RICOR Cryocoolers for HOT IR Detectors
From Development to Optimization for Industrialized Production

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ABSTRACT

The modern needs of the electro-optical market for small low-power and light-weight IR systems are impelling research and development of High Operating Temperature (HOT) IR detectors, requiring development of dedicated "HOT" cryocoolers.
The development of cryocoolers with emphasis on the "SWAP^3" configuration means small size, low weight, improved performance, low power consumption and low price, in order to optimize IDDCA for future hand held thermal sights.

This paper will present the development and the progress made with the new "HOT" cryocooler, including customer data after the evaluation process, performances achieved using a common cold finger, test results update on a large series of production coolers, life and qualification test update and acoustic noise reduction. All the above mentioned information relates to the FPA temperature range of 130 - 200K for various cryocooler models based on rotary & linear design concepts.

The paper will also review the progress with the latest development activities implemented in the cryocoolers and the electronic control modules in order to improve reliability and minimize regulated power consumption.

Keywords: Cryocoolers, SWAP, HOT detector, Infrared, RICOR, Stirling, FPA

1. INTRODUCTION

In the past, standard operation temperature for an IR detector was lower than 77K. A recent survey of the cooled IR detectors market reveals that significant progress in IR detectors technology has been achieved lately, and as a result, their operating temperature has increased to about 150K. Prior to the recent technological advances in detectors, when the typical standard operating temperature for an IR detector was 77K, and sometimes even lower. low FPA temperatures of this kind, required a cryocooler that could provide higher cooling capacity, hence affecting size, weight and power consumption. Therefore an increase in the FPA temperature up to the HOT range (150K and above) improves cryocooler thermodynamic efficiency dramatically and also reduces the detector assembly thermal losses. 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. 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 the 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 inclding an update on the electronics and control.

2. CRYOCOOLER MODELS PERFORMANCE UPDATE

2.1 K562SI - SHORT IMPROVED – Integral Rotary Cryocooler

2 K562 SI coolers were sent to AIM for testing and examination on a IDDCA level. A preformance report was received from AIM after testing. The configuration set up was as described in Figure 1. The results of testing the power consumption at different ambient temperatures with different FPA temperatures are provided in FIgure 2. The results of testing the cool down time at different ambient temperatures with different FPA temperatures are provided in Figure 3. Another test was conducted to determine the stability of the power consumption over numerous cool down cycles. Testing was performed at room temperature with a 140K FPA temperature. Results are shown in Figure 4. A test to determine the stability of cool down time over numerouse cool down cycles was performed at room temperature with a 140K FPA temperature.The results are shown in Figure 5.

■ **CONFIGURATION**

No. of test units: 2
Integration Stage: IDCA
Cooler type: K562SI; PN 765B650A
Coldfinger: short Ti 8mm
Dewar heat load: ~170mW@77K, 23°C
Added electrical load: ~50mW
Input voltage: 12VDC
Cool down time: Uboost=17V; Detector ‚on‘
Switch on power supply until FPA-temperature regulated with accuracy of +/-0.3K

	IDCA#1	IDCA#2
Cooler SN	21-1237	21-1193
Stator / controller SN	B150006	B150020
Coldfinger SN	62-1805	62-1820

Figure 1. K562SI AIM test configuration specification

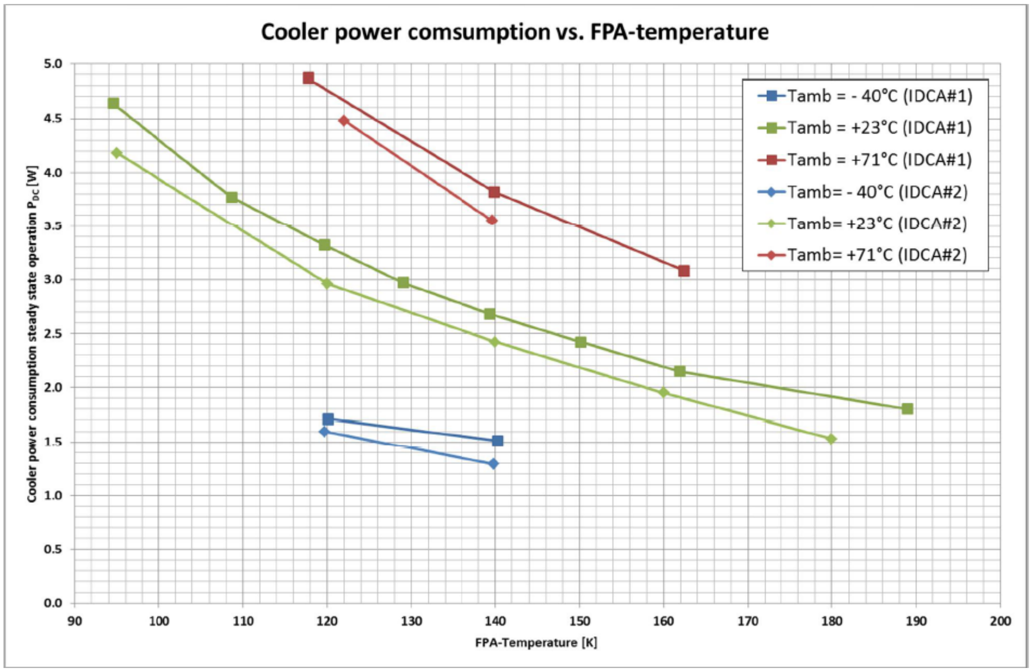

Figure 2. K562SI AIM Preformance to power consumption test results

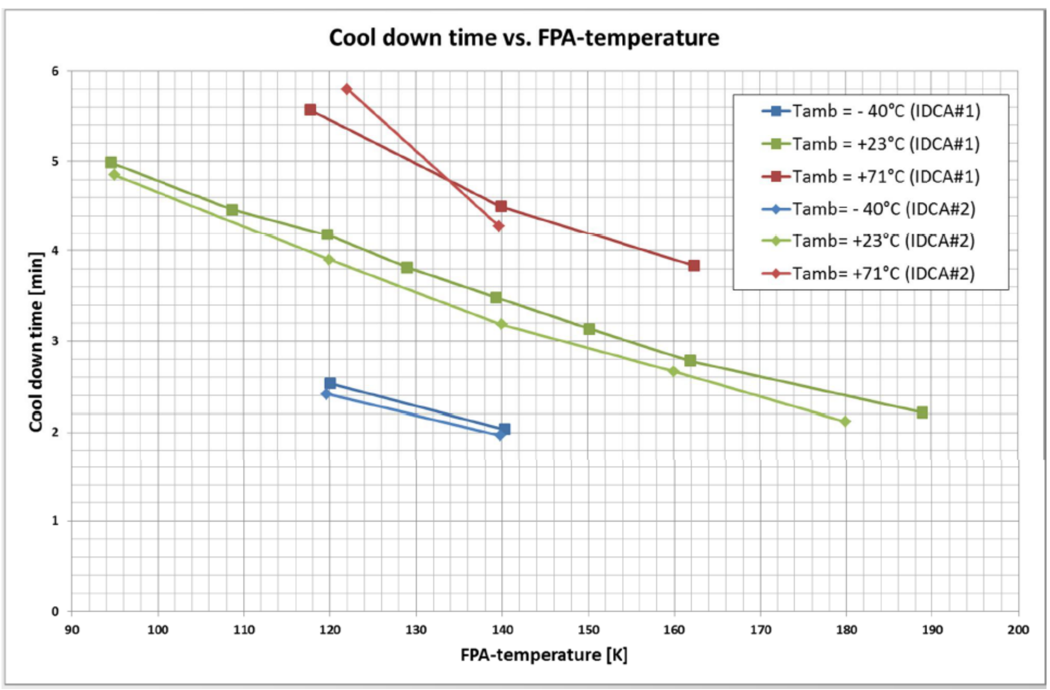

Figure 3. K562SI AIM Preformance to cool down time test results

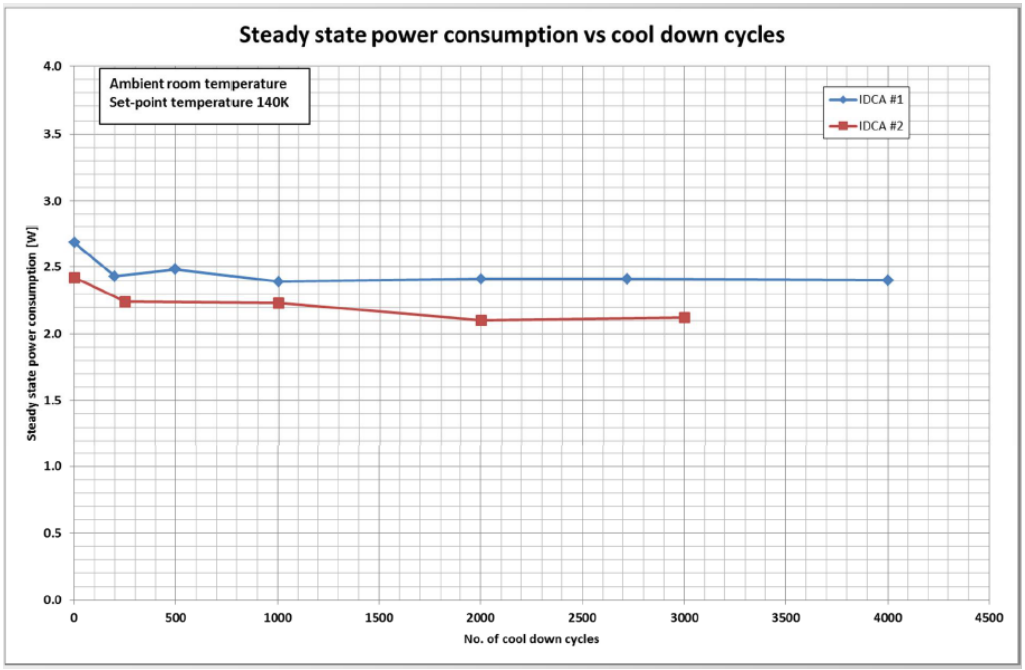

Figure 4. K562SI AIM Steady state power consumption to cool down cycles test results

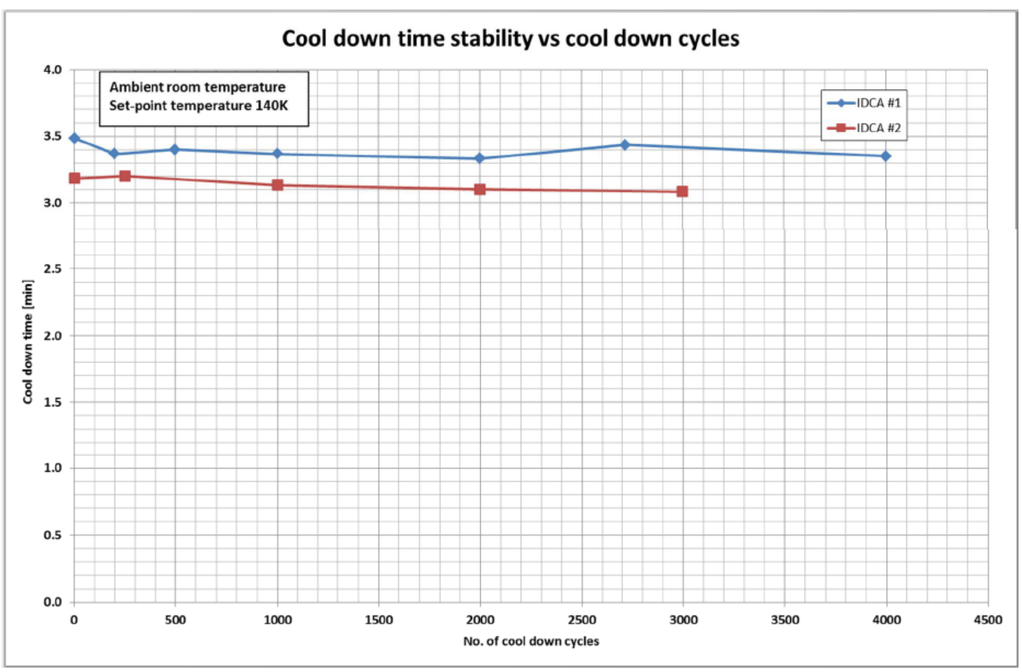

Figure 5. K562SI AIM cool down time to cool down cycles test results

2.2 K562SI Cryocooler test results

During 2016, more than140 coolers were manufactured and supplied. Data recorded from all K562SI coolers was analyzed for statistical performance distribution. All coolers were tested at ambient temperatures of 23°C, -41°C and 71°C with total heat loads of 190mW, 220 mW, 290mW respectively. The FPA temperature of the tested coolers was 140K. The results are shown in figure 6 through 8.

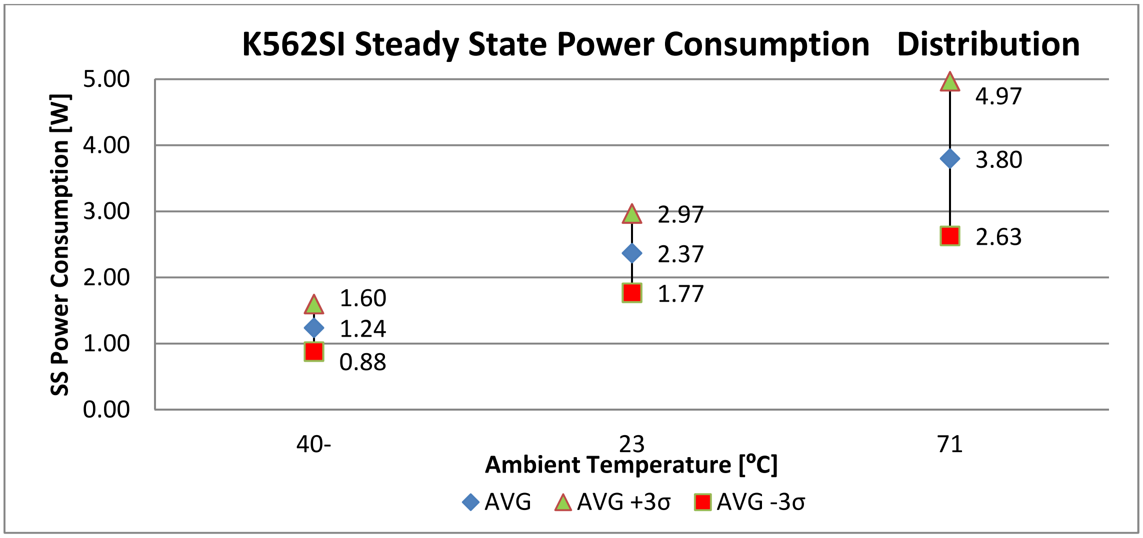

Figure 6. K562SI cooler Steady State Power Consumption Distribution

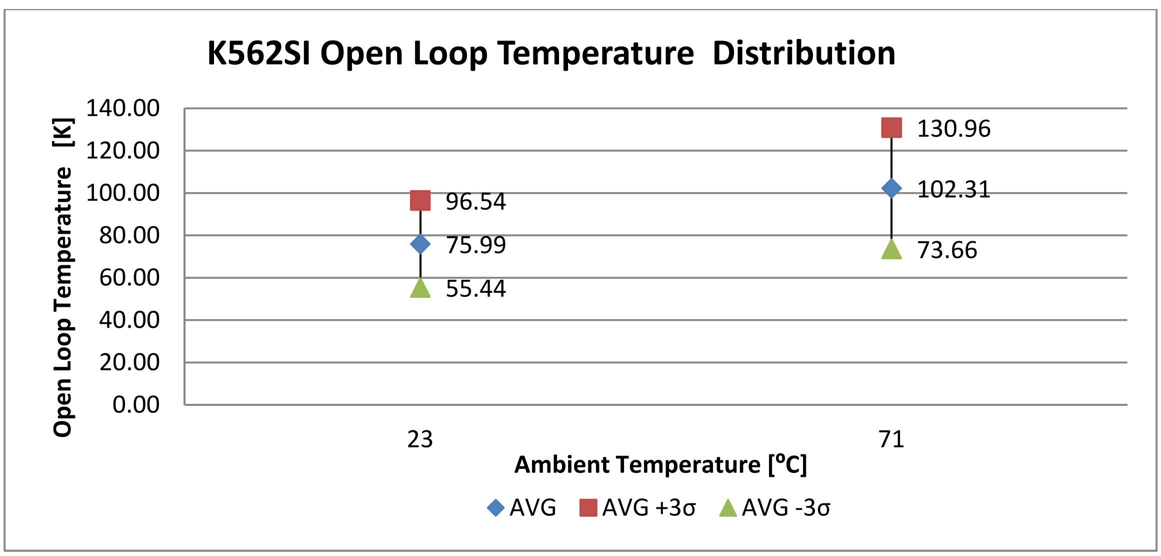

Figure 7. K562SI cooler Open Loop Temperature Distribution

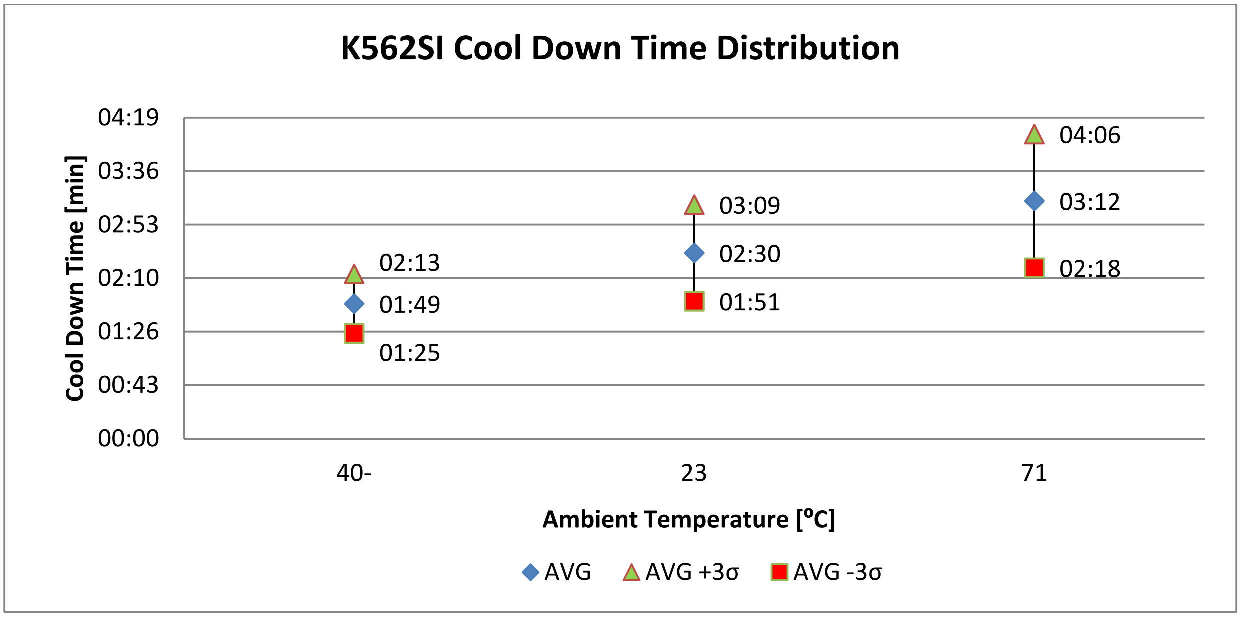

Figure 8. K562SI Cool Down Time Distribution

2.3 K580 Integral Rotary Cryocooler

The K580 cooler has aroused interest and tens of units were sent to customers for evaluation.
One evaluation process was conducted by Sofradir. The K580 test results, as performed by Sofradir, at 20^0C ambient temperature are presented in Table 1. The test results at 71^0C are shown in Table 2.

Table 1. Performance of the K580 In a range of FPA temperatures and a range of added heat load at 20^0C ambient temperature

Steady State Temperature	Measured self-heat load	Max Input Power	Steady State Input power		
	[mW]	[W]	50mW added heat load	100mW added heat load	200mW added heat load
170K	136	8	1.6	1.8	2.2
150K	165	8.3	1.9	2.1	2.6
140K	183	8.6	2.1	2.3	2.9
110K	250	9.3	3.1	3.7	4.4

Table 2. Performance of the K580 In a range of FPA temperatures and a range of added heat load at 71^0C ambient temperature

Steady State Temperature	Measured self heat load	Max Input Power	Steady State Input power		
	[mW]	[W]	50mW added heat load	100mW added heat load	200mW added heat load
170K	203	8.5	2.3	2.5	3.2
150K	244	9.1	3	3.3	4.4
140K	270	9.4	3.4	3.9	5.4
110K	424	10.4	10.4	-	-

To determine drift parameters for the revised common cold finger design of the K580, a drift test was conducted including over 300 runs. Results are presented in figure 9.

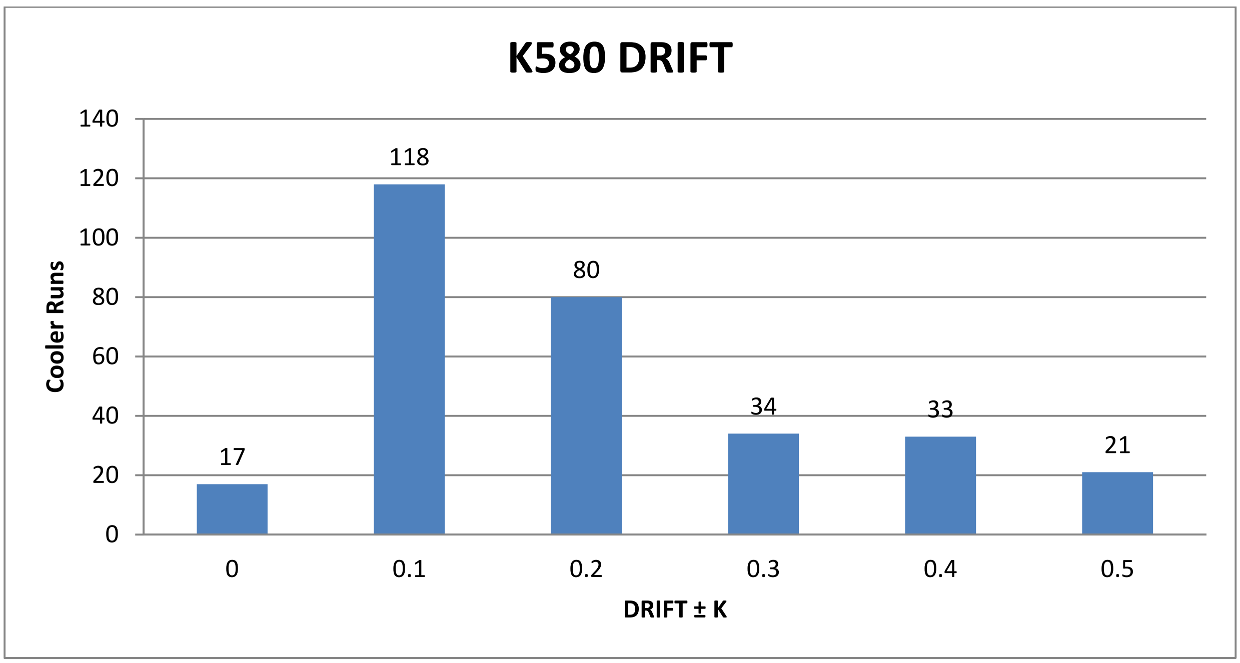

Figure 9. K580 with common cold finger drift test distribution.

Further testing on the K580 cooler was conducted with regard to future optimization processes. Three coolers were tested in a range of input voltage values. All three coolers were run under the same conditions with 185mW @150K @ 23^0C. It can be seen that there is a decrease in input power relative to a decrease in input voltage and an increase in efficiency respectively. The results are shown in Figure 10.

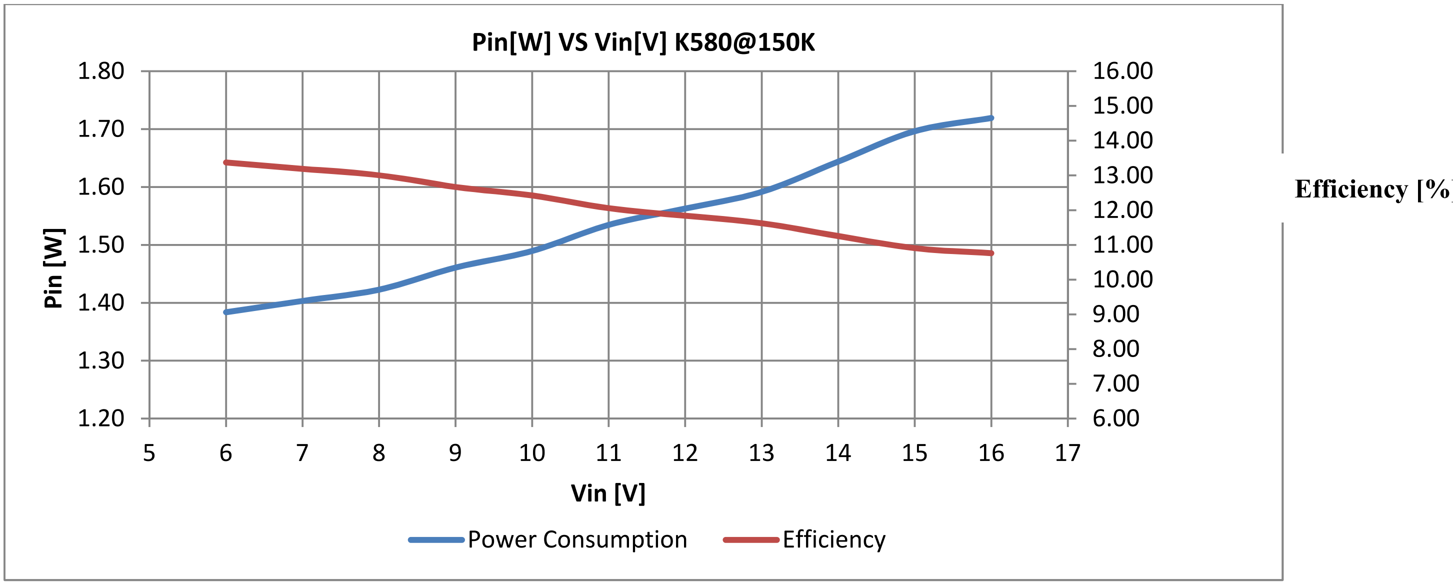

Figure 10. A change in input power and efficiency relative to the change in input voltage.

Since induced forces information was required on the K580 with regard to higher ambient temperatures, a test for induced forces was run at 71^0C. The setup of the test is shown in Figure 11. The results of the coolers running at a 46Hz frequency at 23^0C ambient temperature and at 68Hz frequency at 71^0C ambient temperature are shown in Figure 12 and 13 respectively. The results are compared and summarized in Table 3.

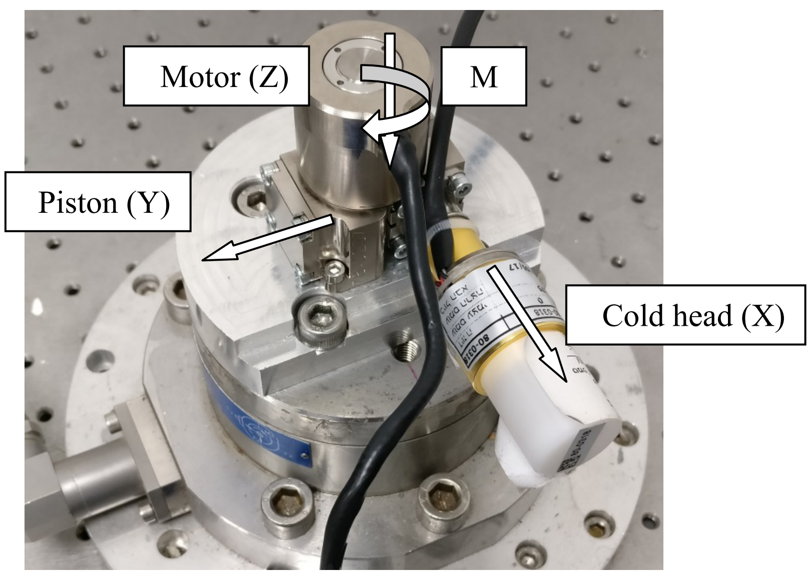

Figure 11. Induced forces set up

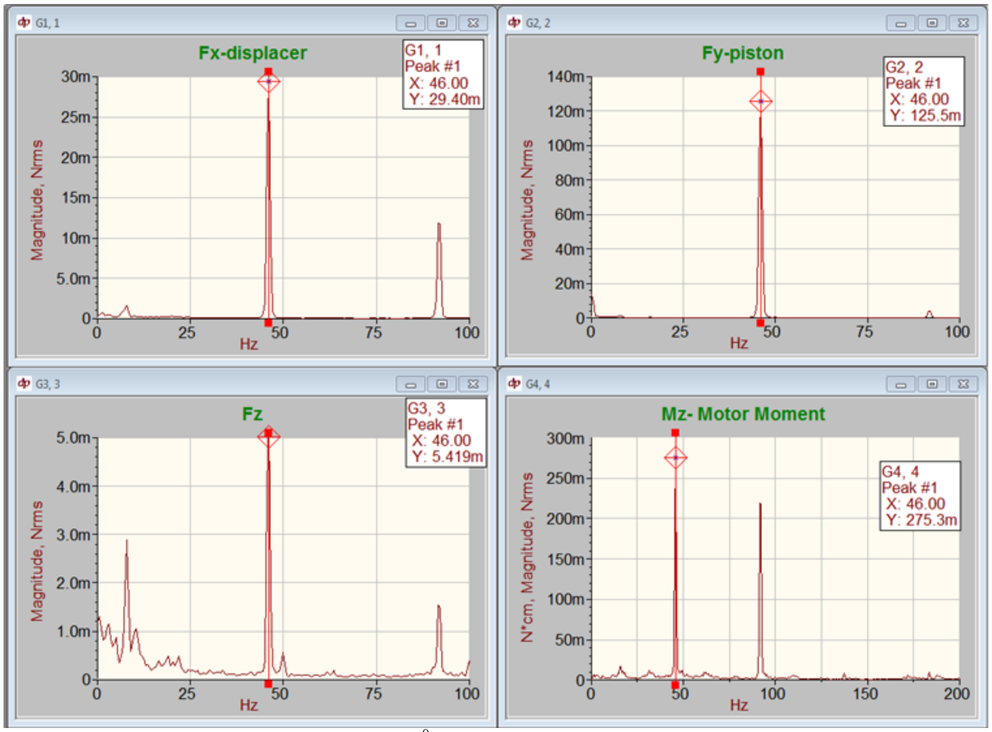

Figure 12. Induced forces results at 180mW@150K@23^{0}C conditions.

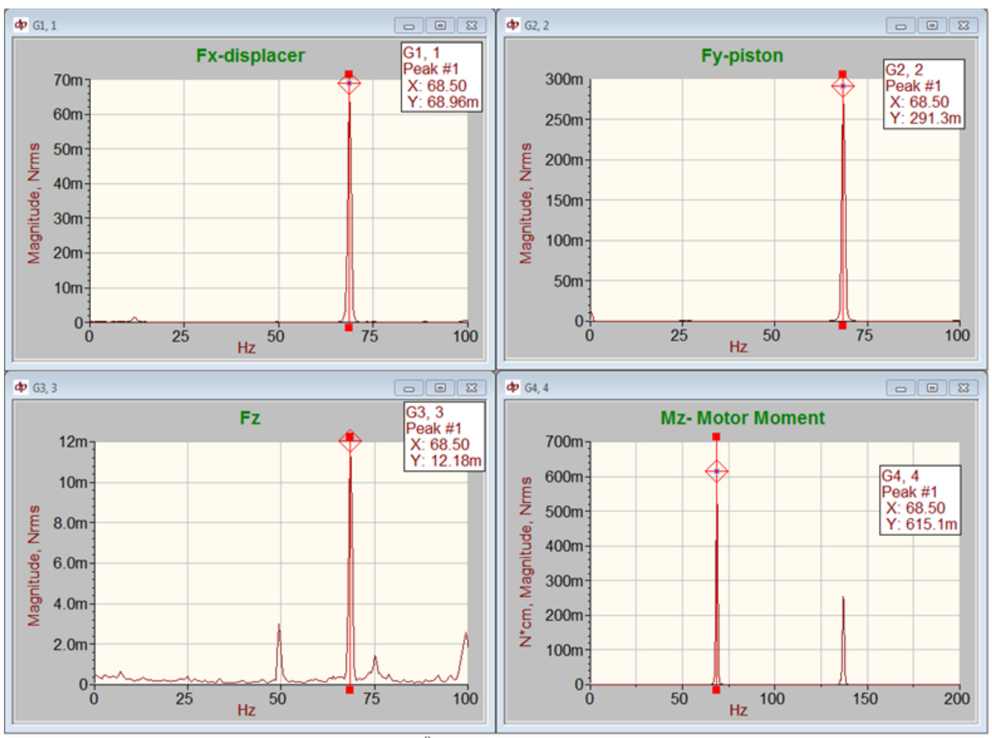

Figure 13. Induced forces results at 260mW@150K@71^{0}C conditions.

Table 3. Induced forces comparison and summary.

Axis	**Force [mN] rms** 180[mW]@150K@23°C	**Force [mN] rms** 260[mW]@150K@71°C
Input Power [W]	1.8	2.8
Piston (Y) **[mN] rms**	125.5	291.3
Cold head (X) **[mN] rms**	29.4	68.9
Motor (Z) **[mN] rms**	5.4	12.2
Motor Moment (M) **[mN*cm] rms**	275.3	615.1

2.3 K588 Split Linear Cryocooler

As the common finger was introduced as a design goal for HOT operating coolers, the K588 underwent a redesign phase to adjust the design to the common finger configuration. As market feedback was received on the cooler parameters, Ricor decided to address not only the common finger issue but also some other parameters. One of the parameters was the weight of the cooler. In the previous design the cooler weight (without the cold finger) was 240 grams. The cooler design process allowed for considerable weight reduction resulting in a 205 grams cooler weight. The aforementioned change was possible after a thorough consideration of several features and a comprehensive analysis process. The interface of the compressor was changed as well. In the previous design, the interface for the motor harness, filling port and cold head gas tube were in a 90 degree orientation relative to one another, demanding that the system allow a three directional approach to the cooler. In the new design we were able to combine the interface face of the motor harness and gas tube, thereby facilitating a design with only two approach paths. A visual comparison of the designs is shown in Figure 14 and Figure 15 respectively. In addition, this change assisted in weight reduction. Another design change addressed the induced forces. With the new design we were able to stabilize the compressor reduced forces. The estimated reduced forces of the K588 cooler are shown in Figure 16. The K588 performances are displayed in Figure 17 and Figure 18. It is estimated that towards the end of 2017, the K588 will begin the process of transfer from design to testing and manufacturing.

Figure 14. K588 compressor original design

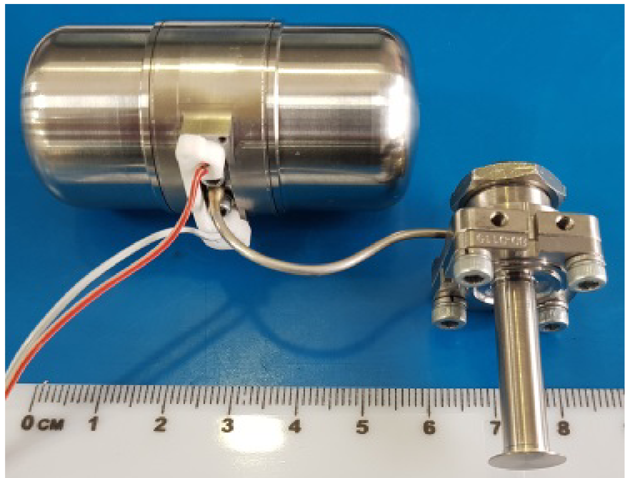

Figure 15. K588 compressor revised design with common cold finger

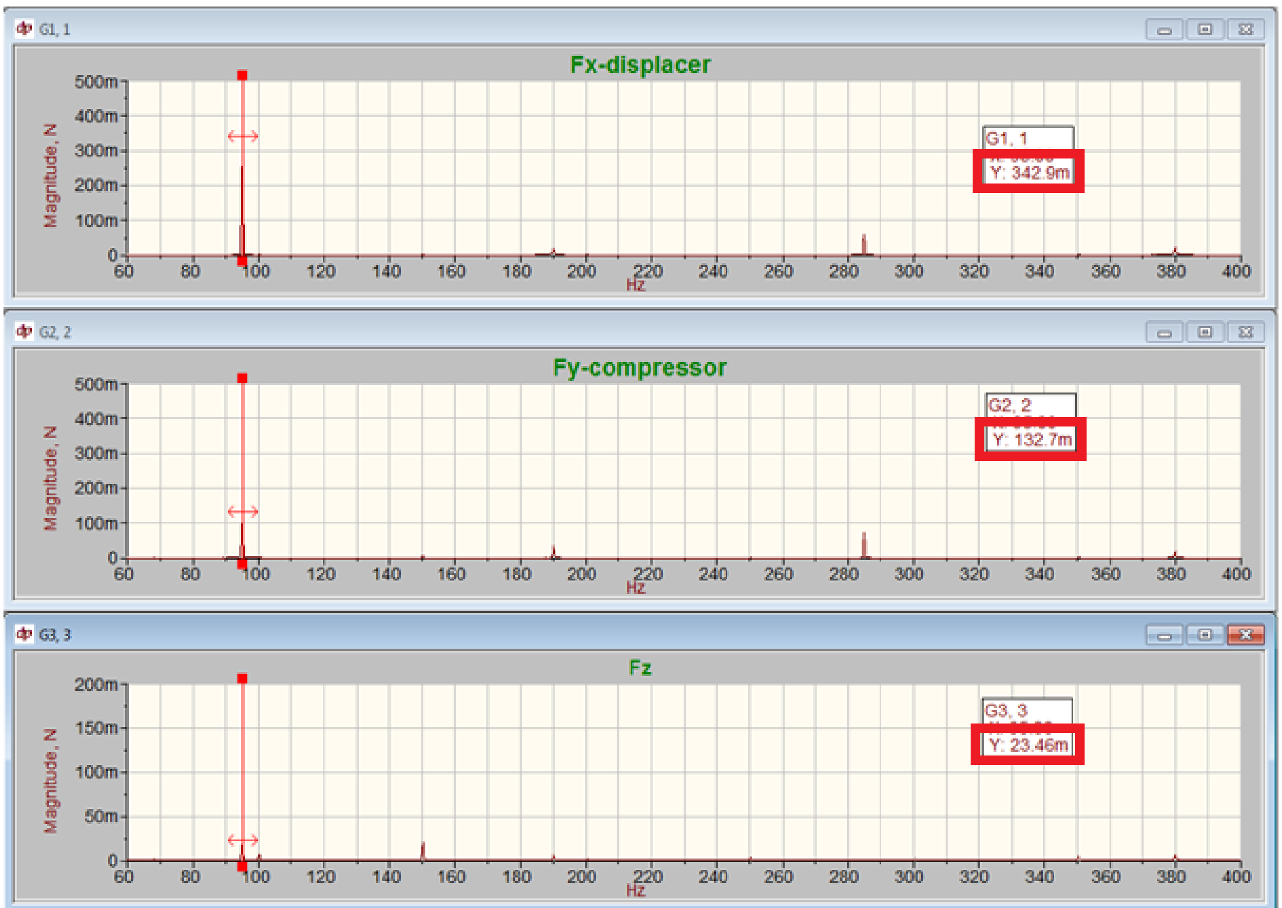

Figure 16. K588 reduced induced forces at 23^{0}C ambient temperature, 180mW @150K heat load.

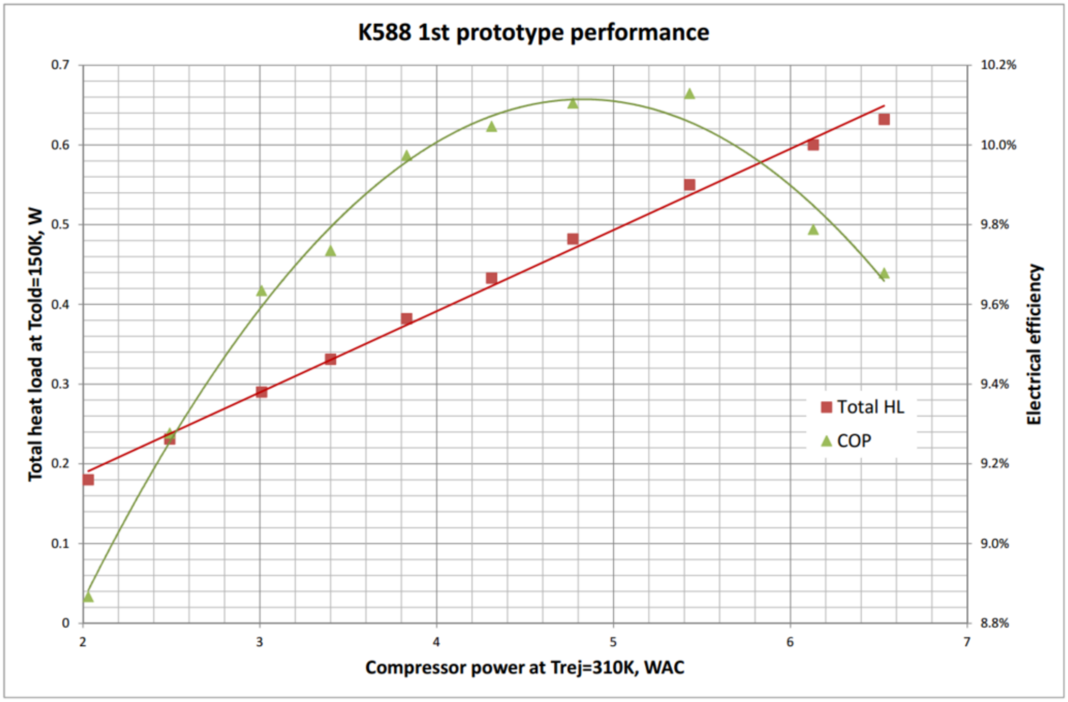

Figure 17. K588 Performance

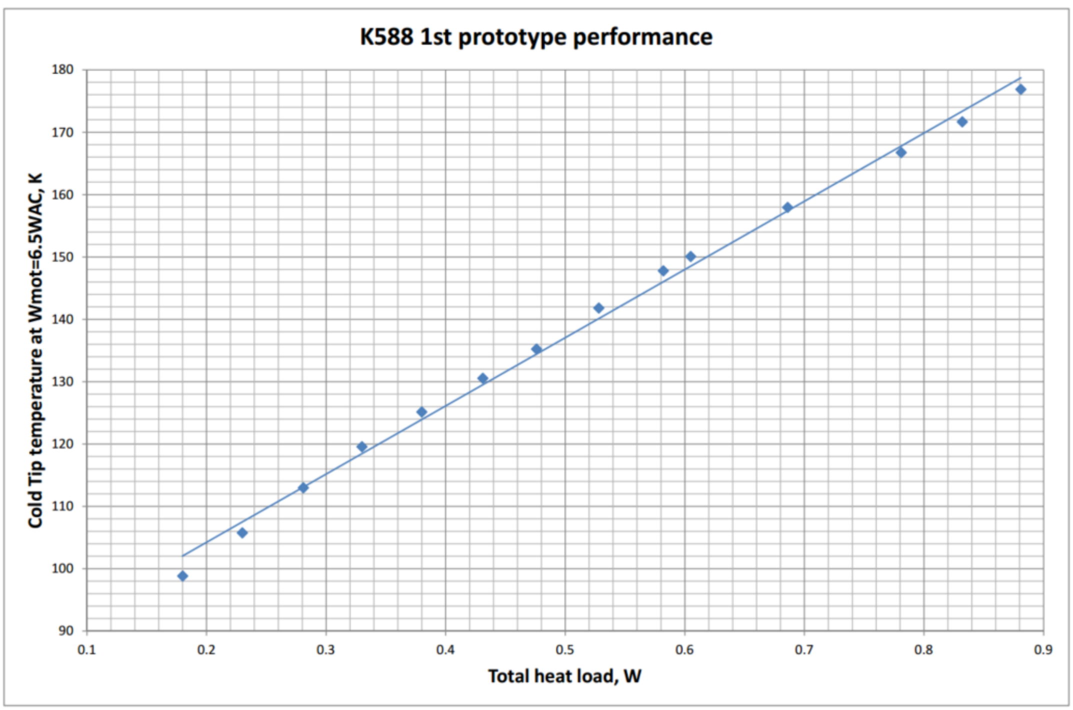

Figure 18. K588 Performance

3. COMMON COLD FINGER

The new common cold finger that was designed in collaboration with market leading companies in order to create a cold finger that will fit a variety of HOT coolers. By doing so, the new common cold finger will eliminate the need to design a new Dewar for each cooler. The new common cold finger 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 the self-heat load while keeping the required rigidity of the cold finger. RICOR maintains that both the K588 and the K580 models are designed to use the new common cold finger.

Figure 19. K580 cryocooler with real working SCD detector

The K580 coolers were tested with both a K580 cold finger and a common cold finger. A performance comparison is presented in Table 4.

Table 4. Performance comparison of the K580 with different cold fingers.

	With K580 cold finger		With common cold finger	
	220mW @ 23˚C @ 150K	**330mW @ 71˚C @ 150K**	**220mW @ 23˚C @ 150K**	**330mW @ 71˚C @ 150K**
Number of coolers	7	7	3	3
Regulated power consumption [W]	1.75	3.2	1.72	3.04
maximum power consumption [W]	9.32	10.76	9.82	10.95
Minimal temperature [K]	95.18	111.14	85.59	104.6

Furthermore, a full performance mapping was conducted to provide accurate comparison between both K580 configurations. Figures 20 through 28 provide the comparison graphs whereas A0 represents the K580 cold finger and A1 represents the common finger configuration.

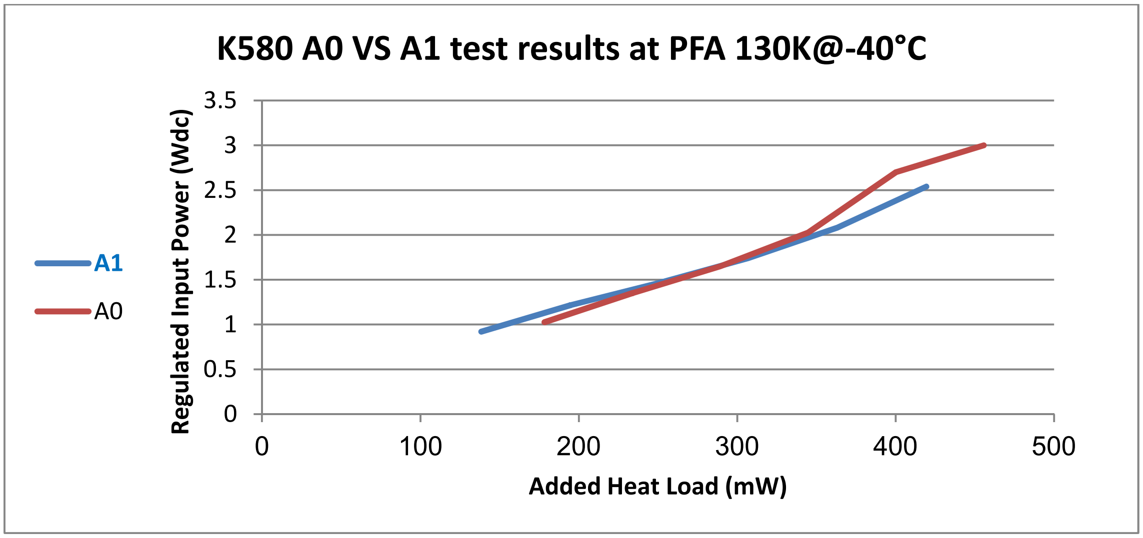

Figure 20. K580 A0 VS A1 test results at PFA 130K@-40°C

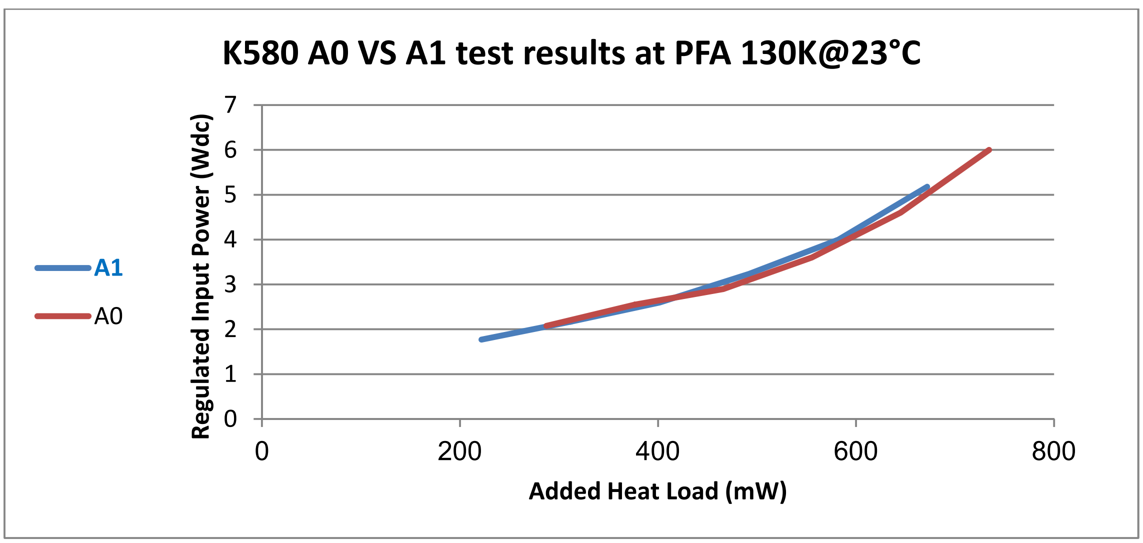

Figure 21. K580 A0 VS A1 test results at PFA 130K@23°C

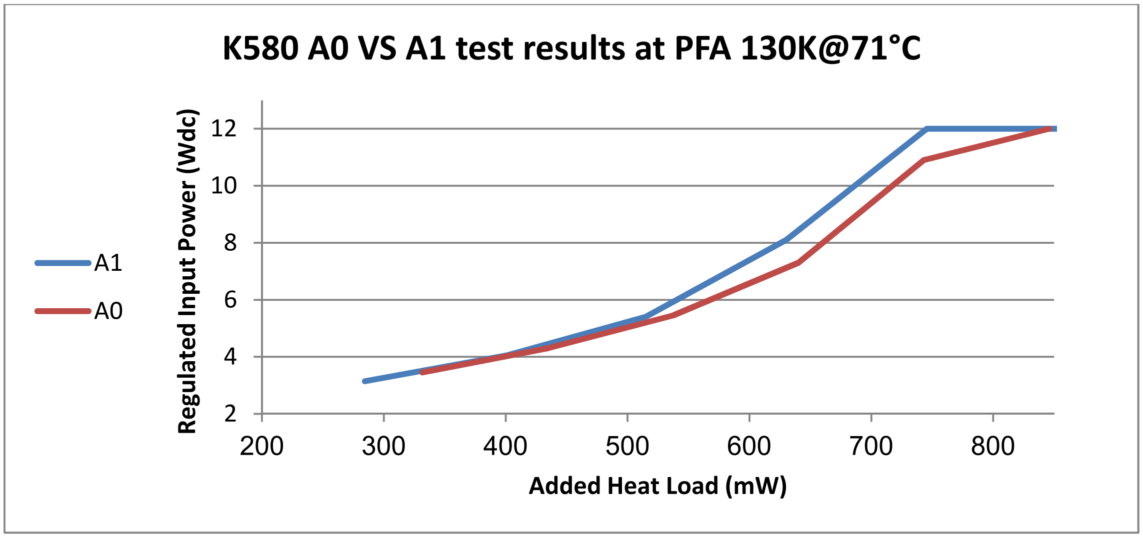

Figure 22. K580 A0 VS A1 test results at PFA 130K@71°C

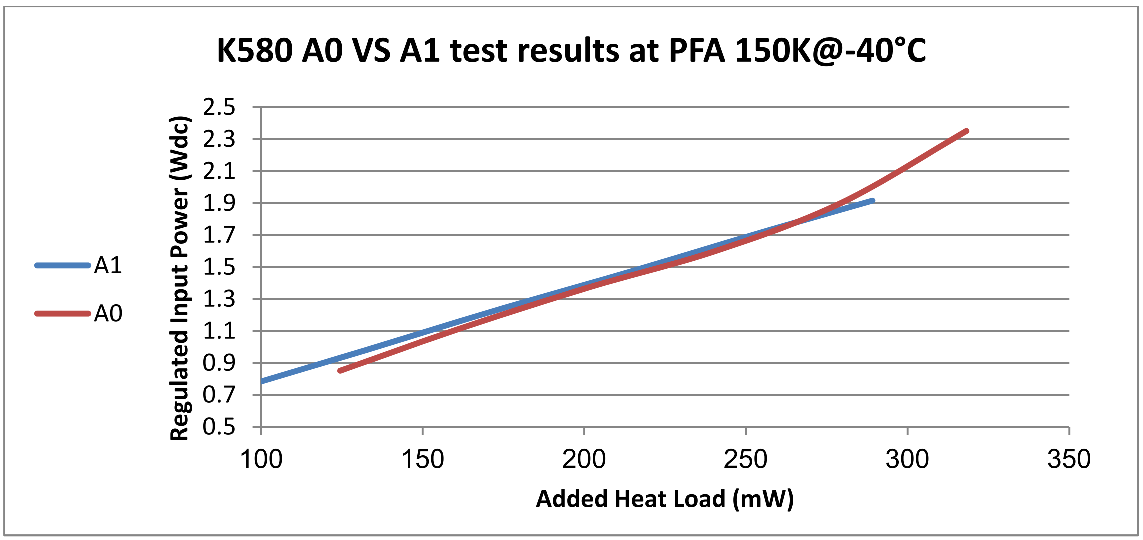

Figure 23. K580 A0 VS A1 test results at PFA 150K@-40°C

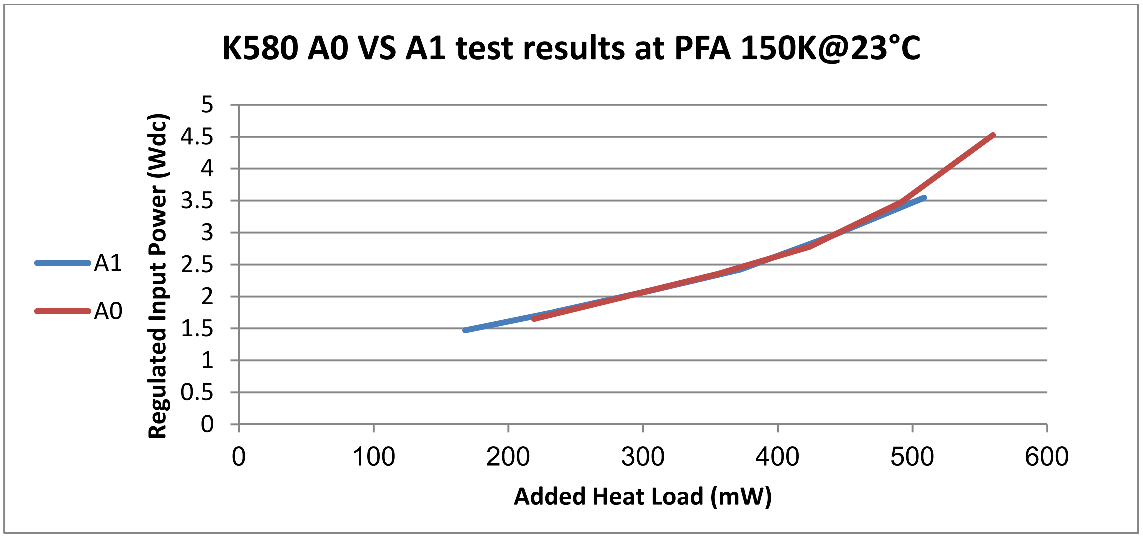

Figure 24. K580 A0 VS A1 test results at PFA 150K@23°C

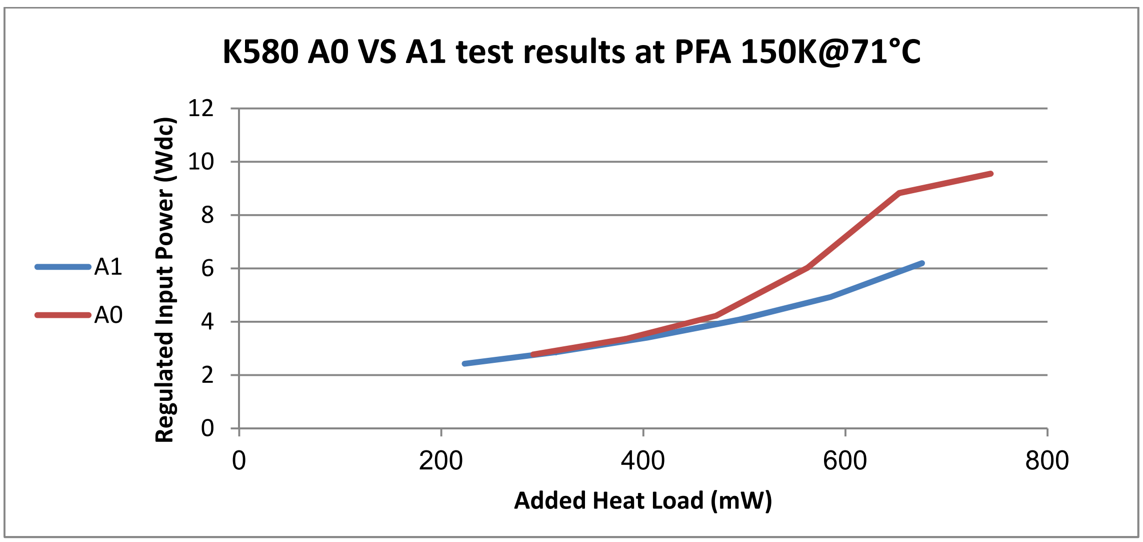

Figure 25. K580 A0 VS A1 test results at PFA 150K@71°C

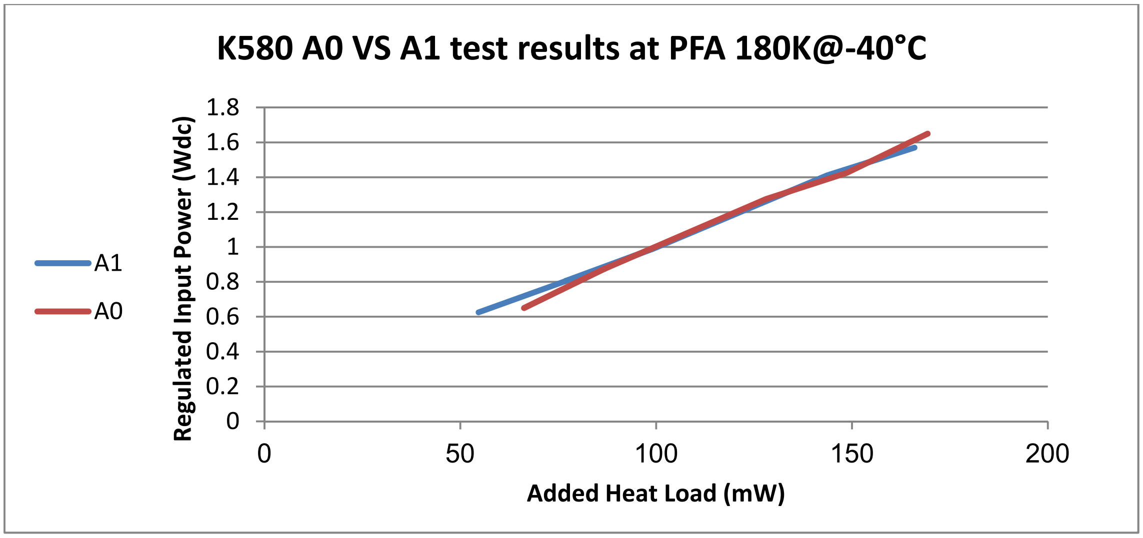

Figure 26. K580 A0 VS A1 test results at PFA 180K@-40°C

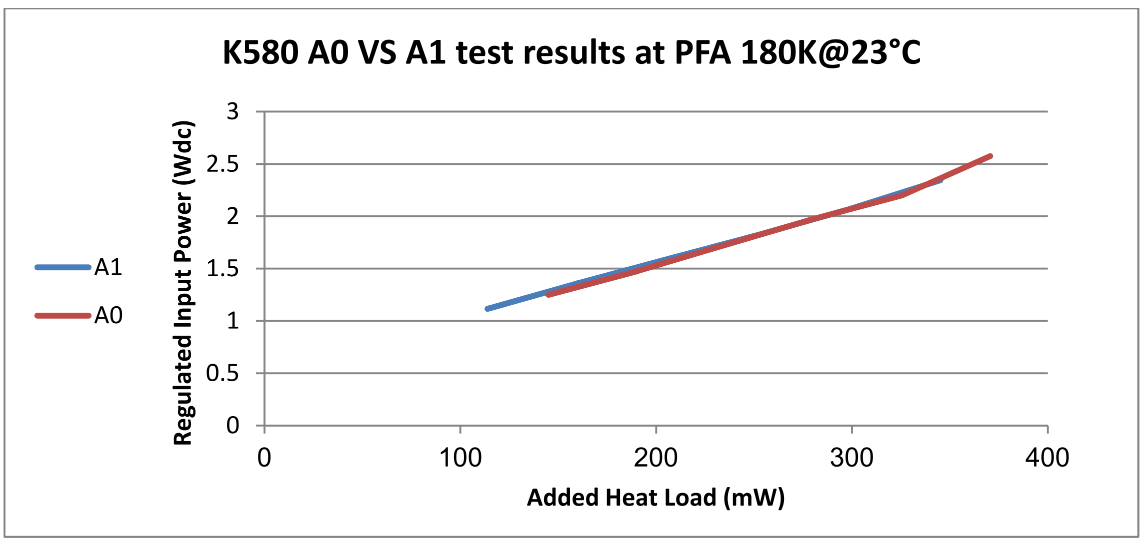

Figure 27. K580 A0 VS A1 test results at PFA 180K@23°C

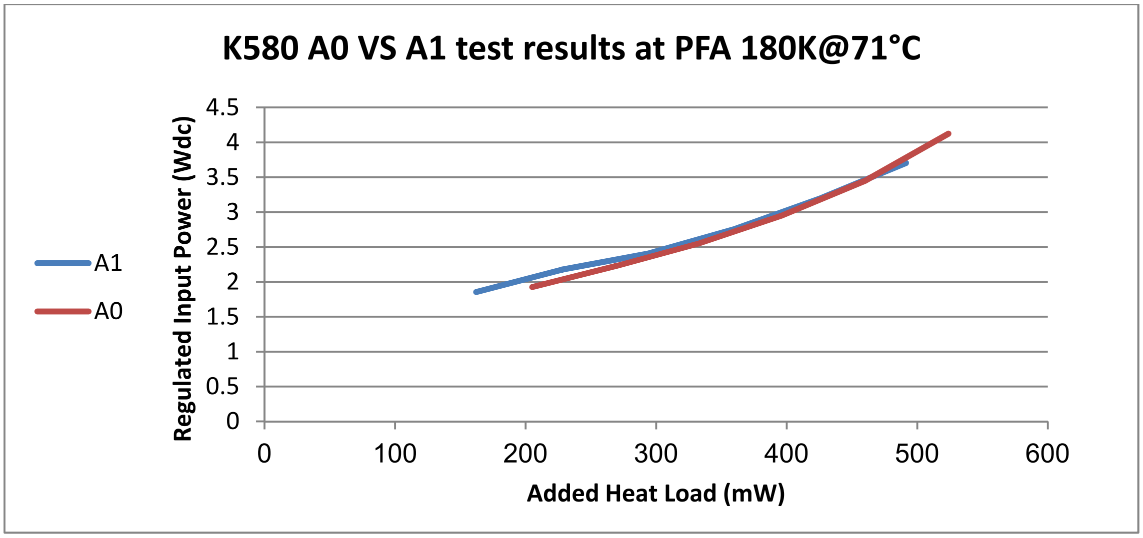

Figure 28. K580 A0 VS A1 test results at PFA 180K@71°C

4. HALT RESULTS

To ensure the quality of the K580 cooler and its reliability in harsh environments, a HALT test was conducted on two K580 coolers. The setup is shown in Figure 29. And the results are summarized in Table 5.

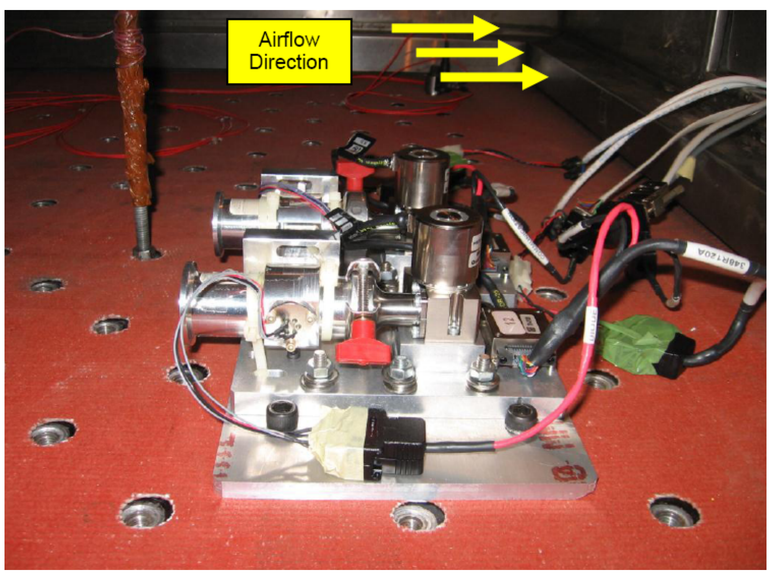

Figure 29. K580 HALT test setup

Table 5. K580 HALT test results.

Test Environment		Test Description	Test Result	Remarks
Temperature [°C]	Vibration			
Minimum temperature	None	-70 °C	O.K.	
Maximum temperature	None	+120 °C	O.K.	
20 °C (room temperature)	Maximum gRMS	+29.0 gRMS	O.K.	Manually Stopped
Temperature cycling	None	-70 °C to+120 °C	O.K.	
Temperature rate per min.		30 °C	O.K.	
Combined cycling	29.0 gRMS	-70 °C to+120 °C	O.K.	
Minimum temperature ramp	0.5 * maximum gRMS	-60 °C	O.K.	
Maximum temperature ramp	0.5 * maximum gRMS	110 °C	O.K.	

5. RELIABILITY EVALUATION

Life testing with RICOR products is an integral part of the development of every cooler. RICOR has conducted extensive life tests for both the K562SI and K580. Dozens of cryocoolers have already undergone, and are still undergoing life tests, as a part of our continuous improvement approach. The current life test status is provided in table 6. The estimated K580 cryocooler life time corresponds to the basic MTTF of more than 15,000 hours. The K580 running coolers setup is shown in Figure 30. The current run status for both regular and common finger models is provided in table 7.

Table 6. K562SI life test

K562 SHORT IMPROVED LIFE TEST			
cooler serial number	21-1427	21-1493	21-1404
Pressure [bar]	13	13	13
Freq. [Hz]	N/A	N/A	N/A
Load [mw]	210	210	210
CT[K]	150	150	150
Motor Temp.[◦C]	45	45	45
Running hours	6969	9019	8747
Average	**8245**		

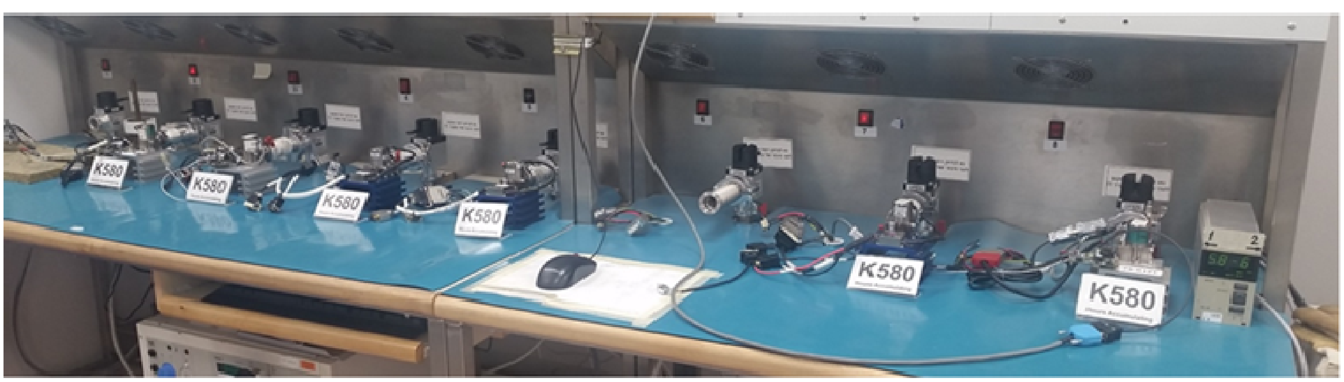

Figure 30. K580 life test running coolers setup.

Table 7. K580 life test

#	S/N	Self heat load	Average power @150K&23°C	Accumulated hours	Status
1	78-0121	210mW	1.49W	13,594 hr	Under test
2	78-0129	220mW	1.63W	10,800 hr	Under test
3	78-0134	235 mW	1.79W	13,593 hr	Under test
4	78-0135	230 mW	1.72W	9,602 hr	Under test
5	78-0228	225mW	1.98W	2806 hr	Under test common cold finger
6	78-0230	225 mW	1.58W	2080 hr	Under test common cold finger

6. FUTURE WORK

Development and qualification of two coolers, the K562S Short Improved and the K580 models has already been completed and the coolers are available as qualified off the shelf products. The K562 life test was launched and 3 coolers have already gained more than 7000 working hours. The K580 controlled life test is planned to be launched during Q1/2017. During 2017, several improvements will be implemented in the K580 cooler and controller in order to improve its-efficiency and to add speed and torque control applications for the reduction of the induced moments and the parasitic power consumption. 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.

7. SUMMARY

RICOR has made significant progress with the development of cryocoolers for HOT IR detectors. The K580 cryocooler, with the common cold finger is a commercial product and joined the K562SI model, after passing the initial development phase successfully. The K562SI has been successfully manufactured in quantities and the statistical data looks promising. The K588 model was re-designed to fit the common cold finger and to meet growing market demands in terms of weight, cost and interfaces. Rigorous testing was done on the K580 cooler to provide data on performance after the introduction of the common cold finger. Evaluation testing of the K580 by clients provides results of performance DDA level. At present it is in continuous supply to a number of customers around the world. The K588, including its new controller, is currently at the testing stage, and soon it will be prepared for engineering series manufacturing and qualification testing. Life testing of both the K562SI and the K580 is still running while K580 with common cold finger controlled life test is at its beginning.

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