Miniaturisation of Rotary Stirling Cryocoolers

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ABSTRACT

The trend for miniaturized Integrated Dewar and Cooler Assemblies (IDCA) has been confirmed over the past few years with several publications of new generation IR detector's working at High Operating Temperature (HOT). This HOT-technology enables the use of cryocoolers with reduced cryogenic power. In the past 2 years Thales Cryogenics BV and Thales-LAS-Fr have jointly developed a new generation of SWaP coolers to be used with the new generation detectors that could bring a competitive advantage to our customers. This new generation SWaP coolers of Thales consists of linear as well as rotary coolers.

In this paper special attention will be given to the design philosophy and performance of the SWaP rotary cooler RMs1. The design hypotheses used could lead to a new generation of rotary coolers which will be very versatile in the different utilization areas not limited to IR sensors.

INTRODUCTION

Cryocoolers are an essential component of cooled Infrared cameras while Rotary Stirling coolers being the most compact solutions available. Thales Cryogenics has launched 5 years ago a new R&D cycle in order to provide SWaP cooling solutions dedicated to HOT detectors (>130K) [1] [2]. Both a linear and a rotary Stirling cooler have been developed. The current paper focuses on the performances and qualification of the mono bloc SWaP rotary cooler proposed by Thales. The large condition of environmental operations where the RMs1 fulfill the requirements open the opportunity to optimize RMs1 products dedicated to specific applications. The present day RMs1 embraces new technologies, in addition to detailed improvements in the design to reduce power consumption and to enable silent operation of the cooler.

GENERAL PRESENTATION OF RMS1

The following paragraph gives an overview of the main characteristics of the RMs1 cooler. All the data provided in this paragraph comes from measurements made on qualification prototypes.

- The nominal input voltage for RMs1 is 12V.
- The RMs1 is designed for performing in a climatic environment from -40°C to +71°C.
- The main dimensions of the RMs1 are presented in the Figure 1.

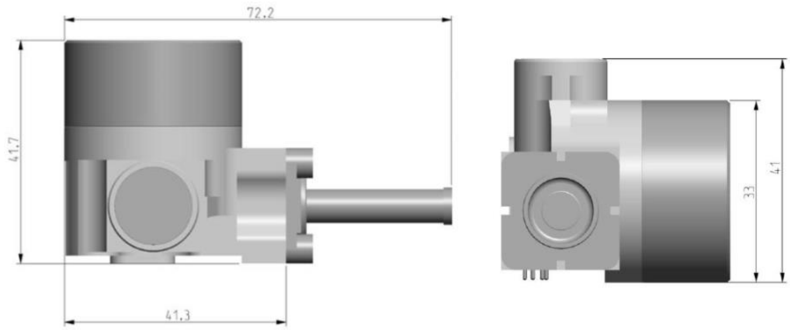

Figure 1. Overall dimensions of RMs1 integrated in common cold finger

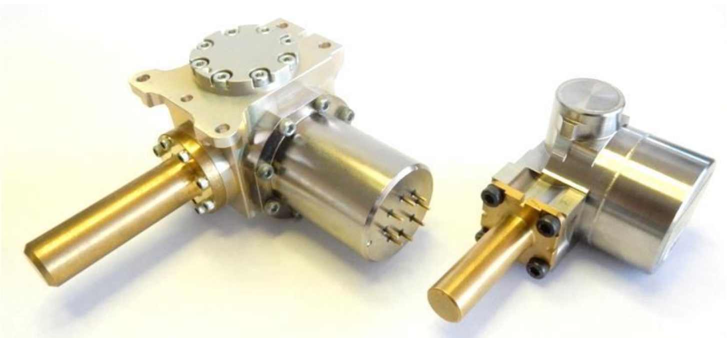

Figure 2. Comparison of the legacy RM2 (left), and the RMs1 (right). Its volume is 45% smaller than RM2 one.

The external volume of an RM2 cooler is 74 cm^3. The external volume of the RMs1 is 40 cm^3 (reduction of 45%) (refer to the Figure 2). The RMs1 cryocooler mass is 142g, compared to an RM2 of 275 gr. This mass is for the cryocooler only and does not include the dewar nor the driver. The RMs1 cryocooler is fully compatible and interchangeable with any cooler fitting in the 6mm common cold finger designed in cooperation with several cooler manufacturers for this type of coolers.

Thales Cryogenics has considered a welded outer shell to avoid leakage due to use of sealings/bolt constructions. As a result, only two remaining dismountable seals are present on RMs1. The interface with dewar is dismountable for integration purposes. The helium tightness at that interface is ensured thanks to a metallic C-seal enabling reproducible helium tightness and detector positioning. The filling port is also sealed with a dismountable metallic seal to enable detector-cooler assembly to be filled with working gas after integration.

PERFORMANCES OF RMS1

In the next chapter, the data provided are average values coming from tests performed during the qualification of the product on 6 coolers and 5 drivers.

Cryogenic performances

The performances presented in this paragraph are related to a dewar with a thermal mass of 120J and a thermal heat load of 150mW (23C – 150K) [3]. The main parameters for all the values are the following: input voltage to the cooler driver electronics: 12Vdc and operating temperature: 150K.

Cool down time: Figure 3 represents the typical cool down time (CDT) measured as a function of the nominal ambient temperature. For a nominal operating temperature of 150K, the cool down time at room temperature is about 2min. At +70°C ambient temperature, the cool down time is about 2min30. The right part of the Figure 3 represents the variation in cool down time for several prototypes from 20°C ambient temperature down to 150K.

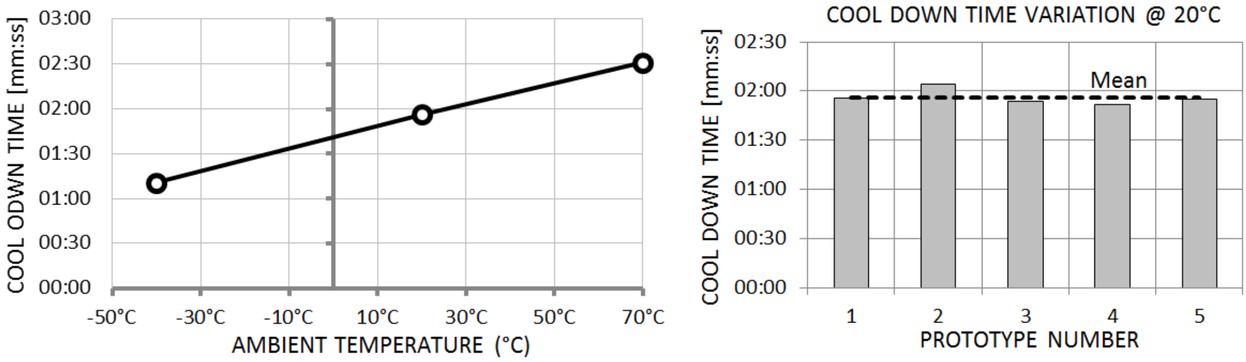

Figure 3. Cool down time as a function of ambient temperature (left), and variability of CDT between 5 units (right).

After manufacturing several coolers, it can be said that the cool down time variation are very low. For 5 prototypes, the mean is at 1min56s and the standard variation is about 5s. In a standard operation, the Hand Held Thermal Imager (HHTI) equipped with an RMs1 is then able to provide a stable high quality image within 2min. Such a short duration seems to meet application needs in most of the cases. It is also a major improvement compared to legacy coolers.

Input power in regulation: Figure 4 represents the typical AC input power measured at the cooler input in steady state operation as a function of the cold temperature set-point and for different ambient temperatures. Finally, Figure 5 represents the input power measured at the cooler input in steady state operation at 150K as a function of the ambient temperature and the total cooling power (that is to say including the thermal losses of the dewar itself).

It can be concluded that at room temperature, and for a nominal cold temperature of 150K, the power consumption of the cooler alone is only 1W for a dewar with a 150 mW heat load.

That power remains quite far from the maximum input power available: the cooler is far from running at maximum speed. This power margin guarantees a good reliability even at high ambient temperature.

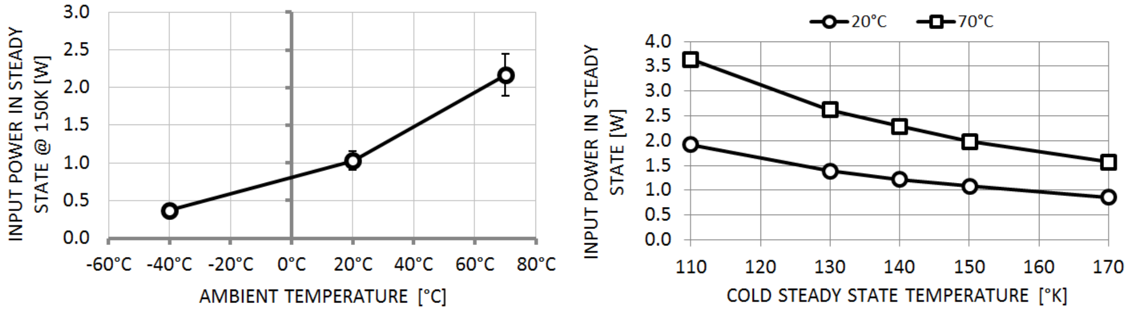

Figure 4. Steady state ac input power as a function of cold temperature and ambient temperature.

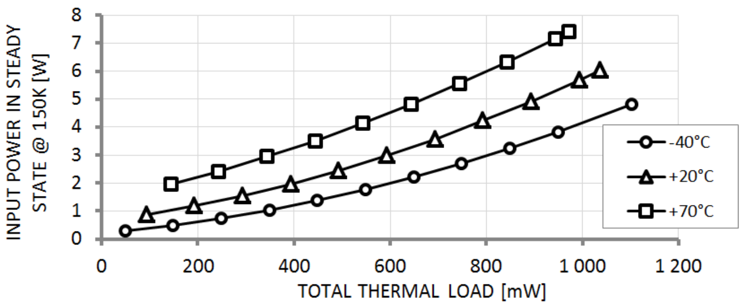

Figure 5. Steady state ac input power at 150K in function of ambient temperature and total cooling power.

Because this cooler is still able to provide 1W of cooling in a steady-state mode at 150K and room temperature, RMs1 can provide a cooling solution to bigger IR-components with large matrix array. The total cooling power remains close to 1 W even at 70°C ambient temperature. This larger cooling power also enables the use of the RMs1 for cooling other sensing devices running at temperatures around 100K.

Total cryogenic capacity: Figure 6 presents the measurement of the total cryogenic capacity of the cooler, including the thermal losses of the dewar itself. The total cooling power is close to 1W whatever the ambient temperature. This shows that the cooler is optimized to cool significant heat loads at 150K but is also able to reach quickly stable operating conditions at lower temperatures i.e. 140K.

Today's HgCdTe HoT technology sensors are known to be have difficulties to reach their optimal performance values (i.e. NETD) at temperatures around 150K [4]. With the current cryogenic capacity of the RMs1 family, the basic definition of the RMs1 can balance existing detector heat load and active dissipation at lower temperatures i.e. 140K with ease. For operating conditions where even more cooling power is required, RMs1's basic definition can be optimized – i.e. by increasing the charge pressure and/or change of some internal components - in order to reach the required lower detector temperatures or to be able to balance even higher sensor heat loads at HoT temperatures. These optimized definitions of the baseline RMs1 will be able to run at the optimal rotation speeds while still ensuring the high reliability of the product.

With a dual set point mode it will also be able to run the sensor at a higher temperature setting to obtain a correct image while preserving battery power, and to quickly cool it down to a lower temperature setting when a better detector performance is required.

Focal temperature stability:

A complete test campaign was realized on the RMs1. From these tests, it appears that whatever the conditions, the cold temperature variation and the input power variation are very stable. Firstly, for the cold temperature, the variations during 10 minutes are always below 0.01 K. Secondly for the input power, the delta during 10 min are all below 0.16 W. Such a good result is linked to a very good drive of the motor by the Cooler Driver Electronic.

Even if stability criteria are given over 10min, one can also underline that the tests was run during more than 16 hours at 70°C ambient temperature. During the whole test, the variations are far below 0.4 K and below 0.15Wdc (refer to the Figure 7).

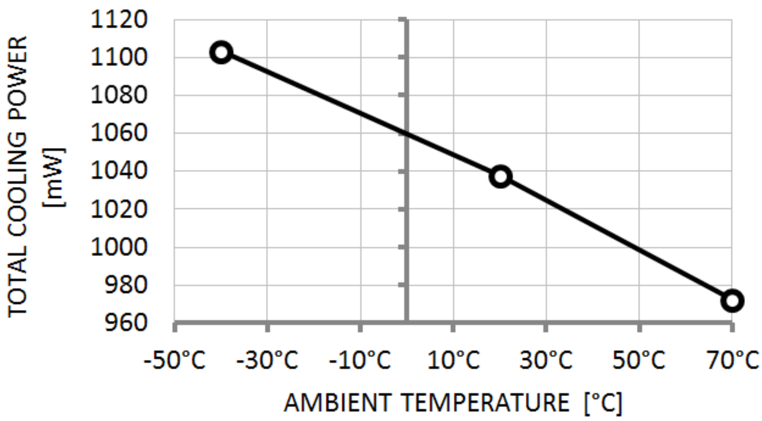

Figure 6. RMs1 total cooling power at 150K in function of ambient temperature

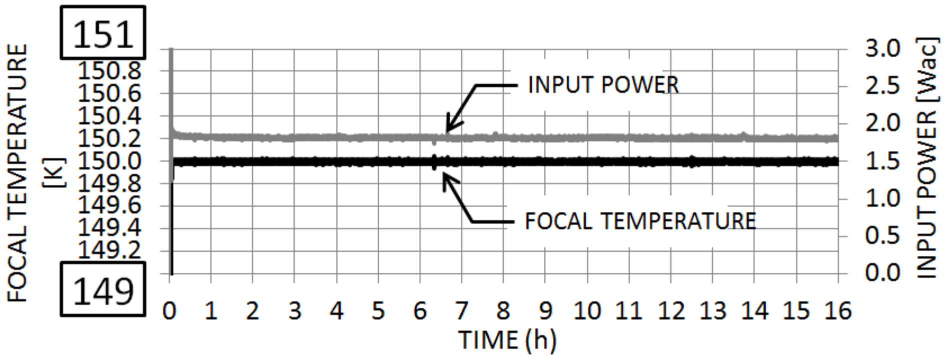

Figure 7. Temperature and input power stability during 16 hours at 70°C. the full scale is +/-1 Kelvin for focal temperature and 0-3W for input power.

Induced vibrations

With regard to the management of the integration of the cooler in the host system, one of the important aspects is the level of vibrations induced by the cooler operation. These vibrations have to be mastered in order to avoid two issues at system level: awkward movement of the sensor to be cooled (source of blur for imager as instance) and the generation of acoustic noise by the system when excited by the cooler induced vibrations.

The RMs1 has been specifically designed to minimize the generated induced vibrations. Figure 9 compares the induced vibrations measured for several coolers. The comparison is made on the three cooler axes (designed as compressor axis, cold finger axis and motor axis, refer to the Figure 8). For these measurements, all coolers are running at the same rotation speed in order to be able to compare intrinsic cooler performances. Moreover, the RM2 global level is added to the comparison. The current level of the RM2 is known and experienced to be compatible with demanding applications like optronics gimbal for airborne applications.

From this comparison, it can be concluded that the RMs1 generates much less induced vibrations than RM2 cooler on compressor axis which was the most critical one. Furthermore, the global levels are similar between all RMs1 coolers indicating that the design and the associated manufacturing processes are fully mastered.

Coupled with its compactness and its power capacity, RMs1 may be a very relevant cooler for devices which have to operate in stabilized mini gimbal applications.

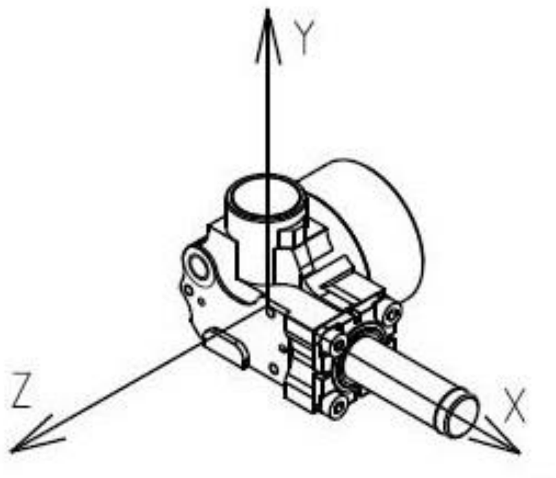

Figure 8. Induced vibrations axis

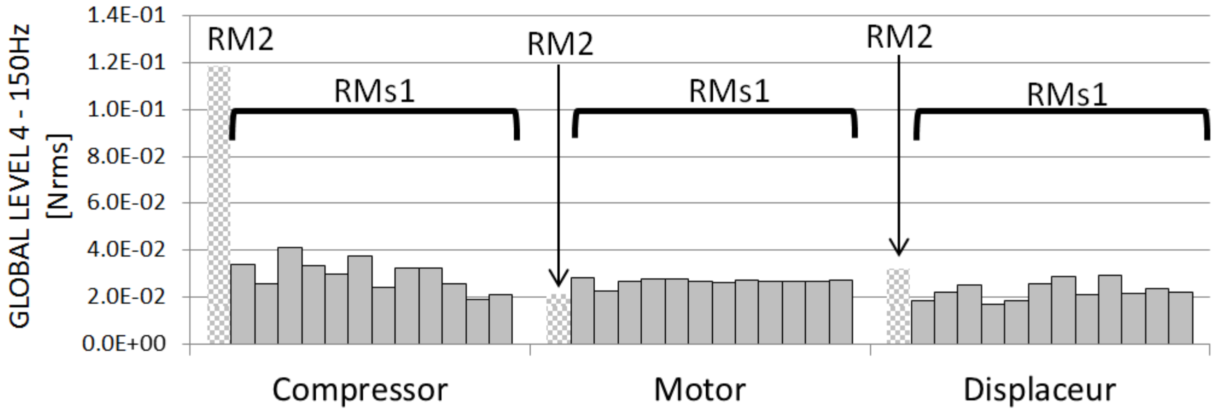

Figure 9. RMs1 global induced vibrations levels for 12 coolers between 4Hz and 150Hz and comparison with RM2

Acoustic noise

With regard to the management of the integration of the cooler in the host system, one of the important aspects is the level of acoustic noise generated by the cooler. Figure 10 represents the results of the measurement performed according to MIL-STD-1474 – non-detectability test.

The RMs1 unit which has been tested is silent at 10m in a steady-state mode at 150K. The impact of the acoustic noise at higher frequencies can be damped with adequate system integration. The global sound power level according to ISO3744 is 43 dBA.

Robustness with respect to environmental conditions:

The possible applications for the RMs1 are very large (portable, vehicle, airborne…). Due to this, the mechanical environments to be sustained by the cooler are very diverse. In order to qualify the product for the widest application range, a maximum spectra in term of mechanical vibrations (Table 1, Table 2 and Figure 11) and shocks (Half-sine shock 100g, 6ms , 3 shocks per axis / direction, Half-sine bump 40g, 6ms duration, 1000 bumps per axis / direction) has been defined and applied to the cooler and driver.

Check after tests: Between each axis or profile, a verification of the equipment performances is performed. No variation of performances has been measured after all the mechanical tests. The acoustic noise, induced vibrations and cryogenics performances are similar before and after the tests.

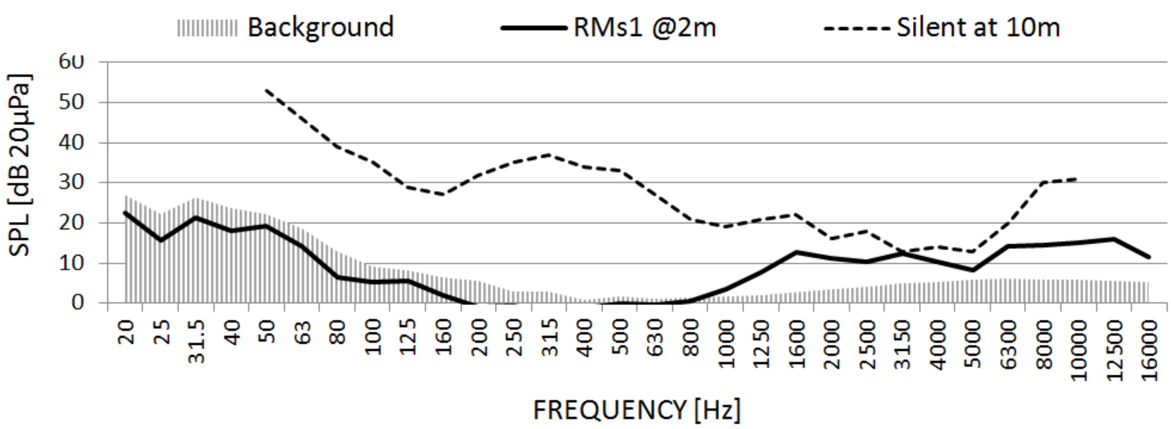

Figure 10. Non-detectability measure in steady state

Table 1. Sine vibration profile 10 sweeps at 1 octave/min per axis, 3 axes

Frequency (Hz)	10	58	58	2000
Amplitude (mm)	0.75	0.75	0.74	6.21E-04
Acceleration (peak) (g)	0.30	10.1	10	10

Table 2. 16 g rms random vibration profile

Frequency (Hz)	Level (g²/Hz)	Frequency (Hz)	Level (g²/Hz)
10	2.00E-01	245	0.3
23	2.00E-01	350	0.3
34	3.00E-01	375	1
110	3.00E-01	385	1
122	2	475	0.1
130	2	800	0.1
140	0.3	2000	1.00E-02

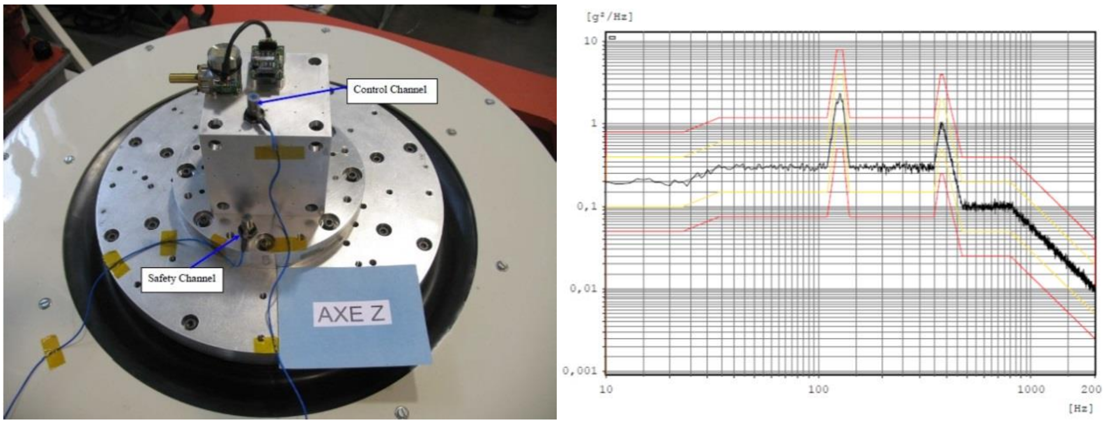

Figure 11. vibration test bench and 16 g rms random vibration profile 16 g rms, Duration: 1 hour/axis, 3 axis

COOLER DRIVER ELECTRONIC

A new generation of numeric electronic driver is developed for RMs1 driving. The name of this Cooler Driver Electronic (CDE) is DE0009 (Figure 12).

The main functions of this CDE are: Motor phases management, Temperature regulation according to thermal sensor information, Analogic interfaces (stand-by / Shut-down / Cooler ready), Hours counter, Safety functions (input current limitation, micro power cut protection, reverse polarity protection, over temperature protection, over voltage protection), EMC filter in order to minimize the emitted perturbations or the susceptibility of the equipment, and Numeric communication through an RS422 interface The communication interface allows to set up the driver but also to have information about the CDE and cooler operations (error code, performance of the cooler, maximum environment seen by the CDE and cooler,…).

The driver is fully qualified for the same environment than the cooler. Moreover it has been designed in order to be able to drive most of Thales RMx coolers. The typical CDE input power is below 0,75W when the communication is activated and below 0,65W when the communication is not activated (cooler in steady state at 150K).

LIFE TIME RMS1

In order to evaluate reliability in an operational profile mission, one have to consider the environmental stresses, the number of operating hours, the focal plane temperature, the number of storage hours. Thales Cryogenics uses to communicate on the reliability in a standard profile called STP profile. MTTF are evaluated in a dedicated accelerated profile which is called A20 profile. The latter has been designed to run continuously at high speed and conversion factors have been established between A20 and operational profile [5]. It must be mentioned that this A20 profile designed for existing coolers remains also relevant for the RMs1 cooler.

Figure 12. Cooler RMs1 and CDE DE0009

Table 3. RMs1 lifetime test

N°	Lifetime test duration (h)	Status
1	5800	Still running
2	4300	Still running
3	3150	Still running
4	2250	Still running
5	1511	Still running
6	1465	Still running
7	450	Still running
8	450	Still running

Today, height coolers are in lifetime tests. Two coolers have operated for more than 4,000 hours in A20 (refer to the Table 3). The parameters checked regularly do not show any variation. These results obtained under accelerated test allow us to prove already a potential reliability of 12,000 operating hours in representative customer application.

Moreover, the RMs1 design takes advantages from feedback obtained on other legacy products like RM2. The latter shown currently MTTF higher than 40,000hr [6] [7]. As a consequence, Thales is confident that the RMs1 will demonstrate the targeted reliability before the end of the year (15,000hr). The actual MTTF could be even higher than that and the RMs1 is expected to be in the same class of reliability than RM2.

CONCLUSION

In 2017, we introduced the first characteristics measured on RMs1 prototypes. The current paper has updated these results with obtained qualification data. The figures are especially obtained on a larger number of units, leading to a better estimation of discrepancy and average values.

It has been proven the RMs1 is a relevant SWaP solution. First, the Size, Weight and Power consumption of cooler has been drastically reduced. But one can also consider that cooler as a SWaP enabler at system level. The power-to-weight ratio is well below the initial target. That is to say that for a lighter weight than other coolers, the thermodynamic efficiency of the cooler is high enough to authorize either lighter batteries, either longer autonomy of HHTI.

The RMs1 could be considered as a breakthrough in the SWaP cryocooler range. The RMs1 offers a differentiation in the Swap domain compared to other marketed products and delivers a great value to applications where SWaP criteria and cryogenic efficiency are of importance. The design choices have also led to a low vibration product, with induced forces significantly lower than the current RM2 and an expected MTTF higher than 15,000hr. For high heat loads, the

RMs1 is a relevant cooler by taking into account a specific version optimized for this kind of application.

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