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 development and optimization of suitable cryocoolers. The current developments at RICOR are focused on the SWAP-oriented design process, meaning small Size, low Weight and low Power consumption, providing proper cryocoolers for future hand held thermal imagers.

This paper shows the progress made during development of "HOT" cryocooler prototypes, and engineering pre-production series cryocoolers working at the FPA temperature range of 130 - 200K. Three different cryocooler models based on rotary & linear design concepts are presented below. 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: Cryocooler, HOT detector, Infrared, RICOR, Stirling

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. Furthermore, 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]. The discussed HOT cryocoolers are optimized for input power below 2W DC, and for fast cooling down using a digital controller with a tunable booster. In order to provide a variety of products selection appropriate for a wider range of customer requirements, RICOR is currently developing two cryocooler concepts: an Integral Rotary and a Split Linear. In addition, a third development was accomplished by improving an existing Integral Rotary cryocooler K562SI as a short-term alternative. Design aspects and performance of the cryocoolers, including two new digital controllers, are described in this article.

2. THE MAIN DEVELOPMENT GOALS

The main development goals planned at the R&D program were as follows:

- Optimization of the regulated power consumption of cryocoolers down to 2W DC at an FPA temperature of 150K, at room ambient temperature
- Development and implementation of a DTC (Design to Cost) process
- Development of an electronic controller able to function at a wide operation voltage
- Optimization of an electronic controller to 90% efficiency
- Development of a uniform low-loss cold finger for designed cryocoolers, in order to allow integration with a uniform detector assembly

3. THE CRYOCOOLER MODELS

The following three cryocooler models that have been developed for HOT applications are discussed in detail, including different design and performance aspects.

K562SI - SHORT IMPROVED – Integral Rotary Cryocooler

The K562SI is an integral rotary cryocooler that was designed for HOT detectors, which is an improved model based on the K562. 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 and (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 outcomes of all these improvements are

- power consumption below 2.5W DC at 140K at 190mW total heat load
- cool down time less than 3:30 minutes (typical)
- gross cooling capacity of 500 mW at 150K at 71°C
- weight less than 185 grams

The improvements of the cooler efficiency were achieved as a result of the thermodynamic aspects addressed using SAGE Stirling cycle simulation software. During the past year the K562SI reached the engineering series stage and was examined in a large number of tests in order to become a qualified product. As of today, The K562SI is a qualified product and is already supplied to a number of customers around the world. In addition, the K562SI is starting a life test and presumably, by comparison, it will be able to work the same number of hours as the regular K562S. The K562SI is provided with the K562S digital controller possessing 80% efficiency. Figure 1 and Figure 2 illustrate the cooler exterior an outline respectively.

Figure 1. K562SI cooler and controller image

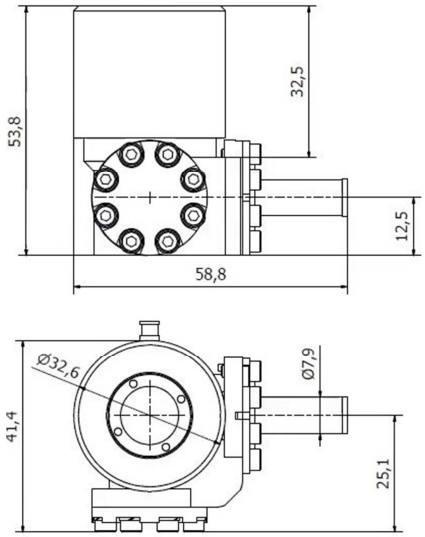

Figure 2. K562SI model dimensions

K580 Integral Rotary Cryocooler

The K580 cooler model design was initiated and performed “from scratch” especially for HOT detectors. It is currently at the engineering series stage and is already supplied to a number of customers around the world as a pre-qualified product. The K580 is an integral rotary type cryocooler emphasizing the “SWAP” approach. The cooler power consumption at the operating temperature of 150K and 180mW heat load is lower than 2W DC. The maximal cooling capacity at ambient temperature of 71° is 500mW total @150K. The cryocooler will be capable of working along basic MTTF >12,000 hours (predicted) at various ambient temperatures from -40˚C to +71˚C. The K580 has a cooling-down rate of 1.2 [J/sec] at an ambient temperature of 23°C, and will typically cool a detector down within 3 minutes. The cryocooler weight is less than 200 gram, it induces less than 10g rms vibrational force, and produces a low acoustic noise meeting non-detectability from a distance of 20 meters. The K580 cryocooler image and dimensions are shown in Figures 3 and Figure 4.

Figure 3. K580 cryocooler and controller image

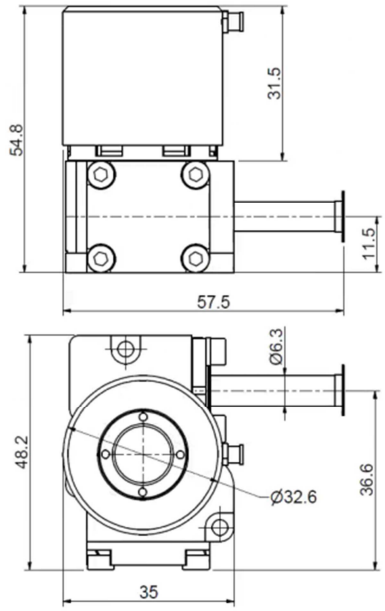

Figure 4. K580 cooler model dimensions

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 predicted basic MTTF of the K588 model is >30,000 hours, and the ambient temperature range is specified from -40˚C to +71˚C. The maximal total cooling capacity at an ambient temperature of 71°C is 500mW @ 150K. The K588 shows a cool down rate of 1.2 [J/sec] at an ambient temperature of 23°C, and will typically cool a detector down to 150 K within <3 min. The cryocooler thermodynamic performance was analysed and optimized using the SAGE Stirling cycle simulation software, chasing the maximum efficiency objective. The actuator was designed using Finite Element Analysis software focusing on the 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 demonstrate power consumption below 2W DC at 200mW total heat load, at 150K FPA temperature. The K588 model image is shown in Figure 5 and the outline dimensions are presented in Figure 6.

Figure 5. K588 cryoooler and controller image

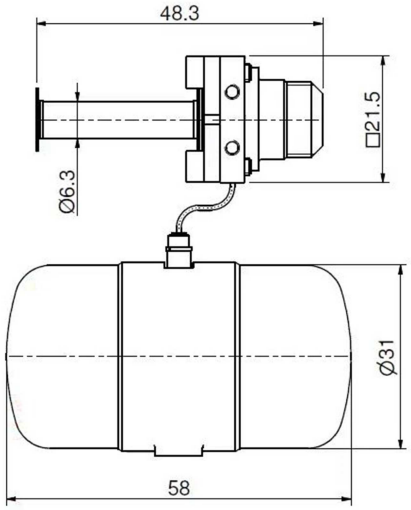

Figure 6. K588 model dimensions

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 uniform enclosure/electrical interface [5]. The new electronic controllers were designed to work within operation voltage range of 4VDC – 15VDC (6V or 12V nominal operation), and were optimized to a 90% efficiency goal. The new hardware and software approach for controlling motors is based on 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 design is based on a dual PCB structure in order to reduce the outline dimensions down to 34 X 32 X 15mm, allowing a weight reduction down to 25gr. The controllers were designed to maintain a detector temperature drift within ±0.2K at short-term temperature stability of ±0.1K. In addition to the main characteristics, additional functionality was developed and implemented as follows:

- Reverse-polarity protection without extra heat dissipation

- Input over-voltage protection without extra heat dissipation
- Sensorless/Sensor Brushless DC motor control
- Commutation protocol – RS422
- Digital temperature control with flexible zoom point
- PID parameters per user definition
- Control of four set points per user definition

The both “rotary” and “linear” controllers are enclosed into a uniform case, providing electrical interface based on uniform connectors in replace of the traditional wire soldering method. These improvements are intended to provide better flexibility during a system assembly and maintenance.

Table 1 shows the main specification parameters of the HOT controller, and Figures 7 and 8 illustrate the external view and outline respectively.

Table 1. Main characteristics of the HOT controller

Parameter	HOT controller –K580 / K588
Controller type	Digital
Efficiency	>90%
Input voltage	4 – 15VDC
Control logic	PID
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

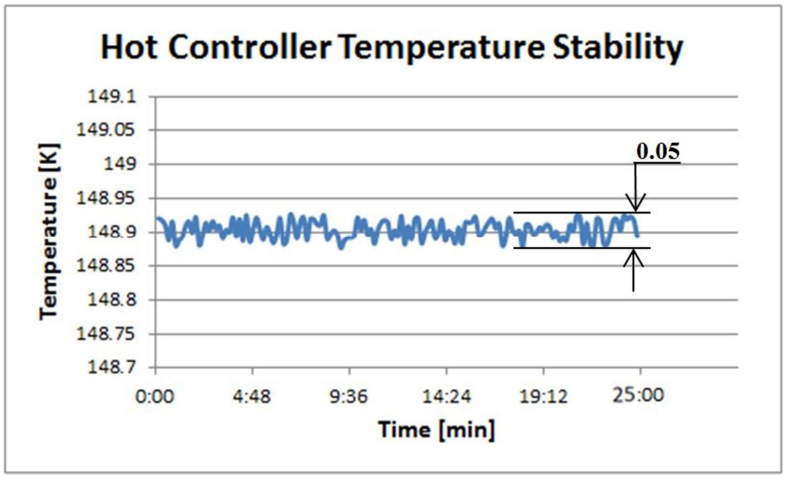

Figure 7. Hot controller temperature stability graph

Figure 8. HOT controller image

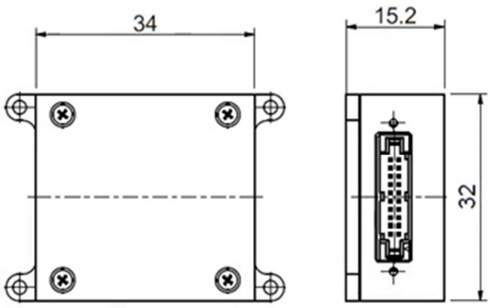

Figure 9. HOT controller dimensions

Cold finger design

The K588 and the K580 models are designed to use the new uniform cold finger that was optimized in terms of materials used, cold finger wall thickness, and manufacturing process, chasing reduction of 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 new uniform cold finger outline adapted to both the aforementioned cryocoolers.

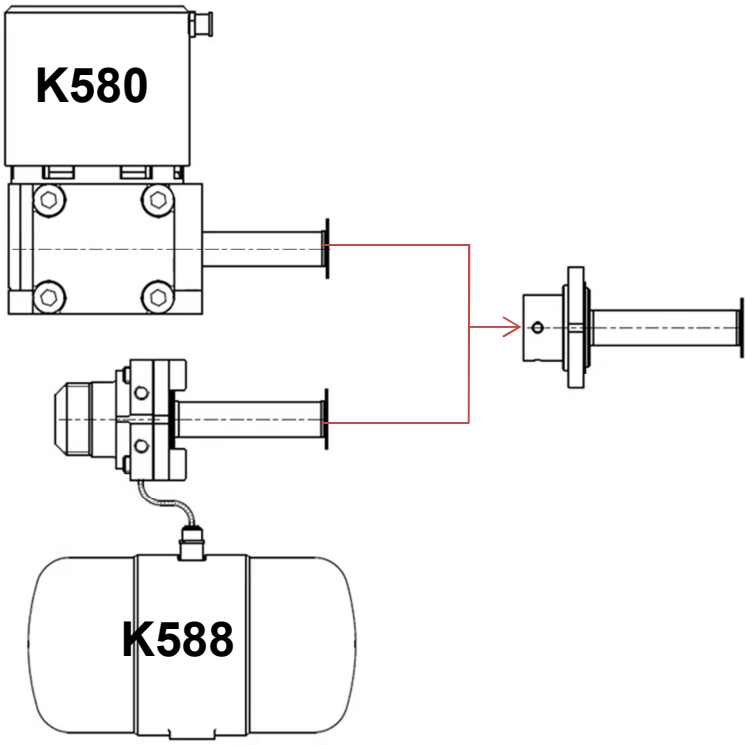

Figure 10- The K588 and the K580 cryocoolers with uniform cold finger

4. CRYOCOOLERS TEST RESULTS

K562SI Cryocooler test results

After the manufacturing of the engineering series, a comprehensive testing was performed on a group of coolers in order to obtain representative average results. The coolers were tested at ambient temperatures of 23˚C and 71˚C, at FPA temperature of 140K. The total heat loads were 190 mW at 23˚C, and 290 mW at 71 ˚C, as shown in Table 2

Table 2. K562SI coolers average tests results

190 mW @ 23˚C @ 140K				
Regulated power consumption [W]	Non-regulated power consumption[W]	Minimal temperature [K]	Cool down time [min]	Temperature stability [K]
2.57	9.37	71.94	2:56	0.06

290mW @ 71˚C @ 140K				
Regulated power consumption [W]	Non-regulated power consumption [W]	Minimal temperature [K]	Cool down time [min]	Temperature stability [K]
4.06	10.35	94.65	3:34	0.06

HOT cryocoolers engineering series tests results

The charts shown below in Figures 11 - 20 illustrate typical performance of certain units of the engineering series HOT cryocooler models discussed above.

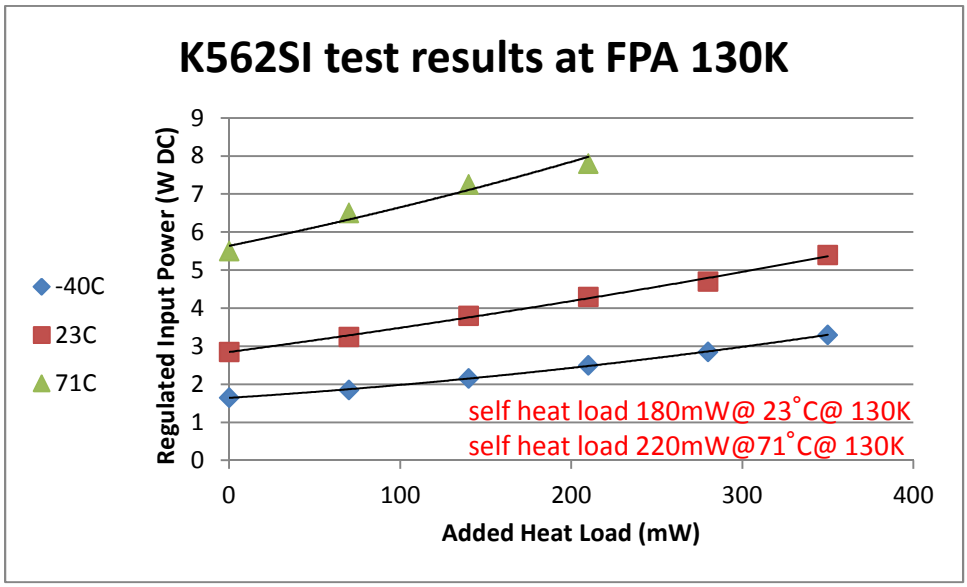

Figure 11. K562SI Cryocooler tests results at FPA 130K

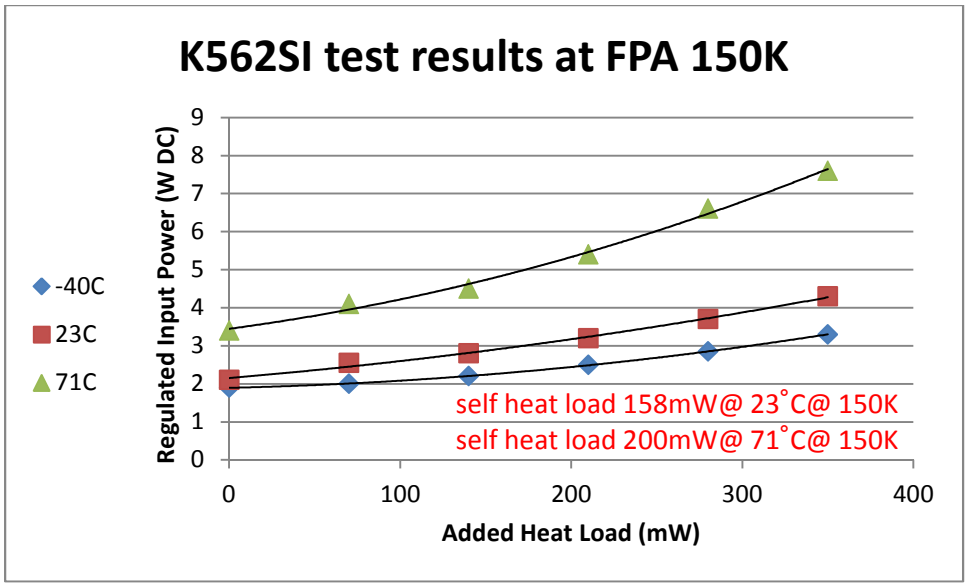

Figure 12. K562SI Cryocooler tests results at FPA 150K

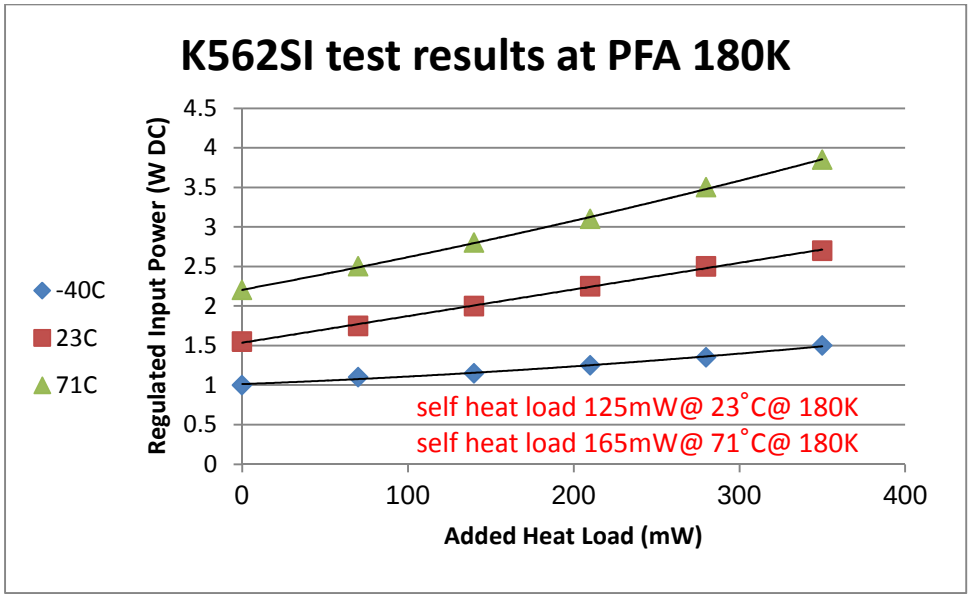

Figure 13. K562SI Cryocooler tests results at FPA 180K

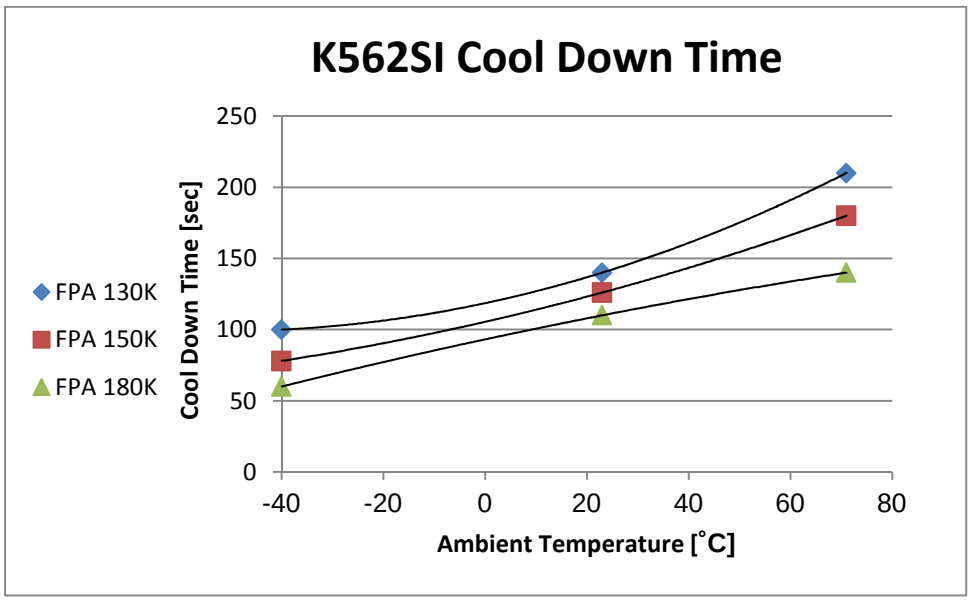

Figure 14. K562SI Cryocooler cool down time tests results

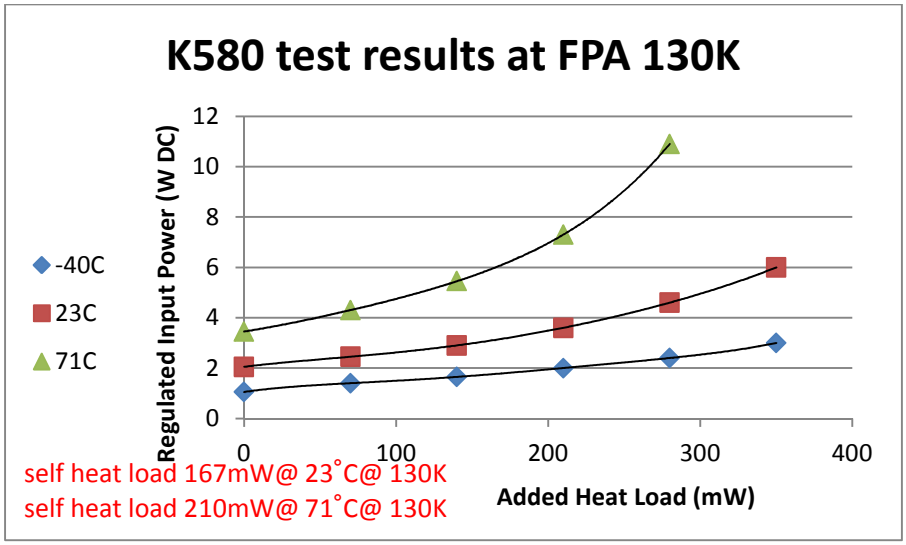

Figure 15. K580 Cryocooler tests results at FPA 130K

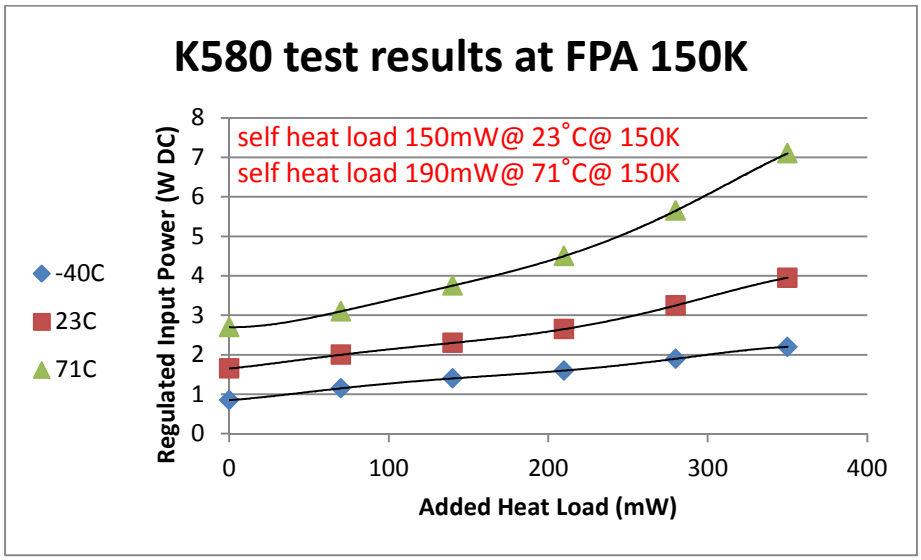

Figure 16. K580 Cryocooler tests results at FPA 150K

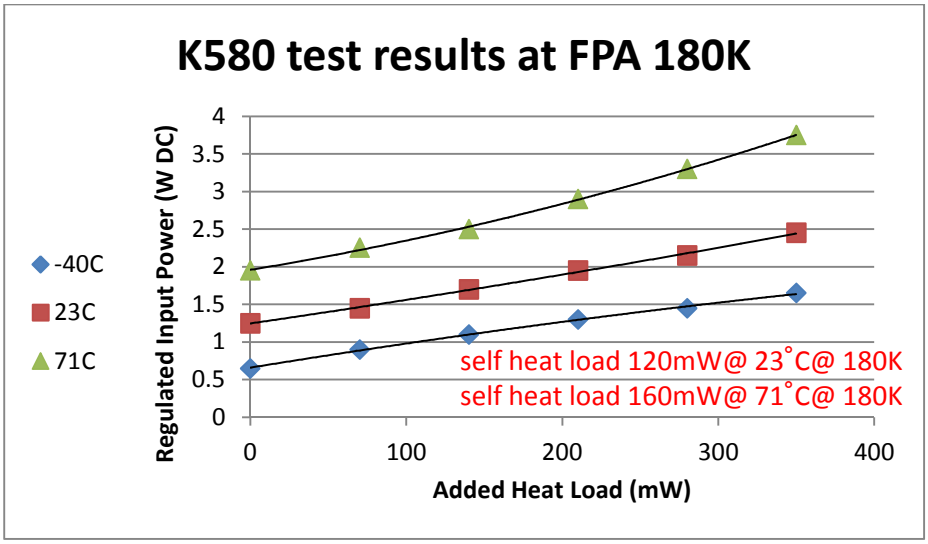

Figure 17. K580 Cryocooler tests results at FPA 180K

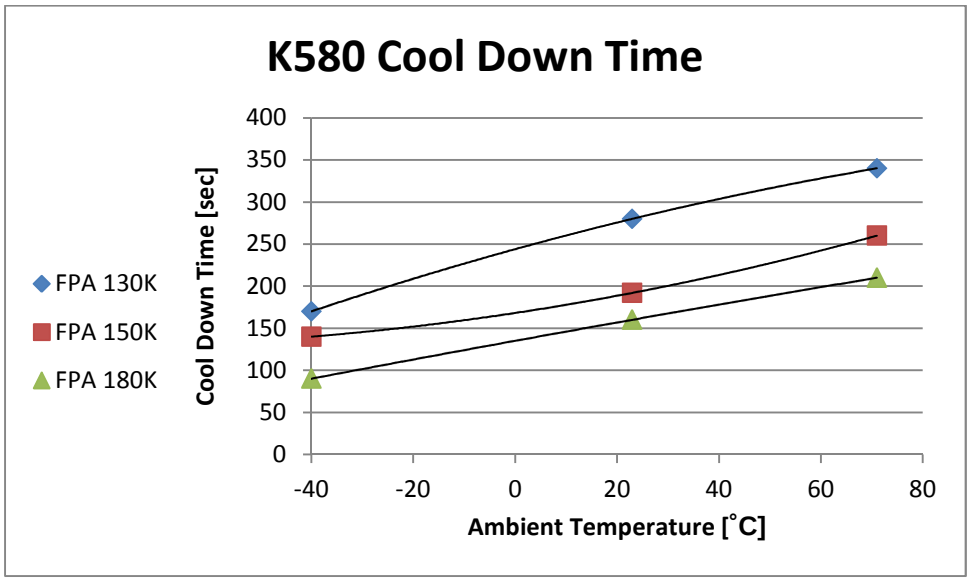

Figure 18. K580 Cryocooler cool down time tests results

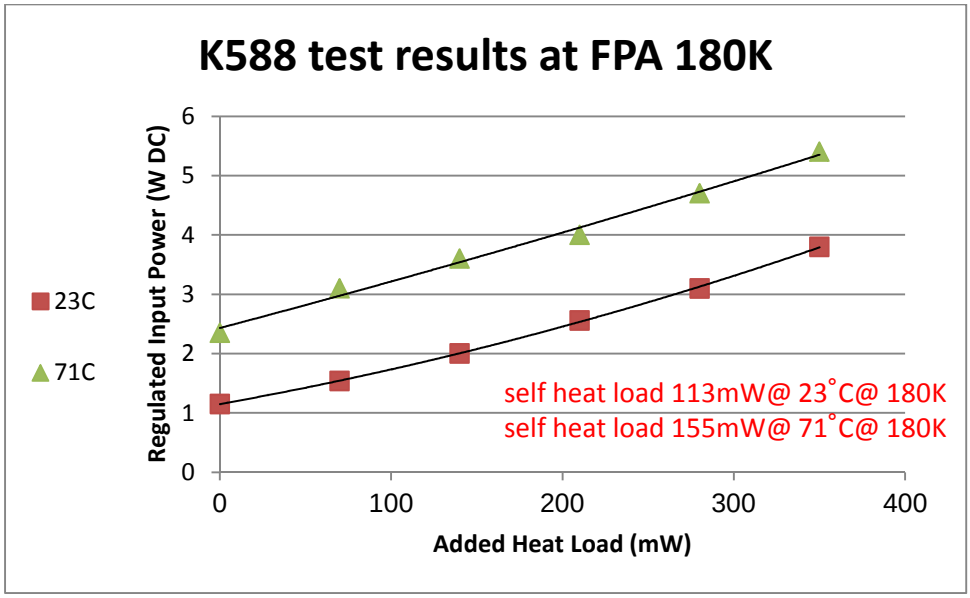

Figure 19. K588 Cryocooler tests results at FPA 180K

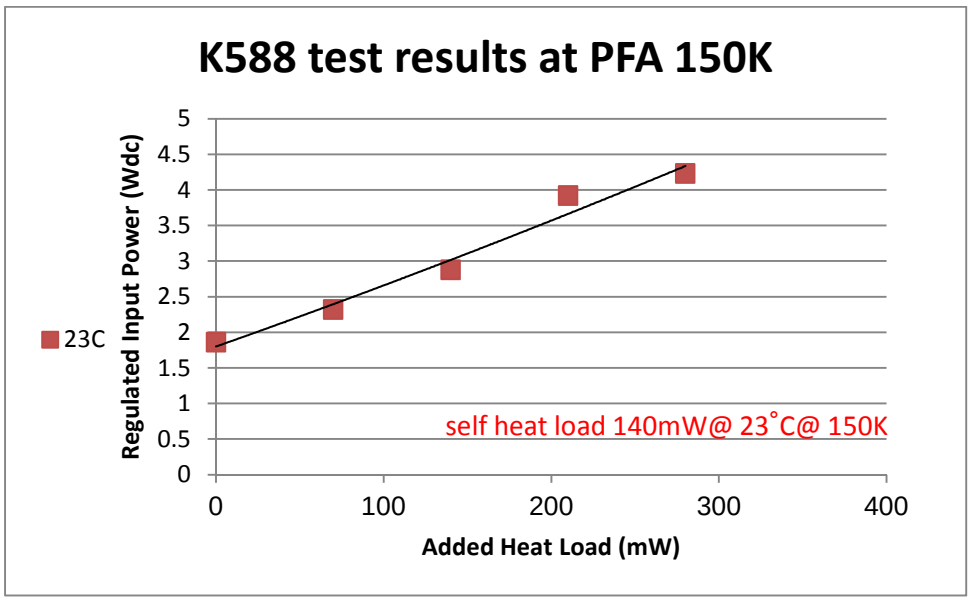

Figure 20. K588 Cryocooler tests results at FPA 150K

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 [6]. On Q3-2015, five K580 coolers and five K562SI coolers are planned to start the laboratory life tests. Based on the K562S proven MTTF (20,000 running hours), the design improvements made on the K562SI model allow maintaining at least the same MTTF. 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 21. 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. The life test is planned to be launched during Q2/2015.

Development of the K580 rotary cryocooler, including the controller, is currently at the finishing phase, during which 10 coolers were assembled and are being tested in pre-qualification tests. An additional plan is to finish the qualification tests, then to initiate life demonstration test. Several units have already been supplied for customer evaluation, while the ramp-up phase of the serial manufacturing is planned for the end of Q3/2015.

The K588 linear cryocooler development has made significant progress over the past year, thus a number of laboratory models are currently available for evaluation and characterization testing. Moreover, the first prototyping demonstrates that the near-specification performance under 2WAC regulated input power at working set-point is already achievable.

Both the cooler and the controller are planned to initiate qualification testing and ramp-up of serial production by Q1/2016, followed by a life test starting in Q2/2016.

7. SUMMARY

Significant progress has been made at RICOR with the development of cryocoolers for HOT IR detectors. Three cryocooler models have passed the initial development phase successfully, and currently are at different phases prior to becoming complete new commercial products. Two controllers were developed in parallel to their cryocoolers, allowing them to meet the highly demanding specification of the HOT systems. The K562SI model was re-optimized relying on a serial product, and is currently suitable for short term system development programs that are seeking an immediate

solution for SWaP-sensitive systems. Today it is a qualified product that is already supplied to a number of customers around the world. The K580 model, including the new HOT digital controller, is currently completing the engineering series phase and will be qualified soon. Meanwhile, the K580 has already been supplied to a number of customers around the world as a pre-qualified product. The K588, including its new controller, is currently completing the prototyping phase, and will soon be prepared for engineering series manufacturing and qualification testing.

REFERENCES

[1] Amiram Katz, Victor Segal, Avishai Filis, Zvi Bar Haim, Ilan Nachman, Eugene Krimnuz, Dan Gover, "RICOR's Cryocoolers development and optimization for HOT IR detectors", SPIE Proceedings, Vol. 9070, 90702N (2014)

[2] Avishai Filis, Zvi Bar Haim, Tomer Havatzelet, Dan Gover, Moshe Barak, "RICOR's Rotary Cryocoolers Development and Optimization for HOT IR Detectors", SPIE Proceedings, Vol. 8353, 83531U (2012)

[3] Alexander Veprik, "Aural non-detectability of portable HOT infrared imagers", SPIE Proceedings, Vol. 8704, 87040R (2013)

[4] A Veprik, S Riabzev, N Avishay, D Oster, A Tuito, "Linear Cryogenic Cryocoolers for Hot Infrared Detectors", SPIE Proceedings, Vol. 8353, 83531V (2012)

[5] A. Veprik, S. Zehtzer, N. Pundak, S. Riabzev, “Compact Linear Split Stirling Cryogenic Cryocooler for High Temperature Infrared Imagers“, Cryocoolers 16 Proceedings, 121-132 (2010).

[6] Racheli Moshe, Shlomi Baruch, Dorit Livni, Victor Segal, Avishai Filis, "Overview and Analysis of Laboratory Life Tests and Field Data for RICOR's High-Reliable Cryocoolers", SPIE Proceedings, Vol. 9070, 90702S (2014)