SPIRE & PACS Sorption Coolers Architectural Analysis Report

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SPIRE and PACS SORPTION COOLER

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ARCHITECTURAL ANALYSIS REPORT

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Resume: SPIRE and PACS Sorption Cooler Architectural Analysis Report.

REVISIONS			
REV	*CHANGE REASON*	DATE	*APPROVED*
A	Creation	2000-12-21	LGM Consultants
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1. Purpose

The cooling of the SPIRE and PACS detectors down to 300 mK will be effected by a helium three sorption cooler.
This study is dedicated to demonstrate what could be the optimal architecture of this sorption cooler, taking into account all the requirements of the system.
In order to achieve that goal, a functional analysis will be presented, and for each of the main functions of the cooler, a study will be performed to establish if there are any possible alternative which could increase the global operational reliability and availability of the cooler.
First of all, a life profile description of the sorption cooler will be provided. Effectively, all considerations that will be made hereafter will integer this life mission profile, and in particular, the fact that it is very important to be able to detect any potential failure of the system before launch (and that it is of no use to detect any failure after launch).

This study, performed over the reference definition of the Sorption Cooler available at the end of march 2001, demonstrates that the architecture applied within this definition presents the optimal reliability and availability compared with all the other architectures potentially conceivable.

Detailed demonstration of this conclusion is provided at § 6 of this document, once an internal and external functional analysis of the system will be performed in order to clearly present the functional interrelationships between all the components of the system also as the undesired events that would occur in case of the failure of any of them.

2. Applicable documents

	Title	Author	Reference	Date
AD1	Instrument Requirements Document	B. Swinyard	SPIRE-RAL-N-0034 Issue 1.0	23 Nov. 00
AD2	ICD Structure cooler	L. Duband & B. Winter	SPIRE-MSS-PRJ-000331	13 June 00
AD3	SPIRE & PACS sorption cooler specifications	L. Duband	SBT/CT/2000-18 Issue 2.2	23 Nov. 00
AD4	Instrument interface document – Part B - Instrument "SPIRE"	ESA	SCI-PT-IIDB/SPIRE-02124 Issue 1.0	1 Sept. 00
AD5	Instrument interface document – Part B - Instrument "PACS"	A. Heske	SCI-PT-IIDB/PACS-02126 Issue 0.5	17 July 00

3. Terms and Acronyms

AD : Applicable Document
CEA : Commissariat à l' Energie Atomique
ESA : European Spatial Agency
ETF : Environment Test Facility
EV : Evaporator
HSE : Heat Switch on Evaporator
HSP : Heat Switch on sorption Pump
MTTF : Mean Time To Failure
N/A : Not Applicable
RAL : TBD
RBD : Reliability Block Diagram
SBT : Service des Basses Températures
SCO : Sorption Cooler (full unit)
SP : Sorption Pump
SST : Support Structure
TBD : To Be Defined
TS : Thermal Shunt

4. Life Profile

4.1 General description

The following life profile description is based on the "*SPIRE & PACS SORPTION COOLER SPECIFICATIONS*" [AD3].
This life profile starts after the construction phase but includes the post-construction test phases.
The mission duration of the equipment being assumed to be of 5 years on earth and 4,2 years in orbit, the life profile is consequently based upon 10 years (5 + 5).

4.2 Life profile table columns

The decomposition of the life is presented hereafter, in § 4.3.
Each column is filled according to the following explanations:

Operation: type of operation applied on the Sorption Cooler (SCO) chronologically listed
Concerned component: component on which the operation is applied
Location: place where the operation is applied, this column is divided into two parts (SPIRE and PACS)
Duration: operation duration
Temperature range: temperature during the operation

4.3 Life profile table

Operation	Concerned component	Location SPIRE	Location PACS	Duration	Temperature range
Leak tightness & Pressure tests	Cooler heart	SBT	SBT	1 Week	Room Temperature
Gas gap heat switch thermal check	HSP, HSE	SBT	SBT	2 Weeks	4K – 300 K
Thermal test program	SCO	SBT	SBT	4 Weeks	0.3 K → 300 K
Storage	SCO	SBT	SBT	TBD	Room Temperature
Transport	SCO	SBT to ETF	SBT to ETF	4 Days	Room Temperature
Vibration tests	SCO	ETF	ETF	1 Week	Room Temperature
Storage	SCO	ETF	ETF	TBD	Room Temperature
Transport	SCO	ETF to SBT	ETF to SBT	4 Days	Room Temperature
Storage	SCO	SBT	SBT	TBD	Room Temperature
Health check	SCO	SBT	SBT	2 Weeks	0.3 K → 300 K
Bake out	SCO	SBT	SBT	1 Week	353 K
Health check	SCO	SBT	SBT	2 Weeks	0.3 K → 300 K
Transport	SCO	SBT to RAL	TBD	4 Days	Room Temperature
Performance Test	SCO	RAL	TBD	TBD	TBD
Transport	SCO	RAL to SBT	TBD	4 Days	Room Temperature
Health check	SCO	SBT	TBD	2 Weeks	0.3 K → 300 K
Cleaning/Packing	SCO	TBD	TBD	1 Week	Room Temperature
Transport	SCO	SBT to RAL	TBD	4 Days	Room Temperature
Delivery	SCO	RAL	SAP/MPE	TBD	Room Temperature
Project test plan	SCO	RAL	TBD	TBD	TBD
Transport	SCO	RAL to ESA	TBD	2,5 Years	Room Temperature
Delivery	SCO	ESA	ESA		Room Temperature
Satellite test	SCO	ESA	ESA		TBD
Storage	SCO	ESA	ESA		Room Temperature
Launch	SCO	Kourou	Kourou		5K
Operations	SCO	Orbit	Orbit	4,2 Years	2K
END	SCO	SCO	Orbit	5 Years	2K

Remark : After delivery of SCO to instruments, it is assumed that :

- Test period has a 2,5 years duration,
- SCO is operating 20 % of the time.

5. Functional description

This part of the Architectural Analysis is devoted to perform a functional description of the Sorption Cooler system (SCO).

5.1 Principle of operation

The basic principle of operation of the 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 (activated charcoal). The amount of gas adsorbed on this material surface is function of pressure and temperature; it increases as the temperature decreases and the pressure increases.
Thus, by varying the temperature of this material, it is possible to provide either a compression or a pumping effect.
Then, the SCO is made of the following components :

- A gas enclosure made of three parts : A Sorption Pump SP (sphere containing the activated charcoal parts), an Evaporator EV (smaller sphere containing a porous material) and a pumping line (10 cm long tube establishing the link between the two spheres connected in its middle part to a 1.8 K cold source through a thermal shunt),
- A support structure dedicated to the mechanical interface of the SCO with its external environment and to its thermal isolation from the external heat or cold sources (one at 4K and the other at 1.8 K),
- A command/control system, dedicated to establish or interrupt thermal links between the different parts of the gas enclosure and external cold heat sink. This command/control system is made of heaters and thermometers located on the Heat Switches (HSP and HSE) also as of the beam of wires connected to the heaters and thermometers located on the different parts of the Gas enclosure.

A more detailed description of each components presented here will be performed later in this document.

The nominal operation of the SCO can now be described :
In idle mode, the EV is connected through its HSE to the 1.8 K cold source and SP is thermally isolated from the 4 K cold source. All the gas is located in SP, trapped onto the active charcoal parts surface.
Then, the SP is heated to 40 K which increases the pressure in the SP and thus, leads to the condensation of the gas into its liquid phase which will be driven and hold at the coldest point which is EV.
Once all the gas will be liquefied and maintained in the porous material located in EV, the HSE will be driven off (resulting in the thermal isolation of the Evaporator from the 1.8 K cold source), heating of the SP will be stopped and the HSP will be driven on (resulting in the thermal connection of the SP with the 4 K cold source). Active charcoal parts of the SP will then perform an evaporative pumping on the liquid bath located in EV, leading thus to a cooling of the bath temperature to 300 mK.
When all the liquefied gas will have return to its gaseous phase, the cycling will be repeated in the same way.

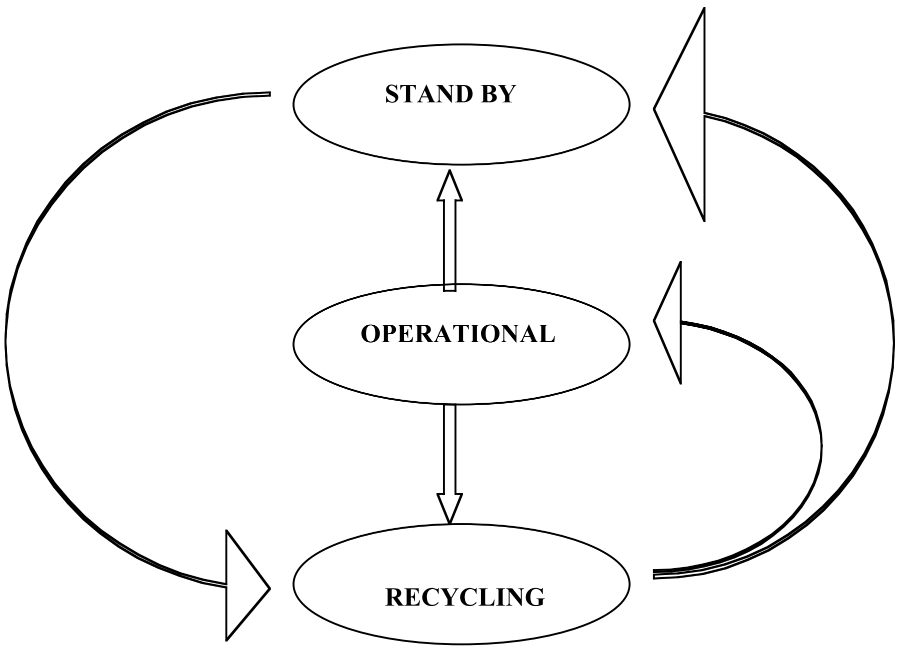
The SCO will be operating, as an objective, on a 48 h duty cycle period :

- 46h operational,
- 2h recycling.

This cycle is divided into three different stages. The first stage is said low temperature phase. During this phase, the SCO is operating at sub Kelvin temperature. Two different modes are available, thermally regulated or unregulated. The second stage concerns the SCO recycling, it comprises sequences of heating and cooling described to decrease the evaporator temperature under 3K.
The third stage, at 1,8K, is said standby, the heat switches and heaters are in the OFF position and the system is ready for recycling.

5.2 Modes transition

The mode sequencing of the cooler is described in the following diagram :



The modes transitions (by activating the heat switches) is driven by hot electronics (DRCU for SPIRE, BOLC for PACS). These drive electronics are identical for both instruments.

5.3 External Functional Analysis

As seen above, the SCO has to interface with its environment to be able to operate.
These interfaces are of three kinds :

-Mechanical interface
-Thermal interface
-Electrical interface

The mechanical interface is performed through the Support Structure (SST) which hold all the components of the SCO and which is linked to the 4 K structure of the S/C.

The thermal interface is effected between the SCO and two cold sources as an input and with the Bolometer array as an output.
The 1.8 K cold source is interfaced with the SCO through two straps, one of which delivers the cooling power to decrease the temperature of the SP once it has been heated and to maintain its temperature at 1.8 K during all the operational phase of the SCO. The second thermal strap interfaces the 1.8 K cold source with 1) the thermal shunt (middle part of the pumping line) which thus realise a thermal shunt between the SP when heated at 40 K and the Evaporator which is at 1.8 K when the SP is heated and 2) the Evaporator Heat Switch to deliver the cooling power to the Evaporator during the recycling phase in order to generate strengths that will drive the liquefied gas from the SP to the Evaporator.

The electrical interface is performed through two connectors located on one of the lateral plates of the SST. Each connector is able to ensure the nominal operating of the Command/Control of the SCO, thus ensuring a global redundancy with complete segregation of the channels. The types of signals received by each connector are current sources dedicated to the powering of the heaters also as to the excitation of the thermometers located on the different components of the SCO. The signals delivered by each connector to the external environment are voltage sources generated by the thermometers located on the components of the SCO. These voltages are a function of the current injected in each thermometer and of the resistivity of these thermometers which is dependant on their temperature.

The modules with which the SCO is electrically interfaced are the DRCU for SPIRE and the BOLC for PACS. Their drive electronics are identical for both instruments.

5.4 Internal Functional Analysis

The purpose of this internal functional analysis is to describe the interfaces between the main components of the SCO and to describe in more details these main components.

5.4.1 Gas enclosure

As described above, the Gas enclosure is made of three parts :

- The Sorption Pump
- The pumping line
- The Evaporator

Each of these parts will be described in more details :

5.4.1.1 Sorption Pump

The sorption pump role, in the system, is when connected to the 2 K cold source, to trap the gas molecules on its active charcoal parts surface, thus generating a pumping effect on the liquid bath located in the evaporator through the pumping line.

It is made of two welded semi-spherical shapes internally housing a copper cylinder "charcoal casing" covered with Stycast glue and filled with active charcoal pellets. The role of the " charcoal casing " is to optimize the thermal conductivity and exchange surface between the heat exchanger and the active charcoal pellets.

A filter maintained by a ring is located at the output of the sorption pump to prevent a charcoal pellet to obstruct the pumping line, in case of gluing process failure.
The main link between this pump and the rest of the system relies on a welded link with the pumping line, and a welded heat exchanger (Pump Cold Tip) with the Heat Switch Pump (HSP).
The functional block named "Sorption Pump" is consecutively made of the following components:

Components	Quantity
_ male pump	1
_ female pump	1
Pulleys	8
Pulleys screws	8
Charcoal casing	1
Active Charcoal pellets	~20 grams
Stycast Glue	
Grid mesh	1
Grid mesh	1
Pump cold tip	1
Heater	2
Thermometer	2
External shape weld (Electron Beam Weld)	1
Pumping line Weld (Electron Beam Weld)	1
SP Heat exchanger Solder	1

Table 1: "Sorption Pump" function decomposition

The Sorption Pump interfaces with the other components of the system through three kinds of links :

- Mechanical link : the SP is maintained in the Support Structure through a mechanical link realised with two kevlar cords that goes around the pulleys located on the _ male pump and the _ female pump and around the pulleys located on the "pump bracket" and which is bent thanks to a blocking system located on the "pump bracket" which will be described in the Support Structure description. The aim of this suspension system is on one hand to ensure a thermal isolation of the SP from the Support Structure which is at 4 K and on the other hand to allow the gas enclosure to withstand the vibration and shock levels that are applied during the launch phase.
- Thermal link : The SP is thermally linked to components of the Command / Control system through a copper braid coming from one end of the Heat Switch Pump, which,

when switched on ensures the thermal link of the SP with the 1.8 K cold source. This copper braid is connected to the copper end of the Sorption Pump, thanks to two screws.

- Electrical link : The SP is electrically linked to the Command / Control system through electrical wires coming from the two connectors located on the lateral plate of the Support Structure. Four wires are coming from each connector to each heater. These wires allow a current circulation through the heater which will then deliver heat to the SP during the recycling phase. Two pairs of wires are coming from each connector to the two ends of each thermometer. One pair of wire is used to deliver a calibrated source of current to the thermometer which will in return generate a voltage potential function of its temperature that will be measured through the other pair of wires. These measures will be later called : SP Temp 1 and SP Temp 2.

5.4.1.2 Pumping Line

The pumping line ensures the heat and He^3 reversible transfer from the sorption pump to the evaporator also as the filling of the gas enclosure during the fabrication process phase.
In order to ensure a thermal shunt for the Evaporator when the Sorption Pump is heated at 40 K, the Pumping line integers a thermal shunt connected to the 1.8 K cold source in its middle part. Thus, a thermal gradient is generated from 40 K at the SP through 4 K at the middle part of the Pumping line until 1.8 K at the Evaporator (during the recycling phase).

The functional block named “Pumping Line” is consecutively made of the following components:

Components	Quantity
Evaporator tube	1
Pump outgoing tube	1
Sleeve	1
Shunt	1
Filling pipe	1
Thermometers	2
Shunt Weld	1
Filling pipe weld	1

Table 2: “Pumping Line” function decomposition

The Pumping line interfaces with the other components of the system through three kinds of links :

- Mechanical link : The Pumping line is welded at one end with the Sorption Pump and at its other end, with the Evaporator, thus ensuring the mechanical link between the Sorption Pump and the Evaporator, also as to the hermeticity of the whole Gas enclosure.
- Thermal link : The Pumping line is thermally linked to the 1.8 K cold source through its thermal shunt.
- Electrical link : The SP is electrically linked to the Command / Control system through electrical wires coming from the two connectors located on the lateral plate of the Support Structure. Two pairs of wires are coming from each connector to the two ends of each thermometer. One pair of wire is used to deliver a calibrated source of current to the thermometer which will in return generate a voltage potential function of its temperature that will be measured through the other pair of wires. These measures will be later called : PL Temp 1 and PL Temp 2.

5.4.1.3 Evaporator

The Evaporator role in a zero-gravity environment is to attract the liquefied gas during the recycling phase and to retain it during the operational phase.
Attraction of liquefied gas is performed by thermally linking the Evaporator to a 1.8 K cold source. Once this liquefied gas have been trapped into a porous material (called PROCELIT) located in the Evaporator it will be maintained there by capillary attraction.

The functional block named "Evaporator" is consecutively made of the following components:

Components	Quantity
_ female evaporator	1
_ male evaporator	1
Pulleys	8
Pulleys screws	8
_ female cup evaporator	1
_ male cup evaporator	1
Procelit (Foam)	TBD
Evaporator cold tip	1
Thermometer	2
External shape weld (Electron Beam Weld)	1
Pumping line Weld (Electron Beam Weld)	1
EV cold tip Solder	1

Table 3: "evaporator" function decomposition

The Evaporator interfaces with the other components of the system through three kinds of links :

- Mechanical link : the Evaporator is maintained in the Support Structure by the same means than the SP and for the same reasons.
- Thermal link : The Evaporator is thermally linked to components of the Command / Control system through a copper braid coming from one end of the Heat Switch Evaporator, which, when switched on ensures the thermal link of the Evaporator with the 1.8 K cold source. This copper braid is connected to the copper cold tip of the Evaporator, thanks to two screws. This EV cold tip also houses connectivity to deliver the 300 mK cold source to the instruments.
- Electrical link : The Evaporator is electrically linked to the Command / Control system through electrical wires coming from the two connectors located on the lateral plate of the Support Structure. Two pairs of wires are coming from each connector to the two ends of each thermometer. One pair of wire is used to deliver a calibrated source of current to the thermometer which will in return generate a voltage potential function of its temperature that will be measured through the other pair of wires. These measures will be later called : EV Temp 1 and EV Temp 2.

5.4.2 Support Structure

The Support Structure (SST) is made of several mechanical parts assembled together with screws, dedicated to mechanically support all the components of the SCO and to thermally isolate the Cooler. It also ensures the external mechanical interface.

The function named "Support Structure", is described hereafter:

Components	Quantity
End plate	1
Lower plate	1
Upper plate	1
Lateral plate	1
Lateral plate mounting side	1
Evaporator bracket	1
Pump bracket	1
Pulleys screws	12
Perforated pulley screws	4
Ratchet wheel	4
Tensioning Pulleys	4
Pawl	4
Kevlar cord (0.50 mm diameter)	2
Kevlar cord (0.29 mm diameter)	2
Centering screws	4

Table 4 : "Support Structure" Function decomposition

The Support Structure interfaces with the other components of the system through two kinds of links :

- Mechanical link : the Support Structure support the gas enclosure through a suspension system based on four kevlar cords. Two of them (of 0.5 mm diameter) maintain the Sorption Pump on both sides of the "Pump bracket", and the two others (of 0.29 mm diameter), the Evaporator on both sides of the "Evaporator bracket". Only one of these suspension system will be described, knowing that the three others are made in the same way.
  The "Pump bracket" is equipped on each face with 5 pulleys, fixed in the four corners. Two of them are located in the same corner and are playing a specific role. The first one features a hole in which one end of the kevlar cord is inserted and a specific node is realized. This pulley has a fixed position and cannot rotate freely around its axis. Then the kevlar cord passes around alternatively one pulley located on the Sorption Pump and the pulley located on the next corner of the " Pump bracket " until it reaches the fifth pulley of the " Pump bracket " located next to the first one. This pulley also presents a particularity in the fact that it is equipped with an asymmetric toothed wheel which is able to rotate only in one way thanks to a pawl fixed on the " Pump bracket ". The kevlar cord is then rounded several turns around this pulley, with its end being blocked under these turns. The right tension of the cord is then obtained by turning the pulley by mean of a dynamometer key. The pulley then remain blocked in its position by the ratchet.

Tension of the cord exert a force upon the longitudinal axis of the gas enclosure which is counterbalanced by the cord placed symmetrically on the “ Pump bracket ”. As mentioned above, the same system is repeated on the Evaporator.
During the assembly process, the Gas enclosure is maintained in position thanks to four centering screws (two of them located on the “ Pump bracket ” and the two others on the “Evaporator bracket”. Once the four kevlar cords are positioned, these screws are unscrewed by a few turns in order to thermally isolate the Gas enclosure from the Support Structure but remain in place in order to limit the amplitude in case of a cord rupture. In such a case, the Gas enclosure would remain in a stable position in contact with one of the four centering screws, due to the efforts applied through the three remaining suspension systems. Then the global efficiency of the Sorption Cooler would be impacted because of the bad thermal isolation of the Gas enclosure from the Support Structure.

The Support Structure also interfaces mechanically with the Command / Control System by supporting the two connectors located on its “Upper plate” and the two thermal switches (HSP and HSE).

5.4.3 Command / Control System

The Command / Control System features the two connectors mounted on the Support Structure, the beam of wires coming from these connectors and going to the heaters and thermometers located on the different components of the SCO and two Heat Switches dedicated to establish or interrupt the thermal link between the Evaporator (Sorption Pump) and the 1.8 K (4 K) cold source.

The Heat switches are using the active charcoal pellets sorption faculty. They are made of two concentric copper cylinders held together by a thin wall titanium tube, and a mini Sorption Pump housing a small piece of active charcoal and gas. Their operating principle is as follows : The mini Sorption Pump is thermally linked to the 1.8 K cold source and also houses two heaters and two thermometers. While the mini Sorption Pump temperature is maintained at 1.8 K, all the gas molecules are trapped on the active charcoal surface, thus creating a vacuum between the two concentric copper cylinders and then establishing a thermal isolation between them. When one of the heaters is excited, the gas molecules are free from the active charcoal surface and will then enable the thermal conduction between the two concentric copper cylinders.

The decomposition of this function is given in the following table:

Components	Quantity
Mini pump	2
Active Charcoal parts	‰ 20 mgr
Mini pump cap	1
Mini pump tube	
Pumping line Weld	1
Glue	
Heater	2
Thermometer	2
Thermal shunt	1
Filling pipe	1
Filling pipe weld	1
Stopper	1
Copper braid	1
Copper switch head	1
Copper pump head	1
Switch head screw	2
Pump head screw	2
Thermal shunt weld	1
Anti-vibration interface	1
Anti-vibration interface screw	2

Table 5: "Heat Switch " function decomposition

6. Architecture Design Analysis

This analysis is based on the previous system functional description.
Its purpose is to identify if any alternative architecture might be envisaged in order to optimise the global reliability and availability of the Sorption Cooler. In a first approach, it has to be mentioned what are the main specification limiting factors of the SCO design, in order not to have to study any alternate solution that would not allow to meet the requirements of the SCO. Then, an estimation of the reliability order of magnitude of each main component of the SCO will be presented to focus on the weak points of the system.
At least, the potential alternate architectures will be analysed in detail to present objective arguments that could lead to retain one of them instead of the others.

6.1 System specifications limiting factors

The first, high level, limiting factor comes from the fact that it has been decided at the project level that the SCO would not be redounded.
The second important limiting factor comes from the allowed weight and volume specifications [AD3]. Based on this data, it appears that the Gas enclosure cannot be redounded because this solution would lead to an increase of the Support Structure not compatible with the weight and volume limitations.
A third limiting factor comes from the efficiency requirement of the SCO also as the life mission duration which implies that the consumption on both cold sources shall be minimised in order to withstand the life mission duration requirement. Without this requirement, it might have been envisaged to suppress the HSP, thus optimising the reliability of the system.

It then appears that the only components that might be redounded (for those which are not already redounded) are :

- The Heat Switches,
- The beam of wires

6.2 Components reliability estimations

The hereafter paragraph is dealing with the estimations made about the Cryocooler components. These estimations have been chosen, because of the lack of such data concerning spatial applications.
All the explanations that will be presented hereafter are based on the hypothesis that the construction and assembly process defined at this time enable the SCO to pass all the environmental test planned all along the ground phase life profile. In the opposite event, some modifications might be applied to the design and assembly process in order to correct the weak points that might be discovered. As an example, if the vibration tests demonstrate that some parts of the Support Structure does not allow to pass the test successfully, its design would be modified in consequence.
Then, the following explanation would have to be considered upon this new design and would thus present the same validity.

6.2.1 Mechanical and non electrical parts reliability estimations

The main part of the Cryocooler is composed of mechanical components. These sets of components include :

- The Gas enclosure with all its sub components,
- The Support Structure
- The Heat Switches and their mechanical and thermal links

As the half time of the life profile is spent in space, mechanical stresses and corrosion are very negligible on these components.
The failure modes and reliability of these mechanical components are more dependent from the construction process than from their own structure.
Considering the Gas enclosure, the main failure mode that might occur would be a Gas leakage which would lead to a loss of the system functionality. Given the welding (Electron Beam Weld) and soldering process of the different components of the gas enclosure also as the vibration tests and health checks that will be performed all along the mission profile of the SCO preceding the launch (including test tools able to detect leakage as low as a few mm3 of gas/year (at ambient temperature), it is easily conceivable that the occurrence probability of such a failure mode during the launch or after is highly improbable, that is to say majored by 10^{-10} failures/hours.
Considering the components housed in the Gas enclosure (active charcoal pellets, procelit, filter), no potential failure mode leading to a reduction of the efficiency of the SCO or to its loss of functionality have been identified.
Other failure modes that might be envisaged would consist in a poor contact between the heaters, thermometers or active charcoal pellets and the mechanical elements on which they are fixed with Stycast glue. Once again, if the SCO success to pass all the vibration tests and health checks during the ground phase of its life profile, one can consider that the occurrence probability of such a failure during launch and after is also highly improbable.

Based upon these considerations, there would be no gain in adding any redundancy to any component (which is not already redounded) of the Gas enclosure.

Considering the support structure, all its components are tightened together with screws inserted in a tapping. Each component is fixed with another thanks to at least two screws (thus ensuring a total redundancy), knowing that each couple of screw and its related tapping is largely dimensioned to withstand alone the higher level of efforts that might be applied to the assembly. Moreover, the assembly process includes the addition of a specific glue proven to keep its physical characteristics at very low temperature in each tapping in order to prevent the loosing of the tightening that might occur because of the vibrations.
Then, here again, assuming that the SCO succeed to pass all the ground phase test, the probability of occurrence of breakage or loosing of the tightening of the Support Structure assembly during launch and after is highly improbable.
Considering the Kevlar cord suspension system, it is very difficult to assert anything about its reliability, unless to say that if it withstands the environmental test which are applying effort levels much higher than those which will be supported by the system during launch, there is no reason for it to fail after. However, it has to be precise the following :
In a preceding version of the Gas enclosure, ears were implemented on the spherical shapes of the Sorption Pump and the Evaporator. The Kevlar cord was passing through these ears for

which a lot of care was taken to ensure a very good state of surface. Nevertheless, it has been considered that this solution was not providing the maximum of guarantees concerning the repartition of efforts on each portion of the cord. Then, the ears have been replaced with pulleys, as described above in this document, which have a smoother surface and regular diameter, as to guarantee an optimised repartition of efforts all along the Kevlar cord. The axis of the pulleys are largely dimensioned comparatively to the tension efforts that are applied.

About an eventual rupture of one Kevlar cord (over four), it can be said the following :

- A priori, in case of one Kevlar cord rupture, the Gas enclosure might be driven to a stable position where the Sorption Pump and/or the Evaporator would be in contact with the centering conic screws. The effect of a contact between the Support Structure and the SP would be minor (decreasing of the life mission duration because of a higher consumption over 1.8 K cold source during the recycling phases). A contact between the Support Structure and the Evaporator would be major because it would then be very difficult for the Evaporator to reach its 300 mK temperature. This effect might be decreased by choosing a material for these centering screws with a very bad thermal conductivity. It might be interesting to perform a test in laboratory with a broken Kevlar cord to verify if the SCO is able to operate and how its performances are lowered by such an event.

The effects of a broken Kevlar cord during the launching phase is considered to lead to catastrophic effect (loss of the mission) but a full numerical model of the whole cooler is currently being performed to evaluate more accurately the impact of such an event on the system .

The other undesired event that could occur to this suspension system is the loosening which might be engendered by the lengthening of the Kevlar cord over a long period of time. Specific tests are presently performed to validate that Kevlar cord should not be subject to a lengthening which is not fulfilling the requirements over a ten year period at very low temperature. The first results of these tests tend to indicate that for a 0.5 mm diameter Kevlar cord, this lengthening should be fulfilling the requirements. Results concerning 0.29 mm diameter cord will be taken in consideration when they will be available. If, as an example, it is shown that a lengthening occurs and which is not fulfilling, it could be proposed to replace the four Kevlar cords by new ones at the latest time preceding the launch.

6.2.2 Electronic components reliability estimations

The electronic part of the Cryocooler is mainly composed of heaters, thermometers, wires and connectors also as the solders which are ensuring their interrelations.

The specified components failure rates can not be obtained from their own suppliers because of the lack of field experience data.

Moreover, the heaters are not used at their manufacturer specified operating temperature.

Besides, the applied powers are very low that is to say that the components are used at about 1 % of their nominal operating power.

Considering these points in addition to the fact that there is no stress applied in the space flight period, the failure rates of these components can be majored by 10^{-10} failures/hours.

6.3 Analysis of the impact of additional redundancies

As seen above, the only components of the SCO that might be redounded are the Heat switches and the beam of wires.

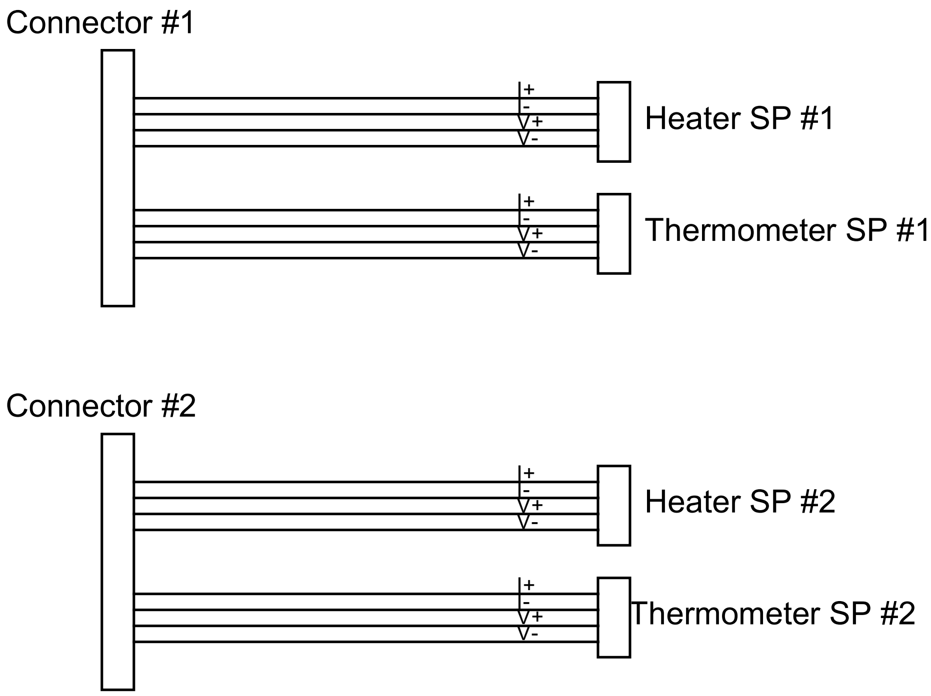
6.3.1 Impact of Heat Switches Redundancy

The Heat Switches, in the SCO, are used to establish or to interrupt the thermal conductivity between two component according to the fact that its mini pump is heated or not through a current circulation delivered to its associated heater.
If any failure occurs to a Heat Switch, leading to the loss of at least one of its properties (establishing thermal conductivity or interrupting thermal conductivity), the SCO would not be able to operate anymore. This is due to the operating principle of the SCO already described in this document.
Due to the criticality of these component, one could think about a redundancy to improve the global availability of the SCO.
Two types of redundancies can be applied : Serial or Parallel.
By implementing two Heat Switches in serial, it would highly decrease the probability of occurrence of the event "Heat Switch unable to interrupt thermal conductivity" but it would multiply by two the probability of occurrence of the event "Heat Switch unable to establish thermal conductivity". As both of these events lead to the mission loss, this shows that instead of improving the availability of the SCO, a serial redundancy of a heat switch would divide it by a factor two. The same result is obtained by implementing a parallel redundancy (in that case, it is the event "inability to interrupt thermal conductivity" which is multiplied by two).

It then appears that the retained architecture (No Heat Switches redundancy) allows the optimal availability of the SCO.

6.3.2 Impact of beam of wires Redundancy

In the present architecture, each heater and thermometer of the SCO is redounded and they are excited or read through two independent channels totally segregated, as described in the following figure :



Each connector is interfaced with an electronic board which delivers the excitation current to heaters and thermometers and read in return the resulting voltage. These two electronic boards are totally segregated.

The retained philosophy at the system level (SCO + Associated electronics) consist in ensuring the SCO regulation through channel #1 as long as this channel will remain totally operational. If any failure occurs to any of the component of channel one, its associated electronic board will be switched off and the control would then be performed through channel #2.

First of all, it has to be determined how it could be detected that a failure occurred on one channel :
A heater is a resistor which has a fixed value “R”. Thus by delivering a given current “I”, one should be able to read a voltage “V” equal to RxI. If it is not so, what could be the reason for that ?

1. No current is delivered to the heater because one of the wire in the current loop is open
2. No voltage can be read because one of the wire in the voltage loop is open
3. A different value of voltage is measured because the resistivity of the heater has drifted

Only the first point mentioned above will lead to the loss of one channel because the important thing related to the heater is to be able to establish or interrupt a current circulation in it. The regulation can be then performed through the measure of the temperature of the thermometer associated to this heater.

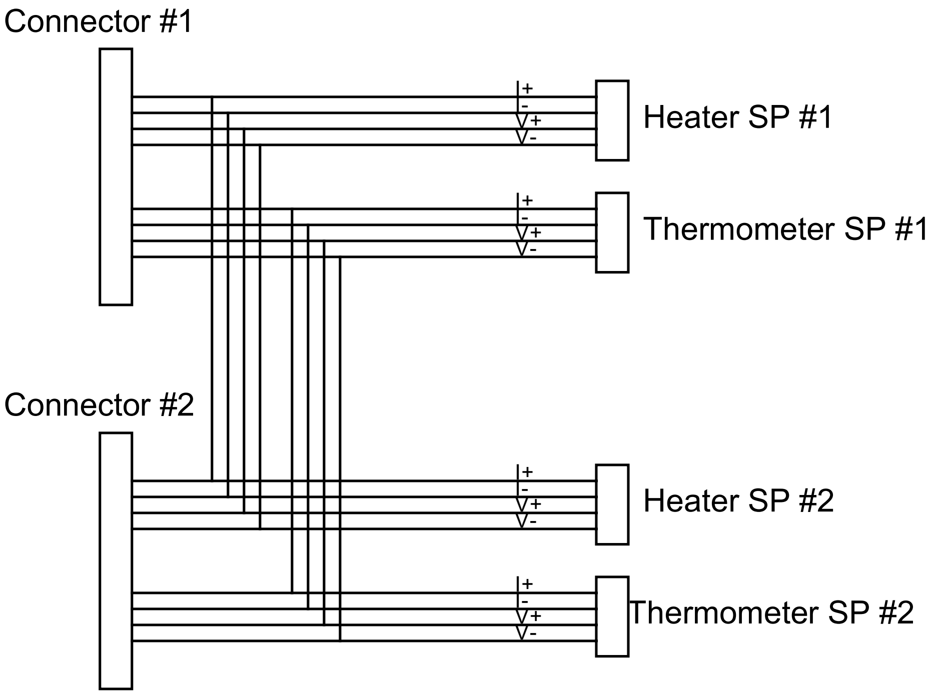
A thermometer is a resistor which has a resistivity which is a known function of the temperature. Thus, by delivering a known current “I” and by measuring a voltage “V”, one can be able to determine the temperature of the component. The major difference between a thermometer and a heater is that for a thermometer we don’t know a priori the temperature that we are supposed to measure and then, even if we know precisely the value of the excitation current, there is no way to determine if the read voltage “V” is really representative of the absolute temperature or not. However, a correlation can be made by the fact that when a heater is excited, the temperature measured through its related thermometer should increase. Furthermore, the absolute range of resistivity values for the thermometer is known (1.5 Kohm – 25 Kohm) and thus, by knowing the excitation current value, one can detect that a failure has occurred if the voltage measured does not fit in the expected range.
Then, if the measured temperature is different from the one expected, the reasons for that could be :

1. No current is delivered to the thermometer because one of the wire in the current loop is open
2. No voltage can be read because one of the wire in the voltage loop is open
3. A value of voltage not in the authorised range is measured because the thermometer has failed

Any of these three failures will lead to the loss of the temperature measurement on the considered channel.

It appears then that with the retained configuration and philosophy at system level, a single failure occurring on any of the heater or thermometer excitation or measurement loop, leads to the loss of the related channel and implies that the control/command will switch to the alternate channel. If a secondary failure then occurs on the heater of the alternate channel (or has already occurred) this will lead to the total mission loss. However, if this secondary failure occurs on the thermometer excitation or measurement loop of the alternate channel, an “emergency recycling” algorithm has been defined to drive the heater’s current regulation, from the nominal durations (in terms of current delivery on the heater) of this regulation.

Given this, one could envisage to implement a redundancy as described in the following figure :



Then, each electronic board would be able to deliver the excitation current and to measure the temperature on both redounded heaters and thermometers of each component of the SCO, thus ensuring a higher fault tolerance and then a higher availability to the system. Effectively, in the preceding configuration, loss of heater #1 excitation and thermometer #2 excitation or measurement would lead to the mission loss when the proposed configuration would not.
However, the proposed configuration present several defaults : The first one resides in the fact that the general principles of segregation between the two channels would not be respected anymore thus enabling failure propagation which is absolutely forbidden in spatial projects. The second one, directly attributable to the first one is the following : Let's assume that it is allowed to power up both electronic boards at the same time and let's consider that the following failure occurs on one of them : the MOSFET used to deliver the excitation current to a heater fails in short circuit. It would then be impossible to stop the heating of the related component of the SCO, thus leading to the mission loss (or to a high reduction of the life time duration of the mission, accordingly to the considered heater).
Given the fact that the probability of occurrence of a MOSFET failure is three orders of magnitude (x 1000) higher than this of a solder or wire breakage in the beam of wires of the SCO, this configuration appears directly to be worst in terms of global mission availability than the retained one.

7. Conclusion

Based upon the detailed analysis of the Sorption Cooler in its actual definition presented in this document, it can be said that there is no gain that could be obtained, concerning its reliability and availability, in modifying any part of its design, assuming that it will succeed to pass all the test plan described in detail in § 4.3. If such was not the case, the potential weaknesses that would be identified at this time would be corrected accordingly.

The study performed over this system has demonstrated that, within the authorised limits fixed by the specifications requirements imposed mainly by weight limitations also as segregation principles between Control/Command channels and given all the redundancies that are already implemented in the retained configuration, there would be no optimisation that could be procured by adding any additional element.

More precisely, it has been demonstrated that, adding a redundancy to the critical components that are the Heat Switches would have a worst impact over the reliability and availability of the system than remaining in the actual configuration.
Considering the redundancy that might be implemented at the level of the internal connectivity of the SCO, even if by reasoning at the SCO level it appears that there could be a gain in adding this redundancy, when the analysis is performed at a higher level taking into account the Command/Control electronic boards, the result is worst than without this redundancy.

Then the success of the mission relies mainly on the manufacturing, assembly and verification process of the SCO on which all efforts shall now be applied rather than the definition which has been proven to be optimal with regard to the imposed limitations.