Cryocoolers for infrared Missile Warning Systems

Avishai Filis, Nachman Pundak, Yoav Zur, Ramon Broyde, Moshe Barak
RICOR - Cryogenic & Vacuum Systems, En Harod Ihud 18960, Israel

ABSTRACT

The growth in world demand for infrared missile warning systems (MWS) has impelled the development of new technologies, in particular, special cryogenic coolers. Since the cryocooler is a core component in MWS 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.

The development focused on a cryocooler regenerator and cold finger optimization in order to achieve high cooling capacity and a thermodynamic efficiency of about 4.4% at 95°C ambient for one of the cooler models.
In order to withstand harsh environmental vibration, the cold finger and outer Dewar structure have been significantly ruggedized; efficient heat sinking methods have been applied and also novel vibration isolation methods have been implemented.

The electronic design concept is based on an analog controller, the PCB of which has been designed with internal heat sinking paths and special components being able to withstand ambients temperatures up to 125°C.
As a final stage of development, such cryocoolers were successfully qualified by RICOR and system manufacture in harsh environmental conditions and life demonstration tests were performed.

Keywords: Cryocooler, Stirling, MWS, COP, Infra Red, IDDCA, RICOR.

1. INTRODUCTION

Missile Warning System (MWS) provides a key element in advanced self protection systems for fighter aircraft, helicopters, transports and commercial aircraft.
By using infrared imagery and signal processing, the MWS detects and tracks an incoming missile's hot plume 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.

Due to the growth in world demand for infrared missile warning systems, RICOR began developing new technologies for cryogenic coolers in order to cope with this demanding application.
Since the cryocooler is a core component in MWS, new cryocooler models and derivatives were developed in order to withstand harsh environmental conditions such as high vibration and mechanical shocks level as well as exposure to extreme ambient temperatures.

It's possible to divide the applications for these missile warning systems into to two levels:

- Level I – helicopters, transports and commercial aircraft with a derived ambient temperature inside the system of up to 85°C and spectral random vibrations of up to 10g rms.
- Level II - fighter aircraft with derived ambient temperature inside the system of up to 110°C with spectral random vibration above 10g rms and catapulting & landing shocks of up to 300g.

2. CRYOCOOLER CONCEPT FOR MWS

The first cryocooler designed by RICOR for MWS application was produced ten years ago. It was a derivative of the K526 model based on a split rotary stirling concept and slip on configuration, namely the cold finger is integrated into the Dewar well. In this configuration there are parasitic heat losses that require extra cooling power from the cryocooler.
The K526 design relied on the free-piston "springless" expander – working on a vibroimpact concept. Due to the nonlinear nature of operation the expander is capable of demonstrating optimal phase lag between the pulse pressure developed by the compressor and the motion of the displacer in a wide range of operational frequencies, heat loads and ambient temperatures.
The drawback of this concept is that microphonics effects arise and they are due typically to the resonant excitation of the lightly damped components dynamically coupled with the IR sensor.

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

- Rotary integral coolers that are compact, thermodynamically efficient and field proven. The latest model named K508N has also been designed to meet reliability enhancement requirements.
- Split linear coolers for considerations of compactness, thermodynamic efficiency and reliability.
- Split rotary coolers for considerations of compactness, heat management and some degree of freedom with the induced forces levels.

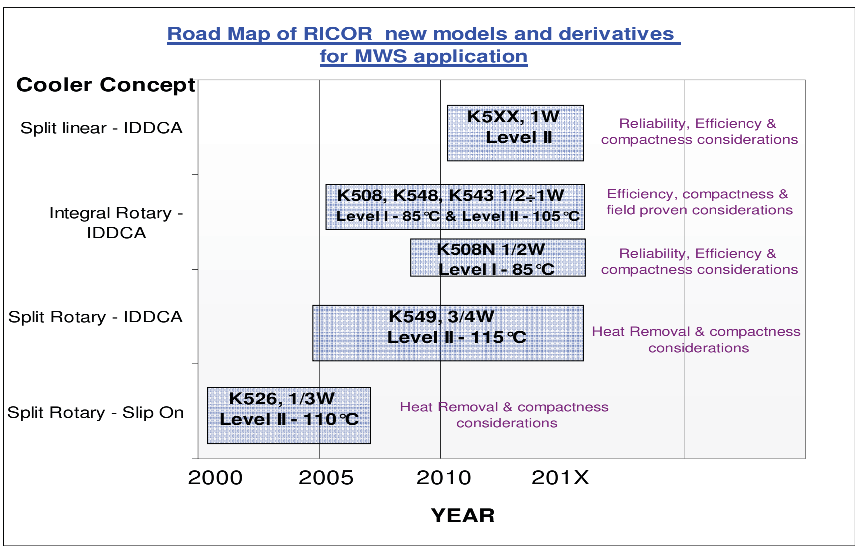


Figure 1 – RICOR road map for new models and derivatives for MWS application

3. DESIGN ASPECTS OF CRYOCOOLERS FOR MWS

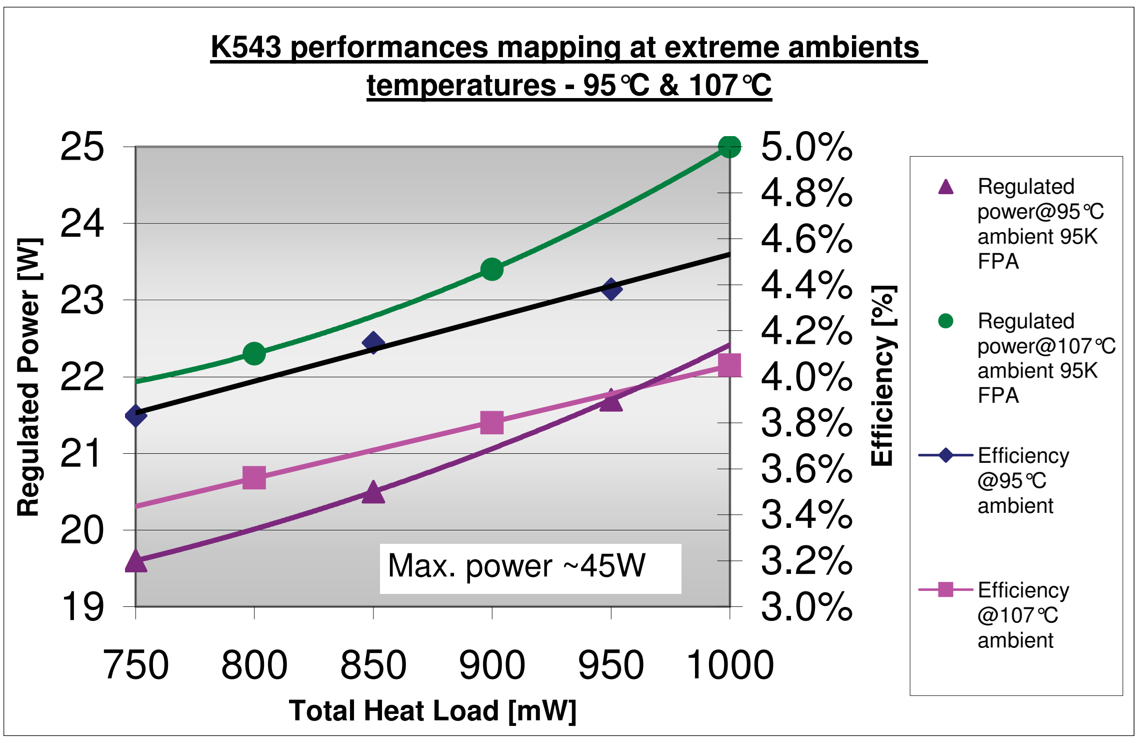
3.1. Cooling Power Optimization

The MWS applications exposed to a non standard large range of ambient temperatures, from -60°C up to 85°C at level I and up to 110/115°C at level II.
The low ambient temperatures could be managed by using heaters inside the IR sensor in order to assure at least -40°C during the start up of the cryocooler. While in the high ambient temperatures cryocooler optimization is needed in order to cope with the high level of Dewar heat losses from conduction, radiation and signal processor active dissipation.

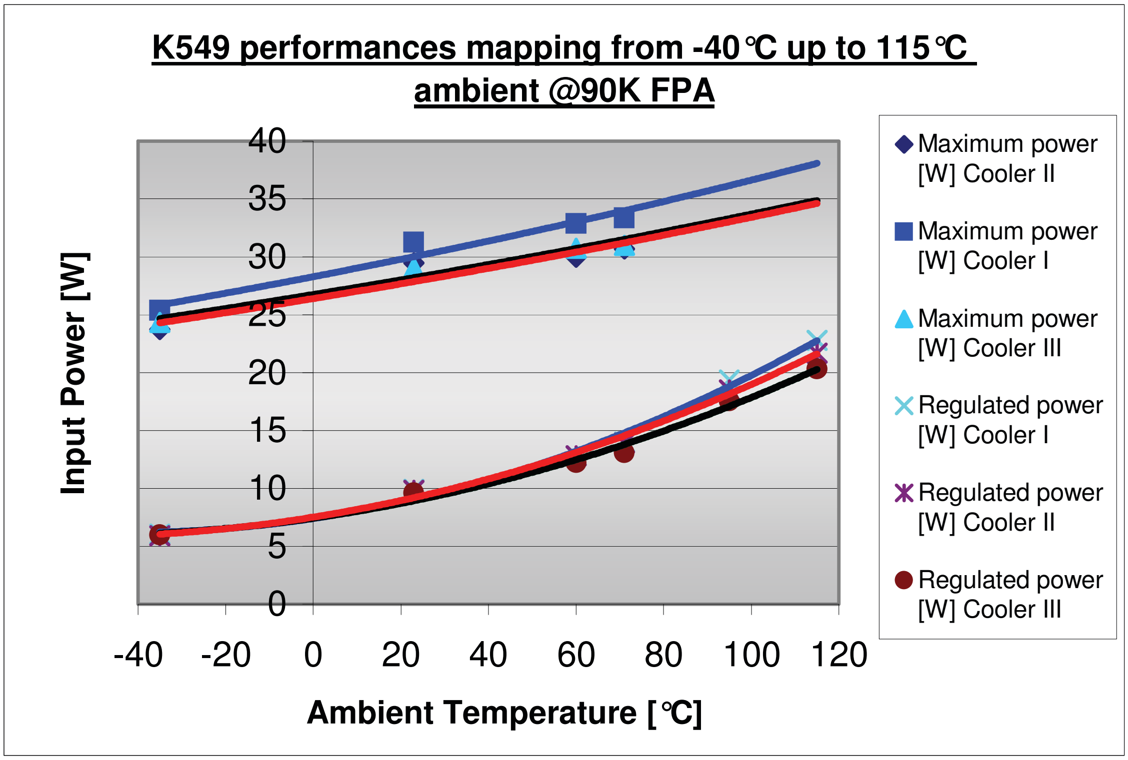
Cooling optimization has been performed on several new models and derivatives based on parameters such as the regenerator fill factor, moving parts clearances, damping coefficient in split configuration, fill pressure, regenerator and cold finger diameters, frequency operation and swept volume.
The cooling capacity of the cooler Qe is proportional to the compressor swept volume (Vc, in cm^3), the mean fill charge pressure (Pm, in atm), the cold tip temperature (Te, in K), and the operating frequency (f, in Hz)

The Detector FPA (Tc) was also one of the key parameters considered during cooling power optimization. The design goal of the advanced detectors for MWS based on single band or dual band/colors is in the range of 80-95K FPA. COP (Coefficient of Performance) of the cooler is the ratio between the amount of heat Qe absorbed by the expander and the amount of heat Qc emitted from the compressor (which is also equal to the work input Wc)

The result of K543 model optimization that operates at 95K FPA and 95°C ambient with Dewar total heat load of 950mW is about 4.4% efficiency which is about 12.6% of Carnot efficiency. (Cooler skin temperature kept up to 10°C above ambient temperature)

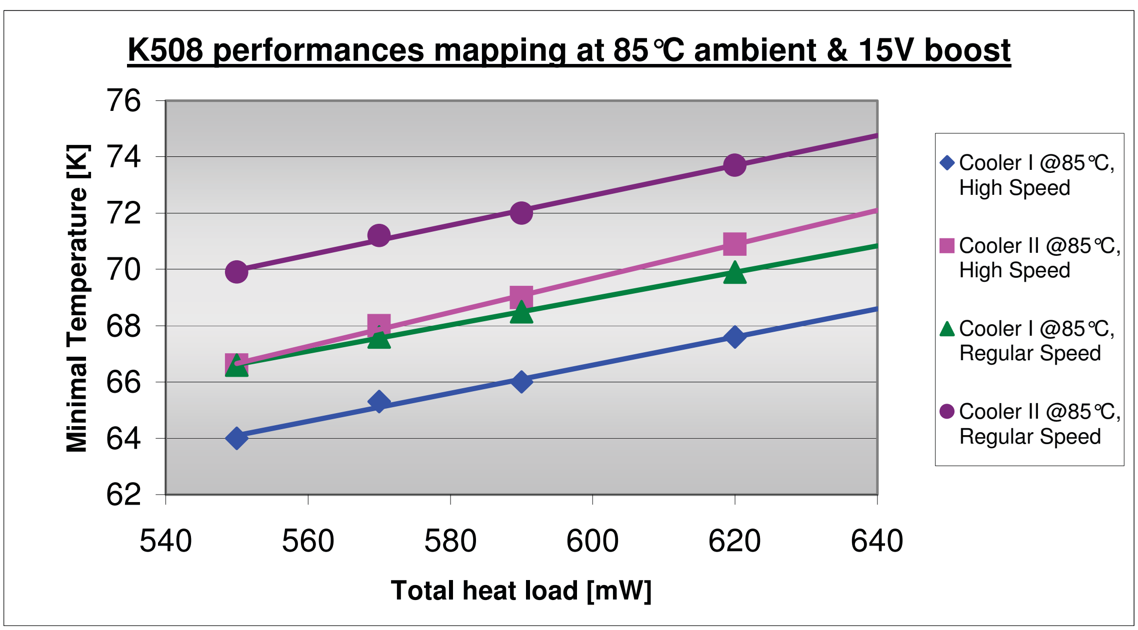


Graph 1 – K543 cooling power optimization at a high ambient temperature of up to 107°C



Graph 2 – K549 cooling power optimization at a high ambient temperature of up to 115°C

One of the main parameters optimized in the K508 derivative for MWS applications was the operating frequency. In order to improve cooling power at a high ambient of 85°C, a mapping of different operating speeds was performed in order to finally optimize the winding design of the DC brushless motor.



Graph 3 – K508 cooling power optimization by operating speed at a high ambient temperature of 85°C

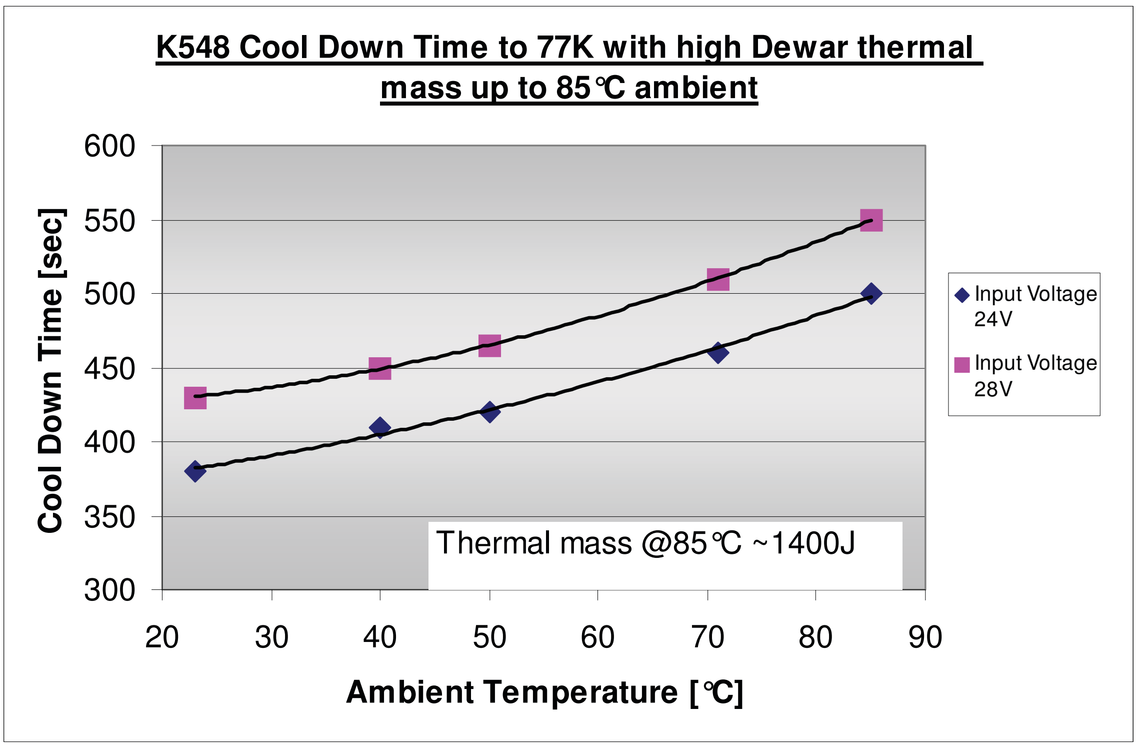
3.2. Cool Down Time Optimization

One of the main requirements of MWS is to achieve a relatively short cool down time for system readiness. Besides the influence of the Dewar Joule mass (Derived from Dewar substrate, cold shied and other components), the trade-offs between, fill pressure, maximum power consumption, boost level and cool down time duration were well studied.

For reliability considerations low fill pressure is preferred in rotary coolers and therefore the optimization is focused on motor speed with the combination of using a booster at the system level during cool down only.

The electronic Controller functions are also used in order to shorten system readiness time:

- The cool down indicator signal activates 2-3K before the FPA temperature reaches the steady state mode used as a trigger for the system early activation until the FPA temperature is stabilized.
- The stand by function used to operate the cryocooler in a saved power consumption mode ~150K with the ability to reach steady state mode in a short time.



Graph 4 – K548 cool down time optimization at a high ambient temperature of up to 85°C

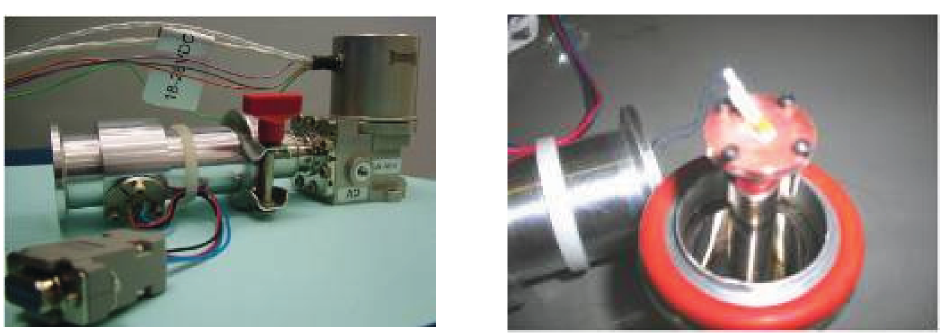


Figure 2 – K548 cooler integrated with simulation test Dewar

3.3. Cold Finger Design

The cold finger design is optimized for MWS by taking into consideration ruggedness requirements in order to withstand harsh external vibration levels and as a result to limit cold finger tip movement to a level of a few microns.
In addition, Dewar heat load balance becomes more critical and each component in the Dewar needs to be optimized in order to operate the cryocooler up to 85°C ambient at Level I and up to 110/115°C ambient at Level II with a reasonable cooling margin.
The outcome of the optimization yielded reinforced cold fingers for reinforced Dewars that are based on a rugged cold finger base with an integral flange, a thin wall thickness tube for heat loss conduction considerations and a light cold tip seat for thermal mass considerations.
New technology for cold fingers manufacturing in a laser welding process was recently qualified by RICOR. In the near future this technology will replace RICOR's traditional technology based on a brazing process.

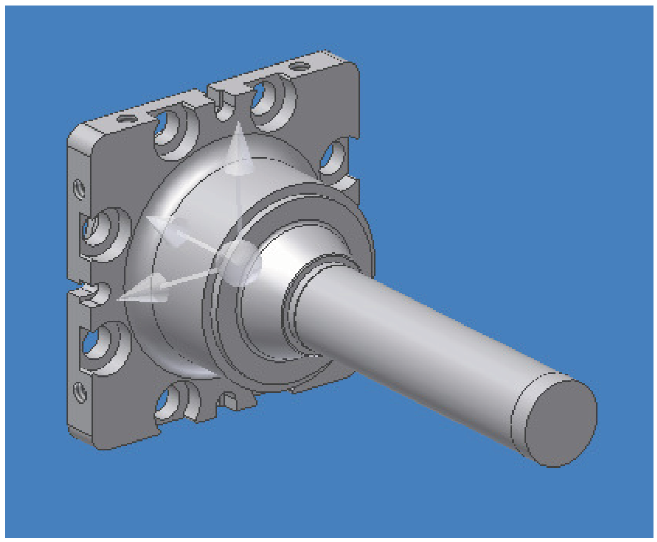


Figure 3 – Reinforced cold finger for MWS applications

3.4. Mechanical Interface and Heat Management

During the development phase, the mechanical interface of the cryocooler is thoroughly examined for considerations of limited volume and mass, heat dissipation from the cryocooler's heat sources to the system chassis, accurate positioning between the clamping surface and the cold finger tip, induced forces etc.
The following design concepts were developed for three different groups of cryocoolers used in MWS:

- Integral Rotary cryocoolers – there are two alternatives for mechanical clamping used also to dissipate the heat by conduction as described in figure 3. The first option includes a novel design with a flange as a part of the compressor housing in order to achieve better and accurate positioning between the clamping surface and the cold finger tip. The second option includes a standard design with a clamping through the bottom of the compressor housing. In order to equip the cryocooler in a system with a small cylinder diameter shape, the electronic controller is separated from cooler's motor and is mounted directly on the system chassis. The heat management from the motor housing is performed by direct conduction to the system through a flexible copper braid or heat pipes.

- Split linear cryocoolers – the mechanical clamping of the compressor is done through the outer cylindrical surface directly with the system chassis and is used to dissipate the heat efficiently. If the level of compressor induced forces is of concern, the outer balancer could be used in order to dramatically reduce the vibrations export. The cold finger is clamped with the system by a frontal flange for better positioning accuracy with the system while the heat is dissipated from the rear side of the expander assembly.

- Split Rotary cryocoolers – the mechanical clamping of the compressor is done directly through the housing with the system chassis and is used to dissipate the heat efficiently. The heat management from the motor housing is performed by direct conduction to the system through a flexible copper braid or heat pipes. The cold finger is clamped with the system by a frontal flange for better positioning accuracy with the system while the heat is dissipated from the rear side of the expander assembly. In a case of relative movement between the compressor and the cold finger/Dewar in the sensor, the gas pipe is designed with some degree of freedom in order to absorb the movement.

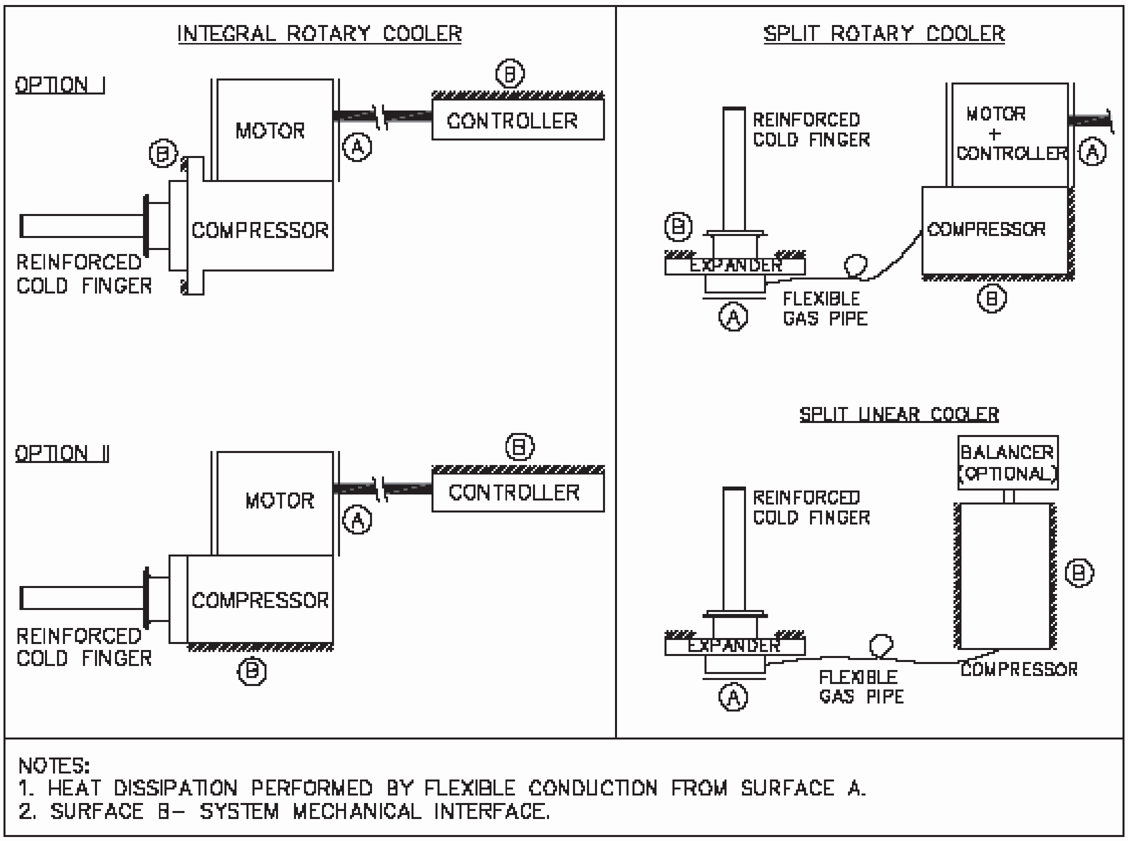


Figure 4 – Mechanical interface and heat management for MWS cryocoolers

3.5. High Temperature Electronic Controller

Cryocooler design for MWS also focused on the development of an improved analog controller based on the logic of the time-tested Hyb18N.

The controller is based on a single compact PCB that contains a temperature controller and motor driver. The components are assembled on one side of the board while the heat is conducted through Vias to the opposite side of the PCB which includes a robust heat sink that efficiently removes the heat to the system chassis – figure 4.

During the design stage, special care was taken to characterize the electronic components to ensure they comply with low offset voltage and high ambient temperature in order to withstand a large operating ambient temperature range of -40°C up to 125°C. The temperature limit of 125°C relates to the operation ambient temperature of the component which is derived from the limit operation junction temperature of the component to 150°C.

The components arrangement on the PCB and the controller's shielded housing also took into consideration aspects of EMI/RFI immunity. The controller is designed to meet low local temperature stability of up to ±0.5K at a given ambient temperature and also a low temperature drift.

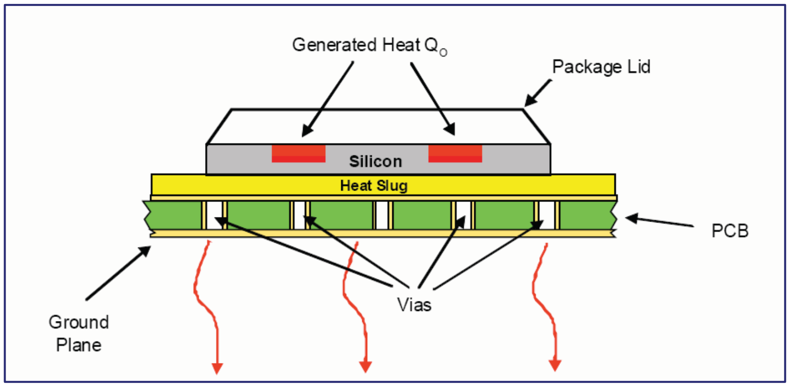


Figure 5 –Heat dissipation concept implemented in a high temperature electronic controller for MWS

3.6. Environmental conditions

In order to withstand harsh environmental conditions, the cryocooler structure and the clamping flanges were hardened for the purpose of increasing the natural frequency of the IDDCA.
In addition, the design of the metal seals used to seal the helium from the external environment is based on c-rings in order to minimize sensitivity of the seals to non standard environmental conditions and to ensure stability of the seal for long term operation without helium leakage.
The manufacturing process optimized in order to assure helium purity and proper cooling functionality during exposure the cryocooler to extreme ambient temperatures.
During qualification, the cryocooler for MWS needs to withstand harsh environmental conditions especially in Level II which includes spectral random vibration above 10g rms, catapulting & landing mechanical shocks of up to 300g and constant acceleration.

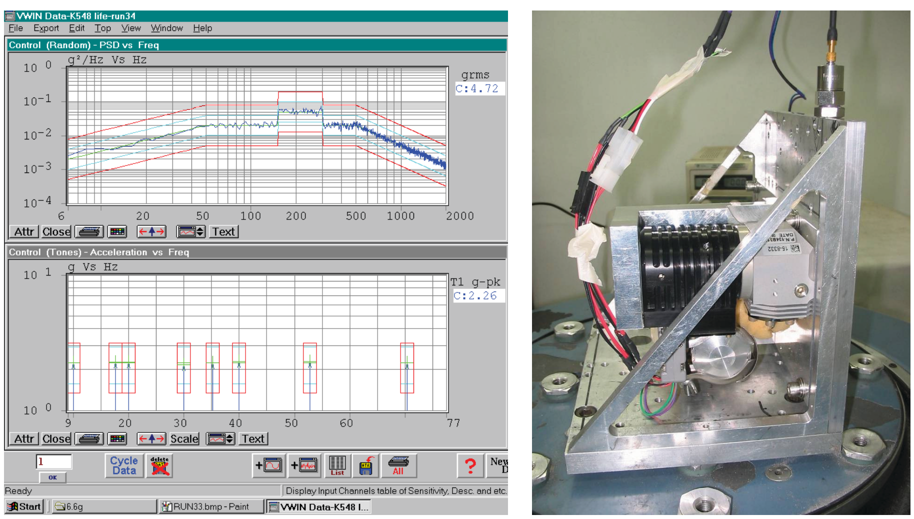
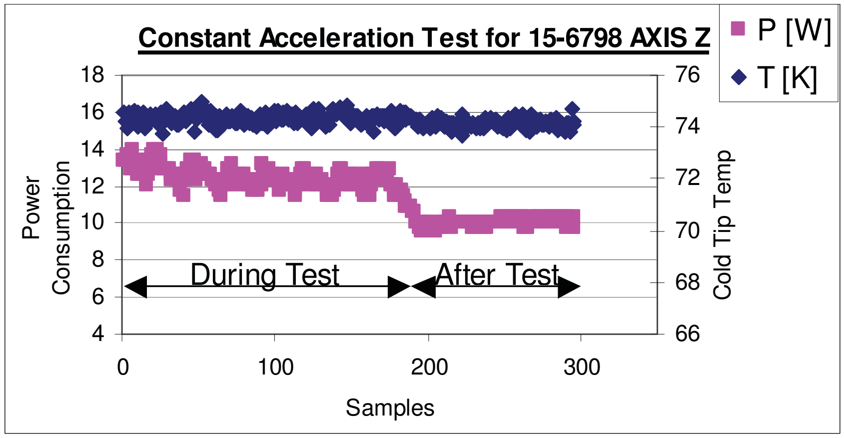


Figure 6 – Endurance vibration test setup

The qualification of the K549 model also included a constant acceleration test performed by centrifugal equipment. The cooler was integrated with a Dewar detector and tested at a constant acceleration of 12g for five minutes in each axis.
As shown in graph 5, during the test the power consumption increased slightly due to normal forces and reduced to the nominal value after the test was completed.

The FPA temperature value and the temperature stability kept constant during the acceleration test and after the test was completed.



Graph 5 – Cryocooler parameters monitoring during a constant acceleration test

4. SUMMARY

A new approach was achieved in the range of cryocooler development for missile warning systems thanks to cryogenic performances optimization conducted especially for extreme ambient temperatures. In addition, a cryocooler design concept was carefully adapted to withstand harsh environmental conditions by means of structure hardening, mechanical mounting and heat dissipation management.

Temperature controller design implemented advanced electronic components in order to withstand harsh environmental conditions by leveraging novel technologies of heat dissipation management.

The technologies developed for MWS applications could also be used for standard tactical applications due to the robust cryocooler design achieved.

In the future RICOR's cryocooler development for MWS will cope with the demand for long life operation and with the requirement for CMWS interface compliance.

REFERENCES

1] Nesher, O., Elkind, G., Francis, G. and Kenan, M. , "SCD solutions for Missile Warning System Applications" , (2006).