operated at a maximum operating frequency of around 60Hz which is equivalent to 3,600 rpm.
- The coolers were soaked in a climate chamber while the motors top skin temperature was controlled to 80°C.

The following parameters were continually monitored during the life test:

- Operating frequency
- Motor top skin temperature
- Accumulated operating hours
- Input Current/power level
- Current/power stability
- Visual inspection

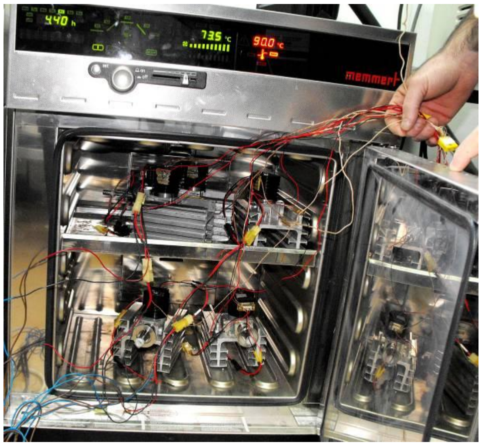

Figure 2: Accelerated Life Test Setup

3.4.2. Notations

θ_1, θ_2 - MTTF of improved and regular item
K - life improvement factor = θ_1/θ_2
T_1, T_2 - life times (Random variables)
$V(.)$ - Variance
$\overline{T}_1$, $\overline{T}_2$ - Mean of T_i, i =1, 2

$\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{K}$, $\hat{V}(.)$ - Point estimates of θ_1, θ_2, K, $V(.)$

The following table summarized the comparative accelerated life test results

Cooler model	**Failure root cause**	**Failure time [hr]**	**Observed lifetime Mean & Variance [h]**	**Weibull distribution parameters' MLE[1]**
K508 #1	8,193	Bearing end of life	Mean: 6120 Var.: ~$3.23 \cdot 10^6$	$\alpha = 6700$ hr $\beta = 4.4$
K508 #2	5,037	"		
K508 #3	5,126	"		
K508N #1	10,768	"	Mean: 11560 Var. ~$3.085 \cdot 10^6$	$\alpha = 12200$ hr $\beta = 8.4$
K508N #2	10,339	"		
K508N #3	13,573	"		

[1] MLE – Maximum Likelihood Estimator

Table 4: accelerated life test results

The point estimate of K is:

(Eq. 12) $$\hat{k} \cong \frac{\hat{\theta}_1}{\hat{\theta}_2} = \frac{11560}{6120} \cong 1.9$$

3.4.3. Confidence Bounds of K

As discussed earlier, we assume that the coolers' life distribution is Weibull.
However:
a) In order not to rely too heavily on this assumption and;
b) Since there is no exact statistical procedure to assign a confidence interval for the ratio of mean values in the Weibull case we decided to ignore Weibull life distributional assumptions and assess the confidence bounds considering only statistical properties of sample means; and to use the general maximum likelihood theory. This theory assumes that the estimators are asymptotically normally distributed.
Although our sample sizes are small (3 each) we employ this theory in order to get an idea regarding the confidence bound on k.

It is worth noting that in [Ref. 7] Snedecore and Cochran have shown that the distribution of the mean of small samples could tend to be normal if drawn from population having a distribution that is not skew (they have shown it for digit uniform distribution 0,1,2…,9, while concluding that even sample sizes of 5 would be enough). This may be the case of Weibull distribution with a large value of β, as found to be in our case.

<u>Calculation Procedure</u>: The derivation of the approximate Upper and Lower confidence bounds (K_U, K_L) of K is as follows:

(Eq. 13) $$\begin{aligned} V(\hat{k}) &= \left(\frac{\partial k}{\partial \theta_1}\right)^2 V(\hat{\theta}_1) + \left(\frac{\partial k}{\partial \theta_2}\right)^2 V(\hat{\theta}_2) \\ &= \left(\frac{1}{\theta_2}\right)^2 V(\hat{\theta}_1) + \left(-\frac{\theta_1}{\theta_2^2}\right)^2 V(\hat{\theta}_2) \end{aligned}$$

Because we do not have data on the exact values of the parameters in the above expression, we substitute their point estimates, i.e.:

$$\hat{V}(\hat{k})=\left(\frac{1}{\hat{\theta}_2}\right)^2 V(\hat{\theta}_1)+\left(-\frac{\hat{\theta}_1}{\hat{\theta}_2^2}\right)^2 V(\hat{\theta}_2)$$

(Eq. 14) $\quad Where:$

$$V(\hat{\theta}_i)=\frac{\hat{V}(T_i)}{n_i},\ n_1=n_2=3$$

Approximated upper and lower bounds at γ confidence level each (γ>50%) for k are derived **as** follows:

(Eq. 15)

$$K_{U,\gamma}=\hat{k}+Z_\gamma\cdot\sqrt{\hat{V}(\hat{k})}$$

$$K_{L,\gamma}=\hat{k}-Z_\gamma\cdot\sqrt{\hat{V}(\hat{k})}$$

Where $Z\gamma$ - is the percentile of the standard normal distribution.

Calculation results: using the former formulas and the test statistics yielding $K_{U,90}$ and $K_{L,90}$ (90% confidence level each):

$$K_{U,90}=\hat{k}+1.281552\cdot\sqrt{\hat{V}(\hat{k})}\cong 2.362$$

$$K_{L,90}=\hat{k}-1.281552\cdot\sqrt{\hat{V}(\hat{k})}\cong 1.438$$

4. SUMMARY

A new approach was achieved in the range of long life rotary cryocoolers development thanks to several novel technologies implemented in the K508N model.
The design goal to almost double the K508N MTTF compared to the standard K508 and to achieve more than 20,000 operating hours achieved (factor of ~1.9 achieved) by the comparative accelerated life demonstration test.
In the frame of reliability work, a new model for assessment of weighted MTTF over multi-phases mission profile presented by RICOR and will be implemented in future reliability evaluations.
The K508N model is designed in orientation with future EO needs such as High reliability, ROHS compliance, mechanical robustness, digital controller in order to form the foundation for future EO systems.

REFERENCES

[1] Kuo D. T., etal, "BAE's Life Results on Various Linear Coolers and Their Correlation with a First Order Life Estimation Method", Cryocoolers 11, ed. Ross R. G., (2001)

[2] Miller, R., Nelson, W. B., "Optimum Step-Stress Plan For Accelerated Life testing", IEEE Trans. Reliability, vol. R-32, pp 59-65, (1983 April)

[3] Nelson, W. B., "Accelerated Life testing Step-Stress models and Data analysis ", IEEE Trans. Reliability, vol. R-29, pp 103-108, (1980 June)

[4] Porat, Z., Sne-Or. A., Pundak. N., et al., "Reliability Assessment Procedure of Cryocoolers", (SPIE 1998/9)

[5] Pundak, N., Porat, Z., Barak, M., Zur, Y., Pasternak, G., "Field Reliability of Ricor Microcoolers", (SPIE 2009)

[6] Reliability toolkit, Commercial Practice Edition, RAC.

[7] Snedecore, G., W., Cochran, W., G., Statistical methods, IWOA State University Press, Seven editions, pp 44-51, (1980)