Advanced Ricor Cryocoolers for High-End IR Missile Warning Systems and Ruggedized Platforms

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ABSTRACT

The growth in world demand for infrared missile warning systems (MWS) has impelled the development of new technologies, in particular, special ruggedized cryogenic coolers. Since the cryocooler is a core component in ruggedized platforms, RICOR has met the challenge by developing new models able to withstand high ambient temperatures above 110°C, as well as harsh vibration levels, both derived from airborne fighter applications.

One of the development efforts focused on a cryocooler regenerator and cold finger optimization, in order to achieve high cooling capacity at 95K FPA and the efficiency of about 5.3 % at 102 °C.

In order to withstand harsh environmental vibration and high ambient temperature range, the mechanical parts of the cryocoolers were designed and tested for a high structural safety factor along with weight minimization.

The electronic design concept was based on encapsulated controllers, the PCB of which has been designed with internal heat sinking paths and special components able to withstand ambient temperatures of up to 125°C.

As a final stage of development, four cryocooler models (K544, K549, K527 and K508) were successfully qualified under harsh environmental conditions, both by RICOR and by system manufacturers. Also life demonstration tests were performed with these models.

The cryocoolers were designed and tested successfully to meet requirements of military standards MIL- STD-704D, MIL-STD- 461E and MIL-STD-810F reflecting real mission profiles in harsh environment.

Keywords: Cryocooler, Stirling, MWS, COP, Infrared, IDDCA, RICOR

1. INTRODUCTION

Missile Warning System (MWS) provides a key element in advanced self-protection systems of fighter aircraft, helicopters, transports and commercial aircrafts. By using infrared imagery and signal processing, the MWS detects and tracks an incoming missile's hot plume instantly as it appears within a protective sphere surrounding the aircraft. The system discriminates between threatening and non-threatening missiles, by evaluating the missile's trajectories. When a threat is detected, the system alerts the aircrew and automatically activates countermeasures. Most of these systems have to comply with harsh environmental conditions, while high temperatures and high vibrations are imposed. Cryocoolers are key component in these ruggedized platforms hence they have to be designed and manufactured according to these demands. Furthermore, since the MWS of an aircraft may comprise multiple IR detectors, in order to cover 360° sphere of threat directions, the required multi-cooler array reliability must be addressed using higher safety factors.

In order to satisfy the growing demand for infrared missile warning systems, RICOR initiated new designs based on a novel design management concept [1] thoroughly addressing the following topics:

- Efficient thermal interfaces

- Ruggedized mechanical interfaces
- Improved precision of detector positioning
- Highly reliable helium sealing concept
- Highly reliable cryocooler mechanism

The "Robustool" method [3] was implemented in order to evaluate the robustness rating at the different stages of the product's life cycle, from concept to production. Since the cryocooler is a core component in ruggedized platforms, new cryocooler models and derivatives were qualified in order to withstand harsh environmental conditions such as high vibration and mechanical shocks level combined with extreme ambient temperatures.

The cryocoolers aimed for survival under harsh environmental conditions were designed on the basis of standard products, in order to keep the long-term production experience acquired, the well-known cooling performances, and field-proven statistics. The new advanced models vs. the standard models are presented in the following Table 1.

Table 1: Ricor cryocooler models for ruggedized platforms

	Advanced cryocoolers model	Based on	Cooling capacity	Cooler type
1	K508N	K508	0.5W	Rotary Integral
2	K544	K543	1W	Rotary Integral
3	K527 MWS Derivative	K527	0.75W	Single Piston Linear (SPL)
4	K549 MWS Derivative	K549	0.75W	Split rotary
5	K572	K527	1W	Dual – Opposed Linear (DOL)
6	K570	K527	1W	Single Piston Linear (SPL)

2. ENVIRONMENTAL REQUIREMENTS TO MWS RUGGEDIZED PLATFORMS

In recent years RICOR has developed new models and derivatives based on the IDDCA concept, which means the cryocooler's cold finger is a part of the Dewar assembly. It's possible to divide these models into three main groups:

- Rotary integral cryocoolers, which are compact, intrinsically robust, and highly efficient thermodynamically. For example, the latest model named K544 (1W cryocooler) has been qualified to meet the most severe environmental conditions.
- Split linear cryocoolers for considerations of long life. The latest model tested successfully for extreme conditions named K527 (0.75W cryocooler)
- Split rotary cryocoolers for considerations of heat management and some degree of freedom with the induced forces levels. The latest model tested successfully named K549 (0.75W Cryocooler) with a "Hybrid - 18N" controller inside

These models were designed and qualified to withstand extreme ambient temperatures and high vibration levels. A cryocooler consumes electrical power which eventually converts to heat in the system. In order to have a well-balanced thermal system, a cryocooler must be designed to withstand the extremely high temperatures developing in system. On the one hand, the dissipated heat warms up the cryocooler's environment, and on the other hand, the cryocooler must start and operate after standing-by in a very low ambient temperature, thus it must be well designed in order meet these requirements. Table 2 summarizes the temperature limits of Ricor's cryocooler models for ruggedized platforms application. In order to meet these extreme temperatures all the materials used in the cryocoolers' mechanism were reviewed and some of them were replaced by more suitable ones. In addition, the manufacturing processes were also reviewed and were optimized for that purpose.

Table 2: Temperature limits

Cooler Model	Low operation limit (°C)	High operation limit (°C)
K508,K508N	-46	+85
K549 MWS Derivative	-46	+106
K544	-46	+102
K527	-54	+85
K570	-54	+85
K572	-54	+85

In terms of mechanical vibration, the harsh environmental conditions are basically divided into three main categories:

- Operational vibration, at which the cryocooler must operate properly keeping the focal plane temperature at specified stability.
- Mechanical shocks, at which the cryocooler has to operate properly.
- Endurance vibration, at which the cryocooler either may or may not operate during the test.

Table 3 shows the three main categories of qualification test levels of vibration.

Table 3: Typical vibration rates

Cooler Model	Operation Random Vibration (20-2000Hz), g r.m.s	Endurance Random Vibration (20-2000Hz), g r.m.s	Mechanical Shock (saw tooth), g
K508,K508N	27.0	27.0	50 (11Msec)
K549 MWS Derivative	15.5	18.8	20 (11Msec)
K544	18.4	21.2	20 (11Msec)
K527 MWS Derivative	12.9	19.8	20 (11Msec)
K570 (*)	12.9	19.8	40 (11Msec)
K572 (*)	12.9	19.8	40 (11Msec)
(*) Under development / design goal			

3. SYSTEM CONSIDERTIONS RELATING TO CRYOCOOLERS

In order to achieve a good interfacing between a cryocooler and a system under harsh environmental conditions, both have to be designed properly. This is due to the cryocooler design may have an impact on the system design, and vice versa.

For example, the rotary type cryocooler is an integral unit comprising compressor, cold head and controller. For most cases, this type can meet all ruggedized platforms thanks to intrinsic rigidity, compact size, and low weight. Another advantage is that typically the thermal, mechanical and optical interfaces are based on a common surface. However sometimes, an additional heat management of controller and motor may be necessary. In this case three additional configurations should be considered:

Split controller: Mount the controller outside the motor subassembly while connecting it by means of the harness (see Figure 9). In this case the heat management of the controller may be improved significantly. For thermal considerations, the efficiency of the controller is between 80% and 90% at steady state operation of the cryocooler.

Thermal management of the motor at system level –The solution could be a mechanical flexible item like copper braid or heat-pipe, in order not to over-constrain the cryocooler mechanically. In most cases the extra heat ejected from the motor surface is about 10% to 20% of the total power of the cryocooler.

Thermal management of the motor at the cryocooler level – Sometimes it is the ultimate solution in terms of thermal management as well as the mechanical interfacing. In this case an extra space for the cryocooler has to be taken into consideration (see Figure 3).

The mechanical coupling of the IDDCA to the system sometimes is not enough for high optical accuracy in terms of geometrical demands like perpendicularity between the cold end tip and the mounting surface. In this case, a simple solution can be implemented while the interfacing surface of the housing is parallel to the FPA (see Figure 1). In this configuration a parallelism of 10 microns can be easily achieved.

The rotary split-type cryocooler is a unit where the cold head is separated from the compressor – motor - controller subassembly. Also in this case, the controller can be separated from the cryocooler as described above. The splitting concept enables the thermal management to be more robust and effective at the system level. The mechanical coupling of the IDDA to the system can be done through the Dewar envelope instead of through the cryocooler's cold head. In most cases the heat rejected from the cold head is about 20% to 40% of the total power.

The linear single piston design is also a split cryocooler, which means that all the considerations mentioned above regarding split rotary type also apply. In general, the linear mechanism gives a long life solution because of the lack of ball bearings. In most MWS un-gimbaled systems the induced forces are a minor issue; therefore, the unbalanced single piston linear type cryocooler is the better solution in terms of size, weight and cooling capacity.

The linear dual-opposed cryocooler is also a split design providing intrinsic vibration cancellation in contrast to the single-piston approach. In this case the balanced compressor is a robust solution for all platforms in terms of cooling capacity and low forces induced by the compressor.

4. DESIGN ASPECTS

As mentioned before, the design of MWS cryocoolers was based on standard products improved specifically to meet ruggedized platforms requirements. In order to achieve this goal, the “Robustool” methodology [3] was implemented, in combination with a risk management program using high safety factors.

“Robustool” methodology

The basic idea is to create a testing procedure that checks the product throughout all development stages. At each stage the procedure examines sensitivity of the product to specified vibration and temperature profiles. Another example is the sensitivity of the design to unexpected usage. The procedure includes basic questions to be answered regarding the product, such as: "Can the product operate at a higher elevated temperature exceeding the specification?" The “Robustool” method relies on the “checklist” that enables a quantitative comparison of a number of concepts in terms of their ability to fulfill the harsh environmental requirements. The following benefits of the method could be emphasized:

- Early evaluation of the product robustness
- Location of the features required improvements
- Obtaining a quantitative score of the product redundancy beyond the specified conditions
- Early addressing of the product improper use

.This methodology is appropriate for every product; however for cryocoolers some unique aspects are also of concern:

- Cooling capacity: To be designed with a margin of >15% in cooling power.
- Skin temperature: To be designed and validated at the temperature gradient (above ambient) >20% from specification, at all conditions.
- Vibration: To be designed and validated for survival under values exceeding the specified levels, until a failure will occur.

Cooling capacity

One of the major considerations is the cooling capacity under extreme conditions. A cryocooler must maintain the target temperature of the FPA at the required value and stability. In order to prevent temperature degradation in time, it is recommended to design and validate the cryocooler for a higher cooling capacity than required in the program. In some cases the cryocoolers are tested and screened out of a large production lot for selection of the best performing units. Table 4 summarizes the cooling ability under different ambient conditions. Screening out of most efficient regenerators, along with pressure and frequency adjustment, is another procedure that was used in some cases.

Table 4: Extended cooling capacity

Cooler Model	High ambient Condition (°C)	Extended Cooling ability	Regular Screening process ability Yes/No
K508,K508N	+85	0.5W@80K	Yes
K549 MWS Derivative	+106	0.6W@80K	No
K544	+102	1.3W@95K	No
K527 MWS Derivative	+85	1W@110K	No
K570	+85	0.75W@80K	No
K572	+85	0.75W@80K	No

Skin temperature

Thermal management of the system is critical for the power consumption and cooling ability of the cryocooler. The main parameter that must be taken into consideration and should sometimes be monitored is the skin temperature of the cryocooler, because it influences the ability to reject the power out of the cryocooler. In most cases the mounting surface of the cryocooler compressor is useful for heat dissipation, and sometimes it is the only place where the heat can be rejected due to the system constraints. So, the cryocooler structure must have as low as possible thermal resistance between all of its components. For example, the K544 thermal interface design included:

- sufficient thermal coupling between the motor and the compressor housing
- "stand-alone" cryocooler controller
- sufficient thermal coupling between the cold finger flange and the cryocooler mounting surface.

Figure 1 shows some design features explaining the above-mentioned considerations.

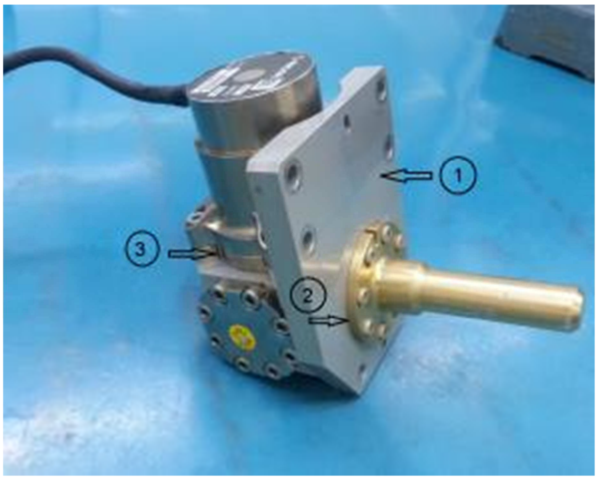

Figure 1: Thermal interfaces of K544 Cryocooler: 1) System mounting surface, 2) Cold finger mounting surface 3) Motor mounting surface

Mechanical vibration

One of the basic ideas in the “Robustool” methodology is to examine the present design, and to look for adapted features allowing it to withstand harsh vibration environment. This process starts with checking all the components and subassemblies of the cryocooler in order to evaluate the structural safety factors. Once this data is available, we can finalize possible features improvements, in order to meet the specified vibration profile. Table 5 summarizes adaption of the basic design features to the requirements specified.

Table 5: Improvements of the cryocoolers features

Cooler Model	Base model	Improvement 1	Improvement 2	Improvement 3
K508N	K508	Compressor mounting	"C" seal type	Bearings
K549 MWS Derivative	K549	Motor – compressor mounting.	Compressor mounting with sized bolts	Rugged controller housing
K544	K543	Motor – compressor mounting.	"Front mounting"	Rugged controller
K527 MWS Derivative	K527	Compressor mounting	Motor clamping	Rugged controller
K570	K527	Compressor mounting	All welded design	Rugged controller
K572	K527	Compressor mounting	All welded design	Rugged controller

The following eight features were successfully redesigned, implemented and validated in the above products.

Compressor mounting to the system

In most cases the compressor is the component of highest mass, therefore a robust mounting is required in order to provide as high as possible structural eigenfrequencies. For example, in Figure 2 it can be seen that the thickness of compressor mounting ears was increased from 3 mm to 5 mm. In a specific case we were noticed that the overall IDDCA structure was improved and the first eigenfrequency exceeded by 300 Hz.

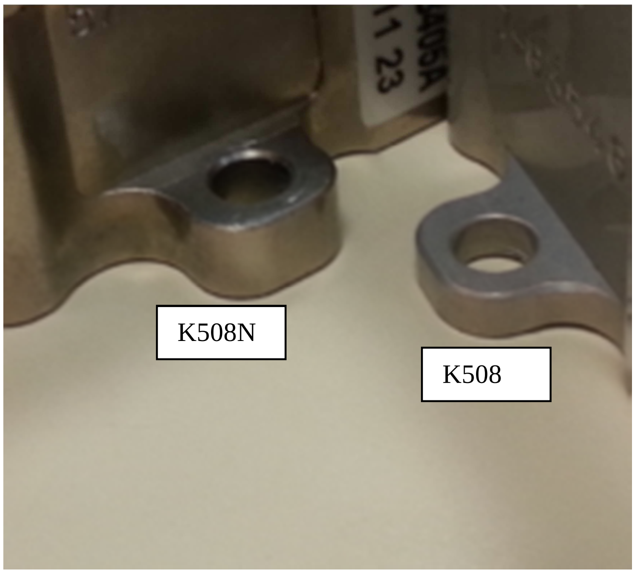

Figure 2: K508N vs. K508 mounting ears thickness

Motor mounting to compressor

The second item of a large mass in the cryocooler is the motor. The motor of the integral rotary cryocooler is mounted outside the working agent domain, which is tightened by a single bolt directly to the thin-walled cover of in-gas rotor. In order to improve rigidity of this structure, two features were redesigned to adapt the product to the ruggedized platforms:

- Four bolts were added in place of the single bolt
- The motor was tightened to the compressor housing in place of the thin-walled cover

Figure 3 shows an example of these features that were implemented in the K544 Cryocooler vs. K543 model. The same idea was used for ruggedizing of the K549 model.

Figure 3: K544 with four motor bolts (on the left) vs. K543 single motor bolt

Compressor front mounting

Front mounting surface of the integral rotary cryocooler is preferable where the ruggedized platform system requires good thermal management, system stiffening by cryocooler structure, and high-precision positioning between the detector and the system that maintains accurate line of sight. Figure 1 is an example of such a design which was implemented in the K544 cryocooler. In Figure 4 is shown another example of a linear-type cryocooler, K527 model, using a compressor front mounting design instead of radial clamping. This approach allows the designer to reduce system overall volume and mass. Figure 5 shows an example of K549 compressor mounted by means of strengthened bolts. FEM analysis was performed in order to evaluate rigidity of the structure while exposed to the high vibration level. Figure 6 shows an example of the eigenfrequency analysis of the cryocooler structure.

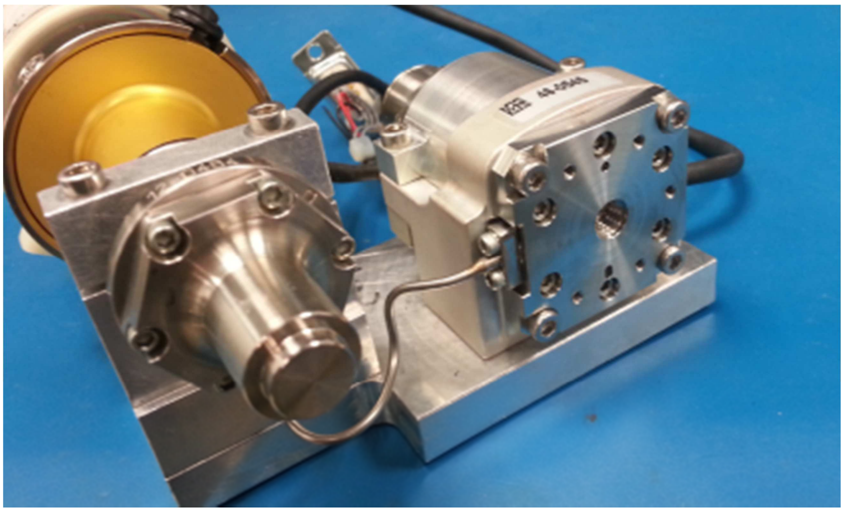

Figure 4: K527 compressor front mounting design

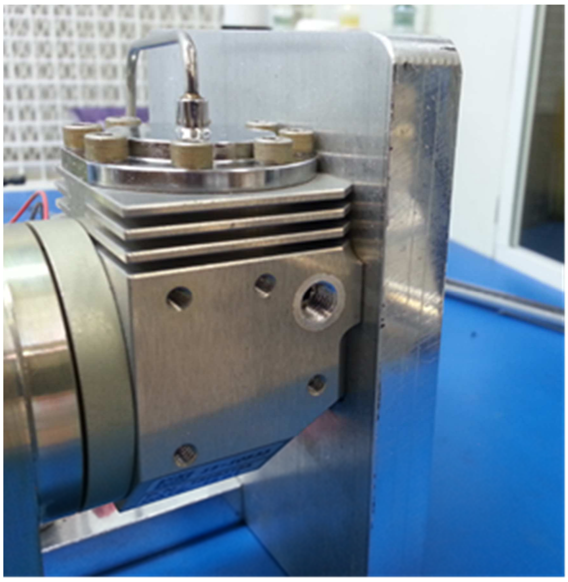

Figure 5: K549 compressor mounting using strengthened bolts

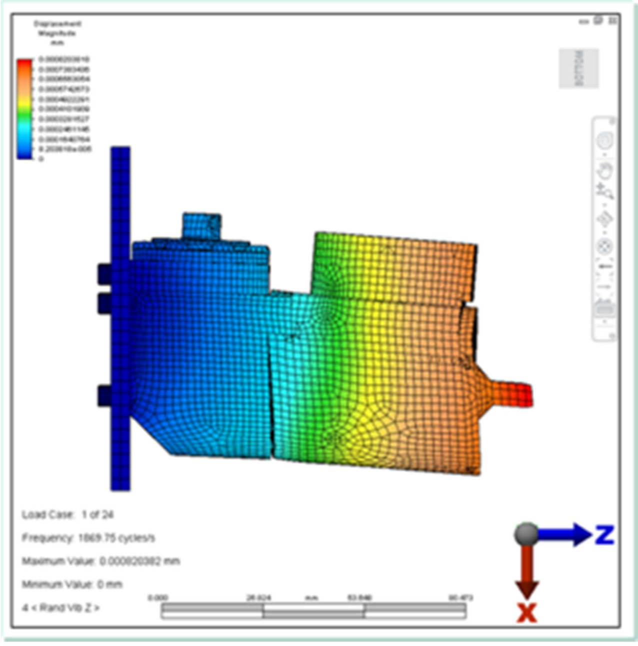

Figure 6: K549 compressor structural analysis screenshot

Motor clamping

Motor radial clamping of the linear compressor is an auxiliary feature providing an extra rigidity to the compressor structure, while it is already tightened to the system by the front mounting. In this case a secondary precaution is needed because of the possible over-constraining of the compressor, which is rigidly mounted to the two different surfaces. The solution used was the semi-rigid radial clamping of the motor. Figure 7 illustrates an example of this feature, which was implemented in the K527 cryocooler model.

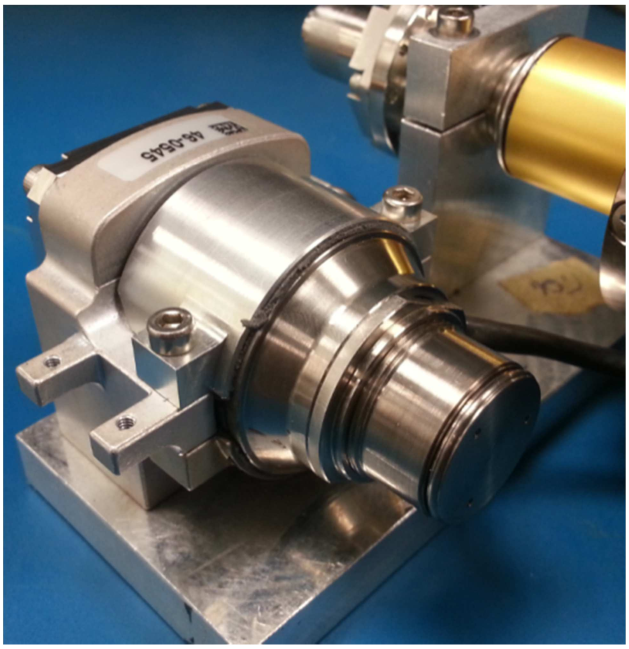

Figure 7: K527 combined mounting design: rigid front tightening and semi-rigid radial clamping

All-welded design

All-welded design is the well-known technology that is usually implemented for enclosure sealing of linear compressors. This feature is always preferable where leakage and size are of concern. From the engineering point of view, the helium leakage of the welded joints is practically negligible; they also show a negligible sensitivity to thermal expansions and mechanical stresses under temperature changes, thanks to the uniform materials involved. Figure 8 illustrates a design of this kind implemented in the K572 model.

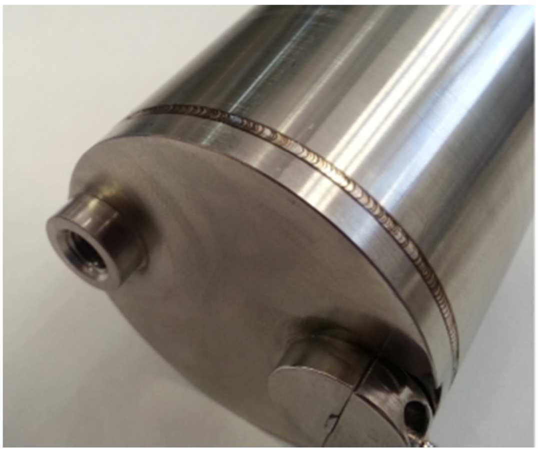

Figure 8: K572 all-welded compressor

Ruggedized controller

Controllers are an essential part of the cryocoolers, thus their design robustness should be thoroughly addressed to comply with the extreme harsh environmental conditions. Two ruggedized controllers were redesigned and qualified at RICOR, one for rotary type cryocoolers, and the second for the linear type. Both were redesigned using FEM analysis tools, and then the design was validated by means of engineering- and quality tests. Figure 9 shows the two mentioned controller types, both of them were designed using robust enclosures comprising the CALMARK clamping feature for better compactness and efficient heat dissipation. Figure 10 shows a screenshot of the FEM thermal analysis results of the controller designed for a rotary cooler.

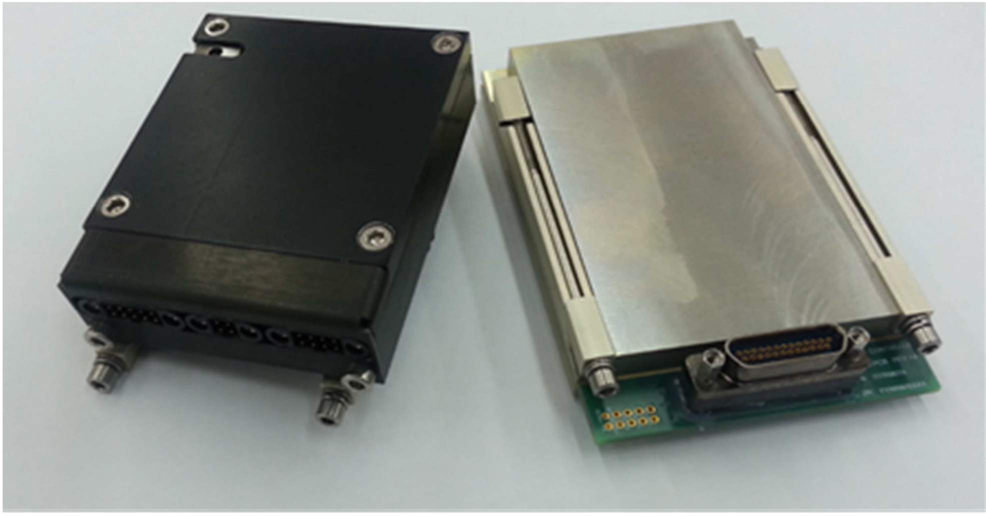

Figure 9: Ruggedized controllers: for the rotary coolers (on the left) and for the linear coolers (on the right)

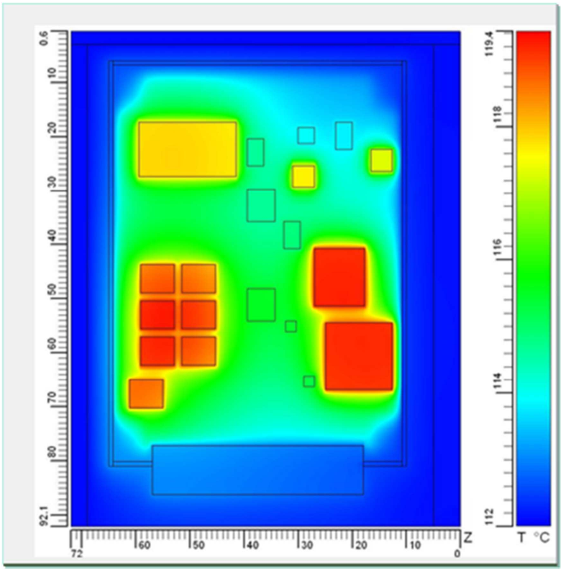

Figure 10: FEM screenshot of controller thermal analysis

Sealing concept

A crushed metal seal is the most common helium sealing type used in cryocoolers. This type of sealing is also well proven for use at ruggedized platforms. An alternative method of sealing is the "C" seal type, which however may sometimes be insufficient to withstand harsh environmental conditions. In order to improve this feature, a ruggedized "C" sealing design was used and qualified with the MWS cryocoolers.

Improved cryocooler reliability

As mentioned in the introduction, most of the typical ruggedized platforms solutions are based on multiple MWS systems per aircraft (up to eight units in some cases). In order to comply with the multi-system reliability demands, the cooler design also has to address a certain extra reliability factor. In the case of the K508N model, two major design features were improved:

- Bearings capacities were increased, keeping the forces imposed at the same level. By doing this, the life time potential of each bearing was increased significantly
- The crushed metal sealing was replaced by a ruggedized "C" type sealing.

In the linear cryocoolers, two major features were implemented:

- All-welded compressor design
- Elimination of the mechanical spring in the compressor

In addition, reliability-related techniques were implemented, such as the special ESS testing procedure and special manufacturing processes. Table 6 summarizes the reliability-related improvements of the cryocoolers.

Table 6: Reliability-related improvements

	Advanced cryocoolers model	Based on	Reliability improvement 1	Reliability improvement 2
1	K508N	K508	Bearing's capacity	"C" seal type
2	K544	K543	Production improved process	"C" seal type
3	K527 MWS Derivative	K527	Special ESS process	
4	K549 MWS Derivative	K549	No reliability new design is needed	
5	K572	K527	Mechanical Springless Compressor (MSC)	All welded design
6	K570	K527	Single piston compressor design	All welded design

5. VALIDATION

During a conventional development process, the first step to be done is a thorough verification of the basic performances throughout a well-defined testing. For all of the above ruggedized cryocooler models, the basic performances were proven previously using the baseline cryocooler models shown in the Table 1. Therefore, the validation process comprised the following two procedures.

HALT procedure

The HALT (Highly Accelerated Life Test) is a well-known procedure that reveals design defects of a product at early development stages. Using this procedure, three cryocooler prototypes were tested in the HALT laboratory upon a shaker inside a climatic chamber, during nominal operation and performance monitoring. As long as the performance monitor shows no major degradation, the vibration and temperature levels were gradually increased up to 30G rms and 140° C. Once one of the tested cryocoolers failed, it was taken for engineering investigation in order to study the failure cause and to provide potential improvement measures.

Qualification procedure

Afterwards the design was approved by QA, the qualification process started. The qualification process is basically identical for all the products. Each qualification program is documented and approved by QA. Table 7 summarizes the qualification status for each model.

Table 7: Qualification status

	Advanced Cryocoolers Model	Qualification status	Qualification Due date
1	K508N	Qualified	October 2012
2	K544	Qualified	May 2014
3	K527 MWS Derivative	Qualification is on - going	June 2015
4	K549 MWS Derivative	Qualification is on - going	June 2015
5	K572	Not started	March 2016
6	K570	Not started	March 2016

6. SUMMARY

Ricor has made progress with a variety of cryocoolers for ruggedized platform applications. The process that was chosen in terms of the strategic plan is to examine existing models and to see what steps are needed in order to qualify them to withstand harsh environmental conditions. The major improvements were made in the area of the mechanical and thermal interfacing, features ruggedizing, manufacturing process adaptation, and ESS procedures definition. The vast majority of the cryocoolers discussed above were successfully redesigned, validated, tested, and are already field-proven. They succeeded in passing qualification programs at IDDC and system levels.

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