RICOR'S K508N HIGHLY RELIABLE INTEGRAL ROTARY CRYOGENIC COOLER

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ABSTRACT

The growing demand for EO applications that work around the clock 24hr/7days a week, such as in border surveillance, emphasizes the need for a highly reliable cryocooler from maintenance considerations and Life Cycle Cost calculations. As a result, RICOR developed a new rotary Stirling model K508N with a main design goal of 20,000 operating hours, double the operating hours performance of the standard K508 model. The secondary goal of the K508N model is to maintain K508 cryogenic performances while keeping all the electrical and mechanical interfaces of the standard K508 so as to enable full interchangeability with a standard K508 for retrofit and for new projects as well.

The K508N includes RICOR's latest mechanical design technologies such as optimized bearings and greases, internal parts arrangement and preloading, advanced seals, advanced plating for external parts, a laser welded cold finger and robust design structure with increased natural frequency compared to the K508 model.

Also included in the K508N is an improved on board analog controller based on a single PCB that contains a controller and motor driver based on the logic of the time-tested Hyb18N. In the next step, an on board digital controller will be implemented as a derivative of the qualified external controller board used with RICOR's K562S model.

The K508N is designed to be fully RoHS compliant, mechanically and electronically as well.

The Cooler MTTF is evaluated by a theoretical reliability study and is also demonstrated by a comparative accelerated life test between three standard K508 coolers and three K508N coolers. This paper also includes intermediate results form the accelerated life test.

The K508N is designed for orientation with future EO needs such as high reliability, RoHS compliance, robustness, a digital controller, in order to provide the foundations of future EO systems.

Keywords: Cryocooler, Stirling, Reliability, Long Life, MTTF, RICOR, Electro Optics, Life Cycle Cost.

1. INTRODUCTION

1.1. Market demand for a long life cryocooler

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.

1.2. The Field Proven Rotary Cooler - K508 Model

In the last 15 years, RICOR fielded more than 55,000 cryoccolers based on the K508 model for different types of applications. The K508 meets the MIL spec requirements of -40℃ up to 71℃ ambient while in a few applications the K508 served up to 85℃ ambient.

The high cooling power of more than 1/2W at 71℃ 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.

1.3. Design Goals for Long Life Rotary Cooler – K508N Model

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 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. CRYOCOOLER DESIGN ASPECTS

2.1. Introduction

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 was 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.

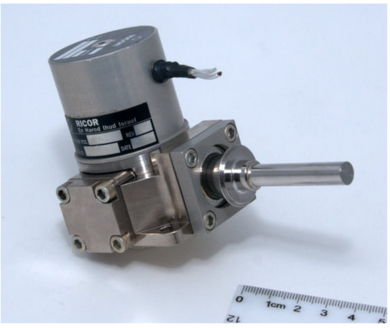

Figure 1: K508N Cryocooler

2.2. Advanced Bearings and Grease Technologies

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℃ [cst]
	Viscosity @100℃ [cst]
	Freezing point [℃]
Physical characteristics	maximum temperature for usage [℃]
	Minimal temperature for usage [℃]
	Vapor pressure [torr]
	Dripping point [℃]
	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.

2.3. Mechanical Design

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 parts of the coolers from considerations of corrosion resistance, electrical continuity and manufacturing process simplification.

2.4. Cold Finger Design

The K508N is designed to work with the standard brazed K508 cold fingers in order to enable interchangeability for existing DDA.
A new technology of laser welded cold fingers was recently qualified by RICOR and was gradually implemented instead of the brazing process. The laser welding process is preferred due to non exposure to high temperature as is the case in the brazing process and therefore less sensitivity to distortion, better repeatability and optimization of the manufacturing process by shortening of the time needed for the cold finger finish process.
RICOR's flexible design includes several types of cold fingers in terms of the cold finger base shape from rigidity considerations, few tube wall thicknesses from heat conduction losses considerations and different types of seats/plugs form detector interfacing considerations.

2.5. Mechanical and Electrical Interfaces

The main challenge of the K508N design was to implement novel technologies in the internal design with limited internal bulk conditions while keeping the external K508 interfaces in order to be fully interchangeable.
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 also was kept the same as in the standard K508.
The K508N's mechanical interface with the system optical bench is done through three bolts and two index pins in the same configuration as defined in the standard K508.
The K508N is driven by the standard stator assembly used to drive the K508. The stator outer housing could be a smooth or a finned configuration, the electrical interfaces are the same as in the K508 and the electrical connection type could be tailored for a specific system.

The stator assembly includes several types of on board electronic controller, the time-tested HYB18N analog controller for retrofit programs, the new analog controller 32 model for new programs and a digital controller for future programs.
The outer differences between the K508N and the K508 are concentrated in three areas: the upper surface of the crankcase was reinforced, the cylinder cover shape was changed from rectangular to square and the clamping flanges were thickened form 3mm to 5mm.
All the three differences mentioned are considered secondary changes that have no impact on interchangeability with the standard K508.

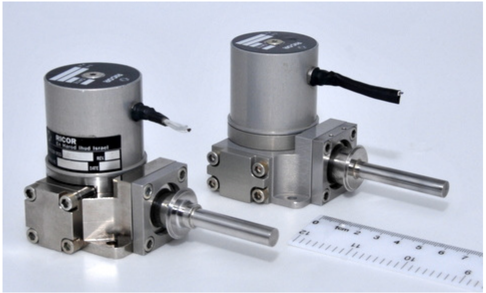

Figure 2: K508N and K508 models

2.6. Electronic Controller Design

Improved Analog Controller – Model 32
The cooler design is also focused on the development of improved analog control based on the logic of the time-tested Hyb18N.
The new 32 model controller is based on a single compact PCB that contains a temperature controller and motor driver. The components are assembled on one side of the board while the opposite side is used for a robust heat sink that efficiently removes the heat by conduction to the motor housing.
During the design stage, special care was given to the characterization of the electronic components that comply with low offset voltage and high ambient temperature in order to withstand a large ambient temperature range of -40℃ up to 85℃.
The components arrangement on PCB took into consideration heat dissipation aspects and EMI/RFI immunity.
The 32 controller can operate from a large input voltage range of 9 up to 32 volt and achieve FPA temperature stability of ±0.5K at a constant ambient temperature and a ±1K FPA temperature drift at an ambient range of -40℃ up to 71℃.

Digital Controller

The next step planned for the K508N model is to implement onboard digital electronic controlling. The plan will include a technology shift from external board to onboard design for the new digital controller developed recently and qualified by RICOR for the K562S model.

The K562S digital controller is based on a main processor in order to drive the K562S sensorless motor. The design is mainly focused on the accuracy level of the cold tip temperature means ±0.2K FPA temperature stability at constant ambient and up to a ±0.5K FPA temperature drift over the full range of ambient temperatures.

Leveraging the abilities of the main process, new approaches have been achieved for rotary Stirling driving and functionality:

- Accumulating operating hours and counting the number of on/off modes is done by software instead of a mechanical device.
- The FPA temperature is tuned by software communication instead of setting a potentiometer, hence providing better controller reliability.
- Signals such as cool down indicator and stand by mode can easily tuned by software.
- As the battery of an EO system is limited by the level of the current, soft start is implemented by software to eliminate inrush current.
- As each type of EO system copes with the trade offs between maximum power consumption in transient mode and cool down time duration until stabilization, booster voltage can be tuned for better optimization.

2.7. Preliminary Cooler Performances

One of the design goals for the K508N was to achieve equal cryogenic performances compared to the standard K508 in order to comply with the same IR detectors format arrays and to be a retrofit alternative if needed.

The overall COP is a product of partial efficiencies of three subsystems: thermodynamic Stirling cycle efficiency, motor assembly efficiency and driver controller efficiency. The efficiency measured at high heat load is 7.3% which is 20% of the carnot efficiency.

$$COP_{Stirling} = Qe / W = Qe / (Wc - We) = Te / (Tc - Te) \qquad (1)$$

The following figures are preliminary test results measured for K508N prototypes during the development phase:

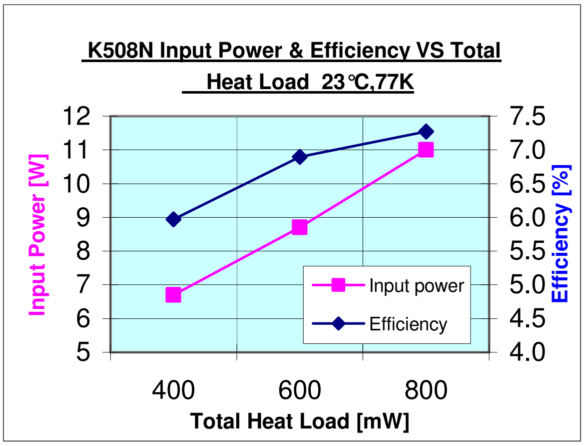

Figure 3: K508N Power Consumption and Efficiency Vs Total Heat Load

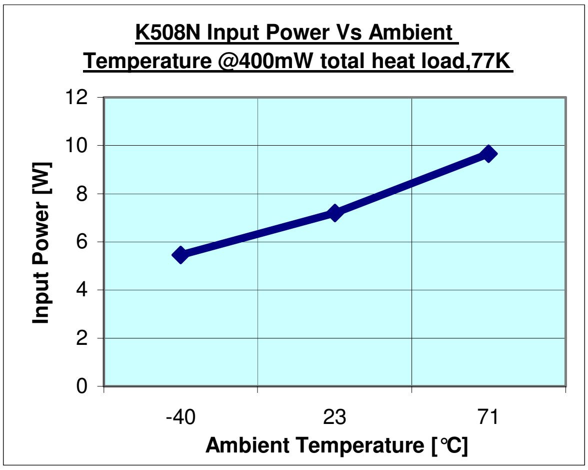

Figure 4: K508N Power Consumption Vs Ambient temp.

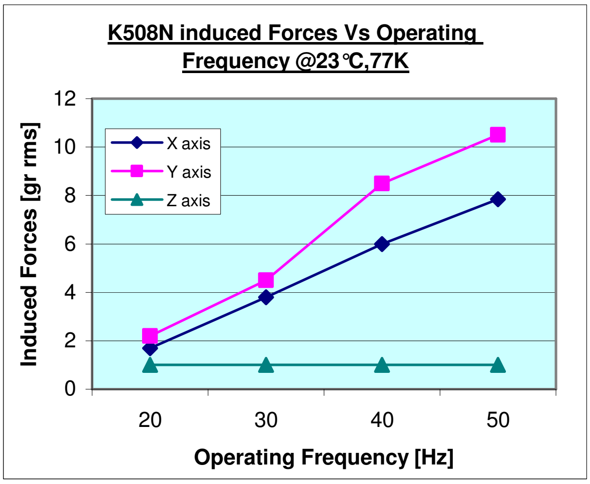

Figure 5: K508N Induced Forces Vs Operating Frequency

3. RELIABILITY EVALUATION

3.1. Reliability Study

The reliability study included analysis of previous accelerated and normal life demonstration tests done at RICOR for the K508 model.
In addition, the current accelerated life test comparison between K508 coolers and the K508N coolers is also analyzed on a periodical basis as long as the test is still running.
The first purpose of this analysis is to evaluate the MTTF improvement factor between the K508 model and the K508N model based on ongoing compared accelerated life test.
The second purpose of the analysis is to evaluate the current K508N MTTF for specific mission profile based on Ground Fixed environment and 45℃ ambient temperature.

3.2. Accelerated Life Test Method

The comparison accelerated life test between K508 model and the K508N model defined as a practical evaluating tool in early stages of the MTTF improvement factor between the two models.
The accelerated test setup includes:

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

The following parameters are continually monitored during the life test:

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

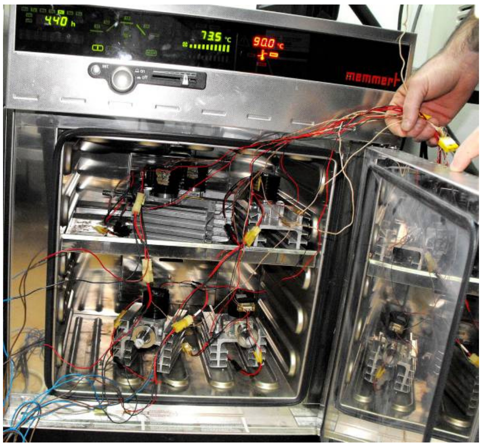

Figure 6: Accelerated Life Test Setup

3.3. Accelerated Life Test comparison between K508 and K508N – Intermediate Results

The following is an intermediate report dated the 17th of January 2010 which includes the operating hours accumulated in the ongoing accelerated life demonstration test:

Cooler model	Test status	Accumulated hours	Failure root cause
K508 #1	ongoing	7,966 hr	N/A
K508 #2	finished	5,031 hr	Bearing end of life
K508 #3	finished	5,126 hr	
K508N #1	ongoing	7,937 hr	N/A
K508N #2	ongoing	7,947 hr	N/A
K508N #3	ongoing	7,596 hr	N/A

Table 2: Intermediate Accelerated Life test results

The K508 test results include two coolers that failed due to bearings end of the life while the third cooler is still running.
As for the K508, and assuming Weibull life distribution, the estimated MTTF is ~6,500 operating hours.

The three K508N coolers are still running and the Weibull β shape parameter can't be evaluated as long as no failure event has occurred.
Under the assumption of β=4, the 50% lower boundary for the MTTF was taken as the MTTF estimate, yielding MTTF of ~10,250 operating hours implying a temporary estimated MTTF improvement factor of 10,250/6,500=~1.6.
The MTTF improvement factor should be increased as the test continues running.

Based on the K508N current calculations of MTTF=10,250 hr, MTTF could be evaluated for a specific mission profile like Ground Fix at 45℃ ambient temperature.
By using the Reliability Engineering Toolkit and transforming the ambient temperature from 80℃ to 45℃, a MTTF value of 21,500 operating hours is evaluated for this application.

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 double the K508N MTTF compared to the standard K508 and to achieve 20,000 operating hours still needs to be approved by the ongoing accelerated life demonstration test.

In the next phase, on board digital control will be implemented in the K508N in order to achieve better temperature stability, lower temperature drift and software communication with the system.
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.

5. REFERENCES

[1] Pundak, N., Porat Z., (2009) "Field reliability of RICOR microcoolers", SPIE conference
[2] Filis, A., Bar Haim, Z., (2009) "Microminiature stirling cryocooler for compact, lightweight and low power thermal imaging systems", SPIE conference