Development and optimization progress with RICOR cryocoolers for HOT IR detectors

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ABSTRACT

The world growth in research and development of High Operating Temperature (HOT) IR detectors impels the development and optimization of suitable cryocoolers. The current developments at RICOR, which include three different cryocooler models and two new controllers, are focused on the SWAP^3- oriented design process, meaning small Size, low Weight, low Power consumption, improved performance and lower production cost, providing proper cryocoolers for future hand held thermal imagers.

This paper shows the progress made during development of "HOT" cryocooler prototypes, engineering pre-production series and qualified production series cryocoolers working at the FPA temperature range of 130 - 200K. The progress with development of electronic control modules providing minimized regulated power consumption is also shown.

The progress in development of cryocoolers reliability is also reported in the paper.

Keywords: cryogenic cooler, HOT application, Stirling cycle, linear cryocooler, rotary cryocooler

1. INTRODUCTION

Analysis of the cooled IR detectors market reveals that during recent years significant progress in IR detectors technology has been achieved, and as a result, their operating temperature has increased above 150K. Before the recent technological advances in detectors, the typical standard operation temperature for an IR detector was 77K, and sometimes even lower. In order to support such low FPA temperatures, a required cryocooler needed to provide higher cooling capacity, hence affecting size, weight and power consumption. Therefore increase of the FPA temperature up to the HOT range improves cryocooler thermodynamic efficiency dramatically and also reduces thermal losses of detector assembly. These are the potential benefits allowing a cryocooler's Size, Weight and Power consumption (SWaP) reduction. Furthermore, this development is focused on the "SWaP3" approach meaning small Size, low Weight, low Power consumption, improved Performance and low Price [2]. In addition to these parameters, a HOT cryocooler is required to provide low acoustic noise, short cool-down time, and highly accurate temperature stability. Based on the characteristics mentioned, a HOT cryocooler for an infrared thermal imager should provide a clear advantage over an uncooled microbolometer detector in terms of power consumption and the smaller optic size required. It is important to add 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]. This article will describe the progress that was made on the 3 new "HOT" cryocoolers, the K562 short improved, an improved model that was based on the standard K562, the K580 an Integral Rotary cryocooler and the K588 a Split Linear cryocooler. Furthermore, this article will include an explanation on the differences between deferent cryocooler concepts.

2. CRYOCOOLER MODELS

2.1 K562SI - SHORT IMPROVED – Integral Rotary Cryocooler

The K562SI is an improved model based on the standard K562 integral rotary cryocooler that was designed and optimized for HOT detectors. The improvements made in this model in order to adapt it as a cryocooler optimized for HOT detectors are (i) a new motor with higher efficiency and improved performance, (ii) a thinner and shorter cold finger that will reduce the self-heat loads and shorten the optical axis length. The cooler also went through technological and manufacturing enhancements of thermodynamic efficiency and reliability. The improvements of the cooler efficiency were achieved as a result of the thermodynamic aspects addressed using SAGE Stirling cycle simulation software. The K562SI is provided with the K562S digital controller possessing 80% efficiency. The outcomes of all these improvements are listed in the following table:

Table 1. K562SI cooler main parameters

Parameter	Design goal
cooling capacity	500mW@150K@71°C
Steady State Input Power	190mW @140K @23°C: < 2.5Wdc typ.
MTTF	>10,000 hours
Ambient Temperature Range	-40˚C to +71˚C.
Cool down time	210J @150K @23°C: < 3:30 min typ
Weight	<185 grams
induced forces	< 10 grf rms

Figure 2. K562SI coolers image

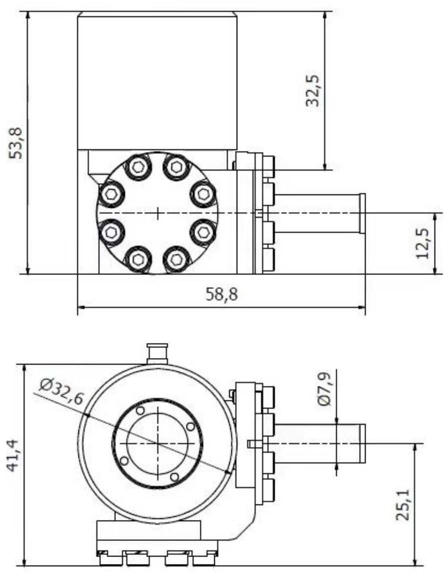

Figure 3. K562SI model dimensions

2.2 K580 Integral Rotary Cryocooler

The K580 is an integral rotary type cryocooler emphasizing the “SWAP” approach. The K580 cooler model design was devised and constructed “from scratch” 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 main parameters of the cooler are listed in the following table:

Table 2. K580 cooler main parameters

Parameter	**Design goal**
cooling capacity	500mW@150K@71°C
Steady State Input Power	220mW @150K @23°C: < 2Wdc typ.
Input Voltage	4-16 VDC
Maximum Input Power	12WDC
MTTF	>12,000 hours
Ambient Temperature Range	-40˚C to +71˚C.
Non-Operational	-55°C to +85°C
Cool down time	210J @150K @23°C: 3:00 min typ
Weight	Cooler 185 gr. Controller 25 gr.
induced forces	< 10 gr rms
acoustic noise	non-detectability from a distance of 20 meters

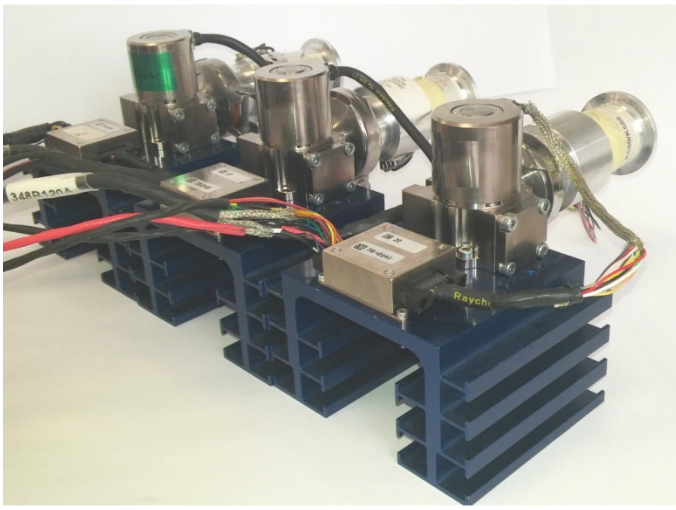

Figure 4. K580 cryocoolers image

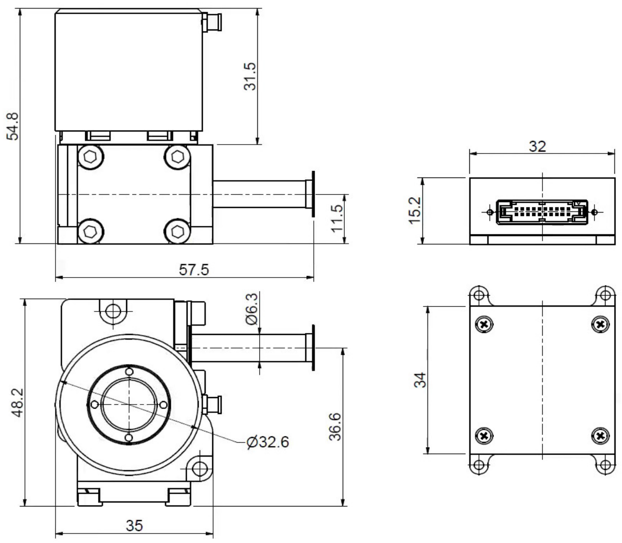

Figure 5. K580 cooler and controller dimensions

2.3 K588 Split Linear Cryocooler

The K588 model is a cooler that was also designed especially for HOT detectors based on a resonant dual-opposed linear compressor. The cryocooler thermodynamic performance was analysed and optimized using the SAGE Stirling cycle simulation software, aiming to achieve the maximum efficiency objective. The actuator was designed using Finite Element Analysis software focusing on maximum efficiency at the cryocooler working point, and highest cooling capacity providing a short cool-down time and good performance at elevated ambient temperatures. The first prototypes demonstrated power consumption below 2W DC at 200mW total heat load, at 150K FPA temperature. The main parameters of the cooler are listed in the following table:

Table 3. K588 cooler main parameters

Parameter	**Design goal**
cooling capacity	500mW@150K@71°C
Steady State Input Power	220mW @150K @23°C: < 2Wdc typ.
Input Voltage	4-16 VDC
Maximum Input Power	12WDC
MTTF	>20,000 hours
Ambient Temperature Range	-40˚C to +71˚C.
Non-Operational	-55°C to +85°C
Cool down time	210J @150K @23°C: <3:30 min typ.
Weight	Cooler 235 gr. Controller 25 gr.
induced forces	< 30 gr rms
acoustic noise	non-detectability from a distance of 20 meters

Figure 6. K588 cryocooler and controller image

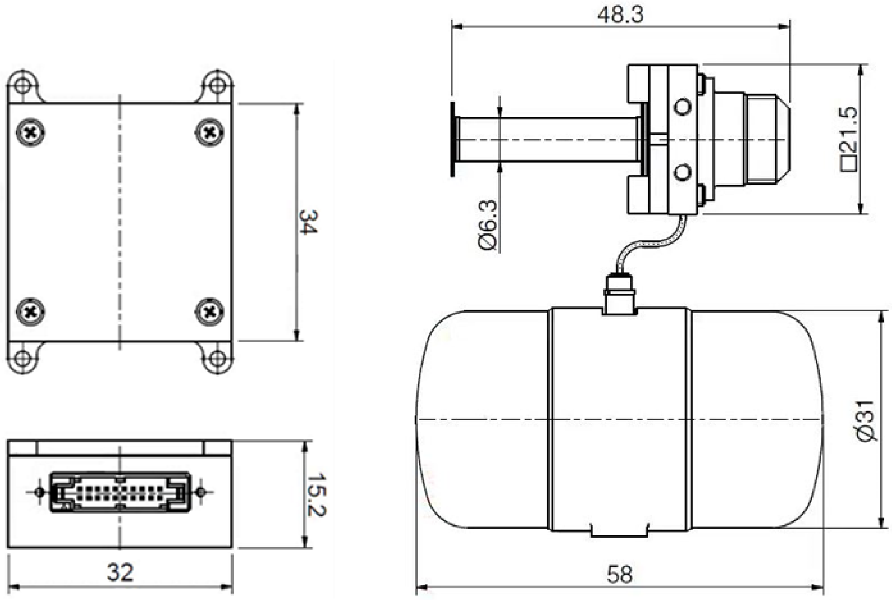

Figure 7. K588 cooler and controller dimensions

2.4 Controller design

The K588 and the K580 are designed to be driven by new compact controllers providing high efficiency, low weight, compact mechanical structure, and a uniform enclosure/electrical interface [5]. The new electronic controllers were designed to work with a new hardware and software approach for controlling the motor's voltage by the "Voltage Control Circuit" principle. Namely, the output AC voltage is independent of the input DC voltage, thus allowing motor operation at various speeds (rotary type) or amplitude (linear type) values. The controller design is based on a dual PCB structure in order to reduce the outline dimensions and the weight. Both the “rotary” and “linear” controllers are enclosed in a uniform case, providing an electrical interface based on uniform connectors in place of the traditional wire soldering method. These improvements are intended to provide better flexibility during system assembly and maintenance. Table 4 shows the main specification parameters of the HOT controller, Figure 7 illustrates the external view and the outline of the controller.

Table 4. Main characteristics of the HOT controller

Parameter	HOT controller –K580 / K588
Controller type	Digital
Efficiency	>90%
Input voltage	4VDC – 16VDC (6V or 12V nominal operation)
Control logic	PID (PID parameters per user definition)
Temperature stability	±0.1K
Temperature drift	±0.2K
Dimensions [mm]	34X32X15.2
Weight [gr]	25
Electrical interface	Samtec TFM-110-02-L-DH 20 pin connector
Communication protocol	RS422
Protection	Reverse-polarity protection without extra heat dissipation
Set points	Control of four set points per user definition
Temperature control	Digital temperature control with flexible zoom point

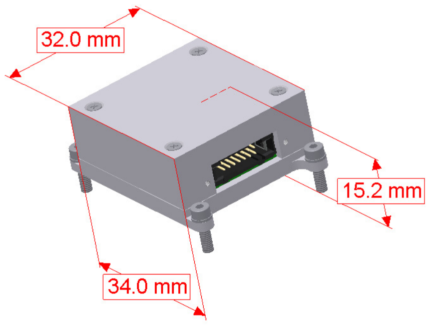

Figure 7. HOT controller dimensions

3. PROGRESS MADE IN THE CRYOCOOLER MODELS

The progress made on the following three cryocooler models that were developed for HOT applications are discussed in detail, including different design and performance aspects.

3.1 K562SI - SHORT IMPROVED

Currently the K562SI is a qualified off the shelf product that is already supplied in large quantities to a number of customers around the world. Furthermore The coolers supplied to customers are tested under different conditions to check their compatibility specification to the requirements. Table 5 presents a comprehensive testing that was performed on 14 K562SI coolers. The coolers were tested at ambient temperatures of 23˚C and 71˚C, at FPA temperature of 150K. The total heat loads were 190 mW at 23˚C, and 290 mW at 71 ˚C.

Table 5. K562SI coolers average tests results

190mW @ 23˚C @ 150K			
Number of coolers	Regulated power consumption [W]	maximum power consumption[W]	Minimal temperature [K]
14	2.37	9.01	76.98

290mW @ 71˚C @ 150K			
Number of coolers	Regulated power consumption [W]	maximum power consumption[W]	Minimal temperature [K]
14	3.87	10.26	103.09

3.2 K580 Integral Rotary Cryocooler

3.2.1 Qualification test

The K580 is currently a qualified product. This qualification test included the following tests:

Table 6. K580 qualification test check list

Requirement	Completed
EMI/RFI	√
Humidity	√
Cooler Induced Forces Test	√
High Temperature	√
Low Temperature	√
Thermal Shock	√
Functional Vibration	√
Endurance Random Vibration	√
Sweep sine vibration	√
Mechanical Shock	√
ESS	√
Acoustic Noise	√
Leakage test-High/Low Temperature	√
Electrical function include on/off tests	√

After each test the cooler parameters are tested in order to make sure that there isn't any degradation in cooler performances such as power consumption, induced forces and acoustic noise. At the present time, a number of coolers have already been supplied to several customers around the world.

3.2.2 K580 temperature stability

Regarding the cooler temperature stability, Figure 8 contains data on the temperature stability of 15 K580 coolers. This chart shows that the maximum temperature stability is ± 0.07 [K] and the average is 0.05 while the spec is ± 0.1K.

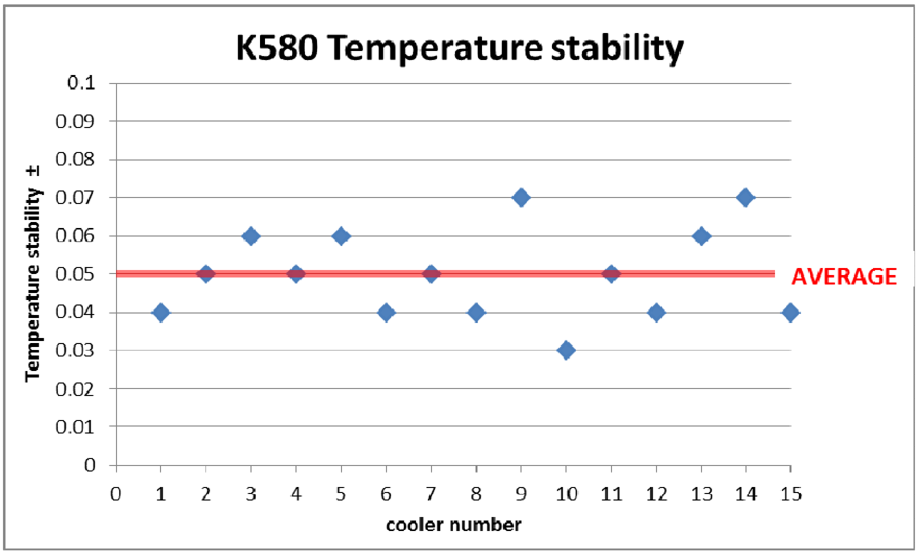

Figure 8. K580 Temperature stability

3.2.3 K580 temperature stability

Table 6 lists data of the induced forces collected from 6 K580 coolers and measured at a fundamental frequency of about 35Hz. Figure 9 below the table describes the axes on which the forces are measured. From this table the maximum induced force derived from the cooler in the x axis is 6.3 gr rms and the average is 5.3 gr rms, while the spec is 10 gr rms.

Table 7. K580 induced forces on X, Y and Z axis

cooler number	Induced forces X gram-rms	Induced forces Y gram-rms	Induced forces Z gram-rms
1	5.8	1.5	<0.5
2	5.7	5.2	
3	4	1.5	
4	4.5	3.7	
5	5.4	1.2	
6	6.3	2.8	
AVERAGE	**5.3**	**2.7**	**<0.5**

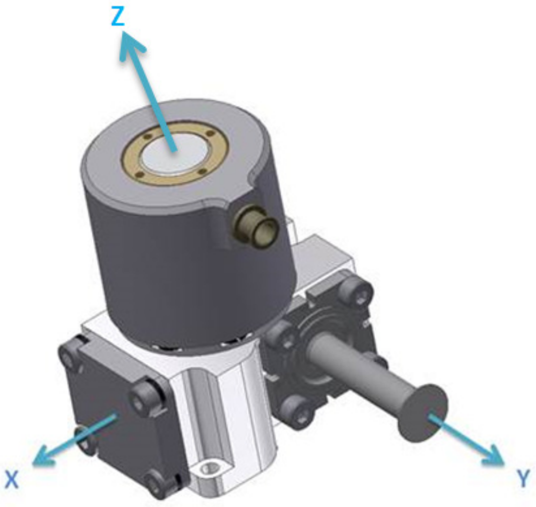

Figure 9. K580 cryocoolers with X,Y and Z axis

3.3 K588 Split Linear Cryocooler

Because of the rigorous demands to meet the "SWAP" approach, there is a need to add additional improvements and new technology in order to meet the uncompromising requirements including price reduction. This is the reason that at present the K588 is being redesigned in order to add technological improvements and to reduce further the parts production cost including the assembly processes. One of the methods to reduce the production cost for example, is to convert the initial production technology from individual parts manufacturing, to mass production technology.

3.4 Cold finger design

The K588 and the K580 models are designed to use the new generic cold finger that was optimized in terms of materials used, cold finger wall thickness, and the manufacturing process with the aim of reducing size and parasitic self-heat load. Various materials, including Titanium alloy and L605 alloy, were examined at different cold finger wall thicknesses, aiming for minimization of self-heat load while keeping the required rigidity of the cold finger. Figure 10 shows the K580 with a real working detector that was built on the new generic cold finger.

Figure 10. K580 cryocooler with real working detector

4. THE DIFFERENCE BETWEEN ROTARY AND LINEAR CRYOCOOLER

Since there is a tradeoff between different cryocooler technologies, two cryocooler concepts are under development: the K580 Integral Rotary Cryocooler and the K588 Split Linear Cryocooler, each one is suitable for different customer needs. The rotary cryocooler is driven by rotation motor and transfers the rotational movement into linear movement by a crankshaft with an excenter in order to move the piston and the displacer. The position of the piston and the displacer form an angle of 90 degrees between them and thereby create the cooling effects. The linear cooler on the other hand is driven by a linear actuator that drives a piston for the purpose of gas compression. The displacer mechanism in the cold head of the split linear cooler is pneumatically driven allowing connection to the compressor by a gas pipe. Regarding the coolers interface, the Split Linear Cryocooler has the advantage of flexibility of its assemblies due to the separation of the cooler's components. The Integral Rotary Cryocooler provides a bit less mounting flexibility, however giving a benefit of higher robustness under harsh environment.

Table 8. The difference between cryocooler technologies

Parameter	Integral Rotary	Split Linear single piston	Split Linear dual opposed piston
Cooling capacity	√√√	√√√	√√√
Steady State Input Power	√√√	√√	√√
Max input power	√√√	√√√	√√√
MTTF	√√	√√√	√√√
Ambient Temperature Range	√√√	√√√	√√√
Cool down time	√√	√√√	√√√
Weight	√√√	√√	√√
induced forces	√√√	√	√√
Acoustic noise	√√	√√√	√√√
Temperature stability	√√√	√√√	√√√
System flexibility	√√	√√√	√√√
System integration	√√√	√	√√

Table 9. The difference between cryocooler technologies from system view

Parameter	Integral Rotary	Split Linear single piston	Split Linear dual opposed piston
Hand held	√√√	√√	√√
gimbals	√√	√√√	√√√
Missile seeker	√√√	√√	√√
Observation system	√√√	√√√	√√√
Missile Warning System	√√	√√√	√√

Parameter	Integral Rotary	Split Linear single piston	Split Linear dual opposed piston
Thermal Weapon Sight	√√	√√√	√√√
Fire control systems	√√√	√√√	√√√

5. RELIABILITY EVALUATION

In recent years RICOR has conducted extensive laboratory life tests. Dozens of cryocoolers have already undergone, and are still undergoing life tests as a part of continuous improvement approach. The life tests are performed under careful supervision, and the cryocooler's operation data are monitored throughout the experiment [7]. The standard K562 has started its life test and accrued more than 8630 working hours at 265 mW heat loads and a motor temperature of 60˚C. When converting the accelerated life test to basic MTTF (230 mW@150K@23˚C) the calculated working hours is increasing to 13500. K562SI is expected to accrued the same amount of working hours as the standard K562 by similarity, in addition The K562SI already started its life tests and has accrued more than 700 working hours at a motor temperature of 45˚C. On Q3-2016, five K580 coolers are planned to start laboratory life tests, and as of today four K580 laboratory coolers are running for the purpose of accumulating working hours and have already accrued more than 7000 hours at room temperature. The estimated K580 cryocooler life time corresponds to the basic MTTF of more than 15,000 hours, while the K588 cryocooler is expected to demonstrate MTTF of above 30,000 hrs.

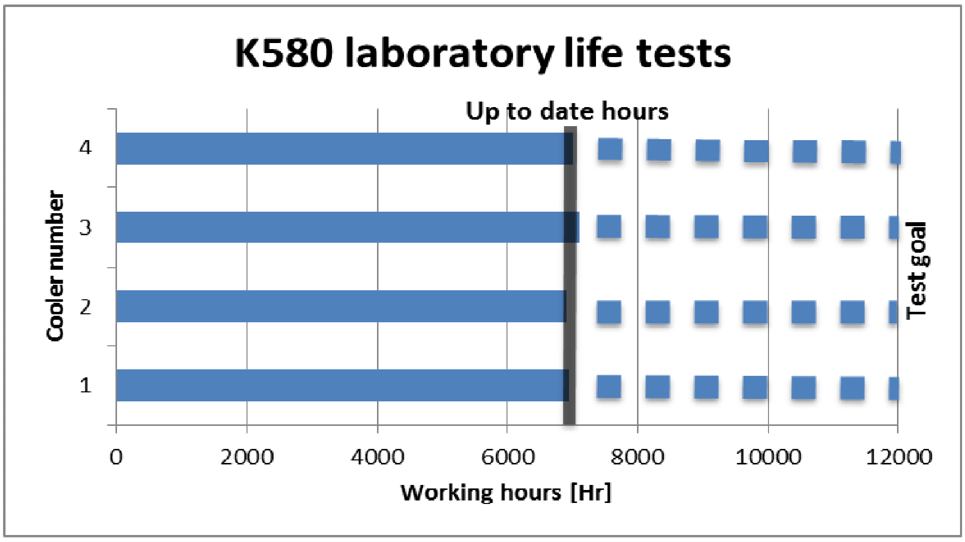

Figure 11. K580 laboratory life tests

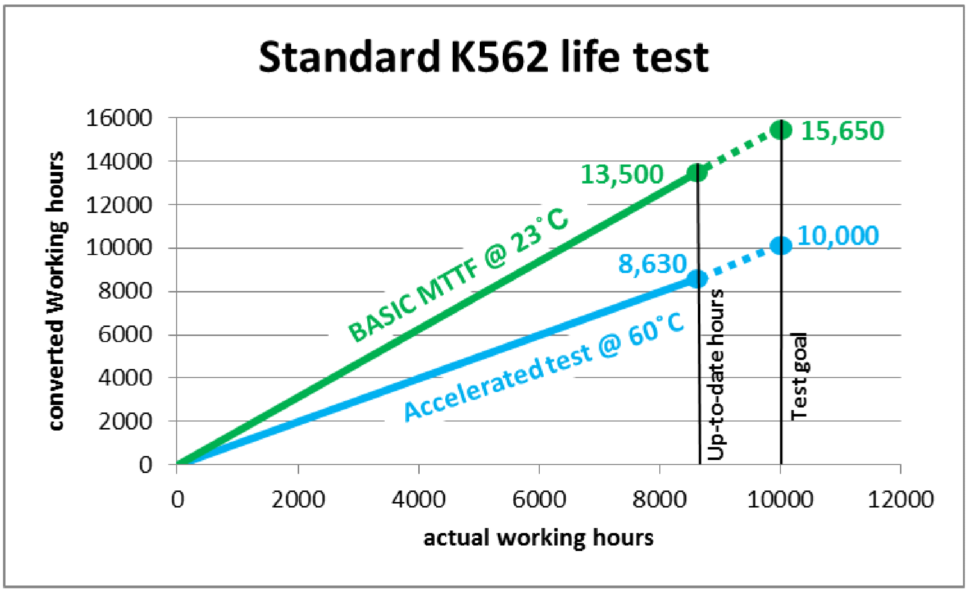

Figure 12. standard K562 life test

Figure 13. Ricor's Reliability laboratory image

6. NEXT ACTIONS PLANNED

Development and qualification of the K562S Short Improved model has already been completed, and the cooler is available as a qualified off the shelf product. At present 3 units are undergoing a life demonstration test and have already accrued more than 700 working hours at a motor temperature of 45˚C.

Currently the K580 rotary cryocooler, including the controller, is a qualified product, and soon will commence a life demonstration test. At present four K580 laboratory coolers are running for the purpose of accumulating working hours and have already accrued more than 4000 hours at room temperature. In addition, several units have already been supplied for customer evaluation, while the ramp-up phase of the serial manufacturing is planned for the end of Q3/2016.

The K588 split linear cryocooler, is now being redesigned in order to meet uncompromising demands including cost reduction and eventually meet the demanding "SWAP" approach. Meanwhile, the first prototype demonstrates achievement of specification working set-point at the power consumption lower than 2WAC. The K588 is planned to be available for customer evaluation by the end of 2016, and to finish qualification test during 2017.

Table 10. HOT cryocooler status

#	Model	Cooler availability for customer evaluation	Qualification completion	Launch Life test	Serial Production Readiness
1	K562 standard	√	√	√	√
2	K527	√	√	√	√
3	K562SI	√	√	√	√
4	K580	√	√	Q3/2016	Q3/2016
5	K588	Q4/2016	Q4/2017	Q1/2018	Q1/2018

7. SUMMARY

Significant progress has been made at RICOR with the development of cryocoolers for HOT IR detectors. Two cryocooler models will soon be commercial products and will join the K562SI model, after passing the initial development phase successfully. Two controllers were developed in parallel for their cryocoolers, enabling them to meet the HOT systems' highly demanding specifications. The K562SI model was re-optimized based on a serial product, and is currently a qualified off the shelf product suitable for short term systems development programs requiring an immediate solution for SWaP-sensitive systems. At present it is in continuous supply to a number of customers around the world. The K580 model, including the new HOT digital controller, is currently a qualified product and soon will start its life test. Meanwhile, the K580 has been supplied to a number of customers around the world as a pre-qualified product. The K588, including its new controller, is currently being redesigned in order to meet the "SWAP" requirements, and soon after the completion of the redesign stage, it will be prepared for engineering series manufacturing and qualification testing.

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