RICOR's Cryocoolers development and optimization for HOT IR detectors

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ABSTRACT

The world growth in research and development of High Operating Temperature IR detectors impels the development process and the optimization of HOT Cryocoolers at RICOR. The development emphasizes the “SWaP” configuration which is Small Size, Low Weight and Low Power consumption, in order to optimize IDDCA for future hand held thermal sights and other various applications.

This paper will present optimization tests results performed on HOT Lab Demonstration Cryocoolers at the temperature range of 130 - 180K FPA and also will review the development activities that will be implemented in order to minimize "Idle electronic and mechanical losses", hence minimizing the regulated power consumption. The new Cryocoolers developed for HOT detectors aim for higher reliability which is analyzed and reported in the paper.

Keywords: Cryocooler, Rotary Integral, Split Linear, Stirling, RICOR, HOT, SWaP, FPA

1. INTRODUCTION

In the past, the typical standard operation temperature for an IR detector was 77K, and sometimes even lower. In order to support such a low FPA temperatures, the required Cryocooler needed high cooling capacity manifested by size, weight and power consumption.

In recent years, there has been significant progress in IR detector technology. Due to improvements in detector technology the operation temperature has increased to temperatures of about 150K (i.e. High Operation Temperature - HOT detectors). The technological approach of increasing the FPA temperature to the HOT range reduces the Dewar Detector thermal losses and improves the Cryocooler thermodynamic efficiency dramatically. By doing this it is possible to reduce the Size, Weight and the Power consumption (SWaP) of the Cryocooler. Furthermore, this development emphasizes the “SWaP3” configuration which means small Size, low Weight, low Power consumption, improved Performance and low Price [2].

By all the characteristics mentioned above the new compact low power and cost HOT Cryocooler implemented in the cooled infrared thermal imager can compete with the uncooled infrared thermal imager based on a microbolometer detector in terms of lower power consumption and smaller bulk derived from smaller optic size. Furthermore it is still generally acknowledged that the cooled detectors are superior to their uncooled competing technology in terms of working ranges, resolution and ability to detect/track fast moving objects in dynamic infrared scenes [3, 4].

HOT Cryocooler is optimized for low input power below 2Wdc, and in addition for fast cool down time by using digital controller with a tunable booster. The optimized Cryocooler for HOT is ideally suitable for hand held systems, lightweight payloads for UAVs and a broad number of other commercial infrared applications.

2. THEORETICAL BACKGROUND

The COP (Coefficient of Performance) of a Stirling Cryocooler is defined as the ratio between the FPA temperature (T_C) and the ambient temperature (T_H) as it is expressed in the formula

$$(\text{Eq. }1)\ \mathrm{COP_{Stirling}} = \frac{\mathrm{T_C}}{\mathrm{T_H} - \mathrm{T}_C}$$

According to (Eq. 1) the coefficient of performance of a Stirling Cryocooler is defined as the ratio between the amount of heat absorbed into the expander and the amount of heat emitted from the compressor. Once the FPA temperature ($\mathrm{T_C}$) is increased from the known 77K to 150K (High Operation Temperature) and the ambient temperature ($\mathrm{T_H}$) stays the same, the theoretical efficiency could be multiplied by a factor of almost 3 [1, 2].

It is clear that the overall COP of the Cryocooler is not dependent only on the Stirling-cycle COP but also on other subsystems as well, including the motor efficiency and driver controller efficiency. In order to achieve higher Cryocooler COP, in addition to the high Stirling-cycle COP, a new approach for a high efficiency motor and a high efficiency controller needs to be developed.

Analysis of market needs reveals that the most important characteristics of a HOT Cryocooler are: low input power, minimal volume, size and weight. In addition, low acoustic noise, short cooling time, highly accurate temperature stability and reduced cost. Since there is a tradeoff between different Cryocooler technologies, two Cryocooler concepts are under development: an Integral Rotary Cryocooler and a Split Linear Cryocooler. In addition, a third development accomplished by improving an existing Integral Rotary Cryocooler K562S Short Improved as a short term alternative. For each IR system, the Cryocooler which best answers the project's critical requirements will be selected. The design aspects of the three Cryocoolers will be described later in this article including the test results performed on their lab demonstrators.

3. DESIGN ASPECTS

After gathering and analyzing all the projects characteristics for a Cryocooler that is optimized for HOT temperature, these are the main design aspects that lead the development process:

- **Emphasis on the "SWaP3" configuration which means Small Size, Low Weight, Low Power consumption, Improved Performance and Low Price.**
- **Regulated power consumption of the Cryocooler should be lower than 2Wdc at room ambient temperature and at an FPA temperature of 150K.**
- **DTC (Design to Cost) - in order to meet the low price demand, a DTC methodology is implemented to allow designers to achieve cost targets that were decided on early product definition stage.**
- **The electronic controller is designed to work with a wide operation voltage and is optimized for a HOT detector with a 90% efficiency design goal in order to reduce power consumption.**
- **A cold finger that can fit both the Integral Rotary Cryocooler and the Split Linear Cryocooler, so the same Dewar Detector could be integrated to both Cryocoolers. In addition, a new measuring method for self-heat load at high temperature operation is under development.**

3.1 Cryocooler design concept

K562S SHORT IMPROVED

The K562S Short Improved is based on the standard K562S and designed to reduce the size, weight and power consumption in order to optimize for HOT detectors. The differences between the K562S and The K562S short improved are: A shorter cold finger in order to reduce the optical axis length, a new motor with improved efficiency, a thinner cold finger in order to reduce the self-heat loads, as well as technology and manufacturing improvements to improve Cryocooler efficiency. In its steady state mode, at room temperature the Cryocooler is designed to work with low input power, below 2.5Wdc at a 150K operating temperature and a 175mW heat load.

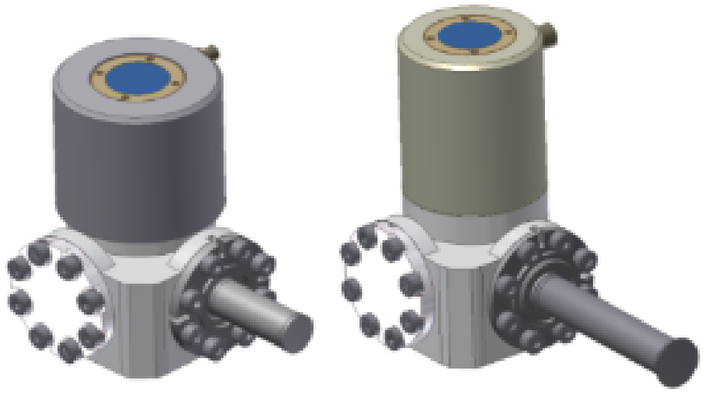

Figure 1 - K562S (on the right) vs K562S Short Improved

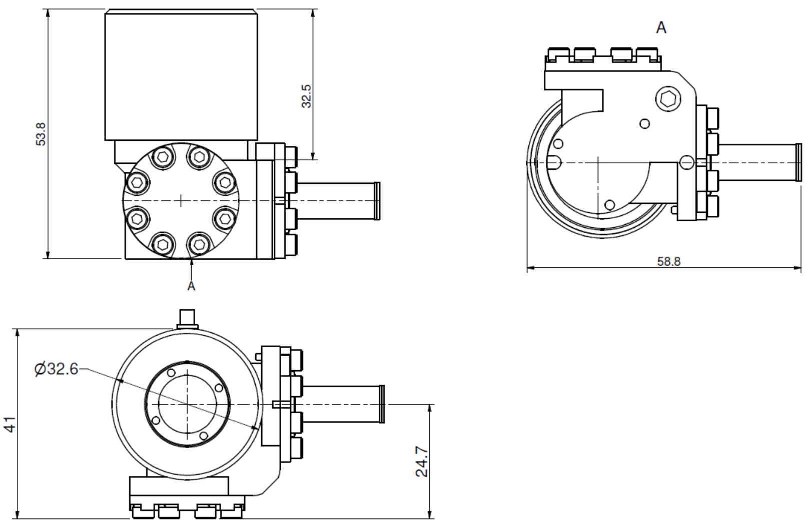

Figure 2 - K562S Short Improved model dimensions

Integral Rotary Cryocooler

The Integral Rotary Cryocooler is designed especially for HOT detectors, based on a new technology in order to reduce the optical axis length and to have an improved efficiency. The reduction of this dimension is possible by moving the cold finger tube to the side of the Cryocooler. The thermodynamic aspects were designed using the SAGE Stirling cycle simulation software according to the maximum efficiency approach. The Cryocooler has a designed gross cooling capacity of 390mW at an operating temperature of 150K at ambient temperature of 71°C. In its steady state, at room temperature the Integral Rotary Cryocooler is designed to work with low input power, below 2Wdc for a 150K operating temperature and 180mW heat load. The Cryocooler has a predicted basic MTTF >15,000 hours and the ability to work in various ambient temperatures from -40˚C to +71˚C. The Integral Rotary Cryocooler has a designed cooling down rate of 1.2 [J/sec] at an ambient temperature of 23°C, and will typically cool a detector within 3 min. In order to meet the SWaP requirements, the Cryocooler weight is less than 200 gram and can enter a sphere of Ø2.5". Furthermore, the Integral Rotary Cryocooler has low induced forces, less than 15g rms and a low acoustic noise.

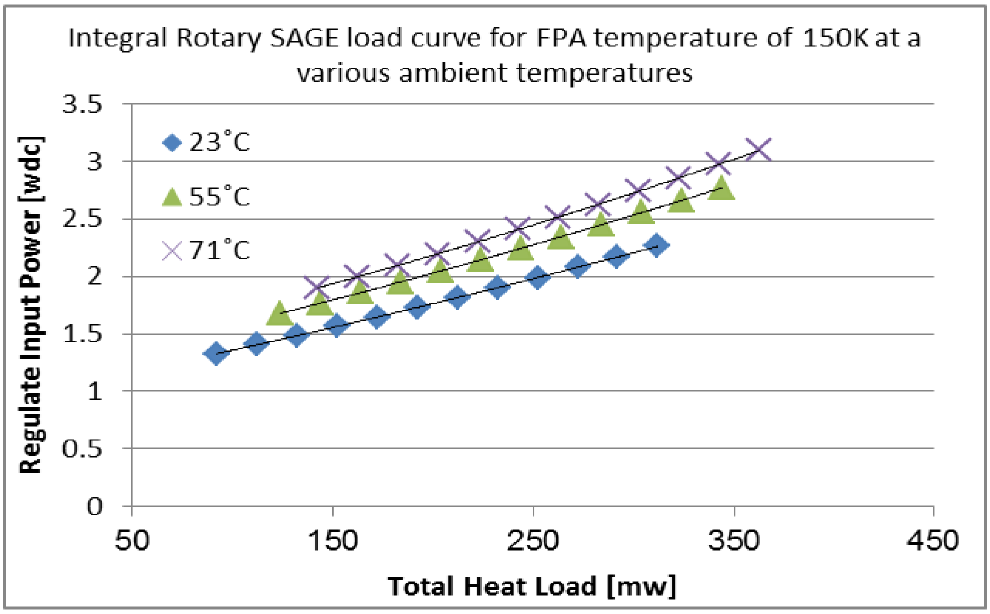

Figure 3 - Integral Rotary Cryocooler SAGE load curves

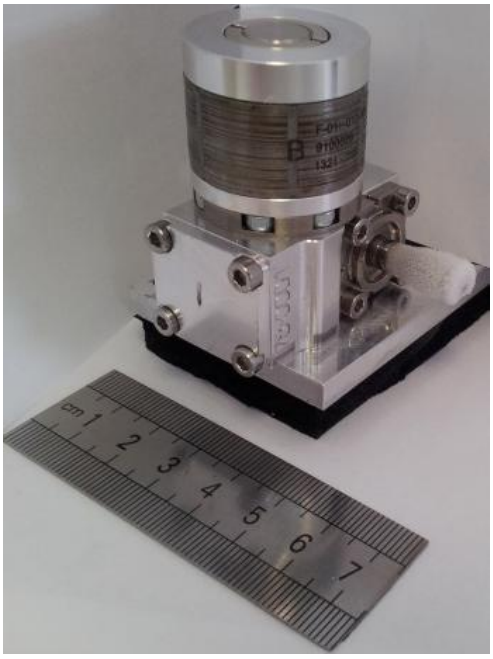
Figure 4 - Integral Rotary Cryocooler lab demonstrator image

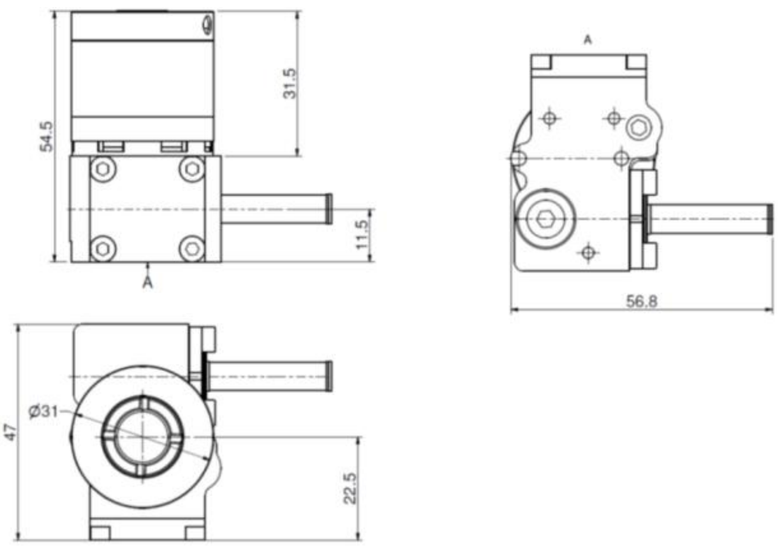

Figure 5 - Integral Rotary Cryocooler model dimensions

Split Linear Cryocooler

The Split Linear Cryocooler is designed especially for HOT detectors, based on a resonant moving magnet concept which leads to a high efficiency operation. The Split Linear Cryocooler has a designed gross cooling capacity of 500mW at an operating temperature of 150K in an ambient temperature of 71°C. In its steady state, at room temperature the Split Linear Cryocooler is designed to work with low input power, below 2Wdc for a 150K operating temperature and 180mW heat load. The Spilt Linear Cryocooler has a cooling down rate of 1.2 [J/sec] at an ambient temperature of 23°C, and will typically cool a detector within 3 min. The Cryocooler has a predicted basic MTTF of >30,000 hours and an ability to work in various ambient temperatures from -40˚C to +71˚C. In order to meet the HOT demands, the Cryocooler weight is less than 240 grams and can enter a sphere with the diameter of 2.5". Furthermore, the Split Linear Cryocooler has a low induced force, less than 15 g rms, and low acoustic noise. The Cryocooler actuator was designed carefully with the "QuickField" FEA software (Finite Element Analysis) with emphasis on achieving the optimal design for maximum efficiency at the Cryocooler working point and extended cooling capacity in order to fit various applications.

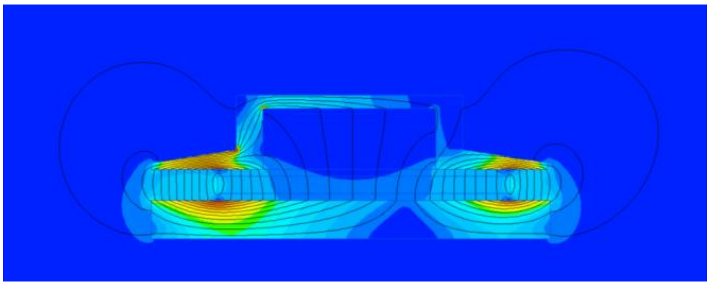

Figure 6 - Screen-shot from QuickField Analysis that shows the flux density gradient on the actuator

The Cryocooler thermodynamic aspects were designed using the SAGE Stirling cycle simulation software according to the maximum efficiency approach.

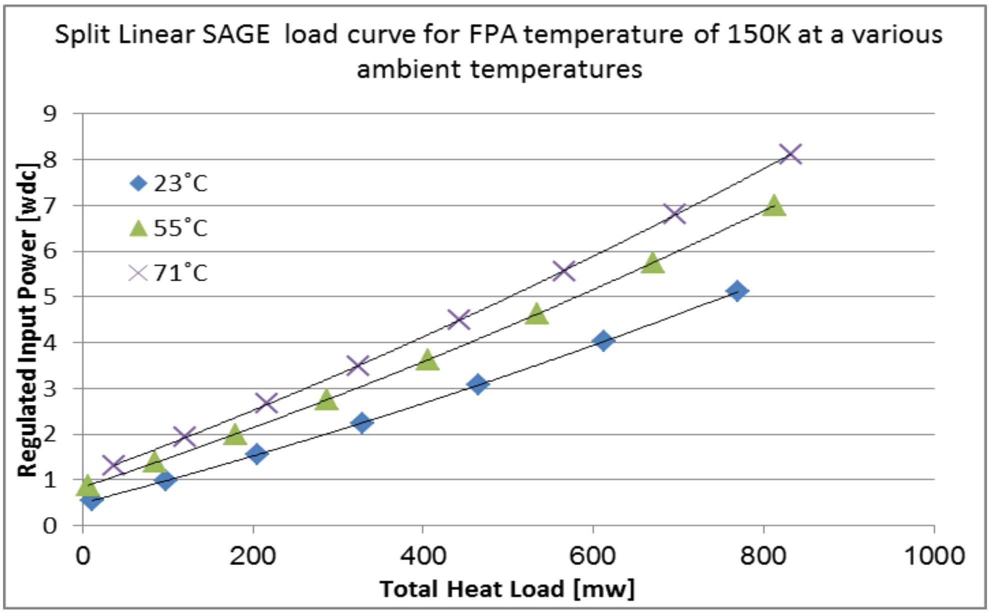

Figure 7 - Split Linear Cryocooler SAGE load curve

Figure 8 - Split Linear Cryocooler image

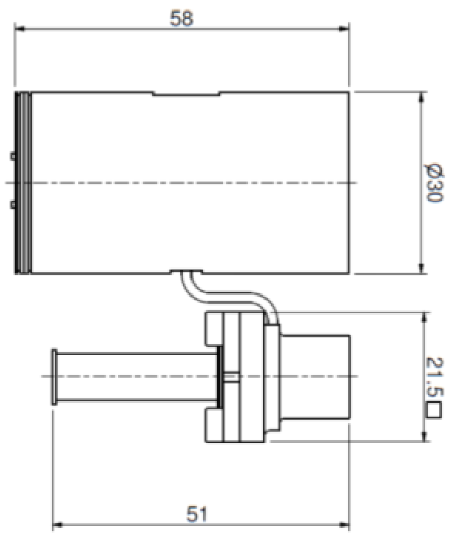

Figure 9 - Split Linear Cryocooler model dimensions

3.2 DTC (Design to Cost)

Design to Cost (DTC) is a methodology which allows designers to reduce production costs and meet targets that were decided in the early product definition stage. During the DTC process, the designers re-evaluate their design until the product achieves its allocated target cost. In DTC methodology, cost is treated as a key design factor, equal to other system design characteristics such as performance, schedule, size etc. In order to meet the low price demand as a part of the "SWaP3" configuration, DTC methodology was implemented in the early development process. The reduction of the price could be achieved by several methods like choosing a cheaper raw material while at the same time preserving the important properties, design the parts at a way that they will required cheaper manufacturing processes in order to produce them, emphasis on buying off-shelf product instead of costume made product, design cheap assembly processes and a robotic design.

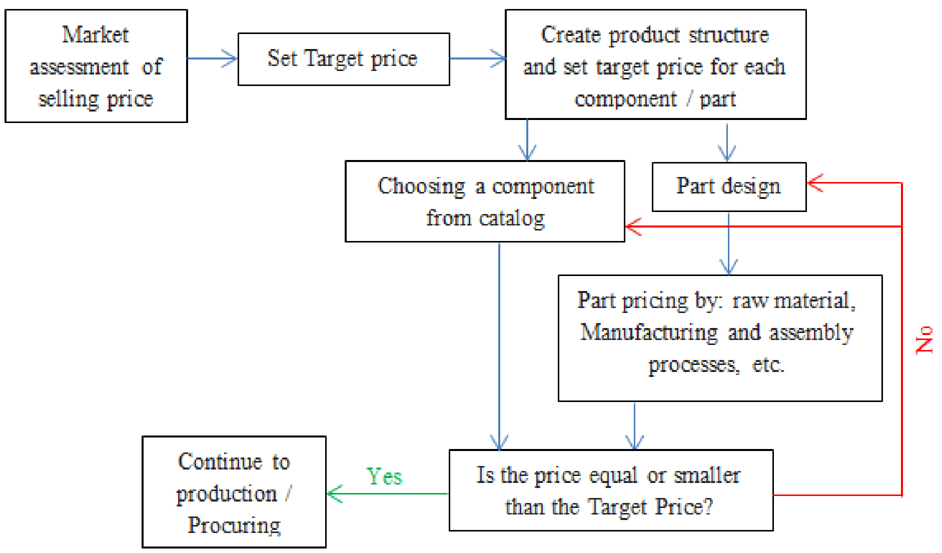

Figure 10 - Example for DTC process on a part

3.3 Controller design concept

It is obvious that a low power compact Cryocooler needs to be driven by a compact controller with high efficiency and low weight [5]. The Cryocoolers will work with a new electronic controller that was designed to work with a wide operation voltage 4VDC – 15VDC (12V or 6V nominal operation) and optimized for HOT detectors with a design goal efficiency of 90%. The electronic controller for the Integral Rotary Cryocooler is designed with a new hardware and software approach for controlling motors with a "Voltage Control Circuit" principle. Namely the motor voltage is not dependent on the input dc voltage, and as a result can work in various ranges of speeds according to the application. The controller is based on a dual PCB structure in order to reduce the outer dimensions (34 X 32 X 15mm) and will weight only 25gr. The controller will have a temperature drift goal of ±0.2K, and a local temperature stability goal of ±0.1K. In addition to the main characteristics, the controller will also have: Complete reverse-polarity protection without extra heat dissipation, complete input over-voltage protection without extra heat dissipation, Sensor-less\Sensor BLDC motor management using the ADUC for motor management, commutation control, and digital temperature control with flexible zoom point, Control logic-PID, 4 user-defined set points, and cool down-gap from stabled temperature user definition. The connection from the controller to the motor and from the controller to the system is based on connectors instead of the traditional wire soldering method. Connecting with connectors will improve the reliability of the controller.

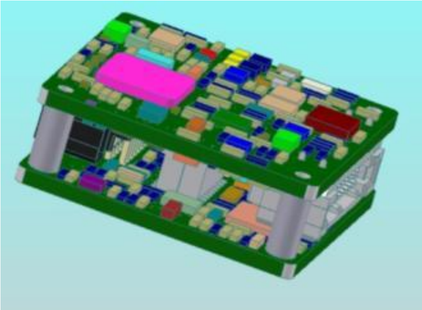

Figure 11 - Digital Controller model

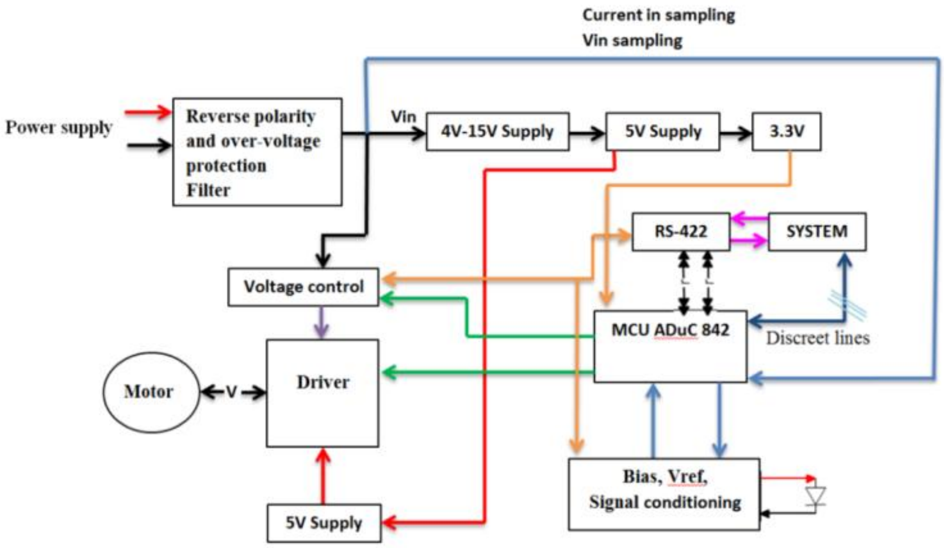

Figure 12 - Controller Block Diagram

Table 1 - Main characteristics comparison between the HOT controller Rotary / Linear and the K562S / K527 digital controller

Parameter	HOT controller –Rotary / Linear	K562S / K527 Controller
Controller type	Digital controller	Digital controller
Efficiency	90%	80% / 85%
Control logic	PID	PID
local temperature stability	±0.1K goal	±0.2K
Drift	±0.2K goal	±0.5K
Dimensions [mm]	34X32X15	63X43X14.2 / 92.5X62.3X19.6
Volume [cm^3]	16.32	38.46 / 112.94
Mechanical interface	Samtec TFM-110-02-L-DH 20 pin	Nicomatic 10 pin / Glenair 25 pin
Power operation	4VDC – 15VDC	8VDC – 15VDC / 21VDC – 32VDC

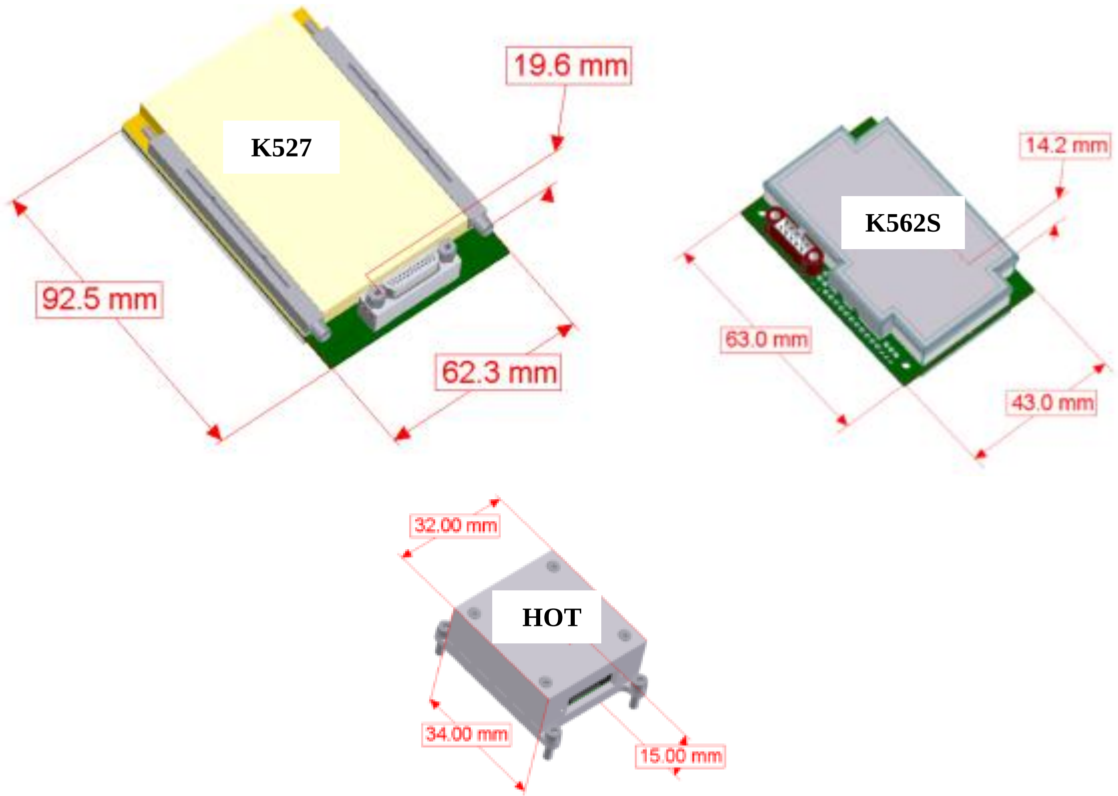

Figure 13 - Controller's dimensions comparison

3.4 Cold finger design concept

The development efforts also include a new cold finger that can fit the two HOT Cryocoolers, the Integral Rotary Cryocooler and the Split Linear Cryocooler, and is optimized by the materials, geometry and the manufacturing process in order to reduce the cold finger size, thickness and self-heat load. Furthermore, it is possible to use various materials and wall thicknesses in order to optimize between the self-heat load and the rigidity of the cold finger.

The Dewar self-heat load is affected by conduction, convection and radiation. Because the Dewar is functioning as an evacuated envelope, the heat losses from convection in the Dewar are negligible. The reduction of radiation is performed using the Dewar shell and by polishing the cold finger's outer surface. The conduction heat transfer is dependent on the material heat transfer coefficient and the material thickness. The heat transfer rate (Q) by conduction in a thin wall thickness tube is:

$$(\text{Eq. }5)\ \ Q = \frac{KA(T_{hot} - T_{cold})}{L}[W]$$

K - Heat transfer coefficient $[\frac{W}{m*k}]$; A - the cross sectional area$[m^2]$; THot – Cryocooler high temperature[K]; TCold – Cryocooler low temperature [K]; L is the length [m].

Writing the equation in order to match the cold finger tube case

$$(\text{Eq. }6)\ Q = K\pi(R^2 - r^2)\frac{(T_{hot} - T_{cold})}{L} = K\pi(R^2 - (R-t)^2)\frac{(T_{hot} - T_{cold})}{L} = K\pi(2Rt - t^2)\frac{(T_{hot} - T_{cold})}{L}$$

Where R is the tube outer diameter, r is the tube inner diameter and t is the tube thickness.

Because the thickness is much smaller than the radius we can say: $2Rt - t^2 \approx 2Rt$

Then the expression for the heat transfer become

$$(\text{Eq. }7) Q = 2K\pi Rt\frac{(T_{hot} - T_{cold})}{L}$$

From $(\text{Eq. }7)$ we can see that the transfer rate (Q) is a linear function of the thickness, and therefore reducing the thickness results in reduced heat transfer across the tube.

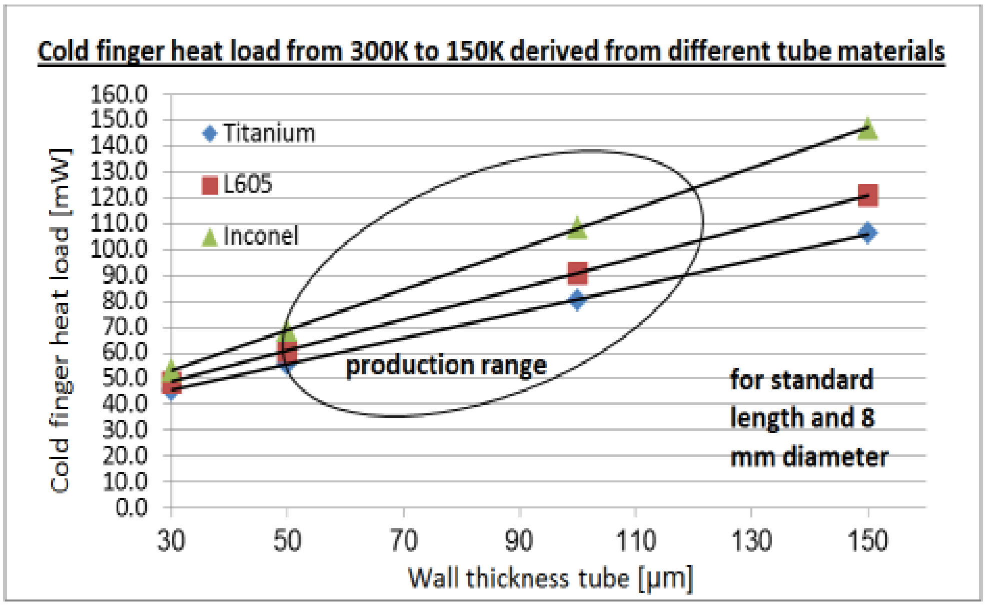

Figure 14 - Heat load study review of different cold finger tube materials

Figure above shows the cold finger self-heat load versus the tube wall thickness, and the production range of RICOR tubes wall thickness. For comparison, the average width of a strand human hair is 100 µm, two times thicker than the wall thickness of the new cold finger.

A new method for measuring the Dewar self-heat load

In the framework of the development of the Cryocoolers for HOT IR detectors there was a need to develop an approach for measuring the Dewar self-heat load over the extended temperature range 130K-180K and beyond.

The traditional method of measuring the Dewar self-heat load is called "boil of rate". In this method, the cold finger interior is filled with N2 liquid and closed by a plug that has a tiny passage allowing a path for the evaporated gas to leave the cold finger interior. Liquid N2 is transferred to the Dewar and boils in it at a temperature of 77K. Once this is done, the vaporized N2 flow rate is measured and multiplied by a coefficient in order to convert the flow to watts. In this method we are measuring the Dewar self-heat load at 77K, while for HOT Cryocoolers we need to measure the Dewar self-heat load at the range of 130-180K. From the literature review, other methods of measuring the Dewar's self-heat load have not been developed so far. In order to meet the project demands, RICOR is developing a new measuring method for the high temperature operation range.

4. LAB DEMONSTRATORS TEST RESULTS

In the first stage of the project, for each model a laboratory demonstrator were developed to evaluate the feasibility of the performance. Test results of the three types of lab demonstrators are presented in the following figures.

Figure 1 shows the K562S Short Improved lab demonstrator test results for a various ambient temperature and for a variable FPA temperature. From Figure 2 we can see that the K562S Short Improved lab demonstrator was able to work with low power consumption, at 2.5Wdc at a 150K operating temperature and a 175mW heat load accordance with the demand.

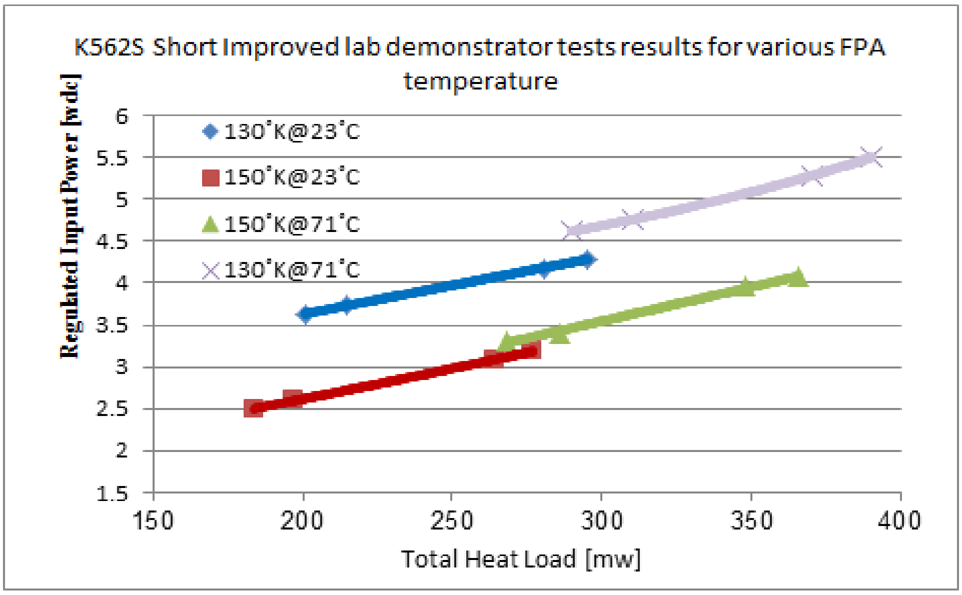

Figure 15 - K562 Short Improved Cryocooler lab demonstrator tests results

The development of the new Integral Rotary Cryocooler include in its new technology and assemblage miniaturization that haven't been tested before. In order to proceed to the next development stage the Integral Rotary lab demonstrator had to show outstanding performance according to the requirements specification and the functioning of the new parts and technology that was implemented in it at various environmental conditions. Figure 3 shows the Integral Rotary lab demonstrator working with low input power consumption at regulated mode with accordance to the demand of power consumption lower then 2Wdc for a 150K operating temperature and 180mW total heat load, and 390mW total heat load at operating temperature of 150K and ambient temperature of 71°.

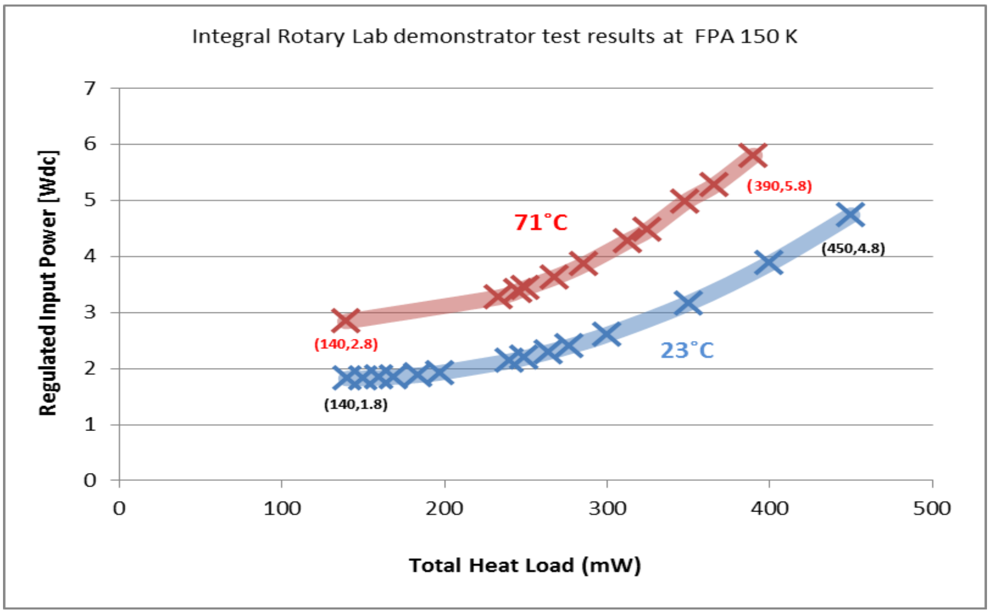

Figure 16 - Integral Rotary Cryocooler Lab Demonstrator tests results

The Integral Rotary Lab Demonstrator tests results were obtained with the K562S digital controller which has a lower efficiency than the HOT controller. Working with the high efficiency HOT controller means that the Integral Rotary Cryocooler will work with a better performance that is equivalent to lower input power and higher cooling capacity.

The development of the Split Linear Cryocooler was involved with a number of analyzes and highly accurate machining, all of those was in order to allow the cooler to meet the high demand HOT spec. Similar to the Integral Rotary Cryocooler , the Split Linear Cryocooler also include in its new technology and assemblage, miniaturization that haven't been tested before. Figure 4 shows the Split Linear Lab Demonstrator test results for a various ambient temperature and for a variable FPA temperature as he will be required to do as a commercial product. The lab demonstrator will need additional improvements and optimization in order to meet the designed goal of 500mW cooling capacity at operating temperature of 150K at ambient temperature of 71°C. The input power requirement of less then 2Wdc for a 150K operating temperature and 180mW total heat load probably would also be maintained after that optimization process.

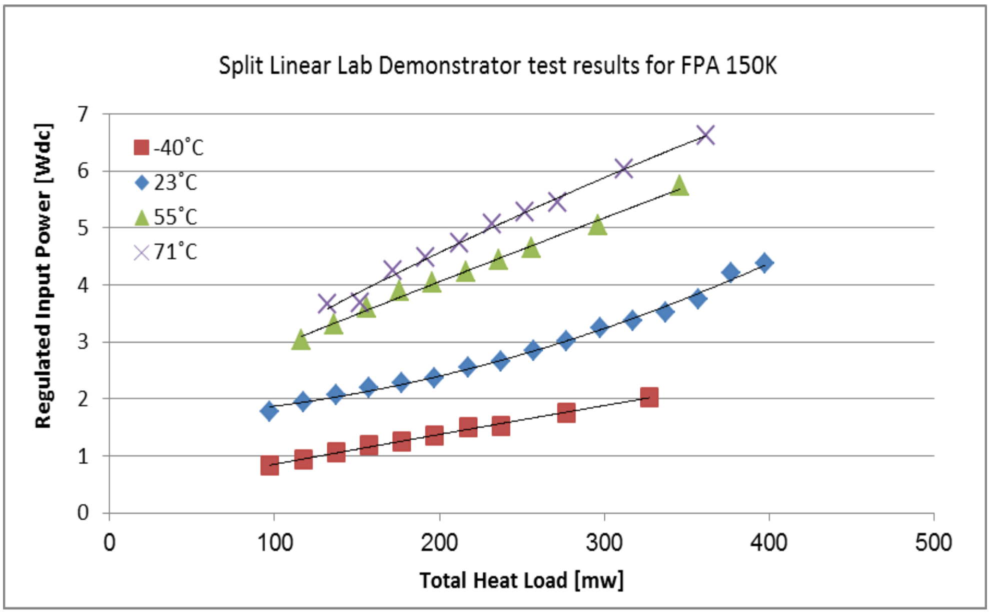

Figure 17 - Split Linear Cryocooler Lab Demonstrator tests results

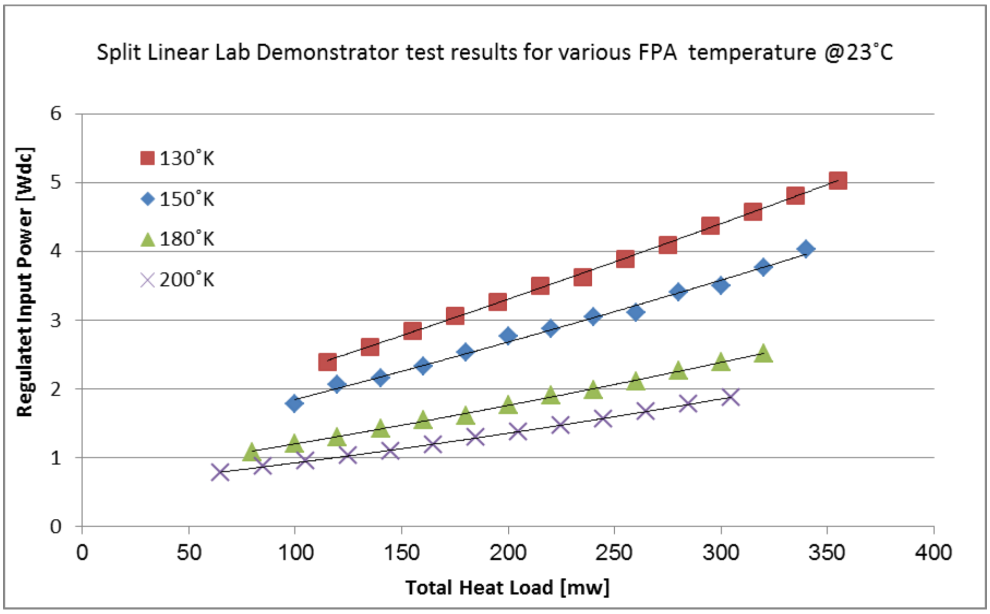

Figure 18 - Split Linear Cryocooler Lab Demonstrator tests results

5. RELIABILITY EVALUATION

During recent years RICOR has conducted extensive laboratory life tests. Dozens of Cryocoolers have undergone and are still undergoing life tests, as part of RICOR's approach for continuous improvement. The life tests are performed under the careful supervision of a technician from the development laboratory, and the Cryocooler's operation data are monitored throughout the experiment. Next figure shows one of many test arrays at RICOR laboratory comprising six K562S - Rotary Cryocoolers [6].

Table 2 - Life test status for K562S Cryocooler

Cryocooler type	Accelerated Parameters	Test Profile and Type	Running hours
K562S	None	23C°@32Hz@20 bar	10,355
			14,232
			15,044
	Temp.	68C°@32Hz@20 bar	6,764
			8,536
			10,749

Based on the K562S MTTF (20,000 Running hours) the design improvements that were made on the K562S Short Improved model is manifested by a shorter cold finger and a higher FPA temperature allows maintaining at least the same MTTF as the K562S.

According to calculations and estimates the Integral Rotary Cryocooler has a predicted basic MTTF >15,000 hours, and the Split Linear Cryocooler will have a predicted basic MTTF of >30,000.

6. DEVELOPMENT PLAN

The above mentioned three Cryocoolers differ by the maturity level, and need to undergo different development stages to become a commercial product. The development stages typically include the following stages: Preliminary design, detailed design, qualification, and industrialization. During the Preliminary Design (PDR), near specification results are achieved, aiming to please key requirements within defined constraints. During the detailed design phase, the design is optimized to meet the specification requirements. During the qualification stage the product is tested and qualified, while during the industrialization stage the production facility is qualified to meet the quality requirements for the serial production, this stage has special significance having the need to adopt the equipment for producing new technology and to test the specific attributes of the new product. A common activity that is equally important for the development of the three Cryocoolers is a process for measuring the thermal load of a Dewar for hot FPA temperatures, where commonly used methods suffer from relative inaccuracy. The process needs to be validated and well defined procedure capable of measuring absolute thermal load.

7. SUMMARY

The first stage of the development towards a commercial product has been achieved. 3 Cryocoolers are at lab demonstrator stage and will soon become commercial products. Furthermore, in additional to the development of the HOT Cryocooler, two controllers are developed in parallel to the Cryocoolers in order to support and allow them to meet the high demand spec of HOT meaning SWaP configuration.

The new approach for the development and optimization for HOT detectors was achieved thanks to several novel technologies implemented in RICOR Cryocoolers. The K562S Short Improved, being the optimized version of a serial product, is ideally suitable for short term development programs seeking immediate improvement in SWaP solutions. The HOT Cryocoolers with the new technological improvement, including improved motor, new controller, thinner cold finger, etc. was tested in the lab and showed outstanding performance that achieved the project targets.

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