1. Applicable and Reference Documents

RD1 – Cryogenic Sorption Cooler “FMEA” Contract Report PL-CSL-SC-99001 for Contract 12942/98/NL/PA (draft June 1999)
RD2 – Minutes of Meeting “CDR engineering model of 0.3K Sorption cooler (contract 12942/nl/pa)” ref: TOS-MCT 2774/BC June 1999.
RD3 - Cryogenic Sorption Cooler “Detailed Design of the Engineering Models – Test Plan”, Contract Report TN/SBT/SC/99-04 for Contract 12942/98/NL/PA (draft June 1999)
RD4 - Cryogenic Sorption Cooler “Technical Requirements for the Engineering Models and Related Preliminary Design”, Contract Report SBT/SC/GS/99-01for Contract 12942/98/NL/PA (draft June 1999)
RD5 – “Discussion on Cooler Redundancy” – SPIRE-RAL-NOT-000339
RD6 – “Report on the Sorption Cooler Redundancy” B. Swinyard; L. Duband – SPIRE-RAL-NOT-000340

2. Introduction

The five bolometer detector arrays in SPIRE will be cooled to ~300 mK by a closed cycle ^{3}He cooler. The loss of the cooler was pointed up as the only potential catastrophic failure for the SPIRE instrument at the PDR in July 1999. Following the PDR the SPIRE project was asked to produce a recommendation on the implementation of the cooler that will minimise the risk of loss of detector cooling, and the subsequent loss of science from FIRST. The present note is the outcome of discussion and evaluation of the options open to SPIRE for cooler redundancy.

3. Scope

In this note we first review the possible failure modes identified for the loss of cooling for the SPIRE detectors. This section is divided into two parts: failure modes for the cooler itself and failure modes associated with the system as a whole – both the FIRST cryostat environment and the rest of the SPIRE instrument – that will adversely affect the detector cooling.

Following this we review the design constraints on the implementation of the cooler before recommending an outline system level implementation of the detector cooling that meets the requirement for maximum redundancy within the resource envelope available.

4. Possible failures of detector cooling

Here we recapitulate the possible failures that can occur and give a commentary on their likelihood. The failure modes are divided into those directly related to the cooler, and those that will affect the cooler performance but are related to the systems design of the instrument and/or satellite.

4.1 Cooler Failure Modes:

1. Mechanical failure leading to loss of coolant:

Under the ESA TRP contract a FMEA has been carried out (RD1) on the cold unit of the cooler prototype design. The draft version of this that we have seen concludes that the major failure risk is leakage of the gas in the cooler due to mechanical failure. However there is some question over the way this FMEA has been carried out (RD2) and we await the final version before reacting to its conclusions.

Whatever the final status of the FMEA for the TRP cooler, we believe that the development programme underway on the cooler (RD2, RD3 and RD4) and the subsequent redesign for the SPIRE specific cooler will actually render this failure mode extremely unlikely. There are some outstanding issues related the titanium alloy Ta6V (examples of contamination that makes it brittle have been reported, etc.) that will be used for the main structural support. These are under extensive investigation as is the behaviour of the Kevlar cords at room temperature: fatigue, creep, influence of pulley diameter, speed of traction, baked or not baked, etc. No peculiar behaviour has been reported to date.

In case we do have a failure of a cord, we believe the remaining cords will sustain the cooler. SBT are currently doing a full finite element model of the cooler and will provide a definitive answer on this soon. In addition, for the flight model, the design of the snubbers (launch bumper stops in case of failure) will be optimised to further reduce the chances of actually breaking and losing the gas.

2. Heat switch fails open or short circuit by mechanical failure

Again we believe that at the end of the qualification we'll have a pretty good idea about whether the heat switches are likely to mechanically fail and what that failure mode will be. The switches are equipped with snubbers (both for the switch end and for the miniature sorption pump) and because of more flexibility in the design (in comparison with the suspended spheres) we can really design very efficient snubbers. We could also further reduce the risk, for instance, by adding an extra tube that mounts around the thin wall tube. Our feeling at this moment is that it is unlikely we'll break one. Further, even if one were to fail mechanically, it is very much more likely to result in a loss of gas and therefore to fail open circuit than it is to acquire a significant thermal conduction by parts of the switch touching internally.

3. Heat switch fails open circuit by harness failure

There are a large number of wires in the FIRST harness and random failure is a distinct possibility. This must be catered for by the use of cold redundancy either by extra heat switches and/or by extra heaters.

4. Pump heater fails off by mechanical failure or harness failure

Mechanical failure here means breaking wires or heater elements internally to the pump. To minimise the risk of this we intend using heaters that are already space qualified although we have yet to identify a suitable product. The pump heaters will also be made fully redundant with two heaters each with double wiring and electronics.

5. Heat switch fails open circuit by electrical failure or pump heater fails off by electrical failure

There will be fully redundant electronics for the cooler.

6. Pump heater fails on by electrical failure or heat switch fails on by electrical failure

This possibility is remote and will anyway be avoided by design of the electronics.

7. Thermal straps between heat switches ends and pump or evaporator ends

Unlikely to fail mechanically, but will require our attention during the design and qualification of the SPIRE specific cooler.

4.2 Systems Failure Modes

1. Mechanical failure of the thermal straps to the main tank resulting in too large a thermal gradient.

This will have a significant impact on performance, in the worst case recycling would no longer be possible. The design and implementation of these straps is beyond the control of the SPIRE project but will need to be closely monitored by us. It should be noted that the SPIRE project has requested that two separate straps are implemented for each of the pump and evaporator heat switches.

2. Unexpected parasitic loads.

For instance such that the heat switches can never be turned off, "large load", or such that the duty cycle efficiency is significantly affected, "small load" of a few µW. The latter possibility should be minimised by careful attention to the thermo-mechanical design and the case of the heat switches is discussed above. However, in the case of the “small load” situation arising after launch we would have to change our observing strategy to accommodate any decrease in cooler efficiency.

3. Mechanical failure of the thermal straps to the detectors leading to a large thermal gradient.

This possibility is difficult to insure against except by careful design and thorough quality assurance procedures and ground testing.

4. Failure to recycle during ground testing due to the orientation

This situation can definitely be avoided during instrument level testing as the instrument will be orientated with the pump vertically above the evaporator. We place a requirement on the satellite level MGSE that we can rotate the FIRST cryostat and the CQM cryostat by up to $\pm 30^{o}$ about the satellite Z axis.

5. Mechanical failure of the cooler mounting support, i.e. the interface with the SPIRE 4-K structure

This will be avoided be design and qualification testing.

5. Constraints on the Cooler Cold Hardware Implementation

The mechanical design of SPIRE has evolved since the PDR and we are now in position to definitively place some constraints on the implementation of the cooler cold hardware:

1. It is not possible to accommodate a second complete cooler.

2. We believe we can fit two extra heat switches within the available mechanical envelope with little impact on the mass of the cooler.

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3. Each additional heat switch on the evaporator adds an extra ~4-5 µW load at 300 mK

4. The parasitic load from the five detector arrays will be ~8 μW with an additional 2 μW for the thermal control circuit. These figures do not include any parasitic load from the mounting of the thermal straps from the evaporator to the arrays and make no allowance for margin.

5. The present 4 litre STP cooler design will be able to lift 10 μW net at the evaporator cold tip with a hold time of 46 hours and a recycle time of 2 hours. The average dissipation into the LHe tank will be 3 mW.

6. Cooler Configuration

In two previous notes that have been circulated within the SPIRE systems team (RD5 and RD6), we have discussed some possible configurations of the detector cooling hardware that would offer various degrees of insurance against the failure modes listed in section 4. Following extensive debate within the team as to the relative merits and technical feasibility of the various options we have settled upon a baseline option as described in this section.

6.1 Assumptions

In coming to the conclusions we have, the following assumptions were made:

Assumption 1: The heat switches will never fail with a significant thermal short.
Assumption 2: It is possible to have double heaters on a single heat switch miniature sorption pump.
Assumption 3: Failure of the thermometers associated with the cooler (not mentioned so far) is not critical to the operation of the cooler and can be accommodated by using other thermometers associated with the thermal straps and detector sub-system.

6.2 Electronics and wiring

See figure 1. All heaters are made functionally cold redundant with double independent wiring to each heater. The independent wiring is connected to one of two fully redundant sets of drive electronics, each of which is powered separately from the system power distribution unit.

If we denote the heaters as ES1 for evaporator heat switch 1 heater etc. and the electronics units as EA and EB then the following combinations of heaters and electronics units are available.

Evaporator Heat Switch	Pump Heater	Pump Heat Switch
ES1.EA	PH1.EA	PS1.EA
ES2.EA	PH2.EA	PS2.EA
ES1.EB	PH1.EB	PS1.EB
ES2.EB	PH2.EB	PS2.EB

Table 1: Possible Combinations of heaters and electronics units

This wiring and electronics scheme means:

Full or partial loss of either electronics A or electronics B leaves full redundancy intact.
Loss of any one wire leaves full electrical redundancy intact
Loss of any two wires leaves full electrical redundancy intact.
Loss of any one heater leaves full electrical redundancy intact.

Although this scheme means that either electronics unit can be used independently of the other and still maintain redundancy, it could be that, if necessary, both electronics A and electronics B could be used together to power individual heaters. This then affords a second level of redundancy at the expense of some complication in the implementation of the electronics and commanding software. This requires further analysis to see if it gives any real extra security.

6.3 Cold Unit Configuration

See figure 1. It is proposed that the heat switches to both the pump and the evaporator will be doubled up with the heat switches placed in parallel. The heaters on each switch are not doubled in this basic configuration as they are already functionally redundant. See the discussion in the next section on what would be done in the case of providing only single heat switches.

Advantages:
This configuration ensures against any single mechanical failure in a heat switch and provides full redundancy for the wiring – all heaters have double wiring provided to them and can be run from either of the redundant electronics units.

Disadvantages:
Extra heat switches increase the mass slightly and may push the volume envelope
Extra heat switches change the design of the cooler from that being developed under the TRP contract; leads to reduction in design heritage.
Extra heat switch on the evaporator leads to an extra 4-5 μW heat load at 300 mK.
Extra heat switch on the pump leads to some increase in the parasitic load on the LHe tank (TBD).

7. Discussion

The following conclusions can be drawn from our deliberations on the redundancy options for the sorption cooler:

- It is not possible to have complete insurance against the random mechanical failure of the cooler pressure vessel or mechanical support – this must be achieved by design and test.
- The wiring and electronics can and should be made fully redundant
- It is possible to give full insurance against the mechanical failure of any single heat switch but only at the expense of reduced thermal efficiency and/or 300 mK performance.

We conclude that we should have a baseline cooler design that has redundant heat switches on both the pump and the evaporator. If it turns out that the qualification programme for the heat switches demonstrates conclusively that they will not fail mechanically we can always thermally disconnect the redundant switches or remove them all together. In the meanwhile the design will proceed assuming they are present in order that the space envelope; mass; interfaces and wiring are correctly incorporated into the system level design. In the event of single heat switches being implemented we will also implement redundant heaters in the heat switch sorption pumps to ensure full electrical redundancy is maintained.

We note that, with a 4 litre STP cooler and a 2hour/46 Hour duty cycle, there is almost no margin on the cooling power of the cooler. This becomes critical with the addition of the extra redundant heat switches and the consequent extra load at 300 mK. The size of the cooler is driven among other things by the requirement to dissipate less than 3 mW average power on the 2 K plate. If this number can be revised then we can change the design to accommodate, for instance, an 8 litre STP unit (TBD) and/or change the duty cycle efficiency. Our preference would be to have a larger cooler as this will be less restrictive in terms of operations. In the framework of the present ESA contract SBT are also working on a ^{4}He cooler. It has been designed as a 8 litre STP unit so basically they have also done a design exercise on a larger cooler. We are now looking at the envelope of this cooler to see if we can accommodate it in the SPIRE envelope. We will also initiate a study into the thermal load from such a cooler if we were to adopt some reasonable margin on the 300 mK load from the detectors and include the redundant heat switches.

One aspect of the system level design that needs clarification is what the SPIRE dissipation into the LHe tank represents as a fraction of the total from the cryostat. We understand from Dornier (J, Schupp – private communication) that, for fixed shield temperatures, each extra mW into the LHe represents approximately 1.5% less lifetime for a nominal 4½ year mission – or approximately 25 days. The SPIRE team would like some confirmation of this number – preferably in the form of a cryostat thermal model.

The decision to implement full mechanical redundancy in the sorption cooler heat switches and to increase the size of the sorption cooler cannot be for the SPIRE project alone. We require guidance from the FIRST project team as to whether they consider the reduction in risk from adopting these measures outweighs the inevitable loss in mission lifetime.

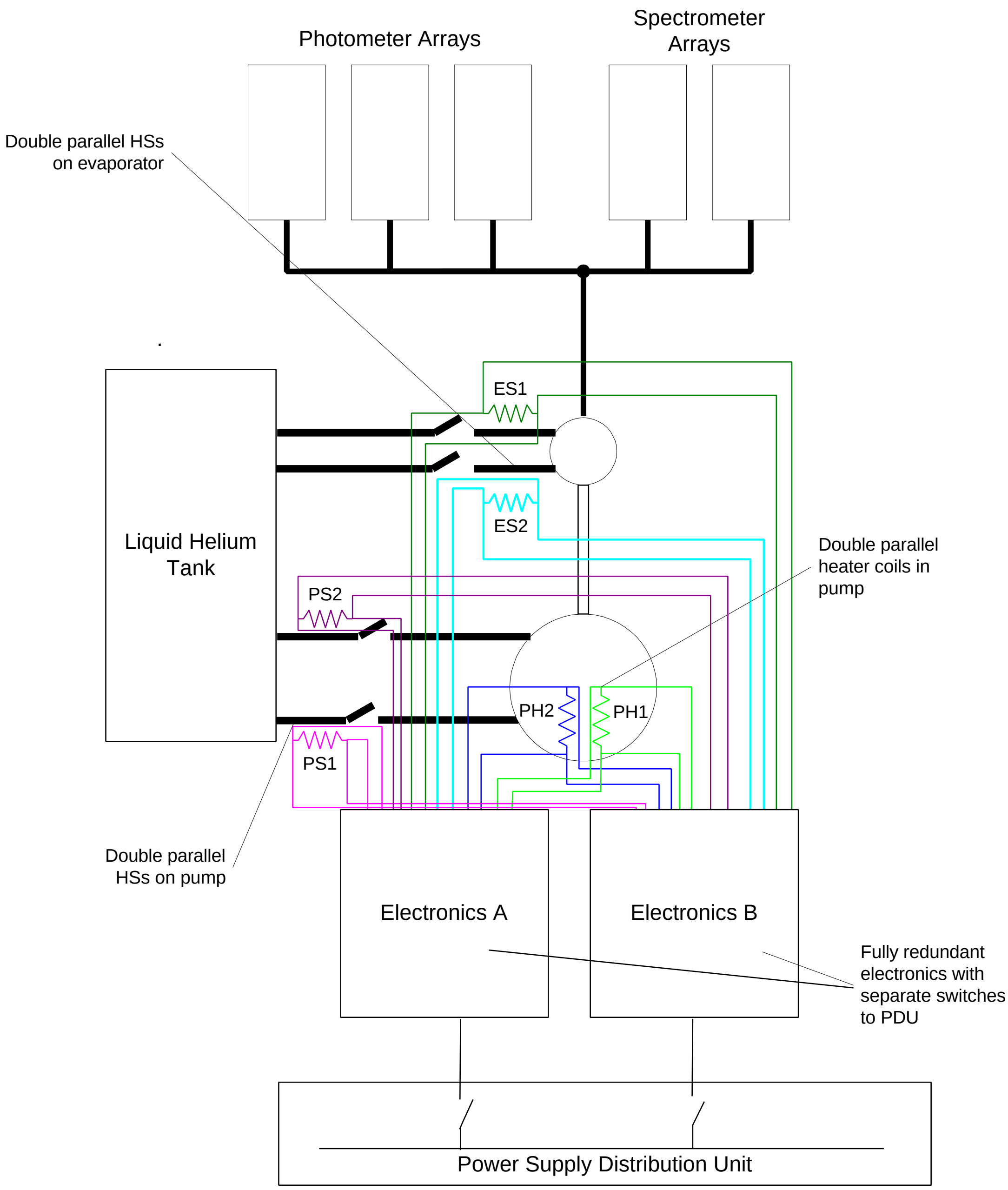

Figure 1: Proposed configuration for the cooler with double parallel heat switches on both the pump and the evaporator. Notice the double wiring onto each heater going via separate connectors to separate electronics units.