RICOR K527 highly reliable linear cooler – applications and model overview

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ABSTRACT

The K527 linear cooler was developed in order to meet the requirements of reliability, cooling power needs and versatility for a wide range of applications such as hand held, 24/7 and MWS. During the recent years the cooler was incorporated in variety of systems. Some of these systems can be sensitive to vibrations which are induced from the cooler. In order to reduce those vibrations significantly, a Tuned Dynamic Absorber (TDA) was added to the cooler. Other systems, such as the MWS type, are not sensitive to vibrations, but require a robust cooler in order to meet the high demand for environmental vibration and temperature. Therefore various mounting interfaces are designed to meet system requirements. The latest K527 version was designed to be integrated with the K508 cold finger, in order to give it versatility to standard detectors that are already designed and available for the K508 cooler type.

The reliability of the cooler is of a high priority. In order to meet the 30,000 working hours target, special design features were implemented. Eight K527 coolers have passed the 19,360 working hours without degradations, and are still running according to our expectations.

Keywords: Cryocooler, Split linear, Stirling, RICOR, MWS, HOT, SWaP, K527

1. INTRODUCTION

As demand for a small, low weight, long-life cryocooler increased [1], RICOR developed a micro-miniature split Stirling single-piston linear K527 cooler. After the initial development, a diversification of the model took place to cover different market demands. The following configurations were developed:

a. A generic configuration for most applications (basic design).

b. A ruggedized configuration for MWS applications.

c. A low voltage configuration for hand held systems [2]

d. A HOT configuration, developed for working with a short cold finger [3,4]

e. A K508 cold head configuration.

Qualification tests were conducted and successfully passed for all configurations. So far more than 400 coolers of different configurations were sold worldwide to a variety of clients and for various uses. In order to provide sufficient reliability justification for the MTTF design, a life test is running at RICOR's facilities, testing the average run time of the K527 cooler at different conditions. The life test is still running and we are providing interim data.

2. CONFIGURATIONS AND PERFORMANCE

As system requirements vary across potential applications, a single cooler is unable to fulfil the entire scope of needs for the complete range. However with a strong basic design, development of several variations of the model can provide sufficient compatibility for a wide range of needs. The K527 split Stirling linear single-piston micro miniature cooler development is such an example. The range of solutions comprises five major versions of the K527 currently manufactured by Ricor. The basic parameters of each configuration are presented in Table 1.

Table 1. K527 modifications data

Parameters	Generic design	K527 for hand held systems	Ruggedized K527 cooler	K527 for HOT detectors	K527 with a K508 cold head
Environmental conditions (*)	GB, GF,GM, AIC	GF,GM	AIF,AUC,AUF, ARW	GB, GF,GM, AIC	GB, GF,GM, AIC
Ambient temperature	-40°C to 71°C	-30°C to 58°C	-54°C to 85°C	-40°C to 71°C	-40°C to 71°C
Temperature stability	±0.2K	±0.2K	±0.1K	±0.2K	±0.2K
Cooler weight (including cold head and controller)	380gr	370gr	520gr	360gr	410gr
Compressor dimensions All in mm	∅34 X 61.5	∅34 X 61.5	□35 X62.5	∅34 X 61.5	∅34 X 61.5
Cold Head dimensions	∅31 X 89.4	∅31 X 89.4	∅36.7 X 89.4	∅31 X 65.3 (Short cold head)	∅31 X 89.4
Steady State input power @ 230C	3.5 WDC @ 200mW	6 WDC @ 200mW	6.5 WDC @ 500mW	4.5 WDC @ 250mW	7 WDC @ 200mW
Cold head temperature	95K	77K	110K	150K	77K
Voltage input	12 VDC	12 VDC	28 VDC	12 VDC	12 VDC
Cooling capacity	670mW @71°C@95K	500mW @71°C@77K	800mW @85°C@110K	500mW @71°C@150K	500mW @71°C@77K
MTTF	>22,500 hrs	>20,000 hrs	>25,000 hrs	>30,000 hrs	>20,000 hrs

Each configuration was tested according to Table 1 and the load lines are presented in Figures 1-2.

(*) GB – Ground, Benign; GF – Ground, Fixed; GM – Ground, Mobile; AIC -Airborne, Inhabited, Cargo; AIF - Airborne, Inhabited, Fighter; AUC - Airborne, Uninhabited, Cargo; AUF -Airborne, Uninhabited, Fighter; ARW- Airborne, Rotary Winged.

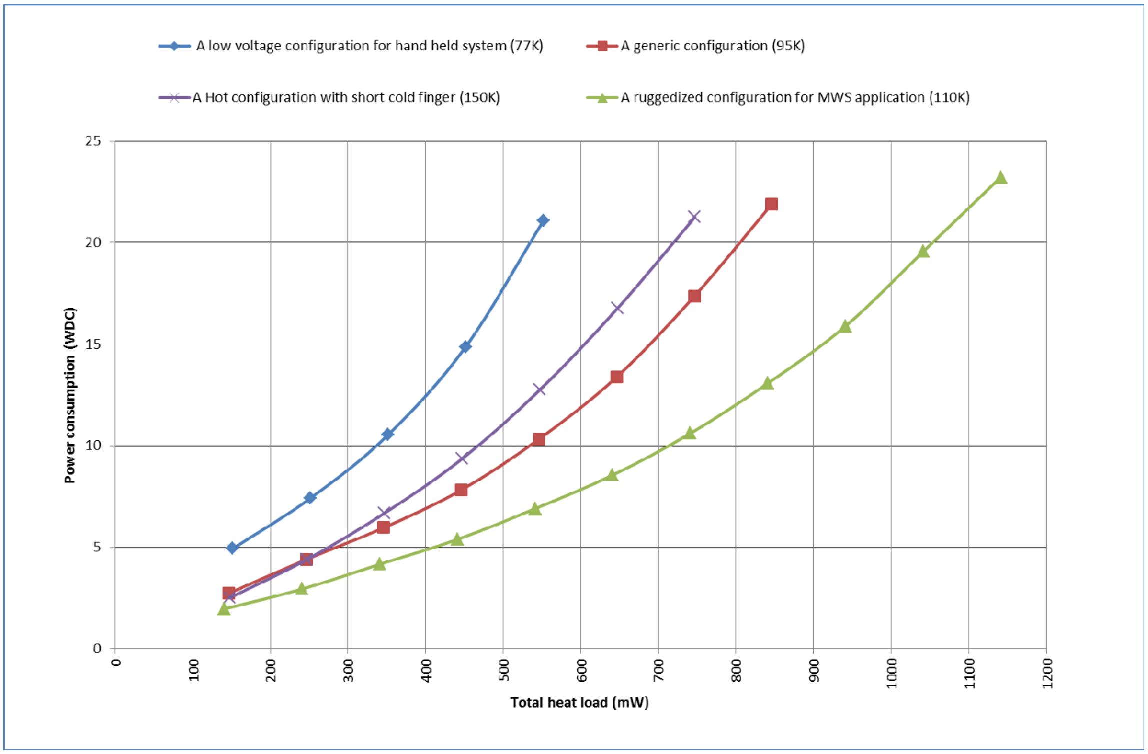


Figure 1. K527 Load lines @ 23°C

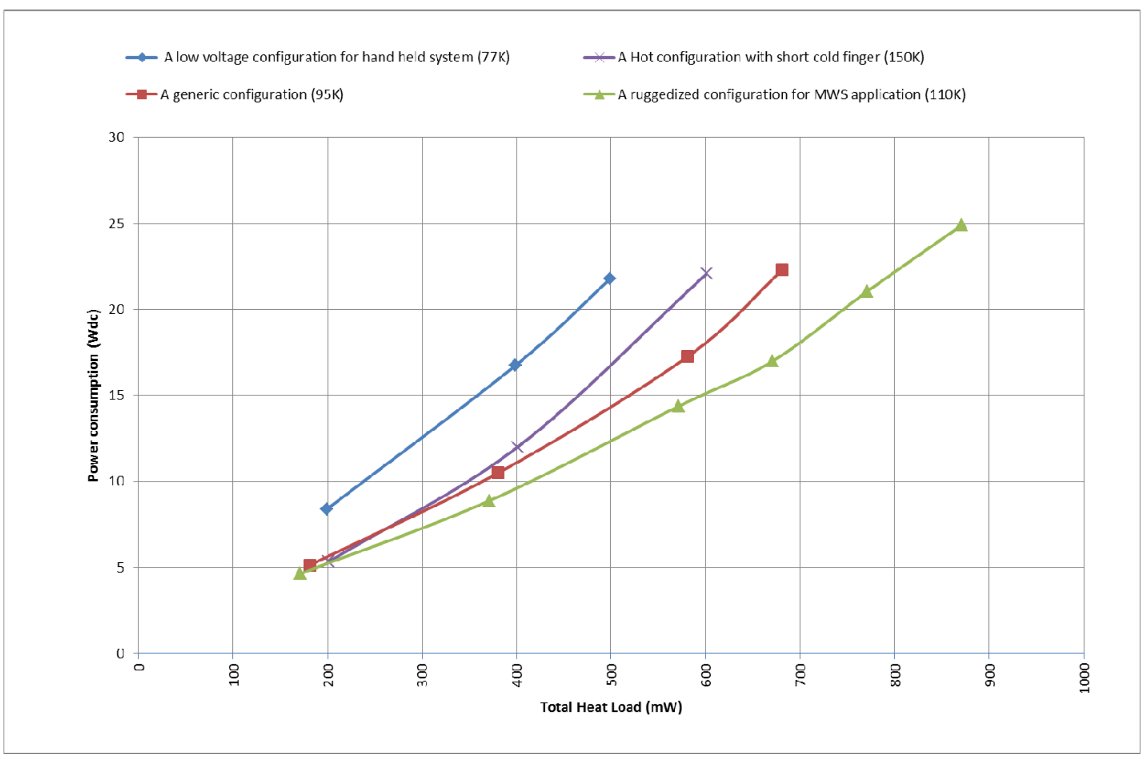


Figure 2. K527 Load lines @ 71°C

2.1 K527 generic version

The essence of the design is the development of a high reliability, low weight and small dimensional cooler according to Figure 3. For that reason, the K527 generic model was designed to work for over 20,000 hours. In addition, the initial design took into consideration the goal of cooler miniaturization producing a cooler weighing less than 400gr including controller and cold finger. The generic K527 cooler is designed to work at ambient conditions of -40°C to +71°C with a cooling capacity of 500mW@71°C@95°K, at the average steady state temperature stability within 0.2°K.

The generic version is a single piston compressor type with the benefit of adding TDA to it when needed. The TDA can reduce the induced forces in the ratio of 20 at least. The cooler's motor is designed outside the gas domain in order to minimize the risk of gas contamination, and to improve reliability and maintainability by elimination of a feedthrough. The compressor can be fixed either around the motor or on the front mounting flange, according to the system architecture needs.

The generic version can be operated either with 28V or 12V controller. The 28V controller is of a standalone ruggedized design, while the 12V controller has small footprint for use in compact systems.

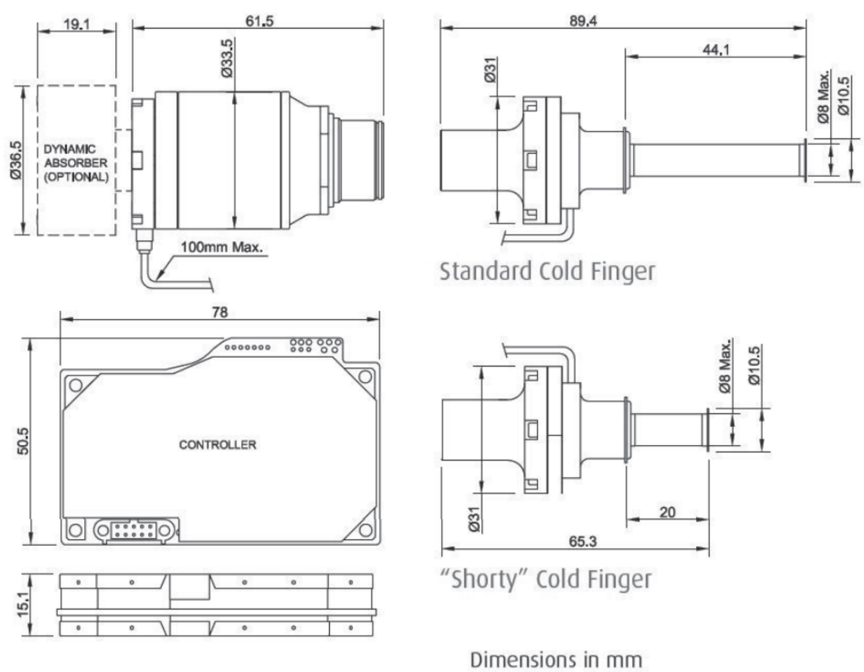


Figure 3. K527 outline dimensions

2.2 K527 for hand held systems

The K527 cooler for hand held systems [5, 6] is a low weight, low power, and low vibration model (see Figure 4). As known, hand held systems operate at a smaller range of ambient temperatures compared to other systems, which means operating at the typical range of -30°C to +58°C. The cooler operates at 12 VDC input voltage to the controller, which is compatible with the majority of the hand-held cameras. Due to the market demand for this cooler, the K527 hand held configuration was adapted to work at 77K, while at this FPA temperature the average temperature stability at steady state is ±0.1K. As the one of the requirements of a hand held system is a low vibration level, TDA is attached to the K527 compressor in this configuration. This allows for suppression of the induced force from 9.4Nrms down to 0.32Nrms, providing about 30-fold suppression, as shown in Figure 5 and Figure 6 respectively.

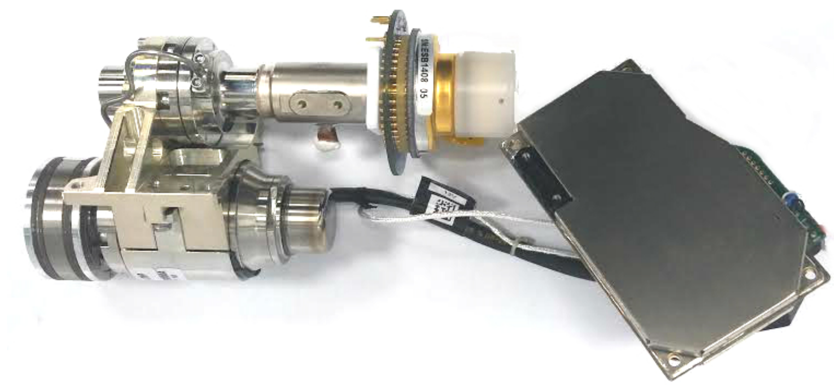


Figure 4. K527 photograph for hand held application (With TDA)

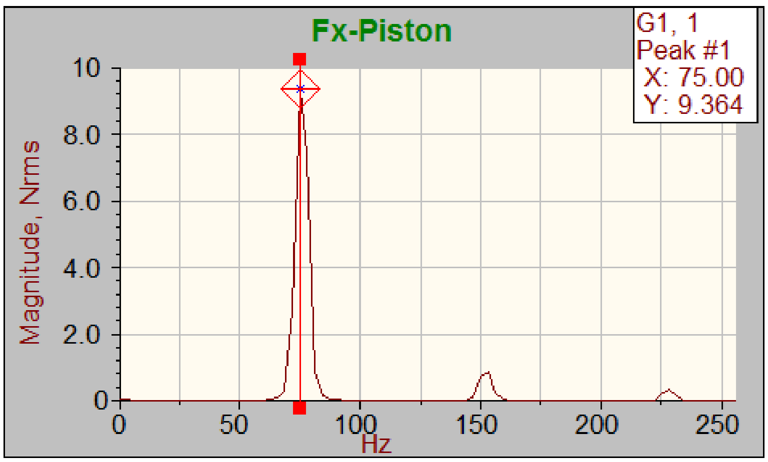


Figure 5. K527 Induced forces without TDA

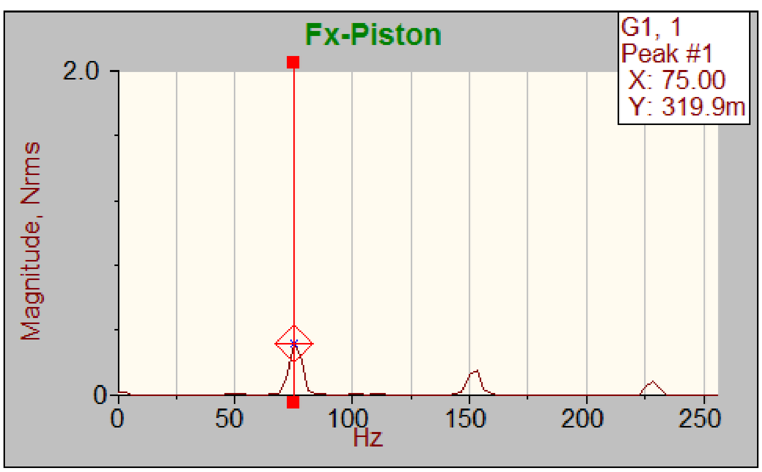


Figure 6. K527 Induced forces with TDA

2.3 K527 for airborne systems (ruggedized version)

The K527 cooler has been modified and ruggedized to meet the harsh ambient condition demands in airborne systems [7], such as high and low temperature, extreme vibration conditions, short cool down time and a low input power at high ambient temperatures (less than 10W). To comply with the extended ambient temperature conditions, the cooler was modified to operate at a -54°C to +85°C temperature range. To evaluate the cooler performance stability, temperature cycles screening was preformed, as per the graph shown in Figure 7.

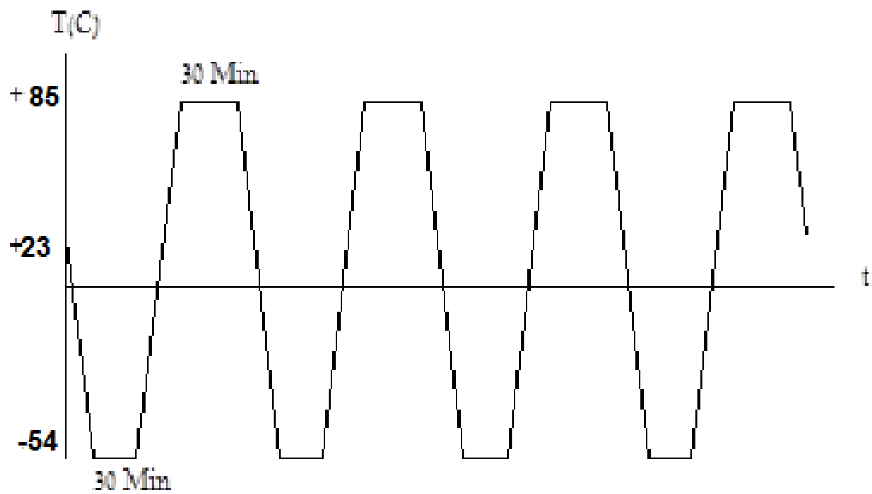


Figure 7. ESS temperature cycles screening

The evaluation was done on more than 20 coolers in order to obtain sufficient statistics; the ATP results after thermal cycles are shown in Table 2.

Table 2. ESS thermal cycles test results

CRITERIA		AVG. Results
23°C	Cool-down time	1’39”
	Steady-state input power	4W
	Steady- state temp. stability	0.07K
	Leak test results	$1X10^{-8}$ SCCS
-54°C	Cool-down time	1’25”
	Steady-state input power	1.4W
	Steady- state temp. stability	0.06K
71°C	Cool-down time	1’49”
	Steady-state input power	6.7W
	Steady- state temp. stability	0.08K
85°C	Cool-down time	3’20”
	Steady-state input power	8.3W
	Steady- state temp. stability	0.1K

To ensure desired endurance to random vibrations, testing was conducted according to the profiles shown in Table 3 and Figure 7.

Table 3. Random Vibration Test values

	X Axis	Y Axis	Z Axis		X Axis	Y Axis	Z Axis
frequency [Hz]	**PSD [g^2/Hz]**	**PSD [g^2/Hz]**	**PSD [g^2/Hz]**	**frequency [Hz]**	**PSD [g^2/Hz]**	**PSD [g^2/Hz]**	**PSD [g^2/Hz]**
10	0.024	0.024	0.024	550	0.33	0.2	0.1
40	0.024	0.024	0.024	600	----	0.6	----
51.7	0.04	0.04	0.04	750	0.33	0.6	----
250	----	0.04	----	850	0.07	0.05	----
300	0.04	----	0.04	1200	----	----	0.1
350	----	1.2	----	1250	0.07	----	----
360	----	----	1.4	1400	0.1	----	----
450	----	1.2	----	2000	0.003	0.001	0.001
500	----	0.2	1.4		12.9 g rms	18.6 g rms	18.3 g rms

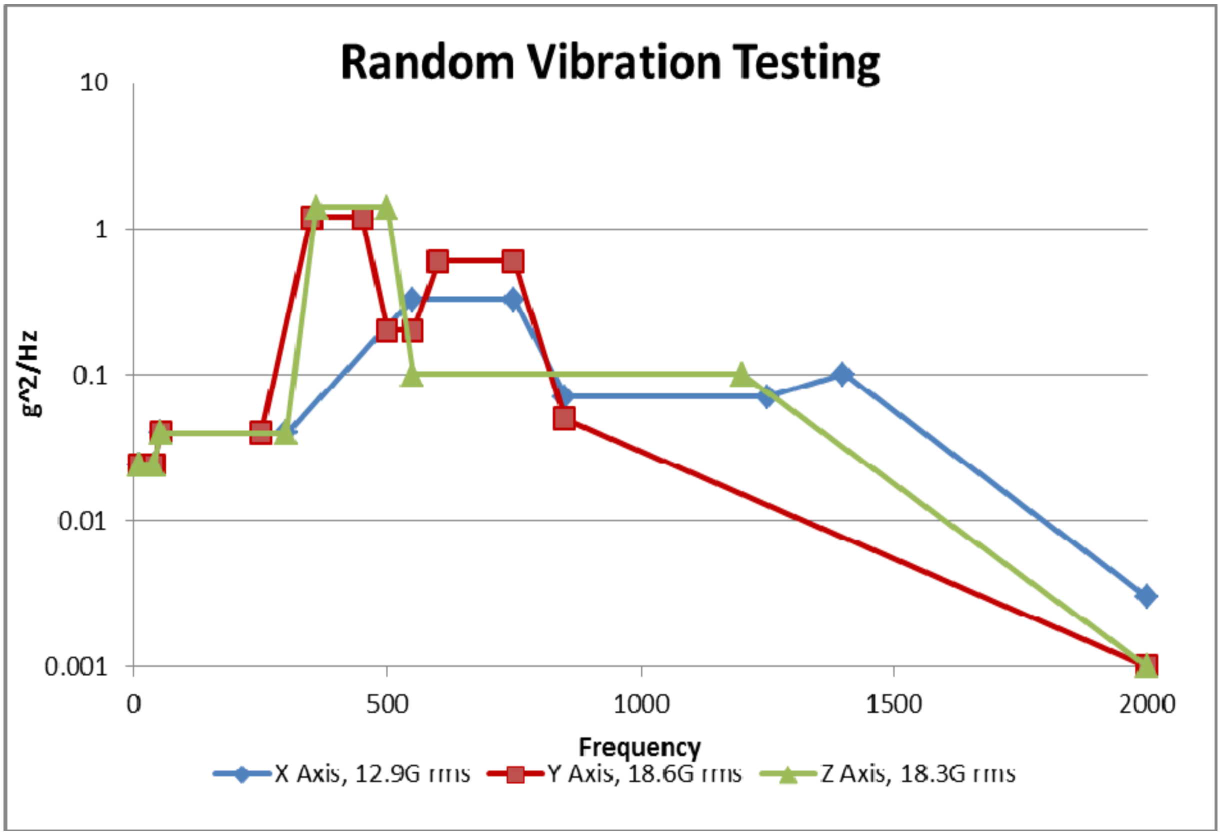


Figure 7. Random vibration test profile

The ruggedized K527 configuration (see Figure 8) comprised a heat-sinking cradle designed to hold the compressor and the motor connector. The 28V ruggedized digital controller was designed to meet the environmental conditions and was tested successfully. The controller has special features providing temperature stability at the specified conditions.

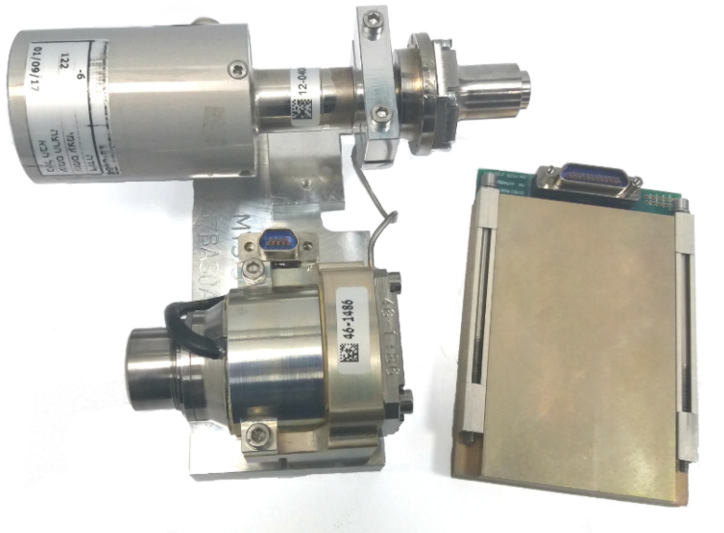


Figure 8. Photograph of ruggedized K527 configuration

2.4 K527 for HOT detectors

With the growing demand for HOT (High Operation Temperature) detectors [6], a K527 configuration was designed to operate at the 140K - 180K range (see Figure 9). In this configuration, the cold head was optimized to fit HOT detector demands, allowing to reduce the cooler weight and to shorten the cold head length. With the 12VDC input voltage, the cooler can obtain low operation power at room temperature in steady state operation, with an average power consumption of less than 3.5W, while maintaining up to 600mW cooling power at 71°C ambient temperature. Being a micro-miniature cooler, the K527 for HOT detectors usually comes with TDA, allowing the reduction of induced vibration down to 0.3 Nrms at the working frequency.

Figure 9. K527 for HOT detector (with short cold finger)

2.5 K527 with K508 cold head

This configuration offers a linear cooler solution of the K508 based detectors (see Figure 10). This design allows for use of the standard K508 DDA (Dewar – Detector Assembly) integrated with the K527 cooler, adding benefits of high reliability, low noise and other advantages. This solution can be implemented also in other arrangements such as generic, hand-held and ruggedized configurations. It can also replace a rotary cooler in existing systems to provide a solution for longer life requirement.

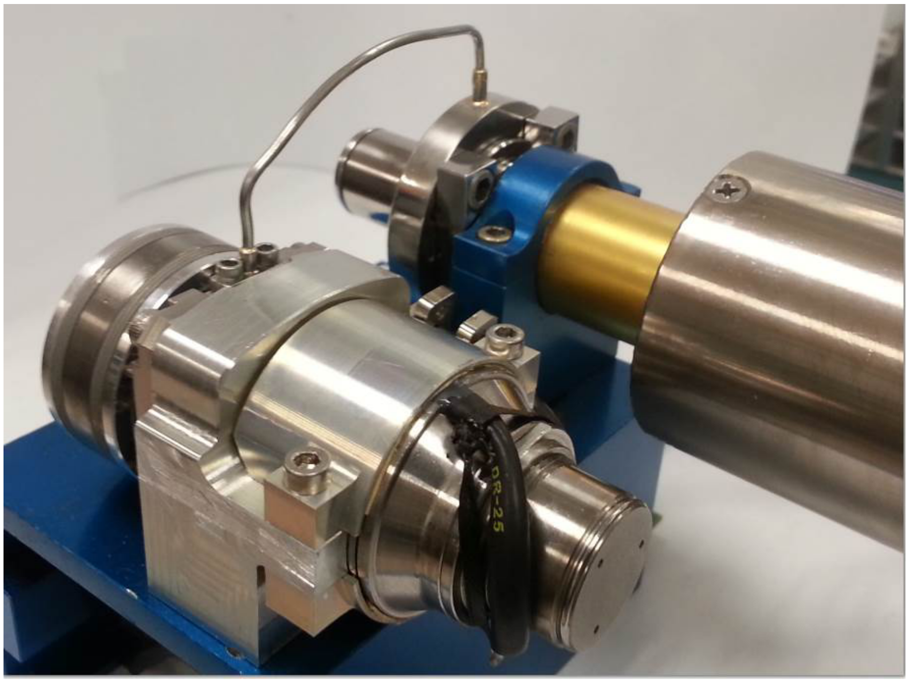


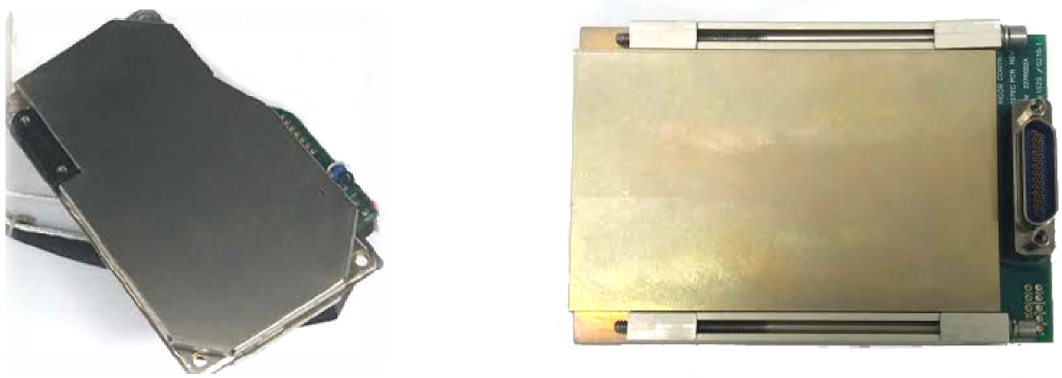
Figure 10. K527 cooler with K508 cold head

3. CONTROLLER

The K527 controller was designed in two main versions – basic and ruggedized (Figure 11). The ruggedized version is characterized by an improved closed loop thermal control algorithm which guarantees excellent temperature stability and low drifts for a wide range of ambient temperatures and input voltages. It has an advanced over-stroking protection mechanism that eliminates over-powering of the cooler, especially during the cool down period. The controller ensures smooth operation and long life of the cooler, even in a case of helium pressure reduction. The ability to detect helium pressure reduction below a critical level, protecting the cooler from over-stroke damage, is also available in that version.

Among other features of the K527 controller are the excellent power dissipation, wide input voltage range , very high power efficiency, high-resolution operation frequency adjustment and low ripple currents. General characteristics of the two controllers are listed in Table 4.

The cooler and the controller have passed successfully Accelerated Life Test (ALT) program at customer level. The controller was continuously operational at the vibration profile (see Figure 12) during 15 hours per axis. This duration is defined being equivalent to 19,400 hours at operational level.



(a) (b)

Figure 11. K527 controller, (a)-basic design, (b)-ruggedized design

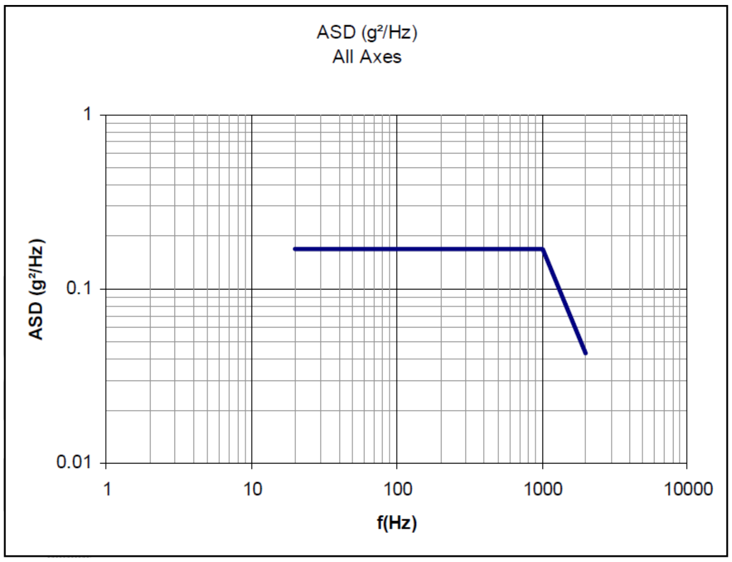


Figure 12. Vibration profile of the ALT program

Table 4. Controller characteristics

	High voltage contoller	**Low voltage controller**
Environmental condition	GF,GM,GB,AIF,AUC,AUF,ARW	GF,GM,GB
Nominal voltage	28V	7.2V
Voltage range	16V-32V	5V-12.5V
Dimension (mm)	93L x 63W x 13H	78L x 50W x 15H
Mass	128 gr	59 gr
Temperature stability	±0.1K	±0.2K
Temperature drift	0.5K	1K
Over-stroking protection mechanism	Advanced	DC offset

4. LIFE TEST

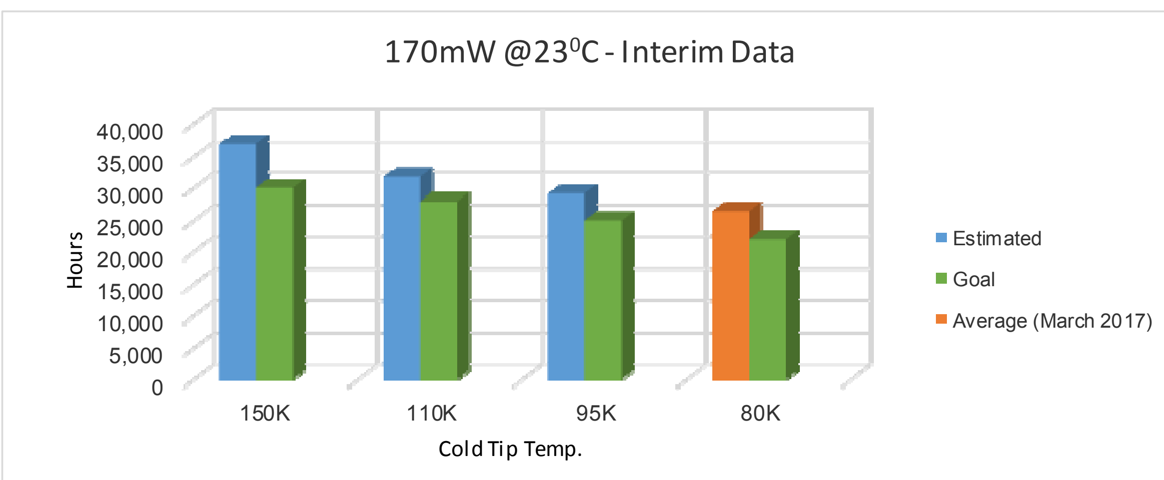
To provide real statistical data and estimate MTTF, a comprehensive life test began on January 2014. The life test data acquisition station is shown in Figure 13. The program includes 8 coolers at the generic configuration. The coolers were divided into two groups; each running with a different heat load. Five coolers were allocated for the 170mW total heat load at 80K, and three other coolers were allocated to run at 290mW total heat load at 80K.

(a)

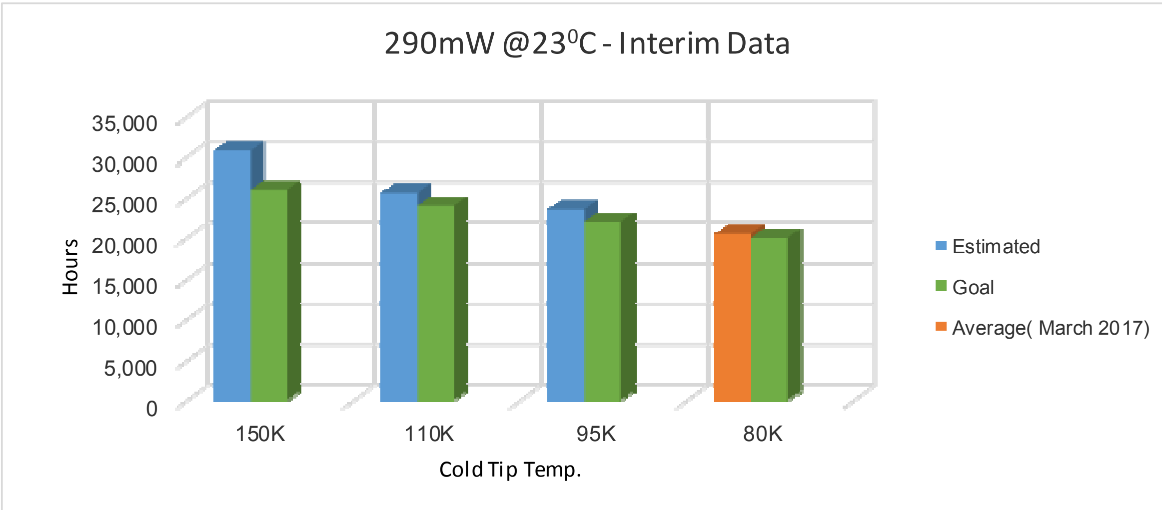
(b)

Figure 14. Life test data acquisition station, (a)-general view, (b)- close-up on the K527 group

Using empirically estimated conversion factors between different FPA temperatures, MTTF values were extrapolated for the FPA's of 95K 110K and 150K. The extrapolation shows that coolers running at 170mW total heat load may demonstrate ability to reach MTTF of 35,000 hours at room temperature and 150K FPA temperature, while the actual average running time measured at 80K is over 25,000 hours. The second group running at 290mW total heat load demonstrates 20,000 average running hours for the actual run at 80K, indicating about 30,000 estimated hours at 150K FPA temperature.. The actual test results at 80K, and other temperature estimations, versus goal values, are presented in Figure 14. Currently all the coolers under test are running and show no indication of end of life.



(a)



(b)

Figure 14. Life test results, (a)-170mW @ 23°C, (b)- 290mW @ 23°C

5. MECHANICAL AND THERMAL INTERFACING

The K527 linear cooler consists of four main subassemblies: compressor, cold head, harness and controller. The controller and the harness must be fixed to the system frame in order to hold them in position at all environmental conditions. The compressor and the cold head can be installed by rigid, semi-rigid or soft mounting. The interfacing method depends on system requirements for minimum induced vibration generated by the cold head and the compressor, as well as on the maximum removal of the heat generated. Four interfacing possibilities are available for the compressor:

a) Rigid, without TDA
b) Rigid, with TDA
c) Semi-rigid
d) Flexible

When interfacing a split linear single piston cooler into a parent system, several issues must be considered in order to use its potential most effectively. The single piston cooler generates induced forces due to unbalanced moving masses inside the compressor and the cold head. Therefore the basic approach is first to understand the need for the TDA.

<u>Rigid interfacing without TDA</u>
Using the K527 cooler in a massive system allows for usage without any means of vibration cancellation, as the massive system can typically reduce significantly vibrations generated by the cooler. Another example for usage of the K527 cooler without TDA is in a systems exposed to external vibrations higher than the vibration generated by the cooler. The mentioned cases allow for a simple conventional rigid mounting of the cooler to the system (see Figure 15)

Figure 15. K527 rigid interfacing without TDA

Rigid interfacing with TDA

Another useful configuration is a rigid mounting of the cooler into the system (Figure 17) with TDA as shown in Figure 16. In such a case the balancer will act against the total mass of the system. Using this method in light-weight systems, a second degree dynamic system is created, where the balancer is working against the superposition of forces coming from the cooler and the system. By solving this equation, the needed TDA mass for a given force set and frequencies can be calculated. As a result, the TDA with appropriate mass is able to provide sufficient vibration cancellation of the entire system. The most efficient arrangement in terms of heat dissipation is a rigid design using efficient heat sinking materials (such as Aluminum or Copper), in combination with a thermally conductive soft pad, reducing heat resistance of the contact surfaces.

Figure 16. K527 Tuned Dynamic Absorber (TDA)

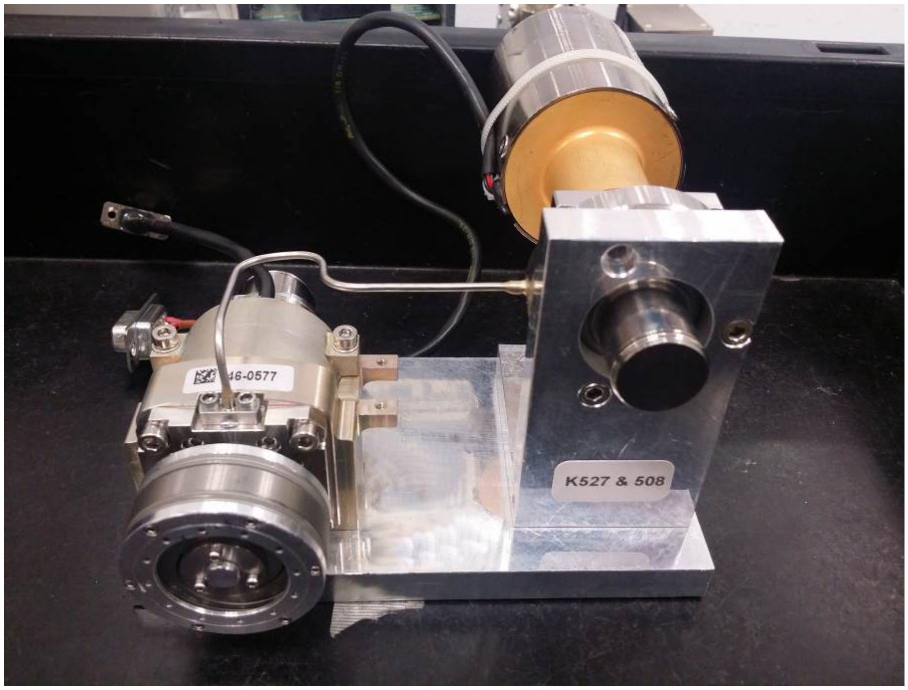
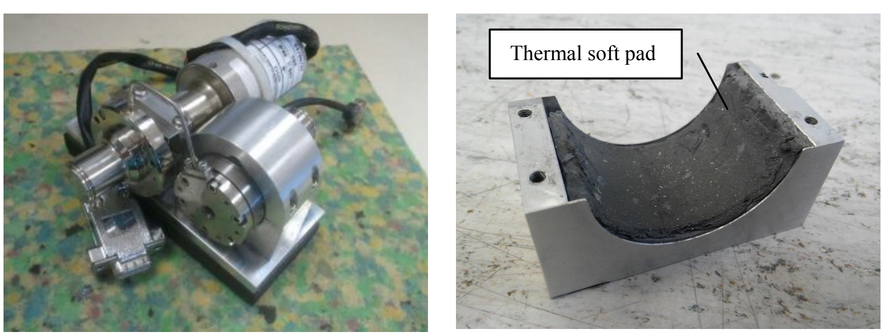


Figure 17. Rigid interfacing with TDA

In some cases, while rigid mounting with a system is not allowed, a dynamic decoupling between the compressor and the system is required. This decoupling can be achieved by the two different mounting techniques as described below.

<u>Semi-rigid interfacing</u>

Thermally conductive soft pads can be used as a low-cost, lightweight solution (see Figure 18 a,b). These thermal pads are placed between the mounting cradle &clamp of the system and compressor. It is very important to choose a suitable thickness of the thermal pad, as its thickness greatly influences the residual vibration level. In essence, choosing too thin pad may cause the whole interface to react similarly to a rigid clamping. The thermally conductive soft pad is also sensitive to the pressure applied during clamping. Therefore, the clamping of the cooler to the system through a thermal pad should take into consideration the thickness and pressure applied to the pad. As a general rule of thumb, we recommend a design based on the 2mm thick pad. Nevertheless, this recommendation can’t replace a detailed design and analysis of the optimal thickness typically yielding a fine-tuning adaptation to a system. When taking into consideration an optimal design, thermally conductive pads can provide sufficient heat dissipation, along with effective vibration control, in most configurations.



(a) (b)

Figure 18. Thermally-conductive soft pad

Flexible interfacing

For this configuration, mounting the compressor upon a suspension made of flexures or leaf springs is required. The spring suspension is able to provide a certain level of vibration cancellation even without TDA. However, in that case relative motion of the compressor against the cold head is noticeable under cooler operation and environmental vibration, thus requiring a long and flexible gas transfer line and/or protective snubbers. When adding TDA, the cooler operation does not cause relative motion of compressor against the cold head, while under environmental vibration this still may happen. In addition, a thermal interface to be designed, in order to provide an effective heat reject from compressor. Therefore, heat removal arrangement must be added to the cooler, such as copper braids shown in Figure 19. The copper braids are connected by one end to the compressor body with a heat sinking clamp, and to the system on the other end. The same setup can be applied for heat sinking of the cold head if necessary.

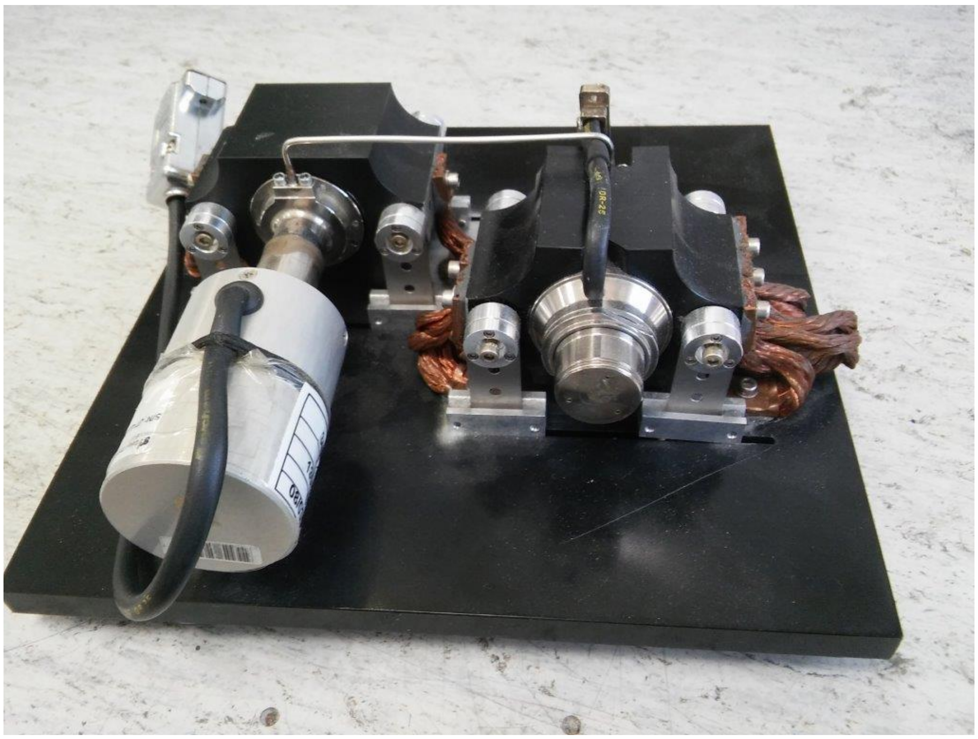


Figure 19. Leaf-spring mounting

Another heat removal setup is when the compressor is placed inside a heat-conductive bushing, combined with a spring suspension described above. The bushing allows for an effective heat rejection from the compressor under any orientation, along with high robustness under side loads imposed on the compressor. The design challenge of such a solution is the need for a special bushing allowing appropriate heat dissipation and life span. The bushing (see Figures 20-21) should be made of a suitable material, providing sufficient life time and heat transfer from the compressor to the system.

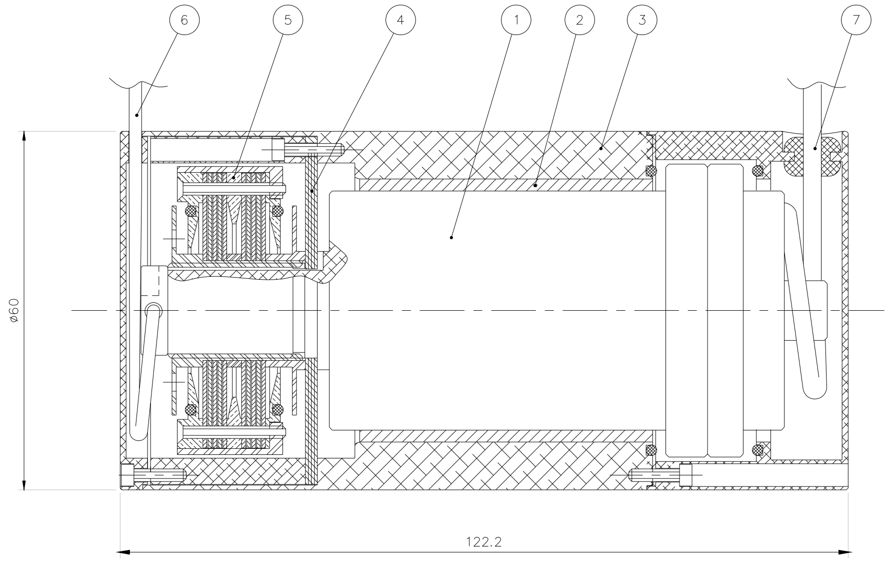
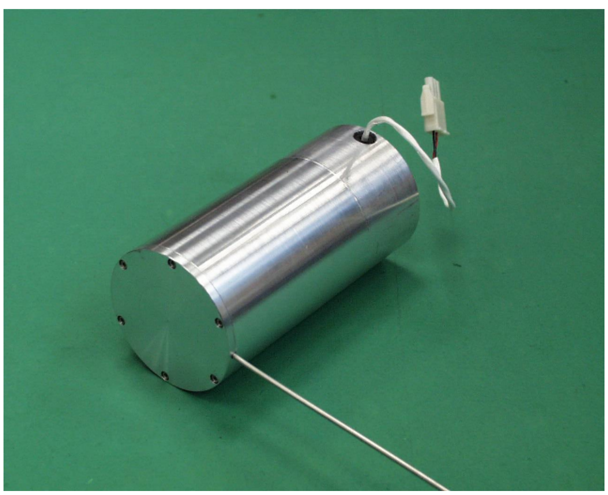


Figure 20: Bushing-mounted compressor cross section


(a)


(b)

Figure 21: Bushing-mounted compressor, (a)-outline view, (b)-parts view

In-line arrangement is generally recommended for a single-piston cryocooler, while the cold head is placed coaxially to the compressor (see Figure 22). As a result, the TDA is able to suppress vibrations of the compressor and the cold head simultaneously, which is the most effective way to control the entire cooler vibration export.

Figure 22: In-line mounting

6. SUMMARY

Ricor has introduced previously the K527 miniature, general use split Stirling linear cryocooler, equipped with an optional detachable Tuned Dynamic Absorber (TDA). Since then, extra efforts have been made to finalize development, creating several variations more suited for market demands. One variation is a low power version with TDA, working in the standard range of temperatures from -30°C to 58°C for hand held systems. Another variation is a ruggedized cooler for airborne systems working in ambient temperatures of -54°C to 85°C. As part of the diversification of the model, a K527 for HOT detector was also developed with a 750mW@150K cooling capacity based on a shorter cold finger version for size reduction. Finally, to provide a longer life alternative solution to the K508 rotary cooler, a K527 modified compressor was integrated with a K508 cold head, allowing integration of the K527 cooler with an existing K508 DDA. The complete range of the coolers has successfully passed all the required qualification testing for mass production. In order to prove the ability of the cooler to operate over 20,000 hours, a life test is currently running, testing 8 coolers at different heat loads, with several coolers passing the 26,500 hours mark.
Finally, to allow correct interfacing of the cooler to the system, several mounting configurations were tested resulting in a range of appropriate thermal and vibration interfacing of the K527 cooler to various systems under different conditions.

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