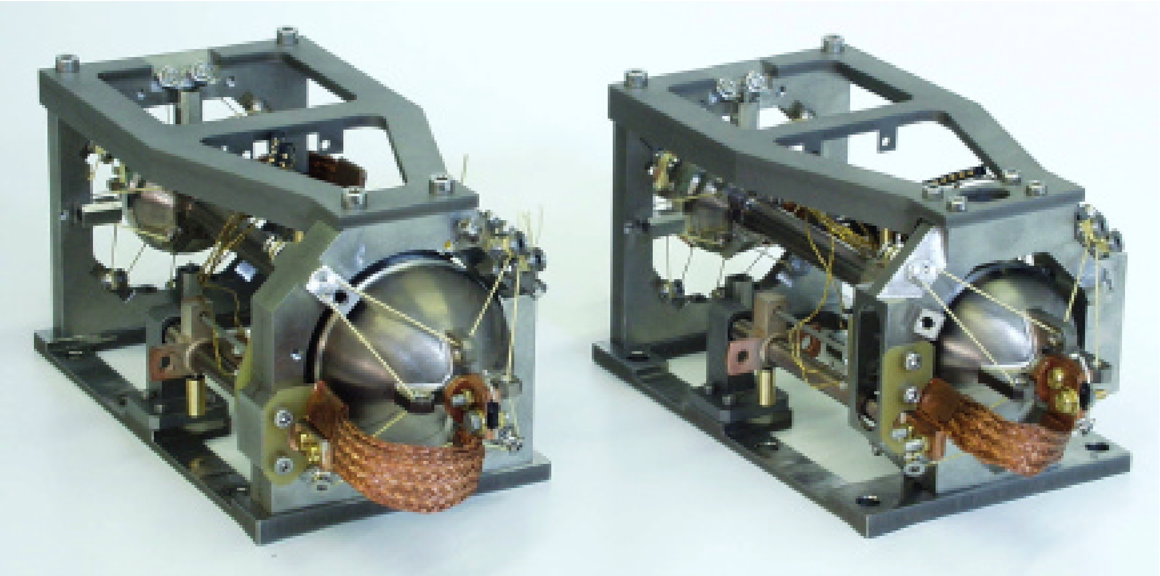
SERVICE DES BASSES TEMPERATURES

CRYOGENIC SORPTION COOLER

ESA Contract # 12942/98/NL/PA



SUMMARY REPORT

Note SBT/CT/2000-44
Project Reference : RP/SBT/SC/00-04
Date : November 2000 – Issue : 1 – Revision : 2
Author : Lionel Duband

<table>
<tr><td>COMMISSARIAT A L'ENERGIE ATOMIQUE
Département de Recherche Fondamentale sur la Matière Condensée
Service des Basses Températures</td><td>Document No.:
SBT/CT/00-44
RP/SBT/SC/00-04
Date : 11/2000
Issue : 1 – Rev. : 2</td></tr>
</table>

ESA Cryogenic Sorption Cooler Contract (12942/98/NL/PA)

<u>CRYOGENIC SORPTION COOLER</u>

SUMMARY REPORT

Written by Lionel Duband

Service des Basses Températures (SBT)
Département de Recherche Fondamentale sur la Matière Condensée (DRFMC)
COMMISSARIAT A L'ENERGIE ATOMIQUE - GRENOBLE (CEA-Grenoble)
17, rue des Martyrs 38054 GRENOBLE Cédex 9, France.

ESA TECHNICAL OFFICER – B. COLLAUDIN (MC DIV)

Distribution List

CEA – SERVICE DES BASSES TEMPERATURES (SBT)
L. DUBAND
SBT Secretary

CENTRE SPATIAL DE LIEGE (CSL)
P. JAMOTTON
Configuration Office

ESA – EUROPEAN SPACE RESEARCH AND TECHNOLOGY CENTRE (ESTEC)
B. COLLAUDIN
J. PINEL

Document Status

Issue	Revision	Date	Modifications
1	0	10/2000	First issue
1	1	06/11/2000	Page 12, 14, 15, 17 and 18
1	2	09/11/2000	Temperature regulation aspect added in conclusion Page 17

CONTENTS

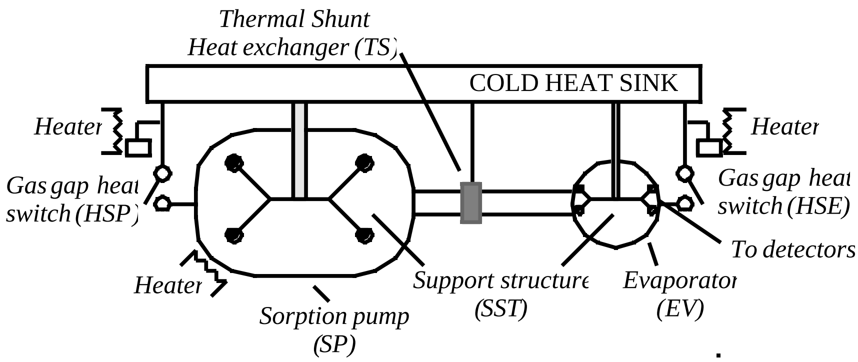
1 Introduction 5
2 Principle of operation 5
3 Sorption coolers design 7
3.1 Design tools 7
3.2 Detailed design 7
3.3 Manufacturing and Assembling 8
4 Performance 10
4.1 Test set-up and test plan 10
4.2 Thermal performance 12
4.2.1 Cryogenic performance 12
4.2.2 Bake out 14
4.3 Mechanical performance 14
5 Foreseen improvements and future work 16
6 Conclusion 17

1 Introduction

This report contains a summary of the work performed in the framework of the ESA contract 12942/98/NL/PA "CRYOGENIC SORPTION COOLER". The overall objective of this contract was to further develop the technology of helium sorption cooling and obtain sufficient confidence that this technology can be used in future space applications with no or only minor modifications. For this, flight hardware philosophy has been followed in term of design, manufacturing, integration, tests qualification and product / quality assurance.
The work was organized in two phases covering an overall period of 24 months. The first phase dealt with the development of design tools. It included a data collection and experimental measurements when the required data were not readily available, necessary for the software design tool. This tool was then used to perform the detailed design of two engineering models, a ^{3}He and ^{4}He sorption cooler.
The second phase was related to the actual manufacturing, performance characterization and prequalification testing of both models.

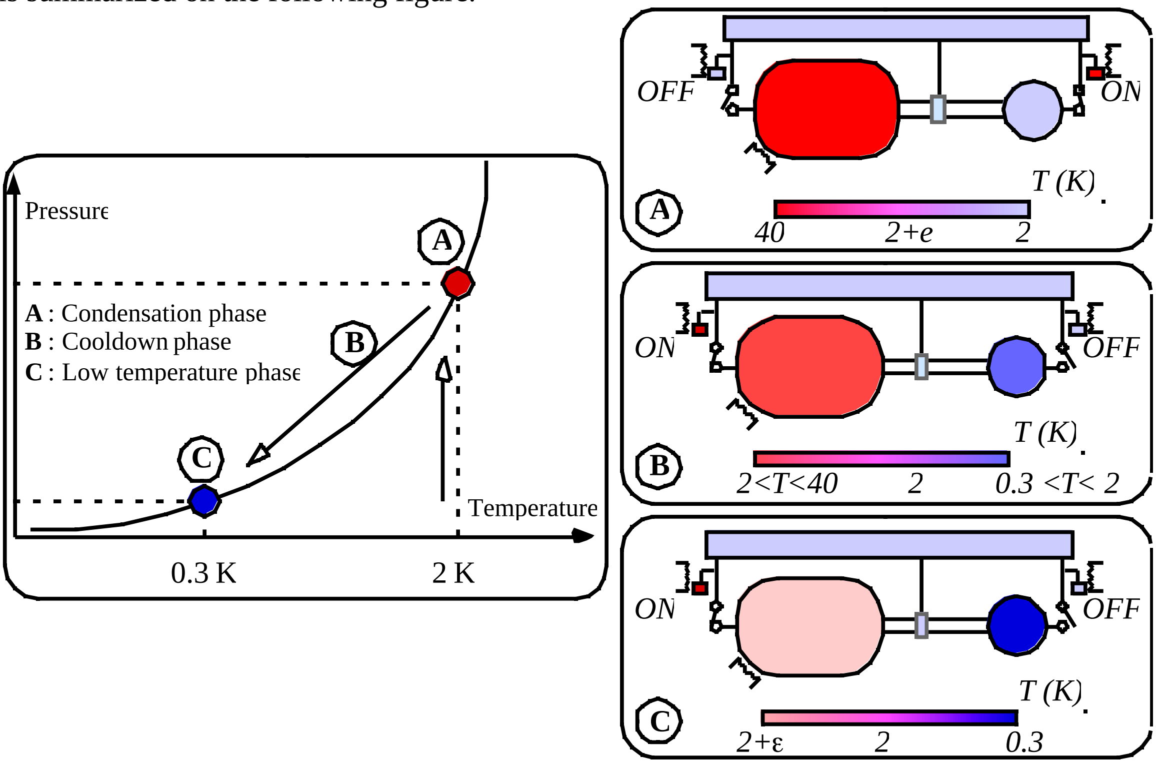
2 Principle of operation

The basic principle of operation of a sorption cooler is to condense liquid helium at some appropriate location and then to lower its pressure to decrease its temperature. The specific feature is the use of an adsorption pump to perform the evaporative pumping. Adsorption is the physical mechanism upon which a gas can be trapped onto a material surface : if a gas is brought into contact with a solid surface, some of the molecules striking the surface will be retained for a finite period of time, resulting in a significantly higher molecular concentration at the surface than in the gas phase. Depending on the magnitude and nature of the attractive forces the effect is described as chemisorption or physisorption. In the first case a chemical bond is formed and the process involves a transfer of electric charges. Physisorption, scope of the present work, relies on the relatively weak van der Walls forces. Evidently material with high specific area, such as activated charcoal (up to 1200 m^2 per grams) are required. The amount of gas adsorbed is then a strong function of pressure and temperature; it increases as the temperature decreases and the pressure increases. Thus by varying the temperature it is possible to provide either a compression or a pumping effect.. In addition physisorption, or the ability to vary the pressure by varying the temperature, can also be used to design very efficient gas gap heat switches.



As shown on the above figure, a helium sorption cooler is basically made of 6 components designated as a sorption pump SP and an evaporator EV connected via a pumping line to a thermal shunt TS comprising an heat exchanger, two gas gap heat switches HSP and HSE respectively connected to the sorption pump (SP) and evaporator (EV), and

finally a support structure SST. SP, EV, TS and the pumping line are assembled to form a unique component which is the actual "heart" of the cooler. This component is held within SST, which provides firm mechanical support (launch environment) while minimizing any parasitic conductive load on the cooler (low temperature environment).
Heat switches are then required for operation of the cooler. The two switches are used to control the temperature gradient. During the condensation phase they are set such that the sorption pump SP can be heated to release the helium gas and such that liquid condensation occurs into the evaporator EV maintained as the coldest point. The liquid is held into EV by capillary attraction inside some porous material : both the surface tension and the vapor pressure provide forces that drive and hold the liquid at the coldest point. Then the switches are set such that the sorption pump is thermally grounded to the heat sink and such that the evaporator is thermally isolated. The sorption pump provides an evaporative pumping on the liquid helium bath which temperature quickly drops to sub-Kelvin temperature. This principle is summarized on the following figure.



Cryogenic switches based upon different physical mechanisms can be used. Gas gap heat switches have been selected as the preferred design for the present projects. Gas gap heat switch utilizes concentric copper cylinders separated by a small gap which is filled with or emptied of He gas to achieve the switching action. The thermal separation between the two ends is achieved by a thin-walled tube which also provides the mechanical support. The presence or absence of gas is controlled by a miniature cryogenic adsorption pump that can be temperature regulated. Thus one of their main feature is the absence of moving part, and consequently operation of the cooler is then fully controlled by three heaters. Note that the heat switch on the sorption pump can be replaced by a passive thermal link but at the cost of some additional power on the cold heat sink. The design and operation of a ^{4}He system is slightly different mostly because of the superfluid ^{4}He film which creeps up the wall of the pump tube and can dramatically degrades the performance. To reduce this effect a small diaphragm can be installed in the pumping line.

3 Sorption coolers design

3.1 Design tools

CEA-SBT has previously developed a specific software to predict the performance of helium sorption cooler from their geometrical description and operating conditions. The model is made up of two modules. In the first one thermal performance such as hold time, ultimate temperature and thermal load are evaluated. In the second module an energy balance is performed and the various energies and powers required and dissipated are computed. In addition various preliminary verifications on the design of the cooler are performed (geometrical, mechanical strength, etc…). This software has been improved in the framework of this contract; in particular it now includes the ^{4}He option. It has been remodeled so new materials can be added easily. In the present version the sorption pump, pumping line and heat switches tubing are assumed to be either made of stainless steel or titanium Ta6V. Indeed recent measurements on titanium alloys have shown this material is of great interest because of a reduced thermal conductivity and enhanced mechanical properties.
This model can thus be used to design sorption coolers versus performance requirements.

3.2 Detailed design

The following table summarizes some of the main specifications for the ^{3}He unit. The ^{4}He unit was designed following the same overall specifications with the exception that it must be able to thermally recycle the ^{3}He unit, i.e. the ^{4}He evaporator provides the cold heat sink for the ^{3}He evaporator, and supplies enough cooling power to cooldown and condense the ^{3}He gas.

Safety	Structural failure mode shall be leak before burst
Mechanical	• Sine sweep vibration 22.5 G peak up to 100 Hz • Random : 20 – 2000 Hz : 6 G RMS • first eigenfrequency above 120 Hz • Shock spectrum of a half sine pulse 0.5ms duration and 200 G (0 to peak) amplitude • Proof pressure : 2.5 x operating pressure
Thermal	• Heat lift capability 10 µW minimum at 300 mK • Hold time no less than 46 hours • Recycling time no more than 2 hours • Time averaged load onto cryostat no more than 5 mW
Geometry and Interface	• Volume and Mass: 100 x 100 x 230 maximum - < 1 Kg • Mechanical interface: with a 4 K structure • Thermal interface: with a 1.8 K pumped helium bath

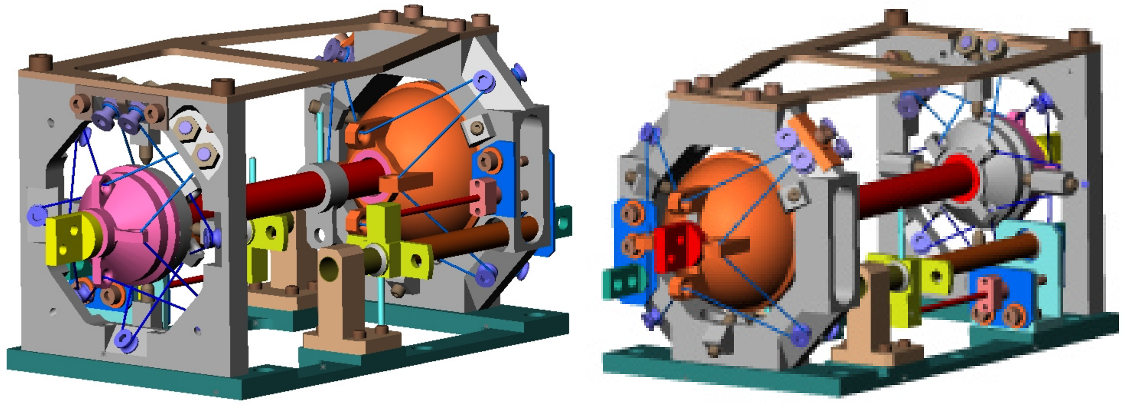
The detailed design of both sorption coolers, ^{3}He and ^{4}He, has been supported using the software model. Details on this design phase are supplied in the technical note “Detailed design of the engineering models” TN/SBT/SC/99-03. One important feature is that most of the cooler, i.e. the evaporator and sorption pump envelope, the pumping line and the heat switches tubing’s and finally the support structure, are made using a titanium alloy (Ta6V). Indeed the use of this material provides three benefits :

- lower thermal conductivity : gain on the parasitic loads
- higher mechanical strength : gain on the tube wall thickness (reduced parasitic load)
- lower density : gain on the overall weight (and consequently on the mechanical performance and/or support structure thermal load)

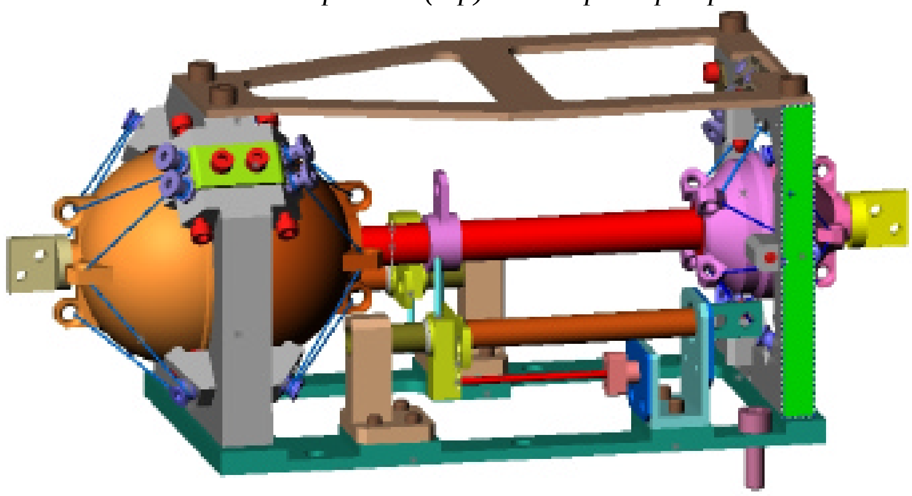
The main characteristics for both coolers are summarized in the table hereafter.

	^{3}He cooler	^{4}He cooler
He charge	4 STP dm^{3}	8 STP dm^{3}
Pressure at room temperature	7.86 MPa	7.97 MPa
Overall dimensions	90 x 90 x 207 mm	90 x 90 x 230 mm
Overall mass	878 grams	1034 grams
Suspended mass (cooler “heart”)	185 grams	258 grams

The drawings hereafter display a couple overall views of both EM coolers. The drawings have been produced using SolidWorks.



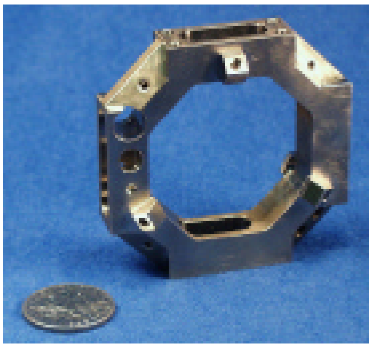
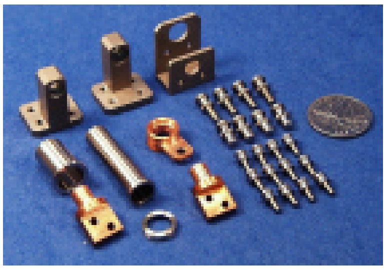
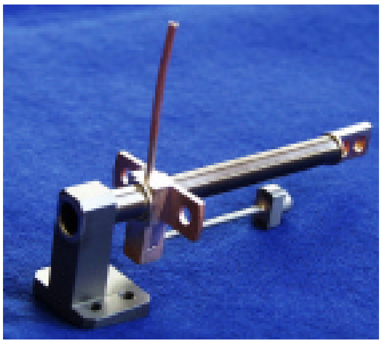
^{3}He cooler Evaporator (top) and sorption pump side

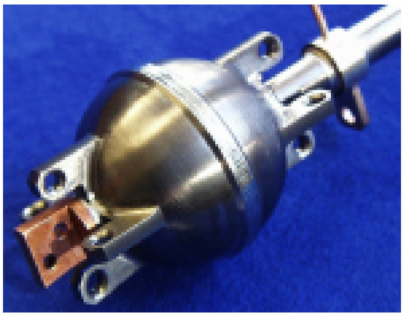
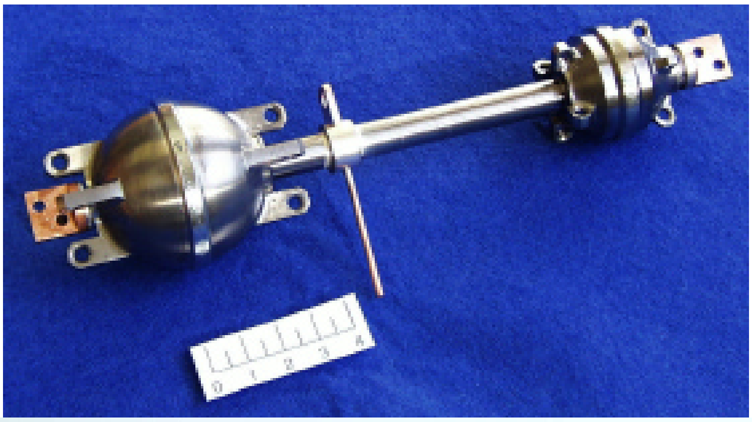
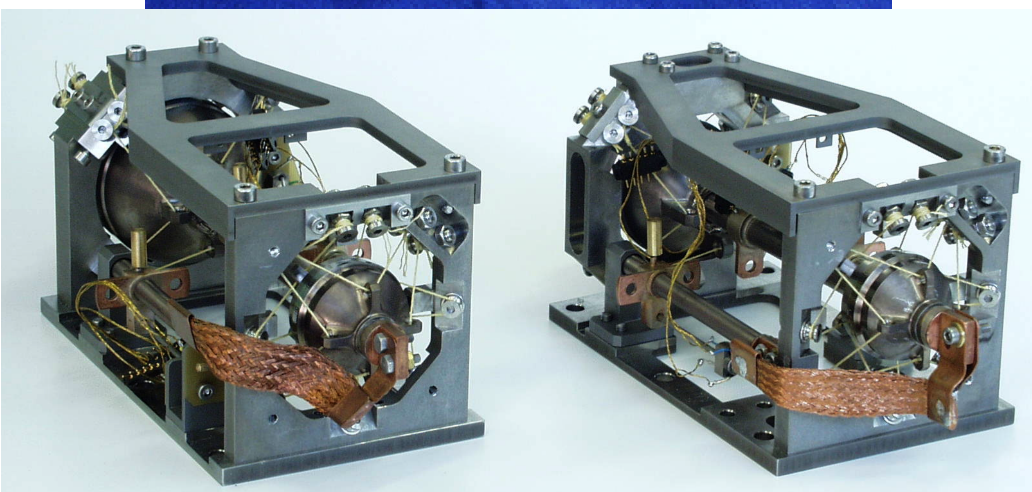


^{4}He cooler - Side view

3.3 Manufacturing and Assembling

The sorption coolers manufacturing was subcontracted to “Outillage et Mécanique Générale” (OMG – Fontanil (FR)). Most of the machining was done by electron discharge machining and numeric lathe. Each part was checked for any geometrical defect.
The assembling of the cooler was then performed in part at CEA-SBT (activated charcoal integration for instance) and in part at SNLS (titanium and copper brazing or welding). Whenever possible the partly assembled cooler was checked against any defect, leaks, etc…
A series of pictures taken during the assembly of the coolers have been reported hereafter.

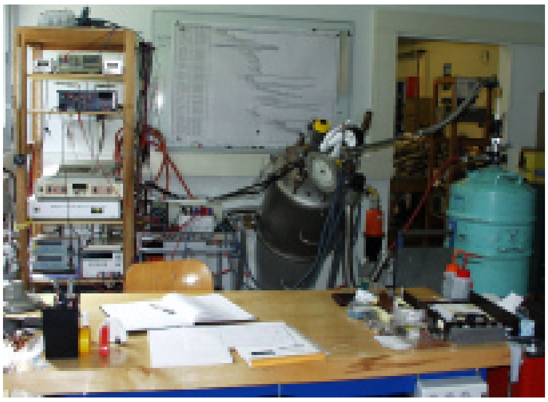




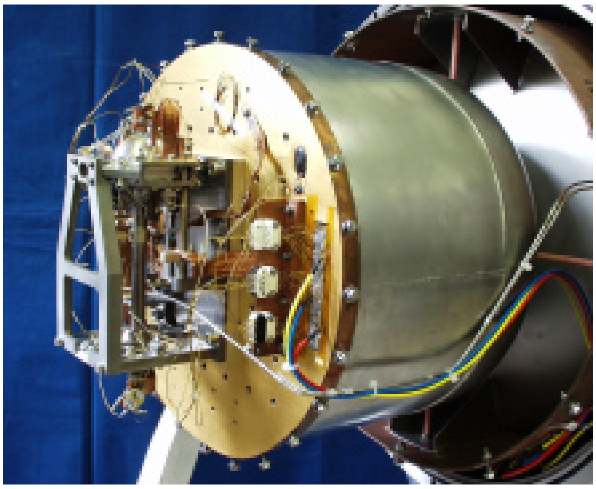





4 Performance

4.1 Test set-up and test plan

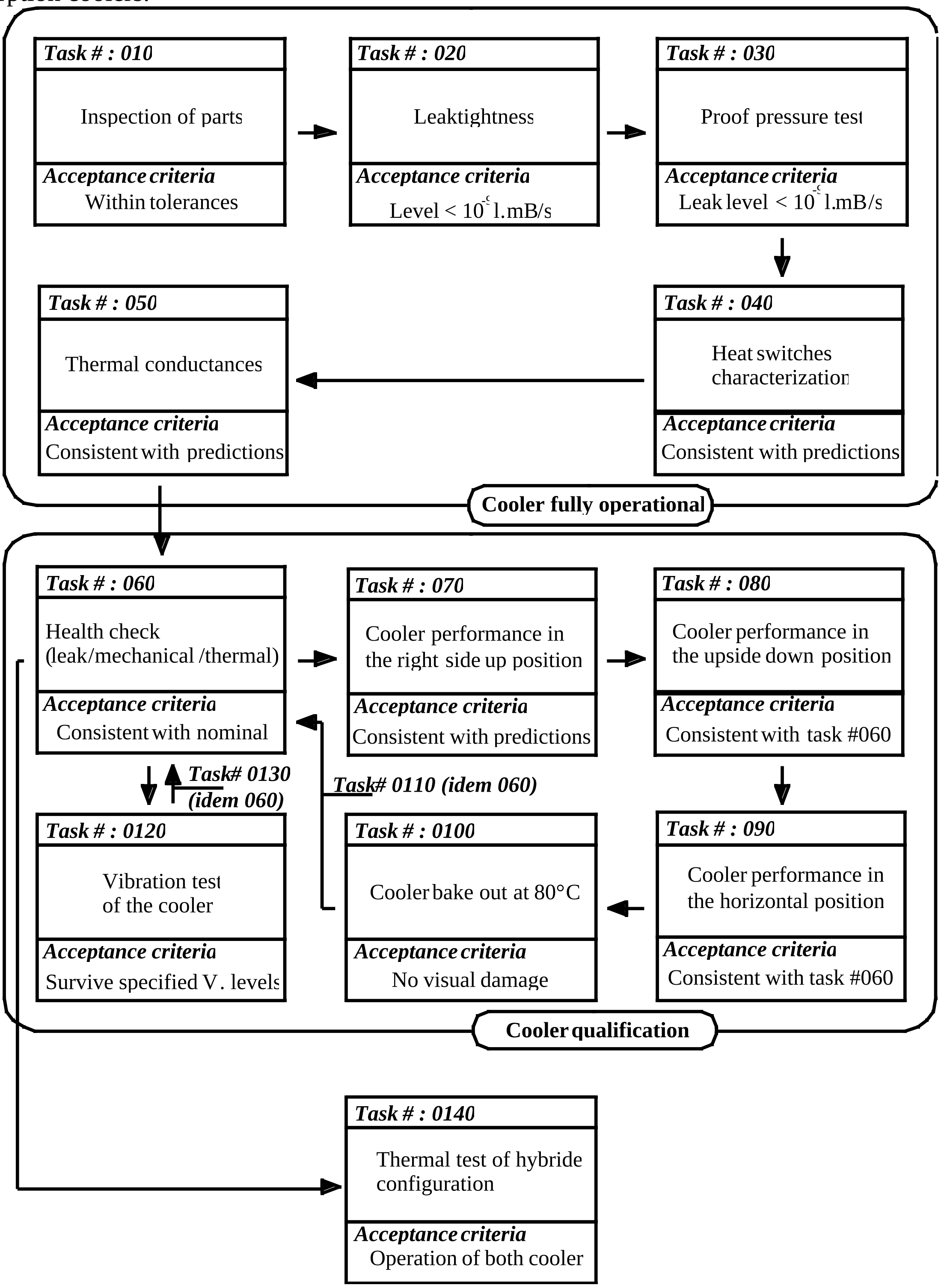
A test cryostat, CRYOTEDI, has been designed and manufactured. This cryostat contains a nitrogen and a helium tank, both supporting thermal shields. A particular feature of this test cryostat is the possibility to operate in any orientation between –90° and +90° as long as the liquid level is equals or below 50% (which is usually the case once the helium bath has been brought down from 4.2 K to 1.8 K). This feature allows to test the cooler rightside-up, upside-down and horizontally. The test set-up then includes typical low temperature equipment's such as liquid level sensor, temperature bridge and controller, voltage and current supply, voltmeter, plotter, etc…The opposite and following pictures display the test set-up and one of the sorption cooler mounted in the test cryostat.





A test program has been established. This plan comprises the tests sequence performed on the sorption coolers which contributed, together with analysis and other verification methods, to qualification. This test program covered the functional, performance and environmental tests required to provide confidence in the ability of the coolers to meet the

specified requirements. Performance measurements have been made before and after the environmental tests, designed to detect changes in performance parameters which could have indicated a potential failure.
The diagram hereafter summarises the sequence of tests which have been performed on the sorption coolers.



The results of the main tests are listed in chronological order in the table hereafter.

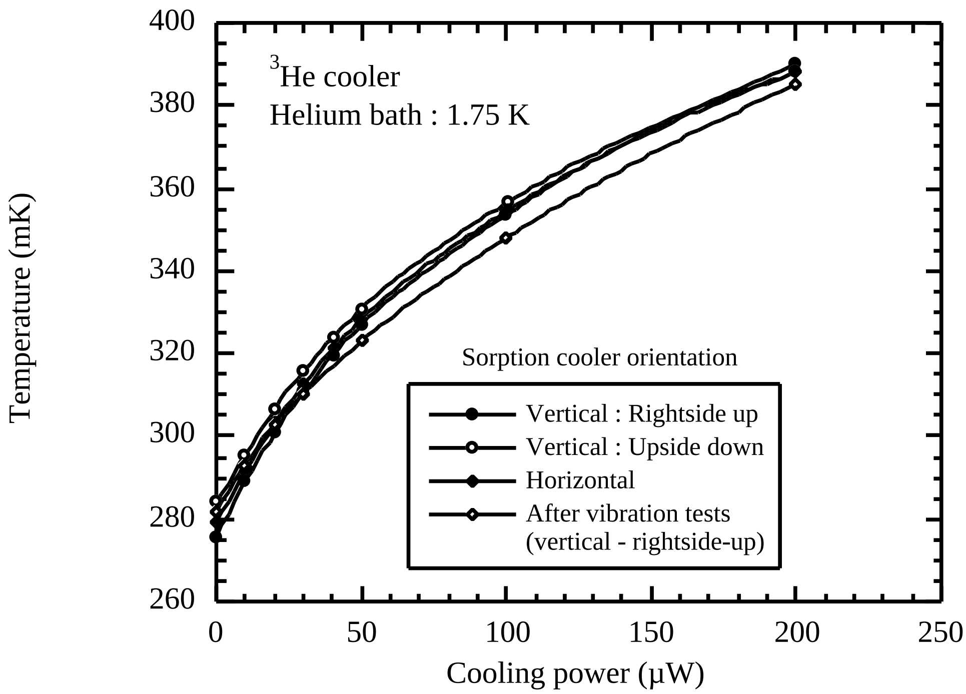
These results are further detailed in the following paragraphs.

Test	Experimental result
Leaktightness and proof pressure test	20.5 MPa for 3 minutes – leak rates < 10^{-10} mb.l^{-1}.s^{-1}
Thermal performance in various orientation (^{3}He / ^{4}*He* cooler : bath @ 1.75 K / *4.2 K*)	^{3}He unit : 264 mK ultimate temperature – 20 µW @ 300 mK ^{4}He unit : 912 mK ultimate temperature – 1.2 mW @ 1.30 K performance orientation indept. for both coolers
Cooler bake out at 80°C for one week	Passed - No problem nor contamination recorded
Verification of thermal performance	Consistent with first set
Vibration tests	Passed
Verification of thermal performance	Consistent with first set

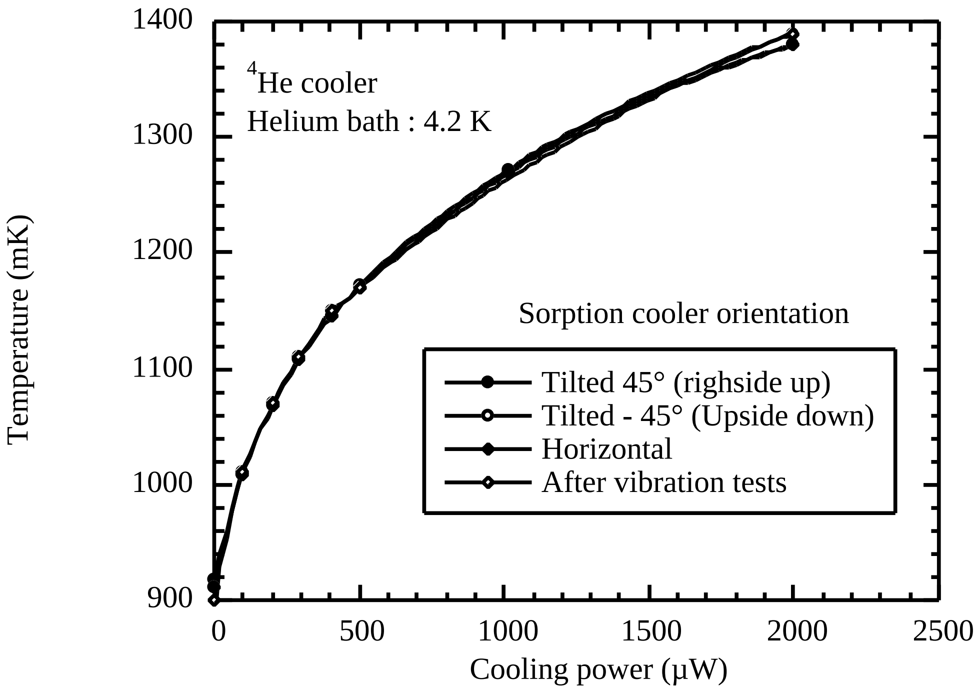
4.2 Thermal performance

4.2.1 Cryogenic performance

We summarize on the following curves the cooling power curves obtained in various orientation, before and after the bake out and vibration tests, respectively for the ^{3}He and ^{4}He coolers. The performance are orientation independent and remain unchanged after the vibration tests (and bake out). Note however that the cooler recycling needs to be performed at an angle of 15° or more (sorption pump above evaporator) to prevent any large convective effect (see TN/SBT/SC/99-01). This effect is only relevant during ground testing.
The no load hold time has not been measured since it extends the cryostat autonomy. However the hold times measured under 200 µW applied load are consistent with predictions. In addition the parasitic load has been experimentally determine to be 11 µW (bath at 1.8 K), in good agreement with the predictions (12 µW).

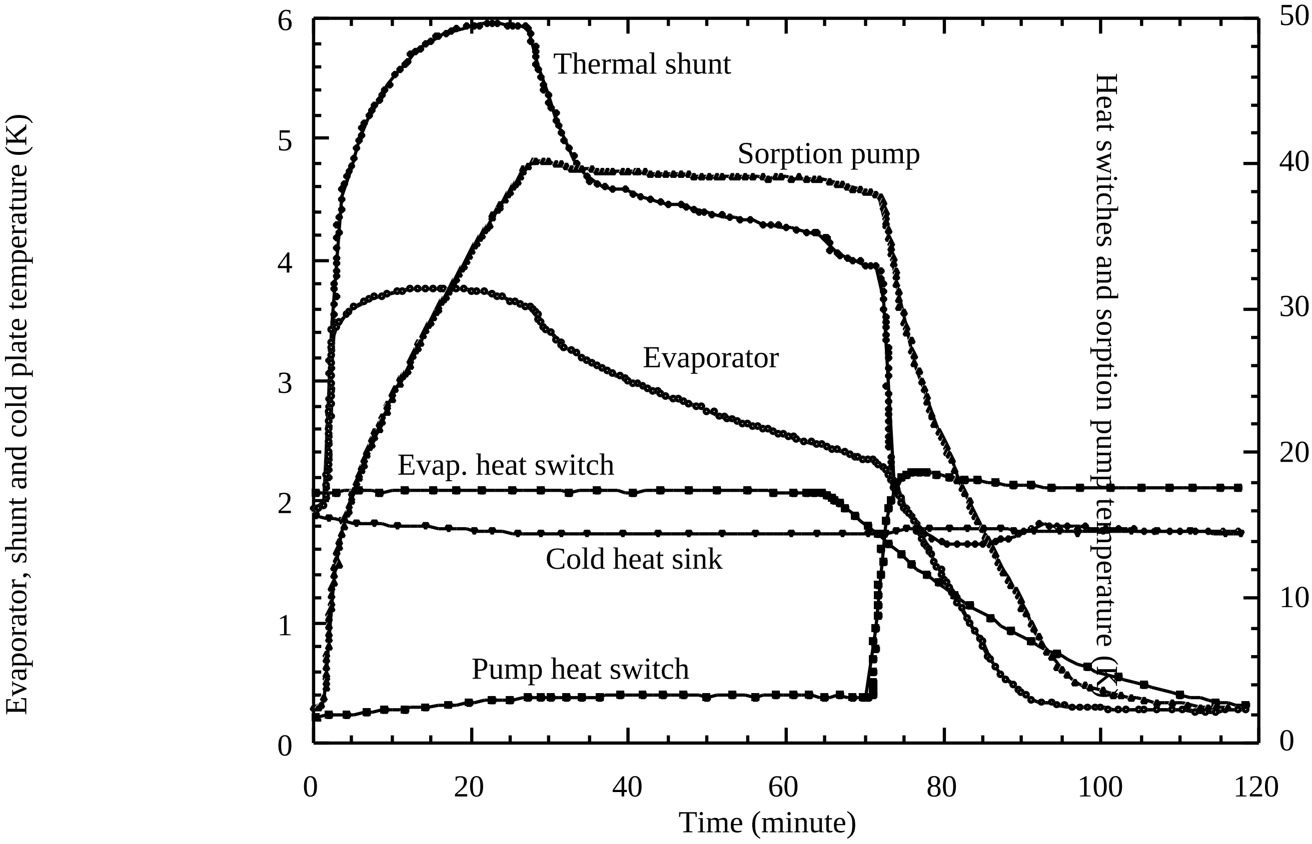


^{3}He Sorption cooler – cooling power curve



^{4}He Sorption cooler – cooling power curve

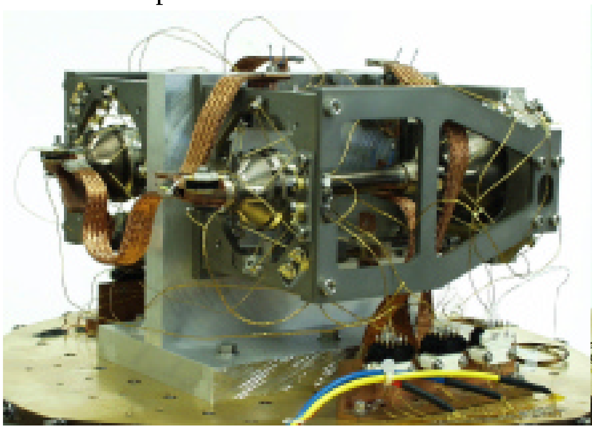
The next figure shows a typical recycling of the ^{3}He sorption cooler. Within 2 hours the evaporator reaches its ultimate temperature.

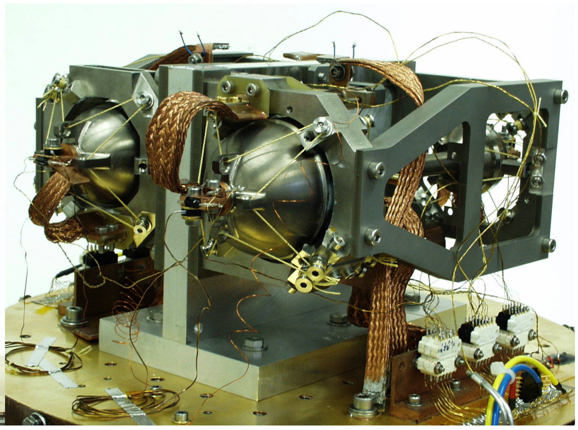


Both coolers were also thermally coupled and tested in an hybrid configuration, i.e. the ^{4}He unit is used to provide a cold heat sink for the ^{3}He unit following :

- both evaporators are thermally coupled
- the ^{4}He evaporator cools the ^{3}He evaporator to below 3 K and allows for condensation
- once the ^{4}He system runs out of liquid, the ^{3}He system cools in turn to below 350 mK

The simplest thermal architecture was used (two evaporators connected by a passive link) since in parallel to this contract CEA-SBT has successfully developed double stage sorption coolers (for ground applications), optimised for this type of thermal operation, and has demonstrated the proof of concept.
The two coupled coolers are shown below.





Evaporator side Sorption pump side

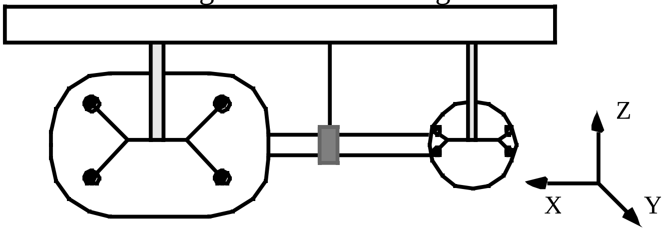
This hybrid cooler was successfully thermally characterized. The full condensation phase (recycling of both stages) required about 4 hours and the ultimate temperature were found to be 350 mK and 750 mK, respectively for the ^{3}He and ^{4}He stage. It has to be noted that once both stages are cold the ^{4}He stage accounts for an additional load to the ^{3}He stage (conductive + superfluid film) and consequently explains why the ultimate temperature of the ^{3}He cooler remains at 350 mK. In a system initially designed for this type of operating conditions the passive copper braid would be replaced by a heat switch, allowing to decouple the ^{4}He stage once the recycling of the ^{3}He is performed.

4.2.2 Bake out

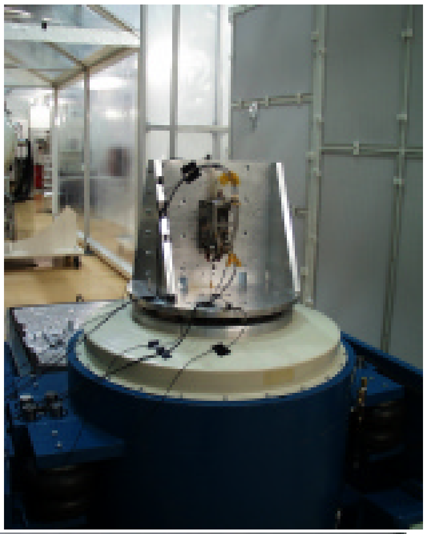
The bake out objective was to demonstrate the coolers could withstand a baking phase without performance degradation, and to verify the coolers are “cleanable”.
Both objectives have been fulfilled with success; the thermal performance remained unchanged after the bake out, and the recorded contamination is within the class 100 in terms of particular and molecular contamination.

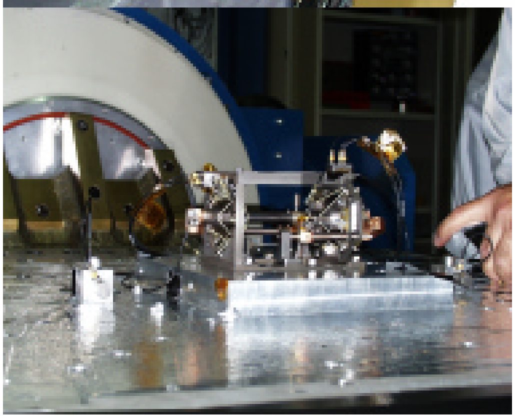
4.3 Mechanical performance

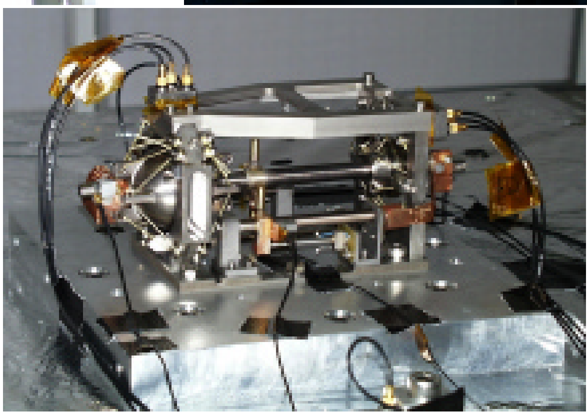
Both sorption coolers successfully passed the room temperature vibration tests which also included shock tests. The strength of the support structure and the resonant frequencies are expected to increase as the temperature is lowered, due to both the increase in Kevlar Young’s modulus and ultimate strength. Cold vibration tests could not be accommodated in the present contract (delay, availability, cost) but should be done for future flight versions. The orientation of the cooler with regards to the axis is given on the following picture.



The main results are summarized in the table hereafter.
The following pictures displays various photographic records of the coolers undergoing the vibration tests.







Resonant frequencies

	^{3}He cooler			^{4}He cooler		
	X axis	*Y axis*	*Z axis*	*X axis*	*Y axis*	*Z axis*
Evaporator	353	765	669	288	743	739
Sorption pump	353	602	665	288	476	499
Pump switch	866	164	150	748	144	124
Evaporator switch	1424	142	154	1779	158	233
Evaporator support	353	595	1546	288	739	302
Pump support	353	602	1359	288	476	296
Thermal shunt	353	602	665	288	476	499

These results call for a few remarks :

1) the low resonant frequencies recorded on the heat switches were somewhat expected, and this the reason why snubbers are included for both the switch end and miniature sorption pump. The efficiency of these snubbers has been demonstrated as no degradation appears on the heat switches after vibration.
2) The resonant frequencies of the support structures in the X and Y axis appear to be the main driver. Clearly in a future version this structure will need to be reinforced.
3) All these resonant frequencies were measured before and after the high G tests and remained unchanged.

The tests were successful and no damage was noticed during and after the vibration sequence. As mentioned before subsequent to the vibration tests both coolers were thermally characterized and no difference in performance were recorded.

5 Foreseen improvements and future work

Both EM coolers successfully went through the qualification program, yet this set of experiments revealed some design aspects which has been or will need to be refined. The main modifications will be :

- The heat switch design will be reviewed. Indeed the experimental data indicated the miniature sorption pump needs to be shielded. As a snubber is required for this small pump it is foreseen to develop an inline design, i.e. the switch will basically be made of two titanium tubes mounted along the same axis on the switch copper base. The miniature sorption pump will be inserted inside one of the titanium tube which will act both as a snubber and a thermal shield. In fact this shield will also prevent the small pump to radiate when the heat switch is maintained in the ON position (15 K pump).

- The support structure will be reinforced.. The goal is to design a structure with much higher resonant frequencies than the cooler “heart” itself, to avoid that the structure actually drives the mechanical behavior. In the framework of the SPIRE and PACS instrument onboard FIRST the present design has to be modified anyway.

- The kevlar tensioning system will be reviewed. In particular the capstan turning and locking method will be improved to allow steps tensioning.

- The thermal straps between the sorption pump and cold heat sink and particularly the strap between the evaporator cold end and the heat switch hot end need to be improved. The experimental results showed this later strap is critical to the performance in regards to two aspects :
    - it needs to be designed flexible to avoid any mechanical constraint on the heat switch thin wall titanium tube, which could lead to some internal contact between the two copper part and significantly impact the cooler thermal performance
    - its overall thermal conductance must be high. A particular attention must be devoted to the thermal contacts. Indeed our measurements indicate these are critical to the performance of the strap.

On a longer time basis work could be performed on the adsorbent. For instance a material (activated charcoal or other) having an adsorption capacity such that during the condensation phase the sorption pump would need to be heated up to a lower temperature in order to desorb the helium, could substantially increase the efficiency of the cooler.

The development of a continuous sorption cooler could in some cases benefit the end user. The most obvious solution would be to cleverly couple two or more sorption coolers with heat switches. This concept certainly requires some major thinking.

An other interesting objective would be to decrease the operating temperature. The ultimate temperature of a “standard” single stage ^{3}He sorption cooler is limited to about 250 mK, thus one possibility would be to couple such a cooler with a NIS cooler (Normal metal – Insulator – Superconductor tunnel junction). With this thermal architecture temperature lower than 100 mK can be expected. NIS coolers are still in the development phase but the preliminary results already show some very interesting performance.

Finally a clear benefit to space mission would be to totally suppress the liquid cryogen (helium bath) to replace the limited lifetime cryostats by mechanical coolers. To date this type of cooler is limited to temperatures around 4.2 K with enough cooling power. Consequently to provide temperatures down to 300 mK requires a double stage sorption cooler. This concept has been validated and no particular problems are expected. If necessary a space-borne double stage unit could be designed and qualified on a limited timescale.

6 Conclusion

Two engineering model sorption coolers have been designed, manufactured and successfully qualified for space application.

The ^{3}He cooler reaches temperature down to 264 mK when operated from a 1.8 K cold heat sink, and provides typical cooling power of 20 µW at 300 mK. It can be recycled in less than 2 hours and once recycled its performance are orientation independent. During recycling and only during ground tests its orientation has to be such the sorption pump is above the evaporator by at least 15° to avoid any convective effect in the pumping line.

The ^{4}He cooler reaches temperature down to 912 mK when operated from a 4.2 K cold heat sink, and provides typical cooling power of 1.2 mW at 1.3 K.

It is important to note that these coolers are single shot systems, i.e. once recycled they can provide a wide range of cooling powers for a limited amount of time, after which they can be recycled again. In that sense they should be seen as energy devices : the ^{3}He and ^{4}He coolers require respectively about 470 and 1515 Joules for their recycling, and then provide useful “energies” of respectively 3.41 at 300 mK and 10.6 joules at around 1 K (parasitic included).

One particular feature of these coolers is that their operating temperature can be easily controled. Indeed there are basically two ways to regulate the temperature of the evaporator. The most obvious one is to directly dump an additionnal power at the cold tip of the evaporator to raise its temperature to the required value. However because of this additional power the autonomy of the cooler can be substantially affected. Moreover for temperature significantly higher than the ultimate temperature of the cooler, this method would require powers so large the regulation could not be effected (rapid exhaust of the liquid bath). A second method by far more efficient is to increase the pressure inside the sorption pump to increase the vapor pressure above the liquid helium bath and consequently raise the temperature. The pressure inside the sorption pump is simply controled by its temperature. Thus by regulating this temperature one can adjust the temperature of the evaporator to basically any value up to the heat sink temperature. This method has been successfully experimentally validated. One clear benefit is that the autonomy of the cooler is not affected and in fact is even increased since the latent heat of helium in the temperature ranges considered (usually 0.3 K – 2 K for ^{3}He and 1 K – 3 K for ^{4}He) increases.

Both coolers have been baked out at 80°C. The thermal performance remained unchanged after the bake out, and the recorded contamination is within the class 100 in terms of particular and molecular contamination.

Both coolers were then vibration tested. The tests were successful and no damage was noticed during and after the vibration sequence.

The table hereafter summarizes their main characteristics and performance.

	^{3}He sorption cooler	**^{4}He sorption cooler**
Overall dimensions	90 x 90 x 200 mm	230
Total mass	870 grams	1030 grams
Number of liters STP	4	8
Internal pressure (20 °C)	7.86 MPa	7.9 MPa
Proof pressure	20 MPa	20 MPa
Lowest burst pressure	36 MPa	36 MPa
80°C baked out	Passed – compatible class 100 particular and molecular contamination	
Vibration tests	Passed – lowest “free” resonant frequency : 353 Hz	Passed – lowest “free” resonant frequency : 288 Hz
Ultimate temperature	264 mK	912 mK
Typical cooling power	20 µW @ 300 mK	1.2 mW @ 1.3 K
Estimated hold time	44 hours with 10 µW applied	3 hours with 1 mW applied

Flight hardware requires product and quality assurance to ensure a high reliability during the lifetime of the satellite. These PA/QA aspects are necessary, but quite heavy. In the field of this contract, a reduced PA/QA program has been used, keeping only the essential of the job to keep the same goal as classical PA/QA, but reducing the amount of work. Thus, the upgrade from this "flight qualified prototypes" to real flight hardware is very small, in terms of technical aspects, of thermal performances and of PA/QA.

The flight model cooler of the SPIRE and PACS instruments onboard the FIRST satellite will be designed based on this heritage.