RICOR development of the next generation highly reliable rotary cryocooler

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ABSTRACT

Early rotary cryocoolers were designed for the lifetime of a few thousands operating hours. Ricor K506 model's life expectancy was only 5,000 hours, then the next generation K508 model was designed to achieve 10,000 operating hours in basic conditions, while the modern K508N was designed for 20,000 operating hours.

Nowadays, the new challenges in the field of rotary cryocoolers require development of a new generation cooler that could compete with the linear cryocooler reliability, achieving the lifetime goal of 30,000 operating hours, and even more.

Such new advanced cryocooler can be used for upgrade existing systems, or to serve the new generation of high-temperature detectors that are currently under development, enabling the cryocooler to work more efficiently in the field.

The improvement of the rotary cryocooler reliability is based on a deep analysis and understating of the root failure causes, finding solutions to reduce bearings wear, using modern materials and lubricants. All of those were taken into consideration during the development of the new generation rotary coolers.

As a part of reliability challenges, new digital controller was also developed, which allows new options, such as discrete control of the operating frequency, and can extend the cooler operating hours due to new controlling technique. In addition, the digital controller will be able to collect data during cryocooler operation, aiming end of life prediction.

Keywords: cryogenic cooler, rotary cryocooler, high reliability, long life, digital controller, bearings, RICOR, K508C.

1. INTRODUCTION

Electro-optical systems are comprised of a number of components, while the cryogenic cooler is one of the most critical of these parts. The cryogenic cooler is classified as an electro-mechanical system, namely, a system that converts electrical energy to mechanical motion of the mechanism parts. In most cases the life expectancy of a mechanical system is thought to be potentially shorter than that of the electronic system, therefore it can be dominant in determining the electro-optical system's overall life expectancy.

A rotary cooler is based on converting the rotary movement to a linear movement by means of bearings, so generally the cooler life is determined by the lifetime of its bearings arrangement comprising different bearing types. By comparison, a linear cooler is designed to convert electrical energy directly to linear movement, without a need in ball bearings, therefore its life is typically thought as longer than the life of a rotary cooler.

Nevertheless, the rotary cooler is often preferable to the linear cooler on account of many parameters, such as weight, compactness, efficiency, better cooling capacity to size ratio, induced forces, etc. Consequently, there is a certain development potential in improvement of the rotary cryocooler life, enabling a better competitiveness with the linear rival.

In order to reach the 30,000 hours target for the K508C model, we work to significantly improve the life expectancy of the cryocooler bearings by engineering and technological enhancements.

2. THE EVOLUTION OF RICOR ROTARY COOLERS OVER THE YEARS

The evolution of rotary coolers can be divided into two principle topics. The first is adaptation to high-temperature detectors enabling reduction of the cooler size, power required and system size. The second topic we will deal with in detail here is extending of the cryocooler lifetime without an impact on its size, weight, performance, price and other parameters.

Ricor cooler model K506 was one of the first integral coolers developed in the 80s. It had a cooling capacity of 1/4W@ 71C and was designed to work for 5,000 hours. Over the years the detectors increased in size and demanded a cooler providing a greater cooling capacity, higher reliability and longer lifetime. For that purpose the K508 cooler was developed, a cooler with a cooling capacity of 1/2W@71C@77K providing 10,000 hours of operation under standard conditions. On account of its robust design, good performance and long life, this cooler is very popular in many systems all over the world.

In the last decade the K508N cooler was developed for the purpose of doubling the life expectancy of the earlier K508 model, while maintaining the same interfaces and performances. In fact the K508N cooler is providing an extended lifetime of approximately 20,000 hours in standard working conditions.

Currently, following a continuous demand for a rotary cooler with a particularly long life expectancy, the K508C rotary cooler was developed. This model will be able of competing with the lifetime of a tactical linear cooler, still keeping all the advantages of a rotary cooler, such as small dimensions, high survivability, robustness and installation simplicity. The K508C rotary cooler is designed to work 30,000 hours and even more, in a case it will be integrated with a detector that works at a high focal plane temperature. Figure 1 present 3D models of RICOR tactical rotary coolers mentioned in this chapter:

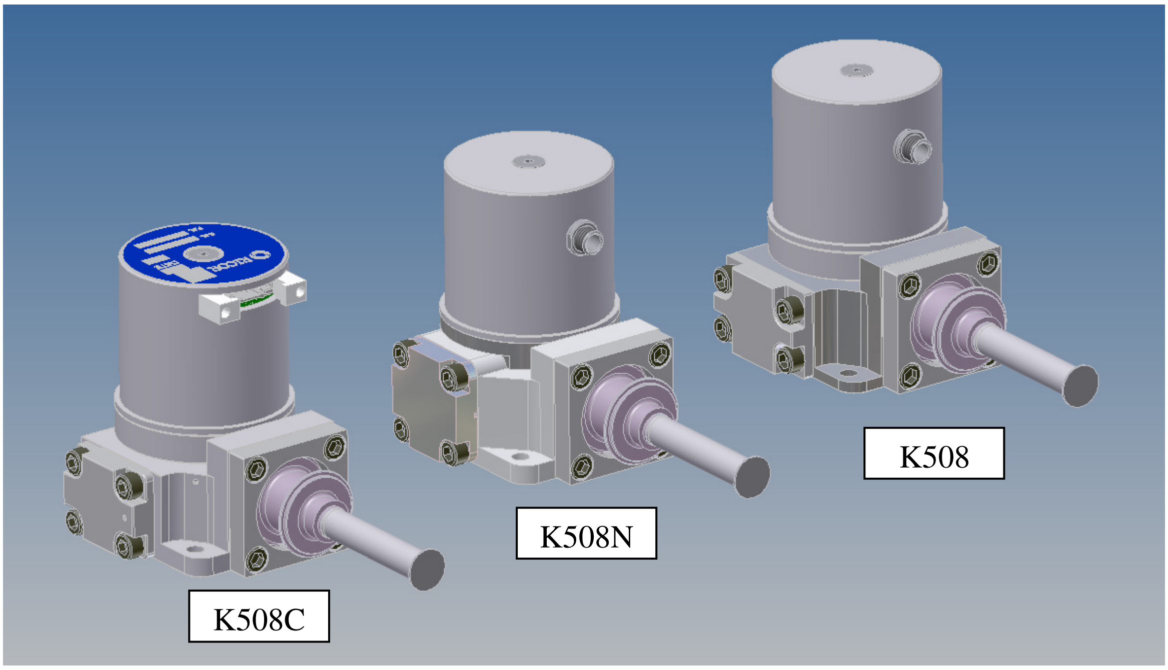


Figure 1. K508, K508N & K508C cryocoolers models.

3. THE DESIGN CONCEPT

A lifetime target for a rotary cooler in terms of 30,000 proven working hours presents few major engineering challenges, while the first and most important one concerns to the components that have the shortest life expectancy, namely the bearings.

In general terms we refer to about $5x10^9$ rotation cycles that a cooler is required to accomplish in its life time. The loading of the bearing is performed in a "pulsing" manner, in effect at every work cycle the force applied on the bearing changes its direction. This type of loading makes the bearing's survivability difficult. The bearing design for a defined load takes into account a number of factors, such as: the bearing's structure, cleanliness and lubrication conditions, structural mass including size, the number of balls, clamping ratio, structure of the cage, preloading rate and definition of the means of lubrication.

The bearing's cleanliness conditions are a significant factor throughout its life. In the literature available a number of articles have been written dealing specifically with the implications of bearings contamination.

Traditionally it can be said that the medium for lubricating cooler bearings is grease consisting of a thickening compound and an oil base, however there are also additional means of lubrication. Choosing all these means in a correct way will dramatically affect the bearing's life expectancy.

As part of the development process, other cooler components and assemblies were analyzed in order to meet the reliability target, namely, parts composed of organic materials, pressure seals, and clearance seals, electrical and electronic items.

3.1 The bearings arrangement

Increasing the capacity of the bearing is typically done by increasing its size, while in some cases it is sufficient to simply increase the number of balls in the bearing. However it is not always possible to keep the bearing size and only increase the number of balls. Therefore in such cases we are required to make an optimal design which takes into account the available spare volume and share it among all the other parts of the mechanism. By doing so, the largest volume is allocated for the bearing with the maximum load requirement, and the bearing with the lowest load requirement gets the smallest volume allocation. The challenge and the desired result of this arrangement is to maintain the ratio between bearing capacity and load required (safety factor) as equal as possible between all the bearings.

3.2 The reliability of bearings in a rotary cooler

The mechanism that destroys a bearing is described as fatigue failure of the surface that comes in contact with revolving elements, races and balls for example. This process causes the bearing to lose its basic attributes such as dimensions and it will fail in a relatively rapid way. Namely, it will break apart, or the friction coefficient will increase to the extent that the bearing will cease to function as a rotary element.

For the purpose of basically calculating a bearing life expectancy we need to know a number of parameters. The list of parameters includes the load applied to the bearing, the dynamic capacity of the selected bearing, the cleanliness coefficient, the lubrication coefficient and the type of loading coefficient. Ambient temperatures directly affect the lubrication coefficient and as the temperature increases, the lubrication coefficient decreases and adversely affects the bearing reliability.

Obviously we are required to ascertain that the temperature in the bearing does not rise above or fall below the critical temperatures defined for the grease. At these temperatures the grease ends its life abruptly and causes the bearing's untimely death.

3.3 Cleanliness conditions

The bearing cleanliness has a very high importance in terms of life expectancy, thus the working environment where the cooler is assembled is vital. It is able of dramatically affect the life of bearings and the rest of the components. The methodology of assembling process of the bearings, and of the entire cooler mechanism, is also of a high importance in terms of reliability and lifetime.

Sometimes it is important to protect the bearing from particles while it is under real operation. Therefore, we use a number of methods that can deal with this subject. Most of the solutions affect the cost of the component, however it is our expertise to examine all the advanced alternatives which can bring the bearing cleanliness conditions to the maximum standard.

3.4 Lubrication conditions

In order to ensure the bearing's working conditions, there should always be a layer of lubrication between the moving parts (races and balls). Choosing the type of thickener and oil is very important for maintaining the abovementioned requirement. The purpose of the thickener is to keep the oil in place till the time it leaves it. The rate of separation of the oil from the thickener depends on the temperature of the grease. In most cases the higher the temperature, the more rapid is the rate of separation. Because the quantity of oil is finite, the life expectancy of the bearing depends a lot on its temperature, that is to say the ambient temperature and the bearing working conditions, i.e. rotation speed and cooler pressure. A surplus of grease in the bearing makes heat sinking more difficult, so empiric information regarding the optimal quantity of grease is required. Ricor has developed an algorithm that deals with a specific grease for calculating life expectancy. In addition, we intend to develop another algorithm for various types of grease.

3.5 Grease definitions

As mentioned the grease is composed of two main components, the thickener and the base oil. The grease has a number of functions:

- to separate between the balls and the races and prevent dry contact between them
- to improve the conductance of heat generated during the rolling process
- to prevent particles entering the path of contact
- to minimize acoustic noise
- to protect surfaces from corrosion

In addition it is possible to improve the grease properties with the help of special additives. While choosing the correct grease, first of all the following parameters need to be defined:

a. intensity of the load

b. type of load

c. grease highest and lowest temperatures allowed under the most severe conditions

d. grease permissible vapor pressure

It is possible to measure the grease properties according to the accepted standards. In recent years Ricor has increased the number of tests required for defining grease properties that can meet the extended life requirements. In order to ascertain in practice the suitability of the selected grease to the lifetime requirement, a statistical test is needed that places as many coolers as possible for the benefit of the test.

A real-time life test proving 30,000 hours may last for more than 3.5-4 years, therefore an accelerated test procedure is essential. It is possible to accelerate the test by modifying three main parameters: heat load, working frequency and skin temperature (providing that all three are within the grease permissible range.) The list of the grease attributes that have to be measured in accordance with the standards is shown in Table 1 below.

Table 1 – Extended Grease Parameters Analysis

Parameter Type	Parameter Name
General	Base oil chemical formula
	Soap chemical formula
	Additive chemical formula
	Chemical stability rate
Physical characteristic	Viscosity @ high temperature
	Viscosity @ low temperature
	Pour point
	Maximum temperature for usage
	Minimum temperature for usage
	Vapor pressure
	Pour point
	Penetration depth
	Corrosion resistance
	Density
	Volatility
	Oil separation
	Evaporation losses
Load testing	Four ball test
	Extreme four ball test
	Wear factor
	SOT test
	Load limits
Life tests	Grease life

4. CALCULATING THE LIFE EXPECTANCY OF A BEARING AND A COOLER

Calculating the life expectancy is based on international standards defining the parameter L10 (hour units) whose significance is – 10% of the bearings' population won't survive the hours specified.

The basic calculation is according to equation 1, where L10 expresses hours.

$$L_{10} = \frac{10^6}{60 \times n} \times \left(\frac{C_r}{P_r} \right)^3 \tag{1}$$

L_{10} : Hours (h)

n : Speed (rpm)

C_r : Basic dynamic radial load rating (N)

P_r : Dynamic equivalent radial load (N)

Ricor has expanded the use of the abovementioned equation and added three significant parameters: a cleanliness coefficient, a temperature coefficient and a lubrication coefficient. Ricor managed to establish these three coefficients following tests conducted on more than 50 coolers.

Today Ricor knows how to determine and verify a cooler life expectancy according to equation 2.

$$L_{10} = \frac{10^6}{60 \times n} \times \left(\frac{C_r}{P_r} \right)^3 \times f_C \times f_T \times f_L \qquad (2)$$

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)

In order to carry out a comprehensive calculation of the bearings system within the cooler we need to calculate the L10 factor for each bearing separately and perform a comprehensive L10 calculation according to equation 3.

$$\frac{1}{L^e} = \frac{1}{L_1^e} + \frac{1}{L_2^e} + \frac{1}{L_3^e} + \ldots.. + \frac{1}{L_n^e} \qquad (3)$$

Figure 2 presents the results of a simulation of a calculated engineered life expectancy that gives recommendations for the designer to select the desired type of solution for the cooler bearings' system.

The graph describes the relative life expectancy as a function of cleanliness coefficient in the cooler bearings. Each curve shows the relative advantage if we select a relatively high cleanliness coefficient (at a maximum value) for one or more bearings, while the rest of the bearings change their cleanliness coefficient from 0.1 to 1. We see that the significant improvement will be received in the region of 0.3 to 0.6 for an improvement in the cleanliness coefficient of one or two bearings.

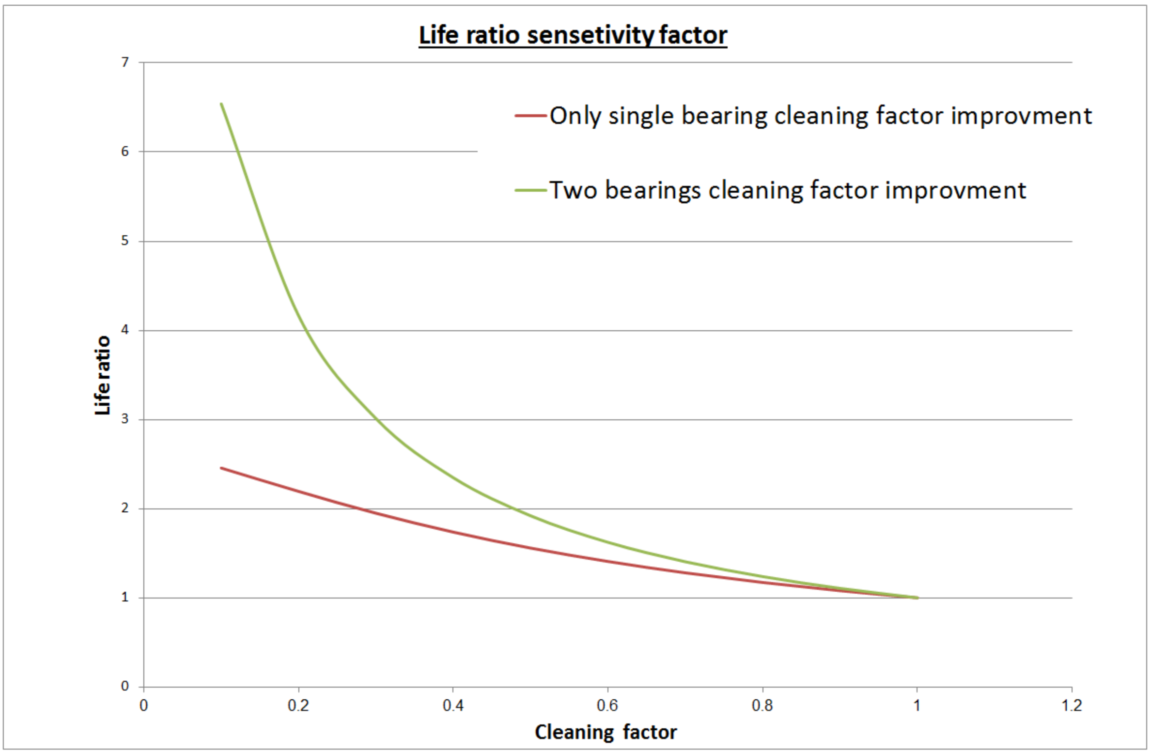


Figure 2. Cleanliness factor influence on a set of few bearings.

5. DIGITAL CONTROLLER

A considerable part Ricor R&D efforts relating to cooler life expectancy and high reliability involves the development of the DC37 digital controller. The controller capabilities are extended in a number of fields.

5.1 Extended operation frequency

The digital controller will have the ability to expand the upper region of the cooler working frequency by supplying additional voltage to the stator. As we know, the parameters affecting the cooler maximum cooling capacity are: Helium filling pressure and the maximum operating frequency.

From equation 1, the bearing's life expectancy is the cubic function of the pressure, whereas the frequency's effect is proportional. Therefore in theory, if we increase the operating frequency and decrease the cooler filling pressure, keeping the same cooling power, it will be possible to extend the bearings' life expectancy.

5.2 Controller operation method

The motor's operating method is based on supplying a constant voltage in a certain "duty-cycle", and the current is determined according to the thermal load applied on the cooler. Currently two more different controlling approaches are being developed, enabling the digital controller to operate by either rotor speed control or torque control. Novel motor speed control dictates constant rotation velocity of the crankshaft throughout all the cooling cycle. This method will reduce the induced torques and will effect a uniform lubrication of the ball bearings throughout the whole cycle. Torque control produces a constant torque of the motor independent of the crankshaft load applied by the cooler pressure pulse. Both methods can affect the type of loading on the bearings and in an initial analysis it is expected to extend the cooler bearings' life.

5.3 Soft start

The digital controller software will enable soft start in the beginning of the cool down process. The soft start will reduce the mechanical load on the cooler internal parts during the kick-off, as well as the electrical load on the controller-driver components, thus reducing mechanical and electrical shocks. The "soft start" function is designed to increase the bearings and electronics components life expectancy.

5.4 Controller alerts

The DC37 controller will have the ability to alert the system and deal with the causes able to adversely affect the cooler life expectancy, such as extreme temperatures, the dewar vacuum degradation over service, and extremely long cool down time.

5.5 Several set point options

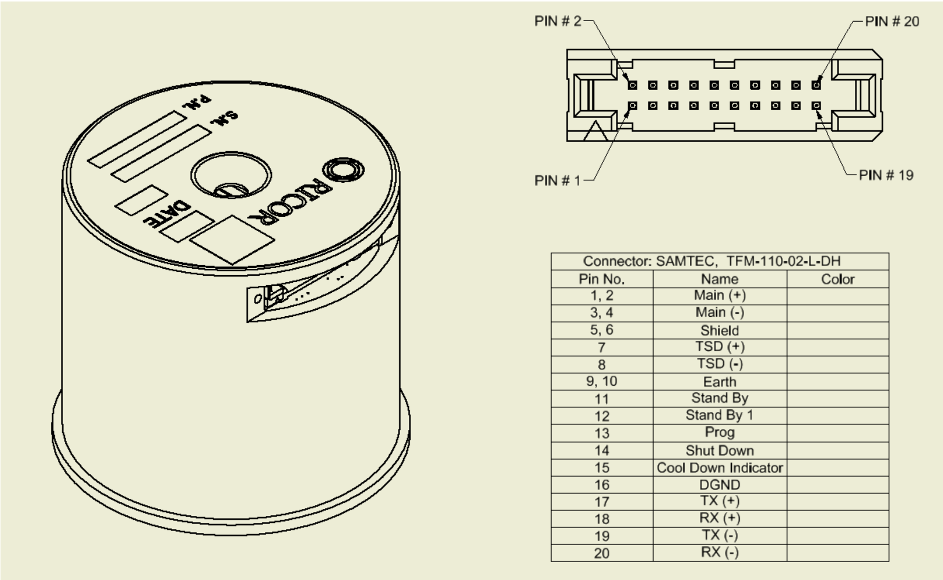
The controller software will have the ability to change the detector stabilizing temperature to a higher temperature, similar to the analog controller's STBY function. In the digital controller it is possible to set four different focal plane temperatures, so if there is no need to work at a low focal plane temperature, the detector temperature can be raised to a higher temperature. This option allows lowering the cooler frequency, thus saving power source energy and reducing the load on the cooler bearings. Moreover, due to the extended operation frequency range, the cooler recovery from the STBY set point will be faster.

5.6 Cooler end of life information

An additional option is designed to provide prediction of the cooler end of life. The digital controller will be able to interface with an external data acquisition system allowing sampling a large number of parameters, such as cooler current and its ripple, focal plane temperature, working frequency, special alerts for user selection etc. By means of smart sampling and analysis of vibrations and other parameters of the cooler, in the future it will be possible to give the system a forecast for the cooler end of life.

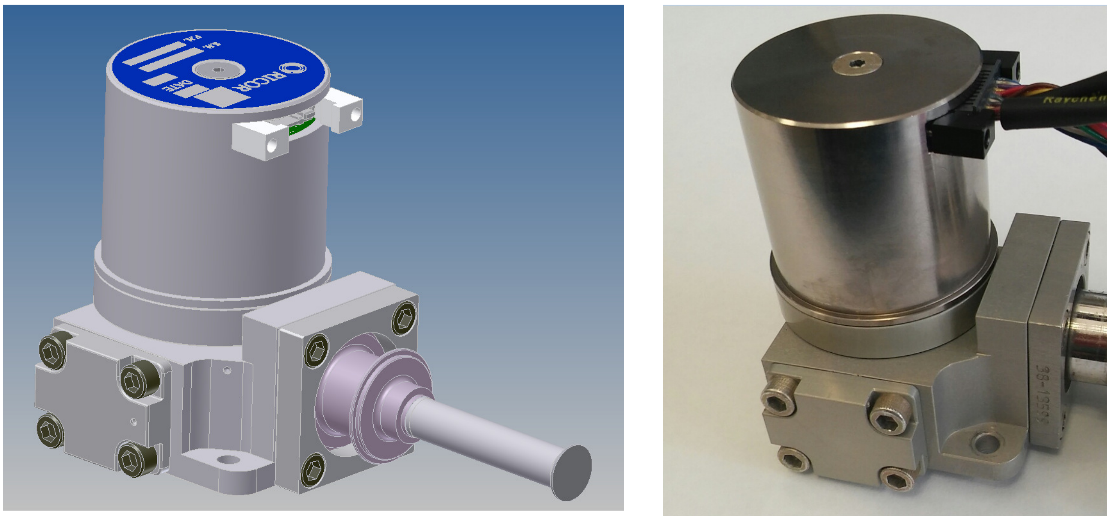
6. INTERFACES

Keeping common cooler interfaces is very important while changing versions of the cooler in an existing system, to prevent undesirable changes in the system design. The K508C cooler will suit the K508, K508N cold finger interface, and also the system mechanical mounting interface. The focal plane axis is located at the same height relating to the mounting surface. The induced forces values will be similar to that of the K508. The cooler required capacities will be similar to those of the K508. The digital controller will be situated inside the existing motor space. The only interfacial change will be in the motor assembly connector and pinout. The digital controller will have an internal 20 pin connector that will enable a direct connection of the communication system to the cooler, namely, it will be possible to change selected parameters of the controller while the system is operating, therefore allowing broad operational flexibility.



Connector: SAMTEC, TFM-110-02-L-DH		
Pin No.	Name	Color
1, 2	Main (+)	
3, 4	Main (-)	
5, 6	Shield	
7	TSD (+)	
8	TSD (-)	
9, 10	Earth	
11	Stand By	
12	Stand By 1	
13	Prog	
14	Shut Down	
15	Cool Down Indicator	
16	DGND	
17	TX (+)	
18	RX (+)	
19	TX (-)	
20	RX (-)	

Figure 3. Motor with DC37 digital controller - electrical interface



(a) (b)

Figure 4. (a) K508C with DC37 digital controller 3D model, (b) K508C picture

7. LIFE DEMONSTRATION TESTS

In order to test the life of the coolers, several comparative accelerated life tests are performed, while during the test all the cooler parameters are monitored at high resolution, until they exceed out of specification requirements.
The test is performed using acceleration factors, such as ambient temperature, cooler frequency, heat load and Helium fill pressure. Relying on analysis and comparison of accelerated life test results between K508, K508C and K508N models, a practical evaluation tool was developed, which allowed estimating improvement factor between the models at early stages of the test.
The accelerated test setup includes:

- 26 K508 standard coolers from RICOR production line
- 21 K508N standard coolers from RICOR production line
- 7 K508C coolers
- The coolers were integrated with standard K508 simulation dewars.
- The coolers were running at 2 different acceleration conditions - 60°C@45Hz and 80°C@65Hz, both at 80K.

The following parameters are continuously monitored during the life test:

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

In Table 2 and 3 below presented are the accelerated life demonstration tests results, together with the estimated life improvement factor K and its confidence bounds calculated by equation (6) below.
From Table 3 we can see that the life improvement factor of K508C is approximately 3. Because the K508 MTTF already proved as 10,000 hours in basic conditions, we expect from the new K508C cooler to reach the MTTF of 30,000 operating hours in the same conditions.

Table 2 – Accelerated life test results, two accelerated test conditions, K508, K508N and K508C coolers

Cooler Model	Accelerated test conditions	No. of coolers tested	MTTF [hours]	$\frac{STDV}{Average}$ [%]
K508	60°C@45Hz, 80K	16	3,317	18.8%
K508N		9	6,378	20.9%
K508C		4	10,826	16.2%
K508	80°C@65Hz, 80K	10	1,860	18.9%
K508N		12	3,604	27.7%
K508C		3	5,691	33.1%

Table 3 – Life improvement factors summary, including upper and lower bounds

	60°C@45Hz, 80K		**80°C@65Hz, 80K**	
$\hat{K}_1 \cong \frac{\hat{Q}_{K508N}}{\hat{Q}_{K508}}$	**1.92**	$K_{U,90} = 2.13$	**1.94**	$K_{U,90} = 2.19$
		$K_{L,90} = 1.72$		$K_{L,90} = 1.69$
$\hat{K}_2 \cong \frac{\hat{Q}_{K508C}}{\hat{Q}_{K508}}$	**3.26**	$K_{U,90} = 3.66$	**3.06**	$K_{U,90} = 3.84$
		$K_{L,90} = 2.87$		$K_{L,90} = 2.27$

Figure 4. RICOR life demonstration test laboratory

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(.)

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

$$V(\hat{k}) = \left(\frac{\partial k}{\partial \theta_1}\right)^2 V(\hat{\theta}_1) + \left(\frac{\partial k}{\partial \theta_2}\right)^2 V(\hat{\theta}_2) \tag{4}$$
$$= \left(\frac{1}{\theta_2}\right)^2 V(\hat{\theta}_1) + \left(-\frac{\theta_1}{\theta_2^2}\right)^2 V(\hat{\theta}_2)$$

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

$$\hat{V}(\hat{k}) = \left(\frac{1}{\hat{\theta}_2}\right)^2 V(\hat{\theta}_1) + \left(-\frac{\hat{\theta}_1}{\hat{\theta}_2^2}\right)^2 V(\hat{\theta}_2) \tag{5}$$

Where :

$$V(\hat{\theta}_i) = \frac{\hat{V}(T_i)}{n_i}$$

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

$$K_{U,\gamma} = \hat{k} + Z_\gamma \cdot \sqrt{\hat{V}(\hat{k})} \tag{6}$$
$$K_{L,\gamma} = \hat{k} - Z_\gamma \cdot \sqrt{\hat{V}(\hat{k})}$$

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

8. ADDITIONAL TESTS AND PLANS FOR THE FUTURE

In addition to the coolers currently running under life demonstration tests as reported in the previous chapter, Ricor is expanding the tests by placing additional coolers in a variety of tests. They will be included in accelerated and standard life expectancy tests, and will also be tested at new working conditions, such as high focal plane temperature for HOT detectors. All the test runs are being carried out for the purpose of increasing the existing coolers sampling and level of confidence, hence ensuring that the cooler will meet the strictest requirements of long life expectancy.

The digital controller has passed a number of initial pre-qualification tests at different voltages, at various stabilization points, and at extreme ambient temperatures, in order to evaluate the real operation in the field.

Two K508C coolers have finished successfully the HALT experiments. In this test the coolers were tested at a combination of very high and low environmental temperatures and harsh vibrations and shocks, thus from this test we learned about the cooler component endurance and the design robustness.

At least three K508C coolers will soon begin the qualification process according to a special qualification plan that incorporates all the environment conditions assembled from projects carried out in recent years.

9. SUMMARY

The cooler life expectancy is a main parameter for systems today, primarily for considerations related to reliability and maintenance cycles. Over the years Ricor has developed a number of tactical cooler models, and in all of them life expectancy has been a major specification requirement.

The K508C is Ricor's next generation for rotary coolers while the major challenge is to meet the ambitious goal of 30,000 working hours. For that purpose, a lot of important design factors were analyzed during cooler development phase, namely bearings design, bearings lubrication, sealing, organic components, mounting an advanced digital controller.

Currently, advanced tests are being conducted on the K508C cooler and the DC37 digital controller to confirm the life expectancy of 30,000 operating hours.

Soon additional coolers will be added to the life tests in order to increase the level of confidence, and qualification tests will be launched. Also, we begin to integrate the K508C cooler with new and existing systems requiring long-life cooler, mainly for 24-7 operation mode.

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