Overview of RICOR tactical cryogenic refrigerators for space missions

Sergey Riabzev, Avishai Filis, Dorit Livni, Itai Regev, Victor Segal, Dan Gover

RICOR Cryogenic and Vacuum Systems, En-Harod Ihud, Israel 18960

ABSTRACT

Cryogenic refrigerators represent a significant enabling technology for Earth and Space science enterprises. Many of the space instruments require cryogenic refrigeration to enable the use of advanced detectors to explore a wide range of phenomena from space.

RICOR refrigerators involved in various space missions are overviewed in this paper, starting in1994 with "Clementine" Moon mission, till the latest ExoMars mission launched in 2016. RICOR tactical rotary refrigerators have been incorporated in many space instruments, after passing qualification, life time, thermal management testing and flight acceptance.

The tactical to space customization framework includes an extensive characterization and qualification test program to validate reliability, the design of thermal interfacing with a detector, vibration export control, efficient heat dissipation in a vacuum environment, robustness, mounting design, compliance with outgassing requirements and strict performance screening.

Current RICOR development is focused on dedicated ultra-long-life, highly reliable, space cryogenic refrigerator based on a Pulse Tube design

Keywords: cryogenic refrigerator, space mission, tactical rotary, Stirling cycle, Pulse Tube, highly-reliable, long-life.

1. INTRODUCTION

Cryogenic refrigerators represent a significant enabling technology for Earth and Space science enterprises. Many of the space instruments require cryogenic refrigeration to enable the use of advanced detectors to explore a wide range of phenomena from space. For more than 20 years RICOR has been involved in supplying cryogenic refrigerators for a range of space applications. For most of the programs, the K508 Stirling-cycle rotary integral refrigerator was typically selected by system developers, to allow completion of specific missions within a spacecraft. Tactical Stirling refrigerators are widely used in ground military and civil applications. Usually they are required to provide high reliability, cost effectiveness, moderate life time, good maintainability, and to withstand harsh environmental conditions. For some of the space missions these requirements can be also acceptable, after the refrigerator has passed certain design customization and comprehensive screening processes, enabling its flight approval for specific mission requirements.

The tactical to space customization framework includes an extensive characterization and qualification test program to validate reliability, design of thermal interfacing with detector, vibration export control, efficient heat dissipation in vacuum environment, robustness, mounting design, compliance with outgassing requirements and strict performance screening. During this activity, the RICOR standard tactical product was flight approved by NASA and ESA.

The very first RICOR refrigerator K506B model was launched in 1994 for the "Clementine" lunar mission. The last one was the K508 model launched in March 2016 onboard the Trace Gas Orbiter (TGO) spacecraft, under ESA ExoMars 2016 Mission. In the interim period, RICOR's tactical Stirling rotary refrigerators were involved in a number of other space programs, after passing thorough design customization and comprehensive testing of qualification, life time, thermal management, and flight acceptance. Current RICOR development is focused on dedicated ultra-long-life, highly reliable, space cryogenic refrigerator model K571PT, based on a Pulse Tube cold head which is driven by a "contactless" ultra-long life dual opposed linear compressor.

2. SCREENING AND CUSTOMIZATION FOR SPACE APPLICATIONS

The purpose of the screening and testing process is to ensure that all refrigerators supplied meet mission requirements as far as possible, and to extend their life expectancy as much as possible within the time constraints of the mission. First, after system definition and specification completion, an ensemble of the "best" refrigerators is chosen from standard production line tests. Then this ensemble is run through a series of specific tests to determine the "very best" of a few refrigerators, which are then customized and supplied to a customer as flight units.

The "best" units are defined as those that will exceed a specified cooling power, for the longest number of mission operational hours, under the required environmental conditions. However, there is no completely precise method to predict the reliability for a single refrigerator, even if the exact operating conditions are known. Also, there is no exact data determining what parameters are governing, and what are the possible failure modes for each condition, so the selection and testing process is one on a "best efforts" basis only.

2.1 System definition stage

At a very initial stage of a dedicated space instrument, a design of the selected candidate refrigerator is usually examined at RICOR in order to qualify it as a potentially appropriate choice for further progress towards the flight units. In parallel, a design of the future space instrument employing a refrigerator is considered by a customer to provide acceptable environmental conditions for this refrigerator, which can operate within certain limitations only. These limitations are typically apply to body temperature and vibration. Therefore a system design has to take into account sufficient heat sinking, preventing overheating and undercooling, vibration isolation during launching, etc. Relying on the system requirements and design adaptation vs refrigerator limitations, customization to be done on a candidate refrigerator is defined. This process may include extended and thorough negotiations between RICOR and a customer using mutual iterative filling in of Matrix Of Compliance (MOC) containing all aspects of environmental conditions, performance, reliability and life time. Moreover, samples of the candidate refrigerator model may go through pre-examination of design during performance pre-qualification testing series, such as harsh vibration, extreme thermal shocks, blast withstanding, etc. After complete agreement of both sides on the final MOC, the design specifications are generated for both the customer system and the RICOR refrigerator candidate. Once this stage is complete, RICOR will be authorized to commence the phase of required design customization and selection of specific candidate units from the production line.

2.2 Engineering Model units selection

The first step in the selection process is the RICOR standard screening process of all production units, more than 1000 per month. Since the primary failure mode of rotary machines is a piston rod bearing, or crankshaft bearing, RICOR's first task is to define the lowest He pressure for which adequate cooling power can be obtained. Up to 40 bar is available, but sometimes 30 bar is expected to provide a sufficient cooling power margin for the mission. In addition, the Helium leak rate must be compatible with the mission length, and therefore should be commensurate with no more than a 5% Helium loss over a 10-year period after manufacture. Each refrigerator, consisting of a standard compressor, standard motor stator, and standard cold finger, is pressurized to a selected He pressure. Then a simulation dewar jacket is placed around the cold finger that contains a temperature diode to measure the cold-finger tip temperature and a resistor to provide a heat load. The refrigerator is then operated in open loop for 48 hours, during this time the following parameters are measured: lowest cold finger temperature reached, average input current, acoustic noise, and relative mechanical vibrations (determined by measuring the acceleration level of an accelerometer on the refrigerator and comparing it to a specific value). The next choice is to choose refrigerators that are expected to have the lowest average operating speed during the mission. It is expected that refrigerators having the lowest values of cold finger temperature and input current would have the lowest average operating speed, and those having the lowest noise and vibration levels would cause the least amount of wear on the bearings. RICOR experts select refrigerators having a high probability to meet mission specifications and measure their cooling power under the specified conditions, as well as perform a Helium leak test.

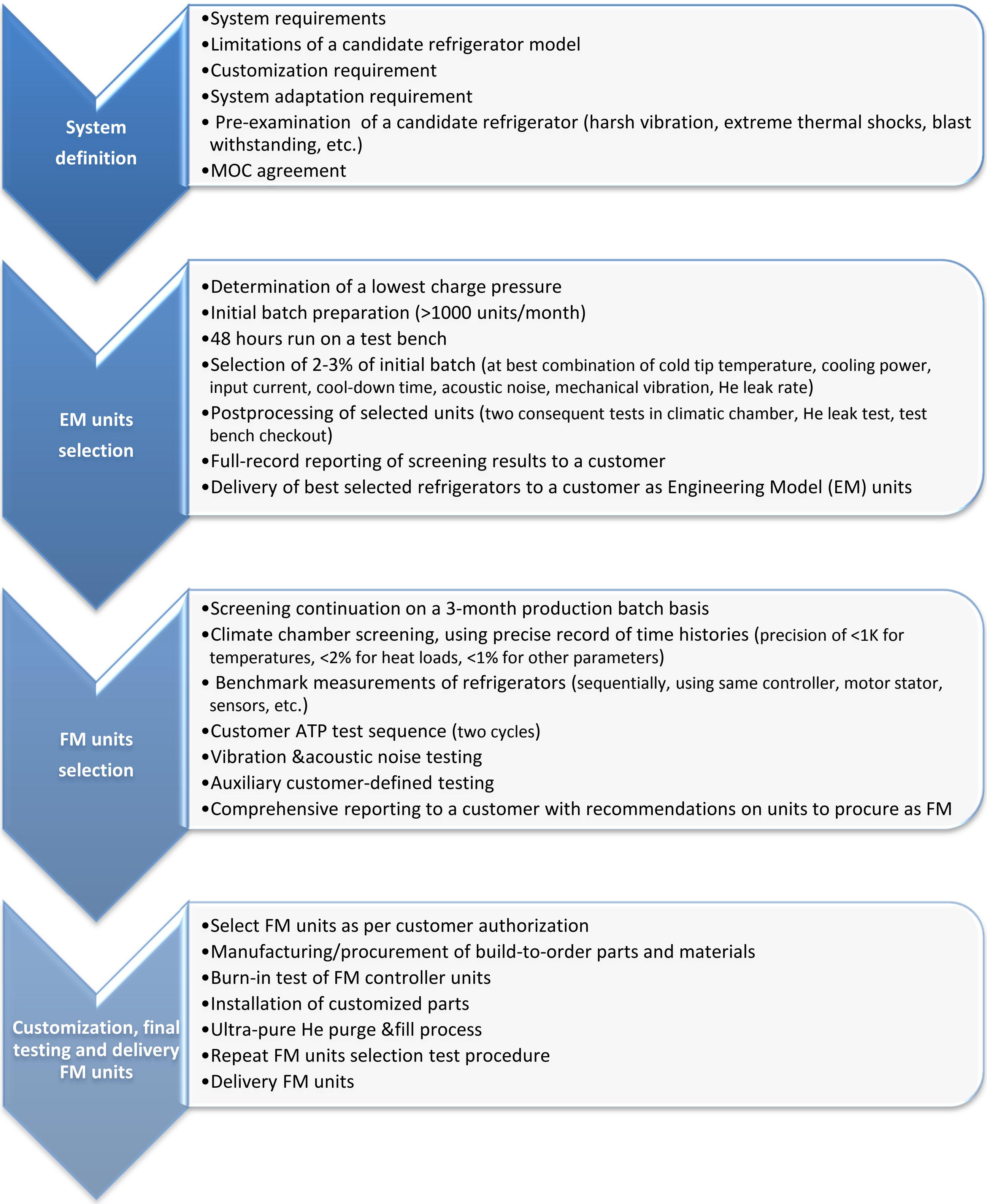


Figure 1. Flowchart of the screening process applied to RICOR refrigerators delivered for space applications

This means refrigerators selected as candidates will have an overall performance (combination of low cold finger temperature, input current, cool-down time, acoustic noise, mechanical vibration, and He leak rate and high cooling power) attained by only 2-3% of the refrigerators produced each month, on an average.

Since cooling power is typically a primary performance selection parameter, once a refrigerator is identified as a potential candidate, its cooling power at room temperature is measured. If the measured cooling power is less than a certain threshold, the refrigerator is rejected. Cooling power is not normally measured during the standard production-line test series, but this procedure ensures a low probability that a refrigerator will be rejected due to low cooling power in the final selection process.

Each candidate refrigerator is then placed in a climate chamber for performance testing at various ambient temperatures. The following parameters are measured: lowest cold finger temperature reached at a certain heat load, peak power consumption during cool-down, average input current at steady state for 77K cold finger temperature, cool-down time to 77K, and many other parameters. The refrigerator will then be run at closed loop and tested for stable operation, monitoring cold finger and compressor temperatures, input power, motor current and speed. This test sequence is repeated twice for each candidate refrigerator. Each candidate refrigerator then goes through another Helium leak test and test bench checkout. This constitutes the completion of the standard RICOR screening process. Once all the refrigerators are selected, RICOR notifies a customer with the full record of test results from the screening process for the selected refrigerator. The best candidate refrigerators selected by this screening are processed on an accelerated schedule as the Engineering Model (EM) and then customized and shipped to a customer. RICOR experts choose a pool of the "best" refrigerators from a batch manufactured over a 3-month period, for further testing and selection as Flight Model (FM) units.

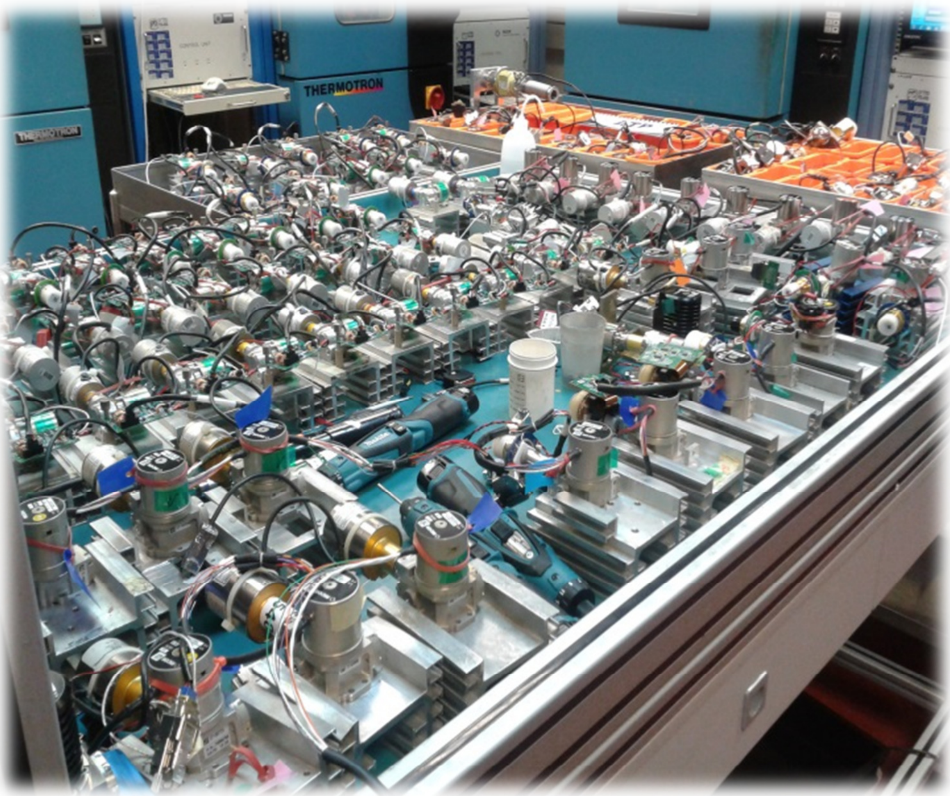


Figure 2. Candidate refrigerators before selection testing for space application.

2.3 Flight Model units selection

The selected pool of candidate refrigerators is further tested in a climate chamber to measure their performance more precisely over the full range of ambient temperatures, so as to differentiate them and select the "best" flight-quality refrigerators. Continuous time histories of the compressor and cold-finger tip temperatures, refrigerator input power, voltage, current and heat load for each unit under test (UUT) are measured and recorded,. Motor speed is also measured for each candidate refrigerator for specific sets of parameter values that are the same for each refrigerator. Temperatures are measured to an absolute accuracy of 1K or better, and all other parameters are measured to an absolute accuracy of 1% or better. The temperature time profile is the same for each refrigerator within 1K, the temperature setpoint for each cold finger is the same within 1K, and the heat load is the same within 2%. In order to maintain these accuracies, special simulation dewars are used for each refrigerator.

A benchmark set of measurements is made to normalize the climate chamber data for each refrigerator. This is done on a benchtop setup at room ambient temperature, measuring each refrigerator in turn with the same controller, motor stator and set of sensors. As an option, this benchmark set of measurements can be made inside a climate chamber at different ambient temperatures.

After the benchmark measurements, climate chamber temperature profiles begin. First, each candidate refrigerator is run through a customer ATP test sequence, however if the above benchmark set of measurements was performed inside a climate chamber at variable ambient temperatures, this test sequence is skipped. Each candidate refrigerator is then fitted with customized modules (motor, controller, etc) according to customer requirements. The refrigerator is then run through a sequence of ambient temperature and operation profiles defined by a customer. This test sequence is repeated twice. The sequence purpose is to identify repeatability of refrigerator performance as one of the important selection criteria, allowing higher confidence level of operation stability onboard a spacecraft.

After this, induced force vibrations along all three axes and acoustic noise are measured for each refrigerator at a recorded set of parameters. Finally, another customer-defined test sequence is performed. The total entire sequence of tests since the initial manufacture covers a few hundred operating hours for each refrigerator.

When this measurement sequence is completed for all candidate refrigerators, RICOR experts thoroughly analyze the data and prepare a comprehensive report recommending which refrigerators a customer should select as the "best". RICOR can send this report to a customer along with all data on all candidate refrigerators, to aid the customer in making the final selection of which refrigerators to procure as Flight Model units.

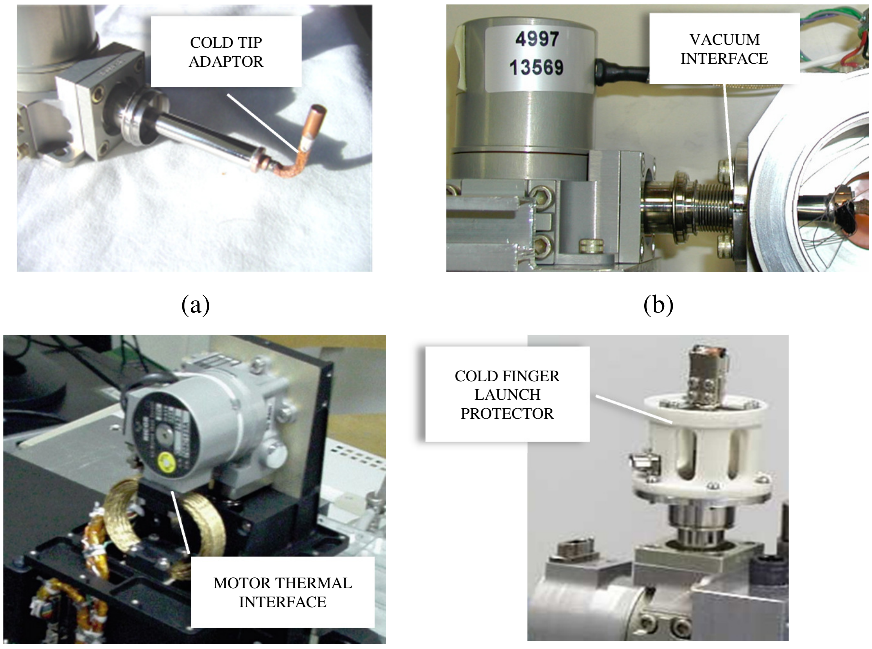
2.4 Customization and final testing

The refrigerators selected as Engineering Model and Flight Model units are customized to a customer build-to-order specifications for certain parts, such as motor stator, controller, cold finger, etc. For example, all refrigerator tests are performed using RICOR standard motor stators, except for the burn-in tests, which are conducted using modified stators. RICOR inspects and tests each stator and selects specific stators for "best" performance. A customer may specify components to be customized, such as capacitors, resistors, etc. In that case these flight-screened components are carefully installed by a RICOR trained technician. The reason for conducting the burn-in tests is to ensure that each chosen flight-quality refrigerator gets a burned-in new electronic component. To improve heat dissipation from the motor module, a specially designed motor housing with a thermal interface can be provided (Figure 3c). After being customized, each selected refrigerator is integrated to a special dewar designed by RICOR and is retested to specifications before delivery to a customer.

RICOR can also provide the option of supplying refrigerators without a controller unit, allowing a customer to develop a controller module embedded in his system electronics, using space-qualified materials and components that have been proven in terms of withstanding radiation levels and other space conditions. In that case RICOR electronics experts do support this activity providing essential information about the controller functionality and design.

Special materials and processes can be used to fulfil low outgassing requirements, with a suitable surface finish ensuring minimum deterioration and maximum product stability. They should comply with TML (Total Mass Loss) of <1% and Collectable Volatile Condensable Materials (CVCM) <0.1% when subjected to a test conducted at +125°C and 1E-6 torr for 24 hours. For example, to comply with these requirements, standard O-rings material may be replaced by VITON which is approved for use in space. Also in the motor assemblies, the standard thermal paste used for the controller heat-sink may be replaced, and the motor windings may pass through a special backing process during 48 hours.

Some customers may require a cold finger to be customized to a thinner tube and a more precise tolerance. This tube customization may provide a few tens of mW added cooling power. In that case RICOR provides available information on allowable forces on the cold finger during launch vibrations, to aid the customer in deciding which cold finger to employ. Ricor can also select cold fingers to provide better than average alignment to match with each compressor and can precisely measure each cold finger selected to ensure best alignment. The purpose of more precise alignment is to ensure more cooling power and less wear of parts over time. Each cold finger can be outfitted with a cold tip adaptor, a copper braid assembly to interface the cold tip adaptor to the detector assembly and a flange to form a vacuum interface (Figure 3a, b). In case there is a need to protect a thin-walled cold finger from damage under a launch vibration, RICOR can design, manufacture and install a special protector arrangement around the cold finger (Figure 3d).



(c) (d)

Figure 3. Customized design examples: (a) – Cold Finger outfitted with cold tip adaptor, (b) –vacuum interface flange with bellows, (c) – special motor housing with integrated thermal interface, (d) - cold finger launch protector arrangement

In order to prevent loss of cooling power over time, RICOR minimizes any contamination of the customized refrigerators during Helium fills, from the compressor, cold finger, Helium container, and plumbing. RICOR cleans all parts as necessary, using ultra-pure Helium, and runs through at least 40 fill/purge cycles. After the first 10 fill/purge cycles, between purges during the next 20 cycles, each refrigerator has its motor shaft rotated appropriately so as to expose new potentially contaminated surfaces. A liquid-nitrogen cold trap may be used to trap any contaminants from the He source. Cold traps or other means can also be used to ensure purged contaminants do not re-enter the system. After the last purge, the refrigerator is filled with Helium at a specified pressure. This procedure is implemented only in the final integration of the flight refrigerators to the dedicated dewars.

After customization, the selected FM refrigerators are tested in a climate chamber at various ambient temperatures, before delivery to a customer. RICOR outfits each cold finger with easily removed but securely attached accurately calibrated temperature diode and heat-load resistor, accurately measuring the heat loads of the special dewars and reporting the values to a customer. Each selected FM refrigerator is then tested as described in 2.3. If any refrigerator does not perform as well as expected, the test setup is examined for flaws. If such flaws are found whose elimination would be expected to improve performance to the expected level, these flaws are corrected and the tests are rerun. If performance remains below that expected, or if no such flaws are found, another refrigerator is selected from the candidates pool for customization and final testing.

3. SPACE MISSIONS RELYING ON RICOR PRODUCTS

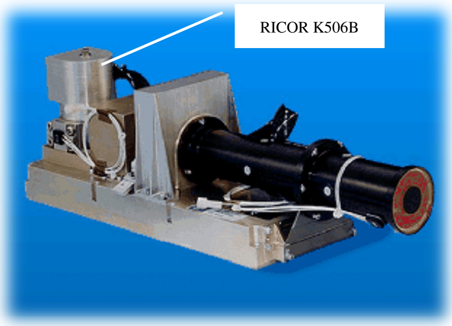
RICOR refrigerators are widely used for many years in a range of the space instruments launched onboard different spacecrafts by the space agencies of USA, Europe and Asia. The most famous of the missions using RICOR products are surveyed here; however there are still a significant number of them remaining beyond this survey, due to information that is unavailable or not authorized for publication.

3.1 CLEMENTINE – 1994

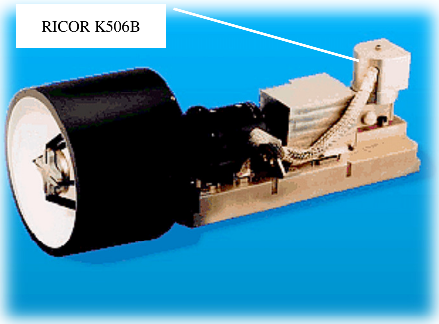
Clementine was a joint project between the Strategic Defense Initiative Organization and NASA. The objective of the mission was to test sensors and spacecraft components under extended exposure to the space environment and to make scientific observations of the Moon and the near-Earth asteroid 1620 Geographos. The observations included imaging at various wavelengths including ultraviolet and infrared, laser ranging altimetry, and charged particle measurements [1].

Clementine was launched on 25 January 1994 at 16:34 UTC (12:34 PM EDT) from Vandenberg AFB aboard a Titan IIG rocket. After two Earth flybys, lunar insertion was achieved on February 21 [2]. The RICOR K506B tactical rotary Stirling refrigerator (the K508 ancestor) was onboard the Clementine spacecraft, in the Near-Infra-Red (NIR) camera instrument. The refrigerator was driven by a HYB-10 controller integrated into the motor stator unit. The camera was designed to study the surfaces of the Moon and the near-Earth asteroid 1620 Geographos at six different wavelengths in the near-infrared spectrum. This experiment yielded information on the petrology of the surface material on the Moon.

(a)



(b)



(c)

Figure 4. (a) - Clementine spacecraft, (b, c) - Near Infra Red instrument with K506B refrigerator.

The camera consisted of a catadioptric lens which focused on a K506B-cooled (to a temperature of 70 K) Amber InSb CCD focal-plane array with a bandpass of 1100--2800 nm and a six-position filter wheel. The image array was 256 x 256 pixels, and pixel resolution varied from 150--500 m during a single orbit mapping run at the Moon. The camera took twelve images in each 1.3 s image burst, which occurred 75 times over the 80 minute mapping span during each five hour lunar orbit [3].

The mission ended on June 1994 when the power level onboard dropped to a point where the telemetry from the spacecraft was no longer intelligible. The K506B refrigerator completed its mission within the Clementine spacecraft without failures.

3.2 CIMEX – 2001

Another RICOR refrigerator was qualified for the Brazilian CIMEX space program, under the Brazilian National Space Activities Program 1998-2007, where a number of scientific and technological missions were planned within the framework of cooperative agreements with foreign Space Agencies. The project CIMEX used a RICOR K508 refrigerator with a Sofradir detector, while the project purpose was to test an infrared CCD camera in space.

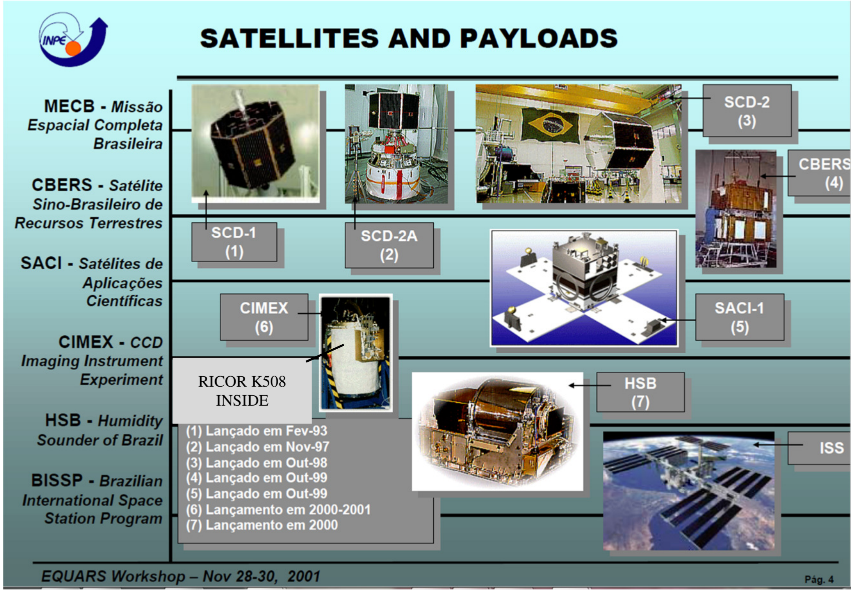


Figure 5. CIMEX project (in the framework of Brazilian National Space Activities Program) using RICOR K508 refrigerator.

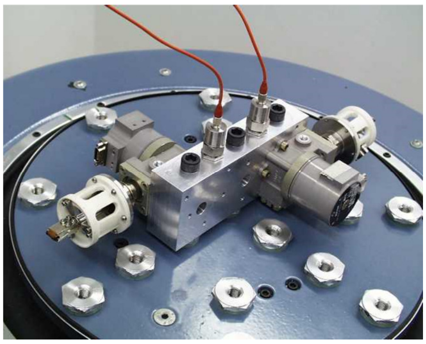
3.3 ROSETTA – 2004

Rosetta was launched on 2 March 2004 and arrived at Comet 67P/Churyumov-Gerasimenko on 6 August 2014. It is the first mission in history to rendezvous with a comet, escort it as it orbits the Sun, and deploy a lander to its surface [4]. The RICOR K508 refrigerator was selected for this mission within the VIRTIS instrument (Visible and Infrared Thermal Imaging Spectrometer). The VIRTIS is able to make pictures of the nucleus in the IR and also search for IR spectra of molecules in the coma. The detection is done by a Mercury Cadmium Telluride (MCT) array for IR, which is cooled by K508 units, and with a CCD chip for the visible wavelength range.

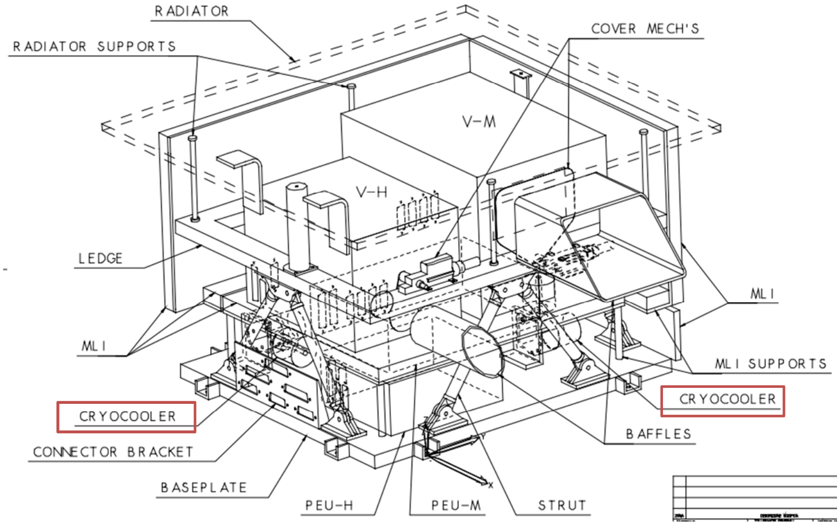
Figure 6. Rosetta orbiter under assembly and test process

RICOR K508	
ON/OFF operation (No)	>2000
Operating life (h)	>8000
Cooling power (mW)	500@ 77K
Input power (W)	14
Induced vibration (N rms)	0.1
Mass (kg)	0.45
Volume (mm^3)	71x60x110
Operating temperature (°C)	-40 - +72
Non-operating temperature (°C)	-56 - +85

(a)



(b)



(c)

Figure 7. (a) - K508 requirements for Rosetta program, (b) - K508 under vibration screening test, (c) - K508 location in VIRTIS instrument.

RICOR supplied several K508 refrigerators for this program which were thoroughly tested and selected before final delivery to the customer. Citation from [6]: “The small mass, volume and power available on the mission, along with the relatively short active operation requirements (only about 2000 hours, but after 8 years of cruise in “hybernation”), and considerations of cost saving, have led to the choice of “tactical” miniaturized refrigerators. Such devices are produced in series by several companies in the world for defense applications. After an extensive evaluation on the refrigerators available on the market, the preliminary choice has been the K508 by the Israeli company RICOR”.

Up to date, the K508 refrigerator installed in the VIRTIS instrument has started its operation after 8 years of voyage through space to the Comet 67P/Churyumov-Gerasimenko, and is currently functioning as specified.

3.4 MESSENGER - 2004

MESSENGER (a backronym of MErcury Surface, Space ENvironment, GEochemistry, and Ranging, and a reference to the Roman mythological messenger, Mercury) was a NASA robotic spacecraft that orbited the planet Mercury between 2011 and 2015. The spacecraft was launched aboard a Delta II rocket on 3 August 2004 to study Mercury's chemical composition, geology, and magnetic field. MESSENGER entered orbit around Mercury on 18March 2011, becoming the first spacecraft to do so. It successfully completed its primary mission in 2012. Following two mission extensions, the MESSENGER spacecraft used the last of its maneuvering propellant and deorbited as planned, impacting on the surface of Mercury on April 30, 2015 [8].

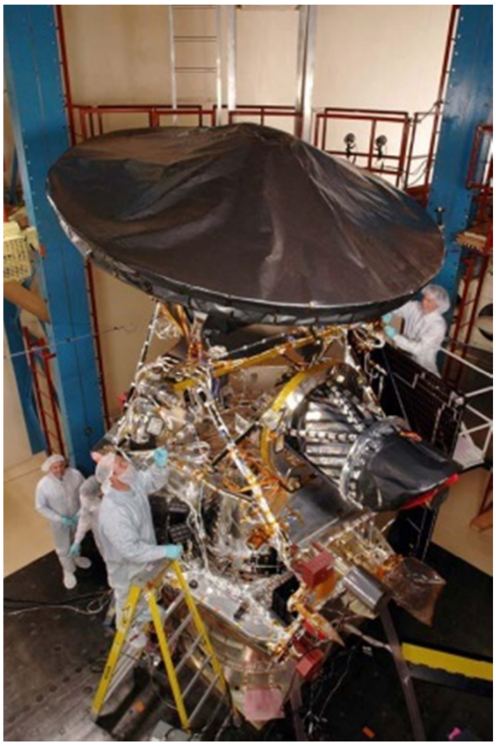
To help it measure surface gamma rays from long distances, MESSENGER used the most sensitive detector available - a high-purity germanium semiconductor crystal. While MESSENGER moved through one of the Solar System’s hottest environments, the crystal had to operate at cryogenic temperatures. Instrument designers addressed this challenge by suspending the detector on thin Kevlar strings inside a high-tech thermos bottle, carrying a small-size and powerful RICOR K508 refrigerator, capable of maintaining the Germanium crystal at 90K temperature. This instrument is called GRNS (Gamma-Ray and Neutron Spectrometer) and is shown in Figure 8b. Its purpose was to measure gamma-ray emissions from the surface of Mercury to determine the planet's composition by detecting certain elements (oxygen, silicon, sulphur, iron, hydrogen, potassium, thorium, uranium) to a depth of 10 cm.

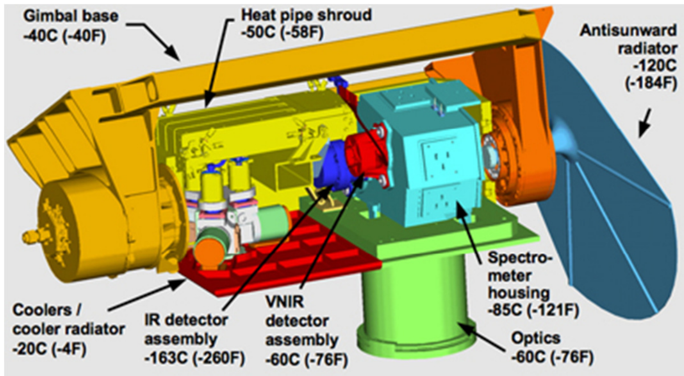
(a) (b) (c)

Figure 8. (a) - MESSENGER spacecraft during integration, (b) - K508 in GRNS instrument, (c) - GRNS prototype.

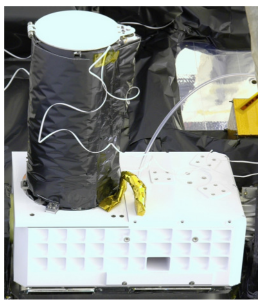
3.5 MARS RECONNAISSANCE ORBITER (MRO) - 2005

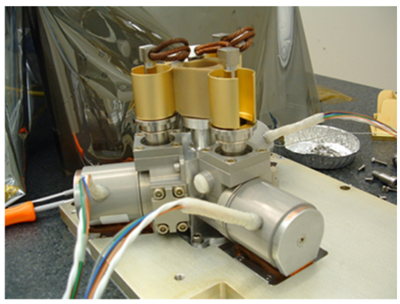
Mars Reconnaissance Orbiter (MRO) is a multipurpose spacecraft designed to conduct reconnaissance and exploration of Mars from orbit. The US$720 million spacecraft was built by Lockheed Martin under the supervision of the Jet Propulsion Laboratory (JPL). It was launched on August 12, 2005, and attained Martian orbit on March 10, 2006. MRO contains a host of scientific instruments such as cameras, spectrometers, and radar, which are used to analyze the landforms, stratigraphy, minerals, and ice on Mars.





(b)





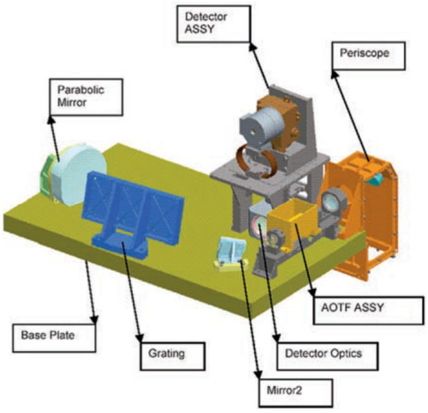
(a) (c) (d)

Figure 9. (a) - Mars Reconnaissance Orbiter under build, (b) - CRISM instrument temperature map with a bundle of three K508 units, (c) - CRISM instrument photograph, (d) - K508 under test before integration into CRISM instrument.

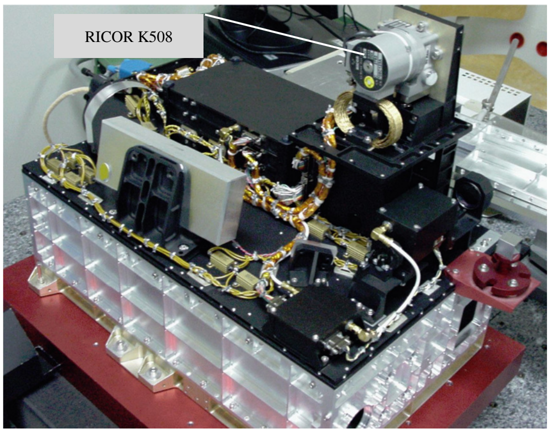
The RICOR K508 refrigerator was selected for use in the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument, which is a visible and near infrared (VNIR) spectrometer designed to produce detailed maps of the surface mineralogy of Mars. HgCdTe IR detector material with a 4050 nm long-wavelength cutoff was used in preference to InSb to provide lower sensitivity to instrument thermal background. It operates from 370 to 3920 nm, measures the spectrum in 544 channels (each 6.55 nm wide), and has a resolution of 18 m at an altitude of 300 km. During more than 10 years after the launch the MRO, the RICOR K508 refrigerators onboard are still continuing to serve in the system enabling spectrometric imaging of Mars surface.

3.6 VENUS EXPRESS - 2005

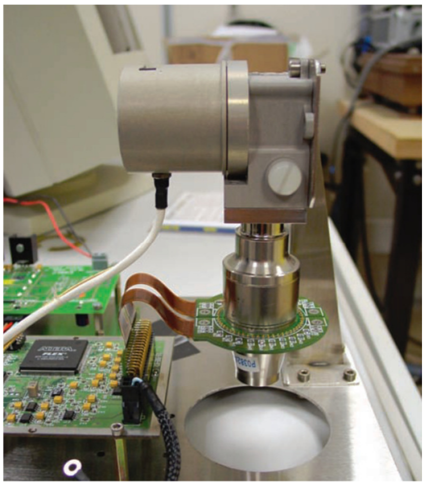
Venus Express (VEX) was the first Venus exploration mission of the European Space Agency (ESA). Launched on 9 November 2005, it arrived at Venus in April 2006 and began sending back science data from its polar orbit around Venus continuously. Equipped with seven scientific instruments, the main objective of the mission was the long term observation of the Venusian atmosphere. ESA concluded the mission on 16 December 2014.



(a)



(b)



(c)

Table 6. SOIR integrated detector cooler characteristics.

IR detector material	HgCdTe
Covered IR wavelength range	1.66–4.4 μm (FWHM)
Operating temperature	< 110K
Pixel configuration	2-D array organised as 320 columns by 256 rows programmable windowing
Pixel size	30 x 30 μm
Output level	1.6 (no light) to 4.4 V (full well)
Linearity (typical)	±1% for 25–92% of full well ±2% for 10–98% of full well
Gain setting	0.7 pF or 2.1 pF integration capacitor
Responsitivity (measured over complete wavelength range)	typical 76 V/nW per pixel @ 20 ms integration time and gain setting 0.7 pF
Readout speed	1–6 MHz for single output
Integration time	Minimum 3 μs; acceptance tested at 20 ms
Detector mounting	In dewar with f/4 cold screen
Integrated microcooler model	K508, modified for space applications (RICOR, Israel)
Steady-state cooling power (beginning of life)	4.1 W typical @ 24 V supply voltage (in 20°C air)
Pre-cooling power (beginning of life)	9.4 W typical @ 24 V supply voltage (in 20°C air)

(d)

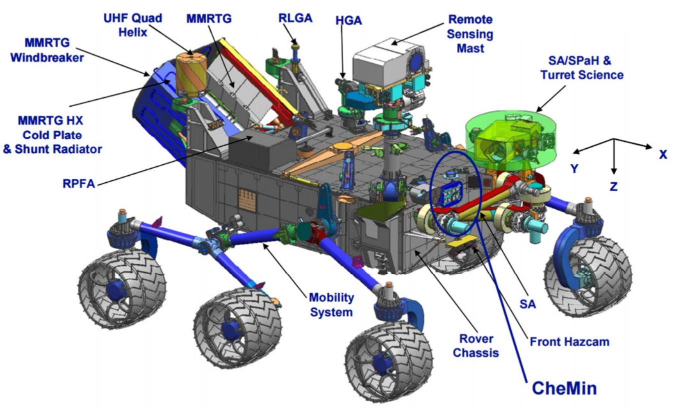
Figure 10. (a)-The layout of the SOIR floor, (b) - the SOIR Flight Model (cover removed) with RICOR K508 refrigerator on top of it, (c) - RICOR K508 refrigerator integrated with SOFRADIR (France) detector type ID MM0067, (d) - detector main characteristics.

The "SPectroscopy for Investigation of Characteristics of the Atmosphere of Venus" (SPICAV) is an imaging spectrometer that was used for analyzing radiation in the infrared and ultraviolet wavelengths. It is derived from the SPICAM instrument flown on the Mars Express. However, SPICAV has an additional channel known as SOIR (Solar Occultation at Infrared) that was used to observe the Sun through Venus's atmosphere in the infrared. One RICOR K508 refrigerator was selected for this instrument in combination with a customized 2-D HgCdTe ID MM0067 detector from SOFRADIR (France), allowing the detector temperature of 90K to be reached within a few minutes [12]. The selected K508 refrigerator had completed his task during the mission successfully, without failures reported.

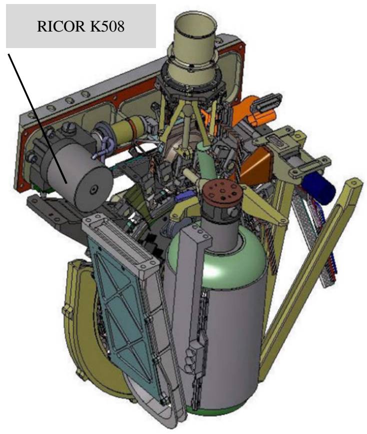
3.7 CURIOSITY MARS ROVER - 2011

Curiosity is a car-sized robotic rover exploring the Gale Crater on Mars as part of NASA's Mars Science Laboratory mission (MSL). Curiosity was launched from Cape Canaveral on November 26 2011 aboard the MSL spacecraft and landed on Aeolis Palus in the Gale Crater on Mars on August 6 2012. The rover's goals include: investigation of the Martian climate and geology; assessment of whether the selected field site inside the Gale Crater has ever offered environmental conditions favorable for microbial life, including investigation of the role of water; and planetary habitability studies in preparation for future human exploration.

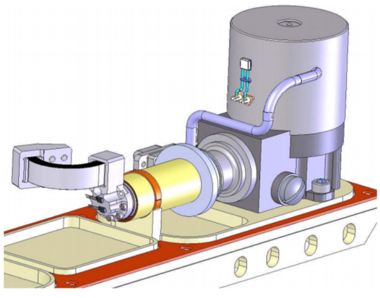
The Chemistry Mineralogy (CheMin) X-ray powder diffraction and fluorescence instrument was built for use on the MSL to make precision measurements of the mineral constituents of Mars rocks and soil. The rover can drill samples from rocks and the resulting fine powder is poured into the instrument via a sample inlet tube on the top of the vehicle. A beam of X-rays is then directed at the powder and the crystal structure of the minerals deflects it at characteristic angles, allowing scientists to identify the minerals being analyzed, using E2V CCD-224 X-ray sensitive 600X600 pixel imager having 40 μm square pixels [17].



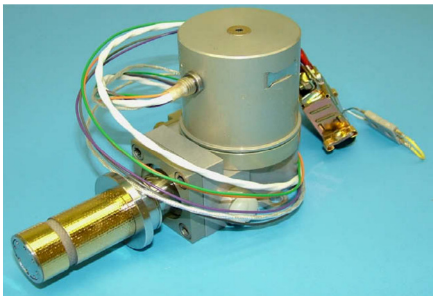
(a)



(b)



(c)

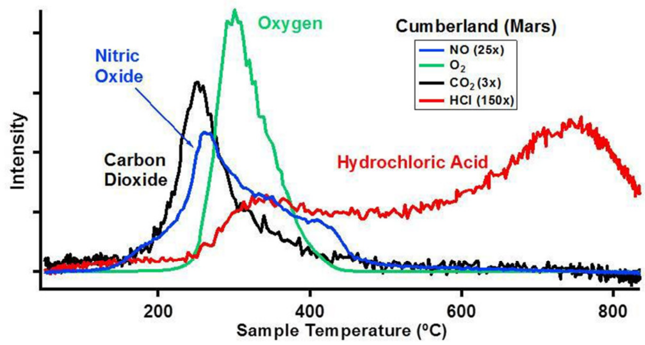


(d)

Figure 11. (a) - The Curiosity Mars rover, (b) - CheMin instrument, shown without external housing, (c) - RICOR K508 refrigerator mounted to the side plate of the CheMin instrument, (d) - RICOR K508 photograph with cold finger bumper attached

The instrument uses the RICOR K508 Stirling cycle cryogenic refrigerator to maintain the CCD at 173K to make X-ray diffraction spectroscopy measurements. In that mission, the K508 was installed with its electronics as-built, with minor customization; it therefore went through an ample testing, extensive characterization and qualification test program, including Flight Acceptance level thermal tests, to validate the refrigerator and its electronics capability to satisfy the instrument and MSL reliability requirements. The K508 refrigerator was selected for its small volume and mass, high cooling capacity, cost effectiveness, previous flight history, and the fact that no other mechanical cooler of its size had any flight heritage [16]. NASA and RICOR teams conducted a comprehensive test program to qualify the refrigerator for the MSL mission. The qualification model refrigerator was subjected to qualification-level random vibration and qualification-level thermal tests; and two coolers completed the life testing successfully.

(a)



(b)

Figure 12. (a) - Hole diameter 1.6 cm drilled into Martian mudstone for materials analysis by CheMin instrument, (b) – Sample Analysis at Mars (SAM) made by CheMin instrument employing RICOR K508 refrigerator.

As the paper is written, Curiosity has been on the planet Mars for more than 3.5 years since landing on August 6, 2012. To date, the RICOR K508 refrigerator is functioning as required for CheMin instrument targets.

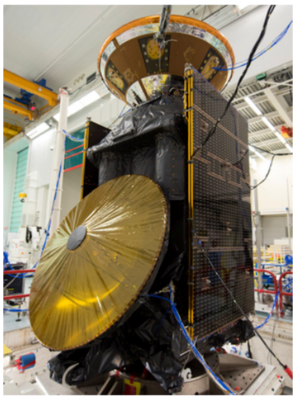
3.8 TGO (EXOMARS) - 2016

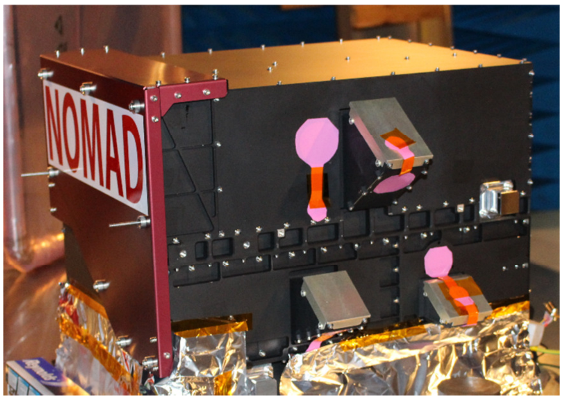
The first mission of the ESA ExoMars program, scheduled to arrive at Mars in October 2016, consists of a Trace Gas Orbiter (TGO) plus an entry, descent and landing demonstrator module, known as Schiaparelli. The Orbiter spacecraft is designed by ESA, while RosCosmos provided the launch vehicle, a Proton rocket.

The main objectives of this mission are to search for evidence of methane and other trace atmospheric gases that could be signatures of active biological or geological processes, and to test key technologies in preparation for ESA's contribution to subsequent missions to Mars. The Orbiter and Schiaparelli were launched together on 14 March 2016 on a Proton rocket, and will fly to Mars in a composite configuration.

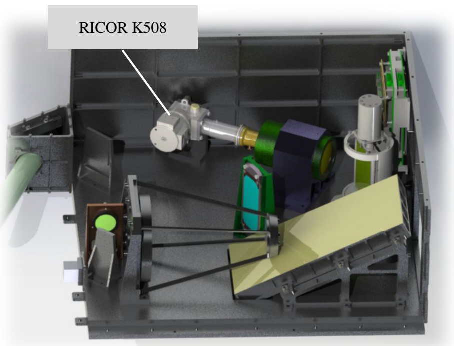
RICOR K508 refrigerator was launched on this spacecraft inside the Nadir and Occultation for MArs Discovery (NOMAD) instrument. NOMAD is a spectrometer suite that can measure the spectrum of sunlight across a wide range of wavelengths (infrared, ultraviolet and visible). This broad coverage of the instrument enables the detection of the components of the Martian atmosphere, even in low concentrations. In addition to identifying the constituents of the Martian atmosphere, NOMAD will also map their locations. The RICOR refrigerator adapted to the mission specification was selected for this mission to maintain a required temperature of the space-grade version of the standard Scorpio MW Sofradir (France) detector 640 x 512 HgCdTe MWIR (15 µm pitch).

While writing of this paper, the ESA TGO-Schiaparelli spacecraft, with RICOR K508 refrigerator onboard, is at the beginning of its way to Mars. The Scientific part of the mission is expected to begin in December 2017, and is planned to run for five years. The Orbiter will perform detailed, remote observations of the Martian atmosphere, searching for evidence of gases of possible biological importance, such as methane and its degradation products. The TGO will also be used to relay data for the 2018 rover mission of the ExoMars program, until the end of 2022.





(a) (b)

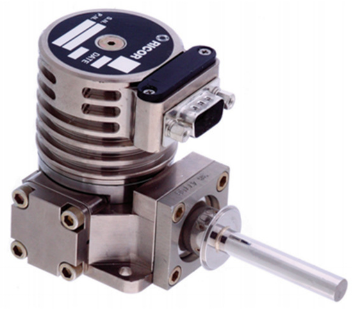


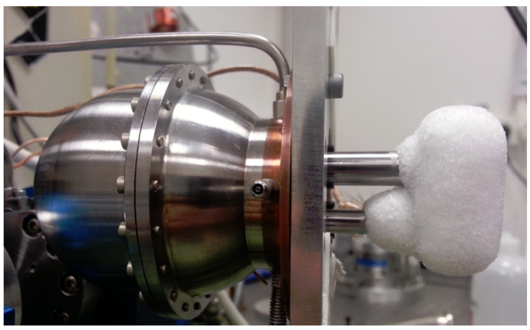
(c) (d)

Figure 13. (a) - ExoMars TGO during testing, (b) – NOMAD instrument, (c) – RICOR K508 refrigerator with Sofradir Scorpio MW detector, (d) - location of the RICOR K508 refrigerator+Sofradir detector in the NOMAD instrument

4. RECENT SPACE DEVELOPMENTS AT RICOR

To date, there are a number of future space application developments with different customers, relying on RICOR products, which are at different stages of negotiations, system definition, design or testing. The new generation of Stirling integral rotary refrigerators, such as the K562S and the K508N are considered worthy candidates for the upcoming missions in space.





(a) (b) (c)

Figure 14. (a) – New RICOR candidates for upcoming space programs: (a) - K562S, (b) – K508N, (c) - K571 Pulse Tube cold head (Bread-Board configuration).

Along with the 20-years heritage of delivering Stirling rotary refrigerators to space systems, RICOR continues developments towards future long-term missions. The mechanism of the miniature rotary refrigerator is based on ball bearings that have a limited lifetime, no more than a few years. Consequently, a refrigerator is usually operated from time to time just for specific tasks at a certain duty cycle. However there are space missions where “24-7” continuous operation of a refrigerator is required for 10 years and more. Therefore, the new project currently conducted at RICOR's R&D is aiming to develop an ultra-long-life Pulse Tube refrigerator driven by a flexure-bearings contactless compressor. The new space refrigerator is specified for >90,000 hours lifetime, providing 1.5W cooling capacity at 77K, and weighing <2.2 kg. The current status of the project is at the very early stage of the Engineering Model design, after successful completion of the design concept proof, using Bread-Board configuration. The project is supported financially by the Israeli Space Agency (ISA) and Israeli Ministry of Defense (IMOD).

5. SUMMARY

The RICOR company has accrued a heritage of 22-years delivering Stirling rotary refrigerators to space systems, using proven design, manufacturing and screening processes. During this period, many RICOR miniature refrigerators have been delivered for different space missions run by NASA, ESA and other space agencies programs. Current developments are focused on continuing the space products heritage, along with R&D of a new long-life highly reliable product based on the Pulse Tube concept. The space-qualified refrigerators are continuously adopted at RICOR as a platform for development of novel technologies for ground-based products, in order to improve their reliability, performance and lifetime.

REFERENCES

[1] Nozette S. et al., "The Clementine Mission to the Moon: Scientific Overview" Science, Vol. 266, No. 5192, 1835-1839, (December 16, 1994).

[2] Dunbar, B., "NASA Missions", (July 15, 2008) http://www.nasa.gov/mission_pages/LCROSS/searchforwater/clementine.html

[3] Grayzeck, E., "Clementine Near-Infrared CCD Camera (NIR)", (12 February 2016) http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1994-004A&ex=02

[4] Coradini A. et al., "Virtis : an imaging spectrometer for the Rosetta mission" Planetary and Space Science, Volume 46, Issues 9–10, 1291–1304 (October 1998).

[5] ESA website, "Rosetta" (20 March 2016), http://www.esa.int/Our_Activities/Space_Science/Rosetta

[6] Coradini A. et al., "VIRTIS, visible infrared thermal imaging spectrometer for the ROSETTA mission", IGARSS'95, Quantitative Remote Sensing for Science and Applications, Volume 2, 1604 - 1606 (July 1995).

[7] Instituto Nacional de Pesquisas Espaciais – INPE, "EQUARS Workshop" (2005) http://www.laser.inpe.br/equars/eng/workshop.shtml

[8] Wikipedia website, "Messenger" (21 March 2016(, https://en.wikipedia.org/wiki/MESSENGER#cite_note-ExMissionCompleted2013-2

[9] Murchie S. et al., "Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO)", Journal of geophysical research, Vol. 112, E05S03, doi:10.1029/2006JE002682, (2007)

[10] Wikipedia website, "Mars Reconnaissance Orbiter" (11 March 2016), https://en.wikipedia.org/wiki/Mars_Reconnaissance_Orbiter

[11] Wikipedia website, "Venus Express" (11 January 2016), https://en.wikipedia.org/wiki/Venus_Express

[12] Bertaux J-L. et al., "SPICAV: Spectroscopy for the investigation of the characteristics of the atmosphere of Venus", ESA Special Publication, Volume SP 1295, 1-40, (November 2007)

[13] Chorier P., Tribolet P., "Latest development for space applications at Sofradir", SPIE Remote Sensing Symposium [6744A-76], Florence, (2007)

[14] Vuillermet M., Chorier P., "Sofradir InfraRed technologies for space detectors", ICSO-2004, ESA SP-554, 759-766, (June 2004)

[15] Korablev O.I. et al., "Compact high-resolution echelle-AOTF NIR spectrometer for atmospheric measurements", ICSO-2004, ESA SP-554, 73-80, (June 2004)

[16] Johnson D.L., Carroll B.C. and Leland R.S., "MSL/CheMin Cryorefrigerator System Requirements and Characterization Tests", Cryocoolers 15, ICC Press, Boulder, Colorado, 621-630, (2009).

[17] Blake D.F. at al., "The CheMin Mineralogical Instrument on the Mars Science Laboratory Mission", 40th Lunar and Planetary Science Conference, #1484, Woodlands, Texas, (2009).

[18] Wikipedia website, "Curiosity (rover)" (5 April 2016), https://en.wikipedia.org/wiki/Curiosity_(rover)

[19] Wikipedia website, "Timeline of Mars Science Laboratory" (31 March 2016), https://en.wikipedia.org/wiki/Timeline_of_Mars_Science_Laboratory

[20] O. Korablev et al., "Three infrared spectrometers, an atmospheric chemistry suite for the ExoMars 2016 trace gas orbiter", J. Appl. Remote Sens. 8(1) 084983 1-13, (2014)

[21] ESA website, "ExoMars Trace Gas Orbiter and Schiaparelli Mission (2016)", (14 March 2016), http://exploration.esa.int/mars/46124-mission-overview/

[22] Royal Belgian Institute for Space Aeronomy website, "ExoMars. The NOMAD instrument", (9 March 2016), http://mars.aeronomie.be/en/exomars/nomad.htm