SPIRE CQM

THERMAL BALANCE TEST REPORT

THERMAL ENGINEERING SECTION				
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CHANGE RECORD

Issue	*Date*	*Section*	*Change*
Draft A	14-Jul-04	-	New Document.
Issue 1	10-Nov-04	ALL	Update the report to include test results from the second CQM Thermal Balance Test campaign.

ACRONYM LIST

BDA	Bolometer Detector Array
^{2}He	Helium 2
^{3}He	Helium 3
BSM	Beam Steering Mechanism
CBB	Cold Black Body
CQM	Cryogenic Qualification Model
DD	Design Driver
DTMM	Detailed Thermal Mathematical Model
FM	Flight Model
FPU	Focal Plane Unit
GMM	Geometrical Mathematical Model
HOB	Herschel Optical Bench
ITMM	Interface Thermal Mathematical Model
JFET	Junction Field Effect Transistor
L0	Temperature Level 0 (~1.7K)
L1	Temperature Level 1 (~4K)
L2	Temperature Level 2 (~12K)
L3	Temperature Level 3 (~15K)
PCAL	Photometer Calibration Source
PTC	Photometer Thermal Control
RTMM	Reduced Thermal Mathematical Model
SCAL	Spectrometer Calibration Source
SMEC	Spectrometer Mechanism
SOB	SPIRE Optical Bench
SPIRE	Spectral and Photometric Imaging Receiver
SST	Stainless-steel
STP	Screened Twisted Pairs
TBC	To Be Confirmed
TBD	To Be Defined
TBT	Thermal Balance Test
TMM	Thermal Mathematical Model

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Summary

The SPIRE instrument has been tested at CQM level. The two thermal balance test campaigns took place in February 2004 and September 2004 respectively.

During the first test campaign, the overall instrument performances were satisfactory with the following exceptions:

- Temperature drops as large as 0.3K at the photometer and spectrometer enclosures strap interfaces have been measured, indicating that the interface joint conductances at the L0 straps were not good enough. The design of the interbox strap and of the L0 enclosure strap interface on the spectrometer enclosure has consequently been re-assessed and a new design was implemented on the instrument for the second test campaign. The goal was to reduce this temperature drop to a maximum of 0.03K.

- Despite the fact that the measured PLW detector temperature was within the specification (<310mK), a 30-mK temperature drop was measured between the evaporator at 265mK and the PLW detector at 295mK. The temperature drop along the 300-mK Busbar exceeded the maximum 10mK requirement as suggested by the thermal model, which predicted a 35-mK temperature drop for similar thermal boundaries. This test therefore confirmed that an improvement in the overall 300-mK Busbar conductance was required. Because of the limited timescale however, the new Busbar design hasn't been implemented on the instrument for the second test campaign.

During the second test campaign, the overall instrument performances were satisfactory (with the exception of the Busbar) and a major improvement has been observed at the L0 enclosures:

- The temperature drop between the two enclosures was reduced to about 0.05K following the redesign of the interbox strap. This new performance is satisfactory as the difference with the 0.03K requirement remains within the uncertainty levels of some of the temperature readings.

In both test campaigns, the cooler recycling went as predicted with the exception of the evaporator heat switch which takes up to an hours to turn ON in comparison with the pump heat switch which actuates within 15 minutes on average. This hasn't however affected the cooler performances in any way (no additional parasitic on the evaporator).

A summary of the preliminary results is given below. Those results (as well as the heat loads flowing at the instrument interfaces) will be confirmed once the correlation exercise with the instrument thermal model will be completed. The initial results however look really promising:

L0 Cryostat Interface Temperature	Estimated Evaporator Average Load	Cooler Hold Time	Cooler cold tip Temperature	PLW Detector Temperature
1.7K	24-26 uW	49 hr	277mK	310mK
2K	36-40 uW	36 hr	286mK	350mK

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1 Scope

The objectives of the thermal balance test on the SPIRE Cryogenic Qualification Model can be summarised as follow [AD1]:

- Validate the SPIRE thermal design as far as the hardware and thermal environment of the calibration cryostat would allow,
- Provide thermal test data for the correlation of the instrument thermal mathematical model and allow accurate predictions of SPIRE flight performances to be obtained.

This document summarises the results obtained during the first and second Thermal Balance Test (TBT) campaigns of the SPIRE Cryogenic Qualification Model (CQM). The models used for these tests will be denominated as CQM1 and CQM2 herein as the CQM was refurbished for the second test campaign.

Section 4 of this document discuss the results for the first thermal balance test campaign while the results for the second test campaign are presented in section 5. In each case, a summary of the post-test review is given, followed by a discussion and analysis of the test results.

Additional material and literature can be found in sections 2 and 3 to support any aspect of the thermal testing which isn't described in detail in this document.

2 Reference Documents

ID	***Title***	***Number***
RD1	SPIRE Thermal Requirement Document	SPIRE-RAL-PRJ-002075 Draft B 13-Jul-04
RD2	Lakeshore Temperature Measurement and Control Catalog 2004	P196
RD3	Private Communication with Lionel Duband	Feb-04
RD4	HERSCHEL – OBA, OBHCL and OBTL 1 & 3 Fluids Mechanics and Thermal Modelisations	HP-2-AIRL-AN-0003 Issue 2 26-Sep-03
RD5	SPIRE and PACS Sorption Coolers SPIRE CQM Tests Report	HSO-SBT-RP-085 Issue 1 13-Aug-03

Table 2.1 – Reference Documents

3 Applicable Documents

ID	*Title*	*Number*
AD1	SPIRE CQM Thermal Balance Test Specification	SPIRE-RAL-DOC-002077 Draft 3 29-Jan-04
AD2	CQM Thermal Hardware Specification 2-2.xls	A.S. Goizel Version 2.2 19-Dec-03
AD3	CQM Thermometers 1.0.xls	Dave Smith 15-Mars-04
AD4	AIV Logbook for CQM Test Campaign 1	-
AD5	SPIRE CQM Thermal Balance Test Specification	SPIRE-RAL-DOC-002077 Draft 4.6 03-Nov-04
AD6	CQM Thermometers 1.5.xls	Dave Smith 24-Aug-04
AD7	Thermal Sensors Parasitic load.xls	A.S Goizel 13-May-04
AD8	CQM2 TBT Campaign - Test Results Summary.xls	A.S Goizel Sept-04
AD9	IIDB SPIRE Instrument	SCI-PT-IIDB/SPIRE 02124 Latest Version
AD10	Thermal Mathematical Esatan Model “spireCQM141203.zip” H:\In Tray\Model Log Files\spire\Documentation\STM-CQM Plan_Procedures\CQM1\CQM1 Correlation\CQM TMM 141203	A.S. Goizel 14-Dec-03
AD11	CQM Thermometers 1.6.xls	Dave Smith 20-Sep-04

Table 3.1 – Applicable Documents

4 SPIRE CQM1 Thermal Balance Test Campaign

This section summarises the test results for the first thermal balance test campaign carried out in February 2004 with the SPIRE CQM1 instrument model.

4.1 CQM1 Post-Test Review

4.1.1 SPIRE CQM1 Configuration

A detailed description of the SPIRE CQM1 build standard can be found in AD5 for more information.

In addition to thermal balance testing, the CQM test campaign was also aiming at testing and validating the performances of the instrument scientific payload in photometer mode (using the working PLW detector). Because of the copper purity used for the 300-mK straps, and at the time, some issues with the cooler performances[1], it had been decided that the SPIRE CQM1 should be operated with only the PLW detector connected to the cooler (in order to limit the total load on 300-mK Busbar and the cooler evaporator). The advantages and disadvantages of this setup have been considered in detail and a summary of this trade-off is presented in Table 4-2.

Table 4-1 describes the setup used during the first test campaign with the SPIRE CQM1.

Interface With	*CQM1*
L2 Shield	PJFET and SJFET thermally coupled to L2 shield.
HOB Sim	PJFET Bolted on HOB with 5 bolts
	SJFET bolted on HOB with 3 bolts[2]
	SPIRE FPU mounted off the Herschel Optical Bench (HOB) Simulator on three isolation supports.
L1	1 thermal strap made of 5 Ns aluminium connects the SPIRE Optical Bench (SOB) to calibration cryostat Level 1. The strap includes electrical isolation.
L0	3 dedicated thermal straps connect the SPIRE Cooler and Spectrometer enclosure to the cryostat L0.
300-mK	Only PLW BDA connected to cooler

Table 4-1 – SPIRE CQM1 Test Setup

1 An additional 8µW parasitic load used to be present on the evaporator. This issue has since been solved following the replacement of the shunt strap.

2 An error in the holes pattern on the HOB meant that the fourth SJFET foot could not be bolted.

Trade-off used to decide upon the BDA detector configuration in CQM1 (Number of connected detectors)	
Advantages	*Disadvantages*
This approach has the effect of reducing the load on the cooler evaporator during operation: ▪ Reduces risk of large temperature drop along the 300-mK Busbar and detector running at excessively high temperature. ▪ Reduces the risk of running the cooler with short hold time periods, which would make the thermal and scientific testing more difficult, as the cooler would have to be recycled more often. ▪ Because the PLW detector and the evaporator cold tip are the only known 300-mK stage temperature during thermal testing, the correlation of the overall 300-mK Level will be quite difficult. This configuration also has the advantage to provide a better insight of the PLW and Busbar parasitic loads only, therefore helping with the future correlation.	▪ The load on the cooler will not be flight representative and therefore it will not be possible to validate the overall thermal design of the instrument at that stage.

Table 4-2 - BDA Configuration for CQM1 - Trade-off

4.1.2 SPIRE Calibration Cryostat

A detailed description of the differences between the SPIRE calibration cryostat used for the CQM test campaign and the Herschel flight cryostat can be found in AD5.

The CQM1 test campaign was the first time the cryostat was being operated with the full SPIRE instrument and the following observations have been made:

- It takes a minimum of 4 to 5 hours to top-up the cryostat L1 Pot with Helium and wait for the L2 shield and HOB temperatures to "stabilise" again. The L1 and L0 interface temperatures on the other hand have a very quick transient and only need a few hours to settle back to their original temperatures after top-up.

Note: Because the Level-1 and Level-0 temperature stages of the instrument are quite isolated from the HOB, their temperatures remain relatively constant and/or stabilise back to their steady-state temperature very quickly. A cooler recycling can therefore be done while the cryostat Level-2 temperatures are still stabilising. Overall, the SPIRE instrument has shown to stabilise very quickly (within 2 to 4 hours) once the cryostat temperatures have stabilised.

- When left thermally unregulated, the cryostat Level-1 (L1) interface temperature remains at ~4.1K, while the Level-0 (L0) interface temperatures seat between ~ 1.3 - 1.4K.

- Because the instrument load observed at the cryostat L1 and L0 interfaces are relatively small, no changes in the L1 and L0 bath temperature have been observed.

- The control of the L0 interface temperatures was performed with a heater on the L0 Helium (He) can. This approach isn't straightforward and requires a constant tuning of the heater in order to obtain the required interface temperature.

- The temperatures at which the cryostat Level-2 and the Level-0 interfaces are run have a direct impact on the cryostat hold time – lower Level-2 temperature and higher Level-0 temperatures shorten considerably the hold time of the cryostat (as both require a larger He mass flow rate).

- The Level-2 temperatures (which include the HOB and the instrument shield) are drifting slightly, but their rate of change is lower that the rate defined for the steady-state criterion. This therefore shouldn't be an issue for the thermal balance test.

All this information is very valuable and was taken into account when planning for the second test campaign. Additional actions have been taken to improve the way the cryostat is operated:

- A manostat has been implemented at the Level-0 to ease the control of the interface temperatures for the next thermal balance testing,

- A new Helium gauge has also been implemented which should provide better predictions for the cryostat hold time. This will greatly help when planning for the thermal testing (i.e. reduces the risks of the cryostat running out of helium before the instrument temperatures have had time to stabilise).

4.1.3 Additional Thermal Hardware

4.1.3.1 Thermal sensors

The thermometry consists of:

- 17 flight sensors mounted on the instrument and driven by the instrument flight electronic (using a 10mV constant DC voltage drive, with the exception of the evaporator sensor which is driven using a 10mV constant AC voltage drive).
- 31 sensors mounted on the cryostat and driven by 218 Lakeshore units (using a 10µA constant current drive),
- 13 additional temperatures sensors used for the instrument monitoring and driven by 218 Lakeshore units (using a 10µA constant current drive). Those sensors provide an additional insight about the instrument thermal behaviour (in critical areas such as strap interfaces) and will greatly help with the correlation of the thermal model.
- The PLW BDA temperature can be obtained with AC load curves, which provide an estimation of the detector temperature at +/- 5mK (according to Jamie Bock).

Additional information about those sensors can be found in AD3.

After cooldown, several sensors appeared to read erroneous data. Table 4-3 provides a list of the non-working sensors.

ID	Description	Status	Reason
S28	Level-0 Enclosure interface temperature at the cryostat shoe.	Seems to read warmer temperature than at the instrument itself	Not calibrated below ~1.55K. Extrapolation has been used below this temperature.
S29	Level-0 pump interface temperature at the cryostat shoe.	Read 1.1K at all time	Open circuit / wiring issue.
S30	Level-0 evaporator interface temperature at the cryostat shoe.	Read temperatures around 3K at all time.	Open circuit / wiring issue.
T_BSMS_1	BSM/SOB I/F (SOB side)	Erroneous Data	Not calibrated below 4.987K
T_BSMM_1	BSM	Erroneous Data	Not calibrated below 4.987K

Table 4-3 – Non-working CQM1 Thermal Sensors

In addition, it has been found during testing that the Lakeshore units initially set to log converted temperature data rather raw resistance data, could not display temperature below 1.4K. The monitoring unit would instead saturate and display 1.4K at all time. Following this, it has been decided to set-up the Lakeshore units to read and log raw data from the sensors (i.e. resistances). This approach also has the advantage that the conversion from resistance into temperature can be reviewed at later stage in case errors were found in the calibration tables.

Some instrument sensors appeared to read temperatures that are lower than the cryostat interfaces, as described in Table 4-4. This discrepancy might be caused by an error in the sensor calibration or by a phenomenon where the sensor is being self-heated, and therefore reads temperatures warmer than they actually are.

Cryostat Interface		Instrument		Error
L0 Enclosures Cryostat Clamp Interface	1.387K	L0 Enclosure Strap Adaptor	1.373K	14 mK
L1 Strap Interface at SOB	4.399K	SMEC Interface at SOB	4.338K	61 mK

Table 4-4 – Possible Sensor Self-Heating Errors

The self-heating issue of the temperature sensors has been investigated in more details in section 4.3.2.

4.1.3.2 Instrument Mechanisms and Internal Power Dissipation

The CQM Photometer and Spectrometer Calibration Sources (PCAL and SCAL respectively) were controlled by the instrument flight electronic whereas the BSM and SMEC STM mechanisms were controlled via the “MCU”.

Some issues have been encountered when operating the SCAL, which are currently under investigation. In addition, instabilities (current oscillations) when operating the MCU have prevented the use of the SMEC and the setting of the BSM power dissipation was itself really tedious.

As a result, the MCU will not be used for the second test campaign. Instead, a simple power supply and a 4-wire measurement will allow the power dissipation of the BSM and the SMEC to be set and known very accurately.

4.1.4 Thermal Test Cases Completed

Several thermal test cases have been performed during the duration of the CQM1 test campaign, which will help to better understand the instrument thermal performances as well as provide data to allow the correlation of the instrument thermal model after the second test campaign.

An overview of the tests performed is given in table 4.4 on next page. More information about procedures followed during the thermal balance test can be found in AD1 and AD4.

The following thermal tests have been analysed in more detailed in the following sections as they presented some interesting characteristics:

- A cooler recycling with the cryostat Level-0 interfaces running at 1.7K is described hereafter.
- The cooler characterisation test was a test suggested by Lionel Duband [RD3]. This test allows to analyse some aspects of the cooler performances for a given thermal environment.
- Finally, the Thermal Balance Test cases have been performed at the end of the CQM1 test campaign for the instrument in Photometer, Spectrometer and Off modes[3]. Steady-State conditions have been achieved for the first two test cases but not in the Off case during which the cryostat ran out of Helium, therefore compromising the thermal balance of the instrument.

The Level-1 interface temperature of the cryostat has been left running thermally unregulated at ~4.1K at all time while the Level-2 has been thermally controlled at 10K initially but also at 12K, and at 17K in nominal operation during others test levels to optimise the cryostat hold time.

The first OFF case allowed to verify the instrument overall thermal performances. An important temperature drop between the calibration cryostat Level-0 interface (at less then 1.4K) and the instrument Level-0 photometer and spectrometer enclosures (at ~2K) could already be observed at that stage. To optimise the cooler hold time as well as the cryostat hold time, it was decided to run the Level-0 at 1.4K instead of 1.7K as initially specified in AD1.

[3] The simulated SPIRE internal power dissipation was non-flight representative due to the mechanism limitations (as explained in section 4.4.2.)

Start Period		***End Period***		***Thermal Test Cases Description***	***Level-2 [K]***	***Level-1 [K]***	***Level-0 [K]***	***Comments***	***Steady-State[4] Reached***
Date	*Time*	*Date*	*Time*						
30-01-04	18.00	31-01-04	20.00	OFF	10	4.12	<1.4	At 13.30 the turbo pump switched off.	-
02-02-04	17.00	02-02-04	21.00	Recycle 1	10	4.12	<1.4	-	-
03-02-04	9.26	04-01-02	10.00	Recycle 2 Photometer mode	10	4.12	<1.4	Load curves taken at same time as the photometer thermal balance case.	yes
04-02-04	12.00	04-02-04	14.00	Cooler Characterisation	10	4.12	<1.4	-	-
05-02-04	7.30	05-02-02	11.30	Recycle 3	10	4.12	<1.4	-	-
11-02-04	8.00	11-02-04	12.00	Recycle at 1.7K	10	4.12	1.7	-	-
12-02-04	18.00	13-02-04	12.00	Photometer with HOB at 17K	17	4.12	<1.4	Lakeshore unit set-up to log raw data.	-
13-02/04	12.00	14-02-04	20.00	All cases: ▪ Photometer mode ▪ Spectrometer mode ▪ Off mode	12	4.12	<1.4	-	 yes yes -

Table 4-5 - Period of Thermal Testing during CQM1 Test Campaign

[4] *Please note that only the test cases where the steady-state criteria have been reached can be used in future for the correlation of the thermal model. Others test cases are shown here because they provide an insight about the instrument thermal performances even so they will not be used for correlation.*

4.2 SPIRE CQM1 Thermal Test Results

4.2.1 Cooler Recycling at 1.7K

4.2.1.1 Cooler Temperatures Before Recycling (when in Operation)

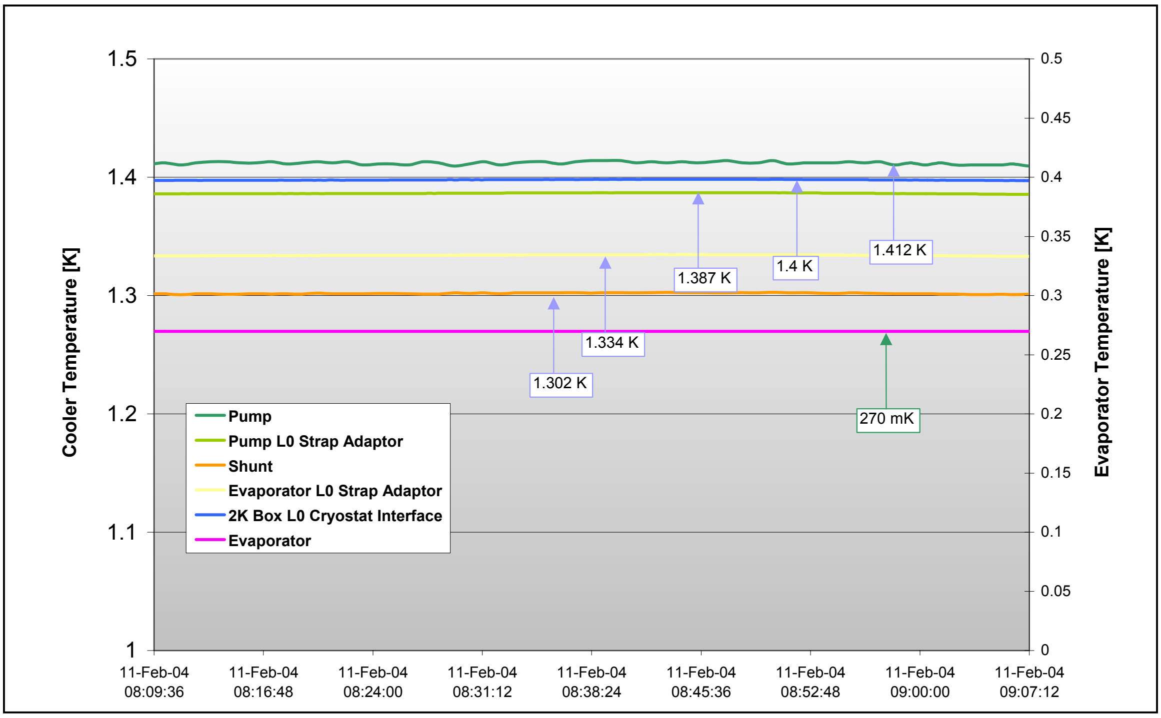

Figure 4.2.1-1– Cooler Temperatures Overview before Recycling (cooler still in operation)

Because the thermal sensors at the cryostat L0 pump and evaporator cryostat interfaces aren't working, the sensor at the 2K Box L0 cryostat interface has been used as an indication of the cryostat L0 Bath temperature (based on the assumption that the Helium pot is isothermal).

In Figure 4.2.1-1 above, we can see that the 2K Box L0 cryostat interface temperature seats at 1.4K at all the time whereas the temperature at the warmer end of the L0 evaporator external strap indicate a temperature around 1.33K. From this observation, it can be concluded that the L0 stage of the cryostat is running at a temperature lower than 1.4K and possibly close to 1.3K, but that the Lakeshore unit (which at that time was still logging converted data) was saturating the signal to 1.4K.

The shunt temperature, which is directly connected to the L0 evaporator strap via a copper strap, appears to have a lower temperature than the strap itself. At first sight, this is not possible as the shunt is located at the warmer end of this strap. According to the thermal analysis predictions, the temperature at the strap is expected to be really close to the shunt one (when the evaporator heat switch is OFF, as during normal operation of the cooler). Further discussion with Lionel Duband [RD3] suggested that cold gas inside the cooler could locally cool the shunt when the cooler is in operation.

4.2.1.2 Cooler Temperature during Recycling

At the beginning of the recycling, the cryostat L0 temperature was increased from 1.4K (which was initially used to optimised the cryostat hold time) to 1.7K (tag number 1 on Figure 4.2.1-2 below). A small overshoot in L0 temperatures can be observed as a result of this change.

The L1 cooler enclosure temperature increases by about 0.5K during the cooler recycling period due to the pump heater operation (this has been predicted by transient analysis with the thermal model in cooler recycle mode).

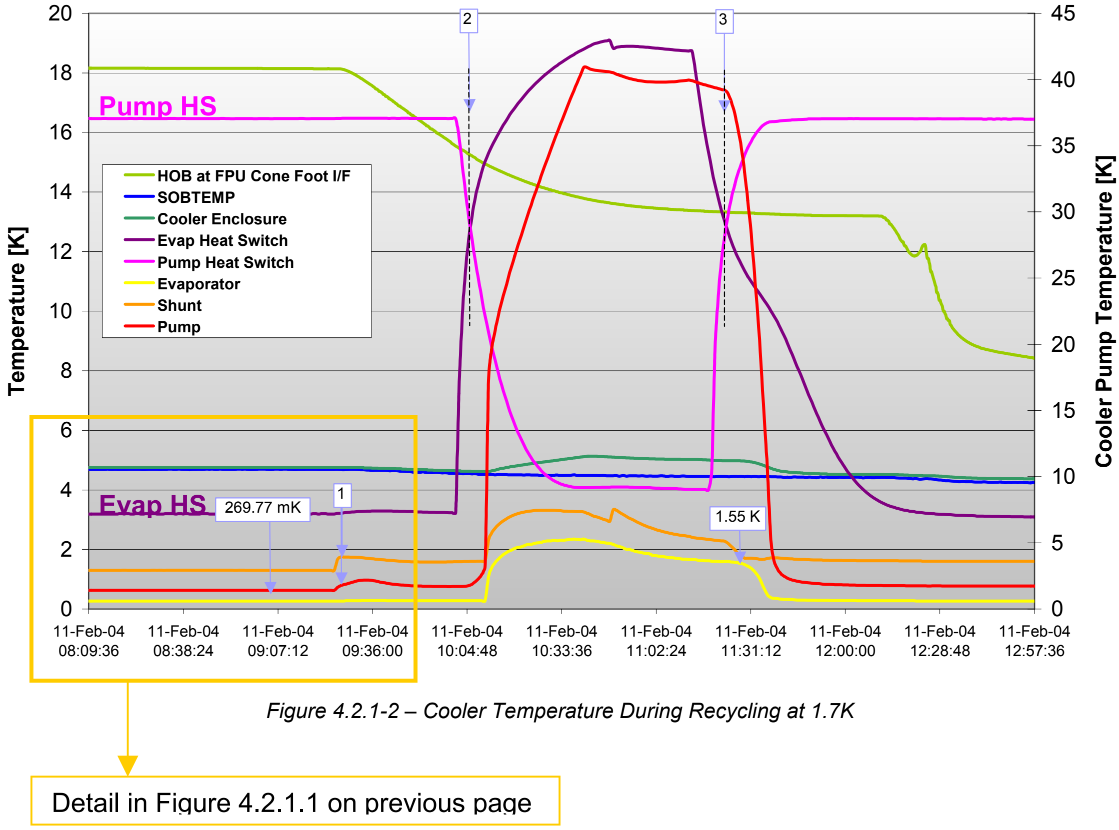

Figure 4.2.1-2 – Cooler Temperature During Recycling at 1.7K

At the start of the recycling the evaporator heat switch is being activated (as described by its increasing temperature) while the pump heat switch is OFF (as described by its decreasing temperature), see tag number 2 on Figure 4.2.1-2.

When the pump starts being heated up, the evaporator and shunt temperatures increase considerably, indicating the beginning of the recycling phase.

The pump temperature is then maintained at a temperature around 40-45K and as soon as the evaporator reaches an acceptable temperature (below 2K), the pump and evaporator heat switches states are inverted, the pump heater is turned off and the cryo-pumping phase then starts.

The pump starts cooling down really quickly and a peak can be observed at the pump L0 strap adaptor as a result of the large heat flowing along the strap (see tag 3 on Figure 4.2.1-3 on next page).

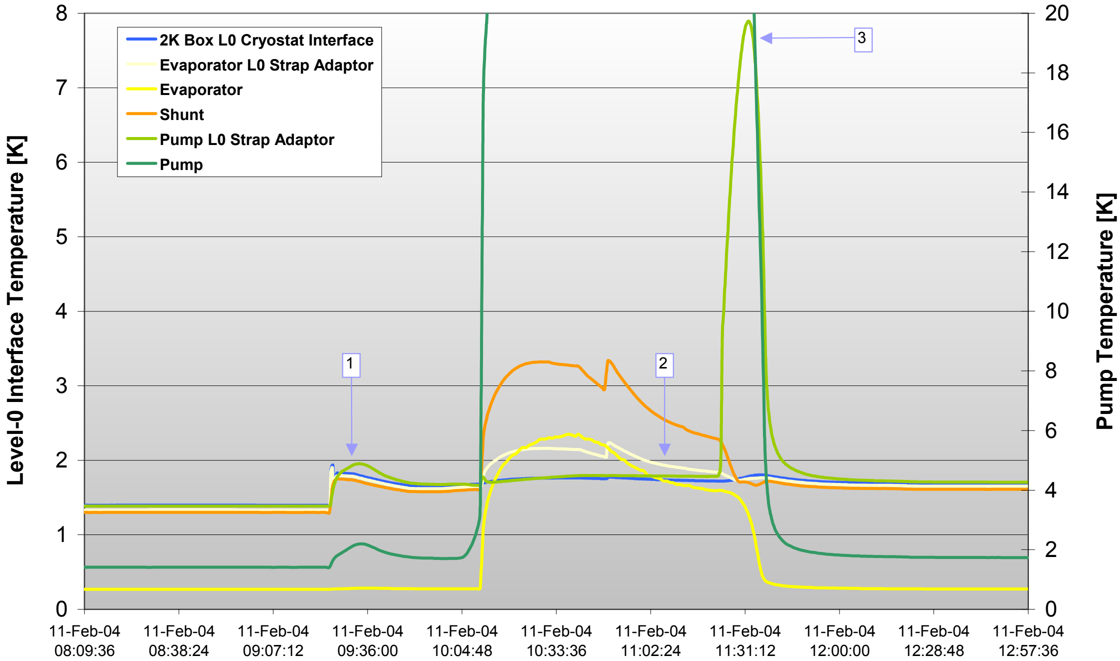

Figure 4.2.1-3 - Cooler Temperature During Recycling at 1.7K

The observed temperature increase at L0 pump strap adaptor goes as high as ~7.9 K when the pump heat switch in turned back ON again.

It can be seen that the evaporator L0 strap adaptor temperature follows a temperature profile identical to the shunt temperature, which confirms that a good thermal coupling exists between the two.

The temperature at the L0 evaporator strap adaptor appears to lie between the evaporator and the shunt temperature during the cooler recycling. This is expected as in this case, both the evaporator and the shunt are thermally connected to the strap (the evaporator heat switch is ON during recycling).

As described previously, during recycling the L0 evaporator strap adaptor temperature profile follows the shunt temperature profile. It has also been observed that an identical temperature profile appears at the 2K-box L0 cryostat interface as described on Figure 4.2.1-4 on next page. This observation allows to confirm that the Helium in the L0 pot is isothermal and that the Helium bath warms up slightly as a result of the cooler recycling.

Despite the fact that the evaporator heat switch takes between half an hour up to an hour to switch on (against 15 minutes on average for the pump heat switch), the temperature profiles of the cooler are as expected.

4.2.1.3 Detector L0 Enclosures Temperature Before and During Recycling

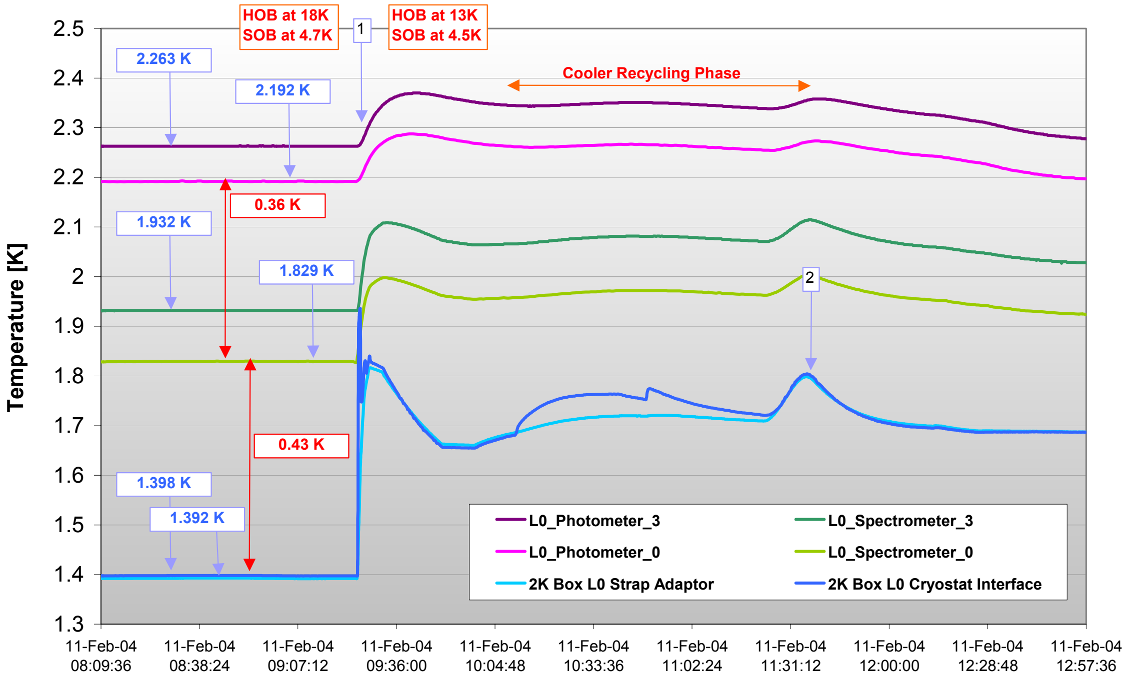

Figure 4.2.1-4 – L0 Enclosure Temperature before and during Recycling at 1.7K

In Figure 4.2.1-4 above, the full thermal path from the cryostat L0 interface to the L0 photometer enclosure is described. The temperature drops at various locations along this path can therefore be analysed in details.

Each L0 enclosure contains 2 thermal sensors, one, which is monitored by the instrument flight elecronics and the other, monitored by Lakeshore 218 units.

The L0_spectrometer_0 sensor (monitored by the instrument flight electronics) is located at the strap interface on the spectrometer box while the L0_spectrometer_3 is located at the foot interface on the spectrometer box.

The L0_photometer_0 sensor (monitored by the instrument flight electronics) is located at the strap interface on the photometer box while the L0_photometer_3 is located close to the PLW interface on the enclosure spine.

It is expected that reading errors introduced by the sensors self-heating and parasitic loads will be slightly different from one sensor to the other because of the difference in the way they are driven. The instrument flight electronics uses a constant voltage to drive the sensors which should have less self-heating errors than the Lakeshore units which use a constant current drive.

<u>Please note however that the relative accuracy between the sensors is what is really important when analysing temperature drops.</u>

In Figure 4.2.1-4, the gradients along the thermal path of the L0 enclosures seem to vary before and during the recycling. It is important to note that the Level-1 temperature decreases by 0.2K during this period. This would most certainly affect the heat loads flowing along the L0 enclosure straps and therefore the temperature drop observed along it.

- Before the recycling, a larger heat flow is expected; therefore a greater temperature drop would be expected at the given interfaces.
- During the recycling, the SOB runs cooler (because of the HOB cooling down) and therefore a lower heat flow is expected; therefore the temperature drop would appear less important. It is important to note however that during the recycling period, the temperatures have not had time yet to stabilise. Those results must therefore be used as an indication only and must not be used for proper correlation exercise.

The temperature drop measured between coldest point on the photometer enclosure and the strap interface on the spectrometer enclosure is ~0.36K for a SOB temperature of 4.69K (monitored by the temperature sensor denominated as SOBTEMP).

The temperature drop measured between the L0 enclosure strap interface on the spectrometer enclosure and the adaptor of the L0 enclosure strap itself, is ~0.43K for a SOB temperature of 4.69K (monitored by the temperature sensor denominated as SOBTEMP).

The following possible causes for such a temperature gradient at those interfaces have been considered and analysed in more details in section 4.3.1 and 4.3.2:

- A higher load on both the 2K interbox strap and the L0 enclosure straps than expected could introduce a larger temperature drop than expected. This could be caused by the following:
  - Larger parasitic loads from the L0 strap standoff mounted off the FPU,
  - Larger heat leak from the L0 enclosure supports and the F-harness,
  - Thermal short with the FPU via the light baffle.
- A very bad joint interface conductance or/and straps conductance could also be the reason for this temperature drop,
- Errors in thermal sensor temperature readings.

A more detailed analysis has been carried out for each of the stated point above and is described in section 4.3.

4.2.2 Cooler Characterisation

4.2.2.1 Test Description and Results

Purpose of the test:

This test allows to characterise the cooler performances by studying the variations in pump temperature for a varying heat load on the pump itself. Following this test, a curve of Pump temperature versus applied power can be plotted and the slope of the curve can then be used to characterise the load on evaporator cold tip based on the assumption that when in operation, the pump sees a heat load equal to 45-50 time the total load on the evaporator at 300mK.

For the cooler characterisation, the following test set-up has been used:

- Cooler in operating mode (evaporator temperature at 300-mK),
- Power is applied to cooler pump by step of 5, 10 and 15 mW,
- The temperature increase of the pump is then measured along with the evaporator temperature.

The cooler temperatures at the beginning of the test were as follows:

Description	*Temperature*
Cooler Enclosure	4.406 K
Photometer L0 Enclosure	2.164 K
Pump	1.42 K
Shunt	1.318 K
Evaporator	264.4 mK

Table 4-6 – Cooler Temperature at beginning of characterisation Test

With Pump Heater resistance of 402 ohms, the following commands had to be sent to the cooler via the flight electronics (see Appendix B for more information on current conversion):

Command to Pump Heater		Current	P
[Hex]	*[Dec]*	*[A]*	*[mW]*
124	292	0.003526	5.00
19C	412	0.004985	9.99
1F8	504	0.006103	14.97
28B	651	0.007889	25.02
302	770	0.009335	35.03
397	919	0.011146	49.94
418	1048	0.012714	64.98
48B	1163	0.014112	80.05

Table 4-7 – Commanded command to the Cooler Pump

The results from this test are presented in the table and figure below:

Pump Power *[mW]*	Pump Temperature *[K]*	Evaporator Temperature *[mK]*
0	1.4178	264.4
5	1.8706	264.6
10	2.2227	264.8
15	2.5368	265
25	3.0929	265.4
35	3.576	266.3
50	4.2267	267.8
65	4.8184	269.1
80	5.3789	271

Table 4-8 – Cooler Characterisation Test Results

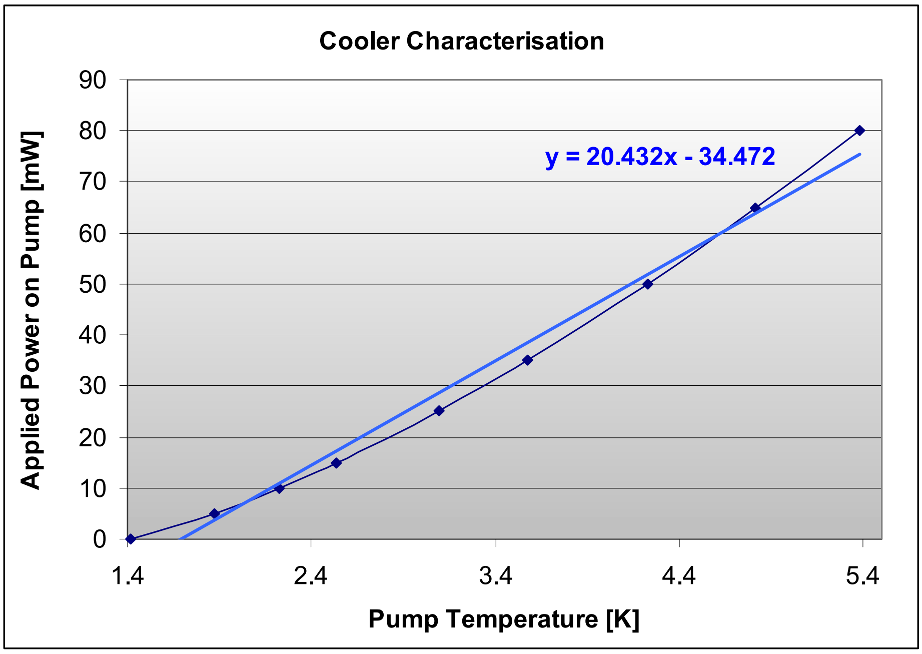

Figure 4.2.2-1 – Cooler Characterisation Test Results

A slope about 20.4mW/K has been measured, corresponding to a typical value for this slope of around 15-20 mW/K [RD3].

4.2.2.2 Cooler Characterisation Analysis

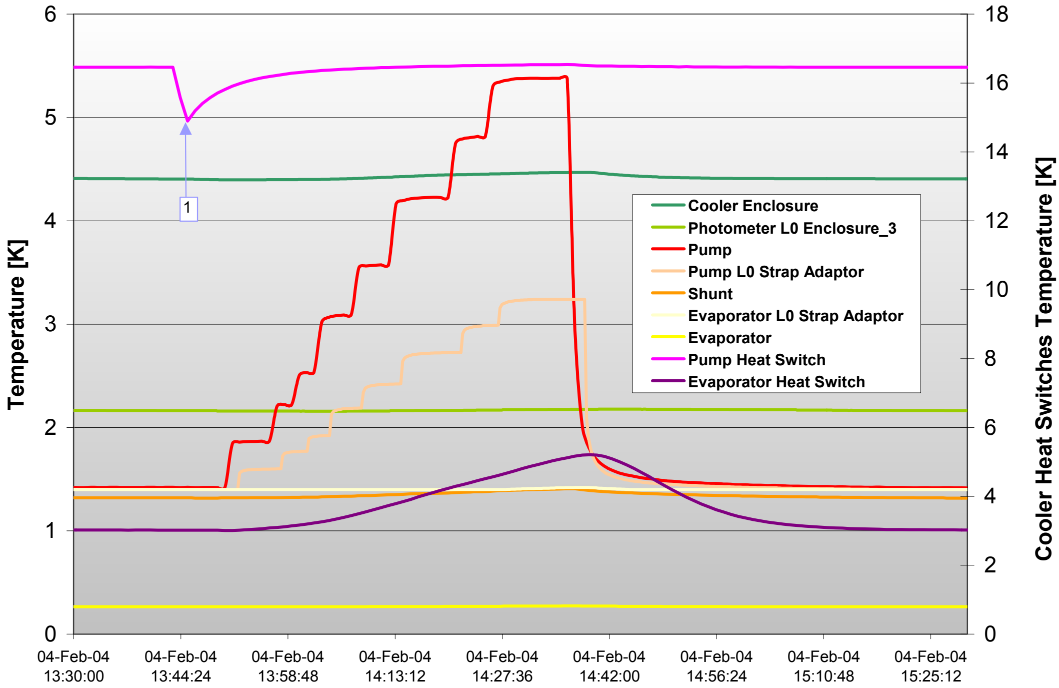

Figure 4.2.2-2 – Cooler Characterisation Test Results

The following observations have been made during the cooler testing:

- The shunt temperature ranges between 1.318K and 1.407K as described by Figure 4.2.2-4 on next page,
- The pump temperature increases from 1.42K to 5.38K, as the power increased,
- The Level-0 photometer enclosure increases from 2.159K to 2.179K,
- The evaporator temperature increases from 264.4mK to 271mK as a result of the pump increase in temperature as described in Figure 4.2.2-3 and Figure 4.2.2-4 on next page.

The L0 Pump Strap adaptor temperature profile follows the pump temperature profile, confirming that the pump heat switch is ON as indicated by the temperature of pump heat switch sieve at ~16.5K.

Note: Following an error in the command sent to the cooler during testing (see test logfile in [AD4]), a glitch can be observed for the pump heat switch temperature as described in Figure 4.2.2-2 by the tag number 1.

The evaporator heat switch sieve is also warming up from 3K to 5K.

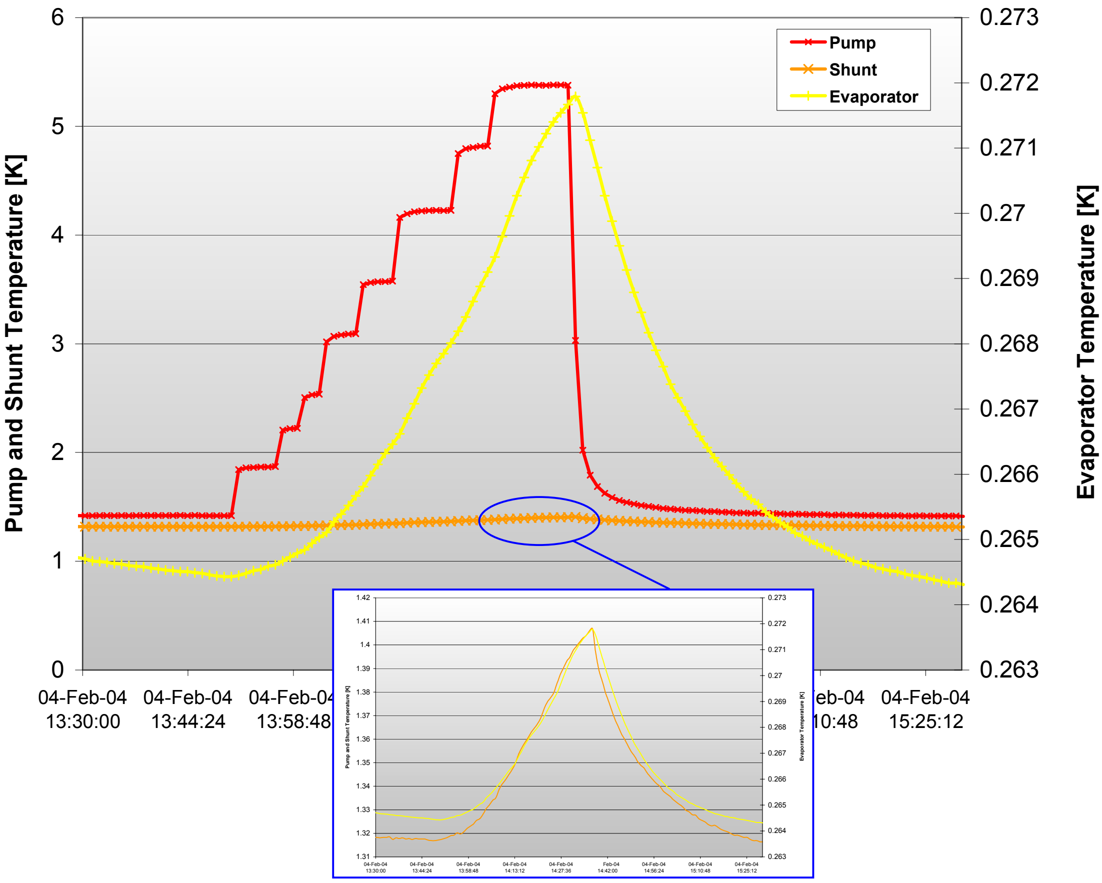

Figure 4.2.2-3 – Cooler Characterisation test Results

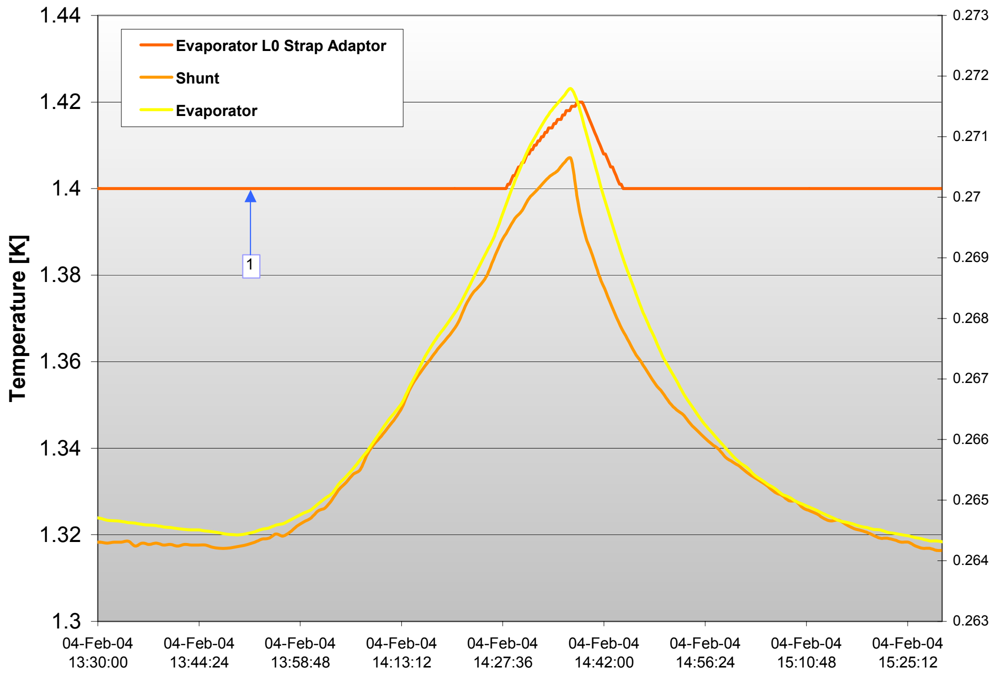

Figure 4.2.2-4 - Cooler Characterisation test Results

4.2.3 Photometer, Spectrometer and OFF Cases

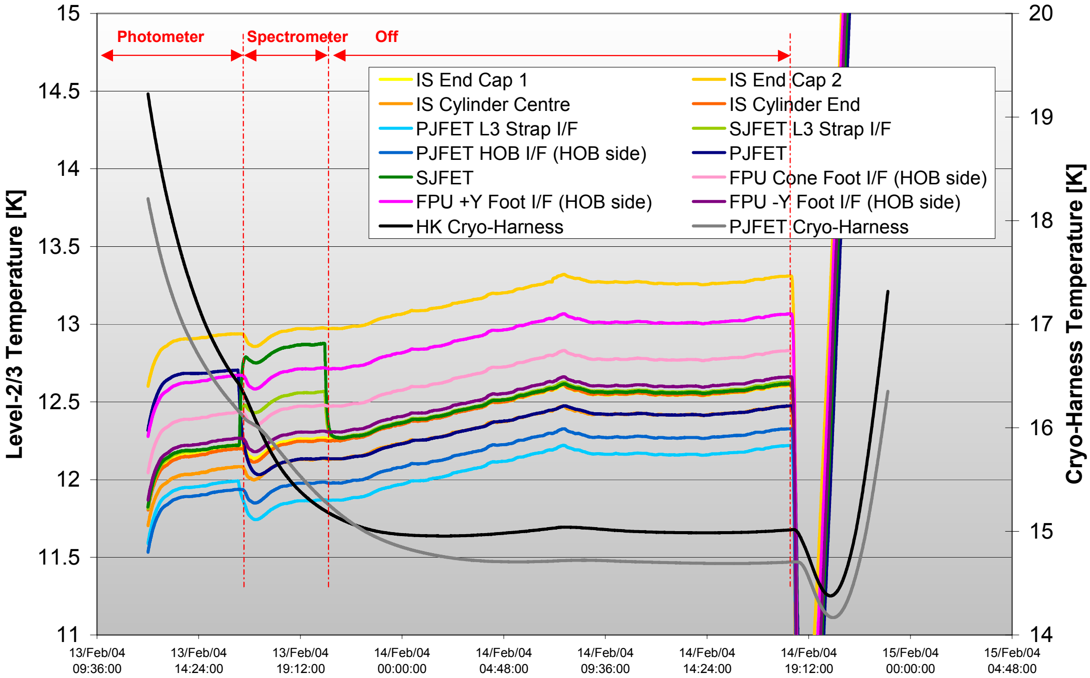

Figure 4.2.3-1 – SPIRE Thermal Balance Test Results

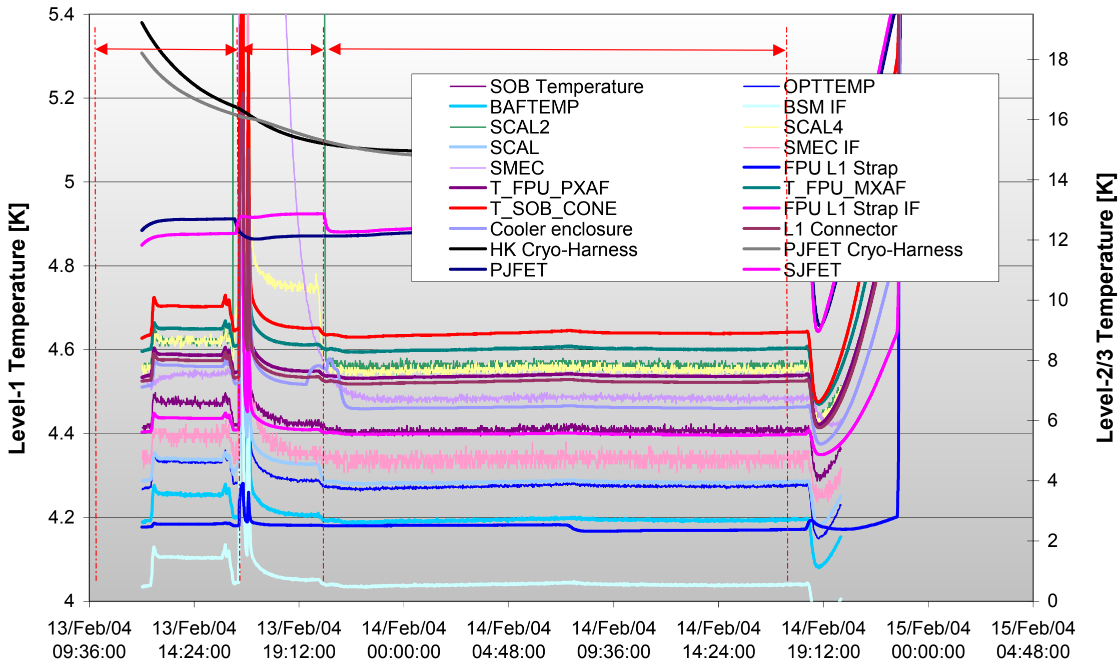

Figure 4.2.3-2 - SPIRE Thermal Balance Test Results

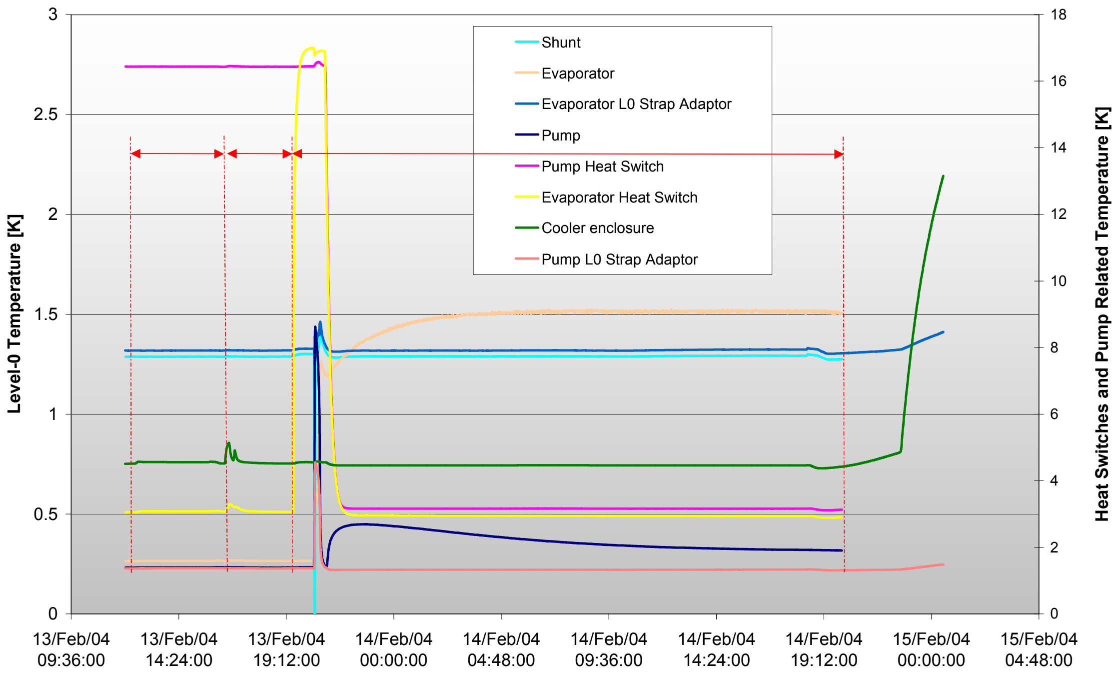

Figure 4.2.3-3 - SPIRE Thermal Balance Test Results

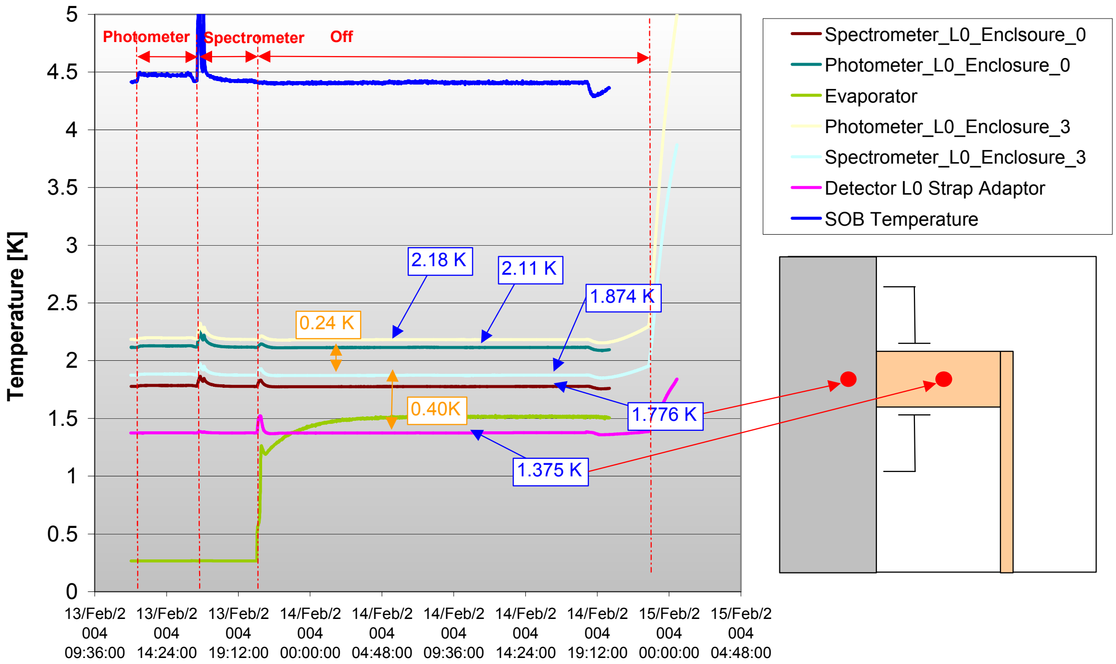

Figure 4.2.3-4 - SPIRE Thermal Balance Test Results

4.3 Additional Analysis

As described in the previous sections, an important temperature drop has been observed at both Level-0 enclosure interfaces. Such a temperature drop at the spectrometer and photometer enclosures wasn't predicted and would introduce larger parasitic loads into the 300-mK stage of the instrument, hence reducing the cooler hold time. A detailed analysis has therefore been carried out to understand the possible causes.

4.3.1 Sensitivity Analysis on L0 Enclosures Heat Load and Interface Joint Conductance

Two possible causes are being considered in this section:

- Could a larger load than expected be flowing on both the 2K interbox strap and the L0 enclosure straps and introduces this large delta T?
- Could the joint interface conductances or/and straps conductance be lower than expected?

The table below provides an overview of the predicted performances for the Level-0 enclosures at a given set of boundary temperatures. Please note that the heat load flowing along those straps is expected to be a lot less for the flight model as the L0 enclosures supports have been replaced with better isolation standoffs.

	Prediction	***CQM1 Results***
Level-1 FPU/SOB Temperature	4.6K - 4.8K	4.4K mean
Level-0 Photo Enclosure Temperature	1.9K – 2K	2.11K – 2.18K
Level-0 Spectro Enclosure Temperature	1.75K -1.76K	1.77K – 1.87K
L0 Enclosure Strap IF Temperature	1.7K	<1.4K
Load on 2K Interbox Strap Load	1.8 mW	-
L0 Enclosure Strap Load	2.6 mW	-
Temperature drop along interbox strap	0.15K	0.24K for L1 at 4.4K 0.36K for L1 at 4.7K
Temperature drop at spectrometer box	0.01K	0.40K for L1 at 4.4K 0.43K for L1 at 4.7K

Table 4-9 – Predictions on L0 Enclosures Temperature and Heat Loads

In addition, the following assumptions were used for the interface conductance of Cu/Al joints (assumptions used by Air Liquid for their thermal modelling [RD4]):

Cu/Al joint conductance at 1.7K = 0.06 W/kN.K per screw

So for the joint at the spectrometer box where 2xM3 were used with an assumed force of 1.34kN on each screw, the overall joint conductance was estimated to be: 0.16W/K.

For the predicted 2.6mW load in table 6.1, this should provide a maximum temperature drop of 0.016K (27 times less than the temperature drop measured during testing).

Assuming the joint conductance at the instrument interfaces match the conductance obtained with the above equation, and that the measured temperature drop is correct as well, this would mean that a 69mW load is flowing along the strap.

The following points could explain such a large heat load flowing on the L0 enclosure straps:

- Larger parasitic loads from the L0 strap standoff mounted off the FPU,
- Larger heat leak from the L0 enclosure supports and the F-harness,
- Thermal short with the FPU via the light baffle.

Although recent analyses have shown that the parasitic load previously estimated for the L0 strap standoffs was underestimated by a factor 5 minimum, due to an error in material arrays (from 0.1mW to 0.5mW), this would not explain such a large load.

A larger load from the supports and the F-harness would mean that the temperature drop between the two boxes would also be important. The predictions show however that the measured interbox temperature drop isn't far from the predicted one (taking into account the possible error in sensor readings and also the difference in boundary temperatures).

Finally, a thermal short between the external L0 enclosure strap and the instrument FPU could be a good reason for a large increase in heat load along the L0 enclosure straps. However, it would also mean that the temperature at the strap adaptor would locally warm up (indicating that an additional load is flowing from that point onwards) and the spectrometer enclosure temperature would effectively follow the strap temperature.

Following the previous observation, it appears unlikely that such a larger load has been flowing on the enclosure straps. If the load isn't the cause, then a poor joint conductance might be.

Assuming the predicted load flowing on the external L0 enclosure strap is within 30%[5] of the real one (2.6mW x 1.3 = 3.4mW) to account for uncertainties in temperature measurements and predictions, and that the measured temperature drop is correct as well, this would mean that the joint interface conductance between the spectrometer enclosure and the external L0 enclosure strap is about 0.008 W/K (20 times worse than the predicted one).

Errors in temperature sensors readings must also be analysed to obtain a full picture of the problem and gain a good understanding of the thermal environment.

[5] Uncertainty Level applicable for space project phase C/D.

4.3.2 Sensitivity Analysis on error in thermal sensor readings

In addition to the analysis of the thermal hardware, it is important to understand the various sources of errors that can be present in temperature readings of thermal sensors.

Errors in temperature readings of thermal sensors can come from various sources:

- The sensor is badly fitted on the surface being measured. This would effectively increase the contact resistance between the sensor and the surface and the sensor would read warmer temperature as improperly heat sunk.

- The conversion of the sensor resistance measurement back into temperature values using calibration curves (ADC accuracy, calibration curve accuracy, …).

- Sensors resistance measurements can also come from:
  - EMF error occur at thermal joint when using DC measurements (as with the Lakeshore unit)
  - Self-heating of the sensor due to parasitic load along the sensor leads if not properly heat sunk as well as to the ohmic heating of the sensor itself.

The Table 4-10 below provides an overview of the estimated temperature error introduced in the thermal sensors. This analysis is based on an assumed sensor/surface contact resistance of 300000 K/W as suggested by lakeshore for Cernox sensors fitted with CU packages.

The EGSE sensors were driven using a fixed current of 10 μA while the flight sensors were driven using constant voltage of 10mV.

A parasitic load of 0.02 μW has been assumed to be coming through the sensors leads, based on the length, diameter, number and material of the sensor leads as described in [AD7].

Sensor	Resistance	Temperature	Current	Self Heating	Parasitic heat	Total	Delta T
CU Package	*ohms*	*K*	*A*	*μW*	*μW*	*μW*	*mK*
PL0 – photo enclosure	954	~ 2	1.05E-05	0.10	0.02	0.12	37.45
PL3 – photo enclosure	955	~ 2	1.00E-05	0.10	0.02	0.12	34.65
SL0 – spectro enclosure	900	~ 1.8	1.11E-05	0.11	0.02	0.13	39.33
SL3 – spectro enclosure	650	~ 1.8	1.00E-05	0.07	0.02	0.09	25.50
Enclosure strap adaptor	1660	~ 1.4	1.00E-05	0.17	0.02	0.19	55.80

Table 4-10 – Thermal Sensor Reading Errors due to self-heating

Note 1: Please note however that the relative accuracy between the sensors is what is really important when analysing temperature drops.

Note2: The data obtained in table 6.2 should only be used as an indication rather than a true performances as the contact resistance of a sensor with a surface might vary from one sensor to another.

Table 4-11 on next page provides an indication of the impact such temperature reading errors would have on the interpretation of the various temperature drops along the L0 enclosures thermal path.

Temperature Drop Between		Error due to self-heating between the two sensors	Impact on Analysis
Sensor 1	*Sensor 2*		
L0 Enclosure Strap Adaptor	L0 Spectrometer Enclosure strap interface (SL0)	Error on sensor 1 (STM) is greater than on sensor 2 (flight).	This would means that the temperature drop at this interface is currently under-estimated
L0 Spectrometer Enclosure strap interface (SL0)	L0 Spectrometer Enclosure foot interface (SL3)	Error on sensor 1 (flight) is larger than on sensor 2 (STM).	This would means that the temperature gradient within the spectrometer enclosure is currently under-estimated
L0 Spectrometer Enclosure strap Interface (SL0)	L0 Photometer Enclosure strap interface (PL0)	Error on sensor 1 (flight) is identical to the one on sensor 2 (flight).	Any error present in both sensors should roughly cancel itself out, which means that the estimated temperature drop is correct.
L0 Photometer Enclosure strap interface (PL0)	L0 Photometer Enclosure Spin (PL3)	Error on sensor 1 (flight) is almost identical to the one on sensor 2 (STM).	This would means that the temperature gradient within the photometer enclosure is currently correct.

Table 4-11 – Estimated Error in Analysis of temperature drop along L0 enclosure thermal Path

4.4 Conclusion

4.4.1 SPIRE CQM1 Thermal Performances Overview

An overview of the thermal predictions for the instrument temperatures and heat flows can be found in Appendix C. This analysis was assuming a specific set of boundary temperatures at the interfaces of the instrument and must therefore be used with care when compared to the performances obtained during the testing as a different set interfaces boundary temperatures were used at that time.

The following general performances have been obtained with SPIRE during the CQM1 test campaign:

Nominal Interface temperatures	
L2 HOB and Shroud	10K
L1 Cryostat Interface	4.12K
L0 Cryostat Interface	<1.4K
Overall instrument temperatures	
SOB temperature Range	4.3-4.5K
L0 photometer enclosure	~2.1K
L0 spectrometer enclosure	~1.8K
Evaporator Cold tip	265mK
PLW BDA Temperature	295 mK

Table 4-12 – SPIRE Overall Performances during CQM1 Test Campaign

The performances obtained for the L0 enclosures temperatures aren't satisfactory, especially for a cryostat L0 interface temperature < 1.4K. Improvement of the joint conductance at the interbox and L0 enclosure strap interfaces is required.

Despite the fact that the measured PLW detector temperature is within the specification (<310mK), the temperature drop along the 300-mK Busbar currently exceeds the maximum 10mK specification in addition to the fact that it sees a reduced load as only one detector is connected to the Busbar. An improvement of the overall 300-mK Busbar conductance is therefore required.

4.4.1.1 Cooler and 300-mK System Performances Observations

- The cooler ran very well with its evaporator cold tip as low as 265mK and a hold time as high as 60 hrs, but the following conditions were applicable at the time of the test:
    - The Level-0 heat sink interfaces were running most of the time at < 1.4K as indicated by the shunt temperature (which is connected to the L0 evaporator strap) which has been as low as 1.3K. This environment isn't flight representative and means that the evaporator temperature has reached temperature as low as 1.5K at the end of the condensation phase during recycling and this would greatly increase the cooler recycling efficiency.
    - The cooler was running with a reduced load on its evaporator cold tip as only one detector was connected. This represents a predicted load of 6.8uW against a total load of 24.5uW for five detectors (both in addition to the cooler internal parasitic loads).

- The evaporator cold tip increased by 9mK when the cryostat Level-0 interface temperatures have been increased from 1.4K to 1.7K (because of the increased parasitic load from 300-mK system and from the evaporator heat switch).
- A 30-mK temperature drop has been measured between the evaporator at 265mK and detector temperature estimated to be between 290mK and 295mK. A 35-mK temperature drop was estimated with the thermal model for a similar Level-0 photometer enclosure temperature.
- A local warn up of 0.5K at the cooler enclosure has been measured when the pump heater is turned ON (as predicted by the thermal analysis in transient mode).
- The evaporator heat switch takes up to an hour to switch ON.
- Sieve temperature increased up to 20K in some instance. Future analysis will have to check what would be the impact of this radiation load on the cooler components.
- Some temperature drift has also been observed at the evaporator cold tip. The impact of such a drift need to be analysed in more detailed and will be used as an inputs for the PTC control algorithm.

4.4.1.2 L0 Enclosures Observations

- It has been observed that the level-0 Photometer enclosure temperature is lagging behind the Level-0 spectrometer enclosure temperature during cooldown and then eventually catched up. This is predictable as the photometer is located at the extreme end of the thermal link.
- Despite the large temperature drop at the spectrometer enclosure, the measured temperature drop between the two enclosures was very close to the estimated one (0.24K versus 0.15K) which confirms that the current 4Nine copper strap and the small epoxy joint area are not good enough and therefore requires some improvement. The goal is to reduce this temperature drop to 0.03K maximum.
- Insight about the dynamic thermal behaviour of instruments in terms of stability and time it takes for the temperature to settle down has been obtained during this test.

4.4.1.3 L1 FPU Observations

No specific observation could be made on the gradient present within the SOB during the various operation modes because of the various problems experienced when running the internal mechanisms.

4.4.2 SPIRE CQM1 – Revisions for CQM2

- A manostat has been integrated on the calibration cryostat to provide a better control of the Level-0 interface temperatures,
- All Level-0 cryostat interfaces will be controlled at 1.7K (rather than 1.4K) to make sure all sensors are within the range of the calibration curves and also be flight representative,
- To avoid any more instability when using the MCU, the SMEC and BSM STM mechanisms will be controlled via a simple power supply using a 4-wire measurement to be able to determine the power dissipated accurately,
- The few lost sensors have been rewired for the next test campaign,
- The lead of all sensors at the Level-0 stage will be better heat sunk and an AC bridge will be used to read the STM sensors out and reduce the error readings due to self-heating,
- The method to perform load curve has been optimised and will allow to obtain the PLW detector temperature on a more regular basis rather than punctually,
- All five 300-mK detectors will be connected,
- The thermal interface of the external strap to Level-0 spectrometer enclosure as well as at the interbox strap has been re-designed and the new interfaces will be implemented on the instrument for the next test campaign.

Details of the next thermal balance test and validation of the thermal design and hardware can be found in AD5.

5 SPIRE CQM2 Thermal Balance Test Campaign

The following sections summarises the test results for the second thermal balance test carried out on September 2004 with the SPIRE CQM2 instrument.

5.1 CQM2 Post-Test Review

5.1.1 SPIRE CQM2 Configuration

A detailed description of the SPIRE CQM2 standard built can be found in AD5.

Table 5-1describes the setup used during the second test campaign with the SPIRE CQM2.

Interface With	CQM2
L2 Shield	Only SJFET thermally coupled to L2 shield.
HOB sim	PJFET bolted on HOB with 5 bolts
	SJFET bolted on HOB with 4 bolts
	SPIRE FPU mounted off the Herschel Optical Bench (HOB) Simulator on three isolation supports.
L1	1 thermal strap made of 5 Ns aluminium connects the SPIRE Optical Bench (SOB) to calibration cryostat Level 1. It doesn't include electrical isolation anymore.
L0	3 thermal straps connect the SPIRE Cooler and Spectrometer enclosure to the cryostat L0 interface.
300-mK	PLW and 4 STM BDAs connected to the cooler

Table 5-1 – Test Setup during the second Thermal Balance Test Campaign

Note: The PJFET was left unconnected to allow a good correlation of the F-harness and the isolation support parasitic loads.

5.1.2 SPIRE Calibration Cryostat

5.1.2.1 Manostat

The implementation of the manostat has proven to be an efficient way to control the temperature of the Level-0 Helium pot temperature. This change also introduced changes in the way the cryostat is operated when the L0 pot is subjected to a large heat input (like for example during the cooler recycling or the pump characterisation test).

The manostat is basically restricting the helium flow therefore allowing a precise adjustment of the temperature of the L0 interfaces. The side effect is that because of the flow restriction when a large heat load is being dissipated into the L0 pot, its temperature starts increasing unless the manostat valve is open again and the flow free to increase to its will.

As a result:

- The L0 interface temperatures during recycling are unstable and varying during the whole recycling period. This behaviour affects the transient profile of the cooler during recycling (in terms of how long it would take for the evaporator to reach 2K).
- The control of the L0 interface temperatures when subjected to a heat load of more than 10mW is difficult and time consuming, as in these cases, the manostat has to be adjusted at all time in order to keep the interface temperature constant. This makes the setup of each case for the pump characterisation test quite difficult to setup.

Despite those side effects, it is felt that the manostat greatly improved the operation of the cryostat during the thermal balance testing.

5.1.2.2 Helium Leak

After the first week of thermal testing, the cooler performances appeared to be degrading slowing but constantly (i.e. in term of cooler hold time and cold tip temperature). Further investigation suggested that a helium leak inside the cryostat might be the cause for the cooler performance degradation: i.e. effectively, the presence of helium in the cooler enclosure could potentially create a thermal path from the 4K stage to the cold tip and introduce an additional load on the evaporator.

In order to confirm this possibility, one decided to warm-up the L0 stage of the instrument to 4K as well as to leave the vacuum pump pumping during a whole weekend. The operation of the cooler following this “temporary warm-up” demonstrated then that the cooler performances were back to normal.

This experience demonstrated that helium leak can have a considerable impact on the overall thermal performances of cryogenic instruments and that the use of the vacuum pump as well as a temporary warm-up of the instrument is a successful method to correct for this problem.

5.1.3 Additional Thermal Hardware

5.1.3.1 Thermal Sensors

Several thermal sensors appeared to have inconsistent temperature readings despite the fact that:

- Some of the previous defective thermal sensors had been rewired between the two test campaigns,
- The use of an AC bridge, which has allowed to reduce reading error and uncertainties of some sensors.

Table 5-2 below provides an overview of the non-working sensors as well as a possible cause for the reading errors:

Stage	Location	Name	Type	Description	Defect
Level - 2	Spectrometer JFET Strap I/F	S17	EGSE	SD	OC
Level - 1	Cryostat L1 Clamp I/F	S26	CRYO	CX	CA
	SPIRE SOB L1 Strap I/F	T_SOB_L1STR	EGSE	TVO	CA
	BSM	T_BSMM_1	FLIGHT	CX	CA
	BSM I/F with SOB	T_BSMM_1	FLIGHT	CX	CA
Level-0	Spectrometer Enclosure	T_SLO_1	FLIGHT	CX	CA / SH
	Spectrometer Enclosure	T_SLO_3	EGSE	CX	OC
	Photometer Enclosure	T_PLO_1	FLIGHT	CX	CA / SH
	Photometer Enclosure	T_PLO_3	EGSE	CX	CA / SH
	L0 Enclosure Strap Adaptor	T_L0_DSTR	EGSE	CX	CA / SH
	L0 Evaporator Strap Adaptor	T_L0_ESTR	EGSE	CX	CA / SH
	L0 Evap Strap Cryostat Interface	S28	CRYO	CX	CA / SH
	L0 Pump Strap Cryostat Interface	S29	CRYO	CX	OC
	L0 Box Strap Cryostat Interface	S30	CRYO	CX	OC

Table 5-2 – Defective Sensors During Second Test Campaign

Legend:

SD	Silicon Diode	OC	Open Circuit
CX	Cernox	CA	Out of Calibration
TVO	TVO	SH	Self-Heating

A more detailed analysis has been carried out and is presented in section 5.2.1.

5.1.3.2 Instrument Mechanisms and Internal Power Dissipation

- The use of a temporary heater mounted on L0 photometer enclosure has proven really successful as it allowed:
  - The characterisation of the L0 interbox strap,
  - To obtain a better insight about how the parasitic load into 300-mK subsystem varies with the temperature of the L0 enclosures.
- The heater mounted on the BSM STM was implemented using a 2-wires configuration. This mechanism couldn't therefore be used as part of the thermal balance test as the power dissipation could not be computed very accurately in this configuration.

5.1.4 Thermal Test Cases Completed

Table 5-3 below provides a summary of the test completed. A description of those thermal tests can be found in AD5 for more information.

Thermal Characterisation Tests			
Test Description	**Test # in AD5**	**Completed**	**Steady-State**
Thermal Sensor Characterisation	B-I	For 1uA, 10uA and 316nA excitation current on AC bridge, at 1.7K.	yes
Pump Performance Characterisation	C-I	For Pump Heater dissipation of 15, 30, 45 and 75mW.	yes
Pump Heat Switch Performances	Additional test	For Pump Heat Switch operated with 0.4mW instead of 0.8mW.	n/a
L0 Interbox Strap Characterisation	F-I	For 5mW and 10mW dissipated on the L0 photometer enclosure	yes
Photometer JFET Characterisation	G-I	For 20mW and 40 mW dissipated by PJFET CQM modules	yes
Thermal Balance Tests			
Test Description	**Test # in AD5**	**Completed**	**Steady-State**
OFF Mode	TBT1	-	yes
Photometer Mode - Cold	TBT2	With the cryostat Level-0 was maintained at 1.7K	yes
Photometer Mode - Hot	TBT3	With the cryostat Level-0 was maintained at 2K	yes

Table 5-3 - Thermal Test Cases Completed during second Test Campaign

All tests were completed with the cryostat interfaces temperatures set as follows, with the exception of the *Photometer Mode – Hot* (see note below):

- Level-2 at ~15K,
- Level-1 at ~4.2K,
- Level-0 at ~1.7K.

Note:

The Spectrometer Thermal Balance Test 3 originally planned in AD5 has been replaced with a “Photometer Mode – Hot Case”. In this test, the cryostat L0 interface temperatures were set at 2K which represents the worst case interface temperature that could be provided by the Herschel Cryostat, in flight.

5.2 SPIRE CQM2 Thermal Test Results

5.2.1 Thermal Sensors Self-Heating Characterisation

5.2.1.1 Test Results

A number of EGSE thermal sensors have been connected to a 370 Lakeshore Unit or AC bridge allowing the investigation of the thermal performances of the sensors (in terms of sensor self-heating and interface conductance) for different excitation current (from 316 nA up to 10 uA).

Figure 5.2.1-1 below describes the temperature readings from the sensors as the excitation current changes. It can be clearly seen that an important self-heating is taking place when a 10 uA excitation current is used. A third test has been carried out with a current excitation of 316 nA. No further reduction of self-heating has been registered in this configuration and the temperature readings appeared to contain more noise. This last test allowed to confirm that a current excitation of 1uA was optimum at the selected temperature (~1.7K) and offered the best compromise between sensor self-heating and signal to noise ratio.

Table 5-4 on next page provides a more detailed overview of the sensors performances, which are then discussed in more details here after.

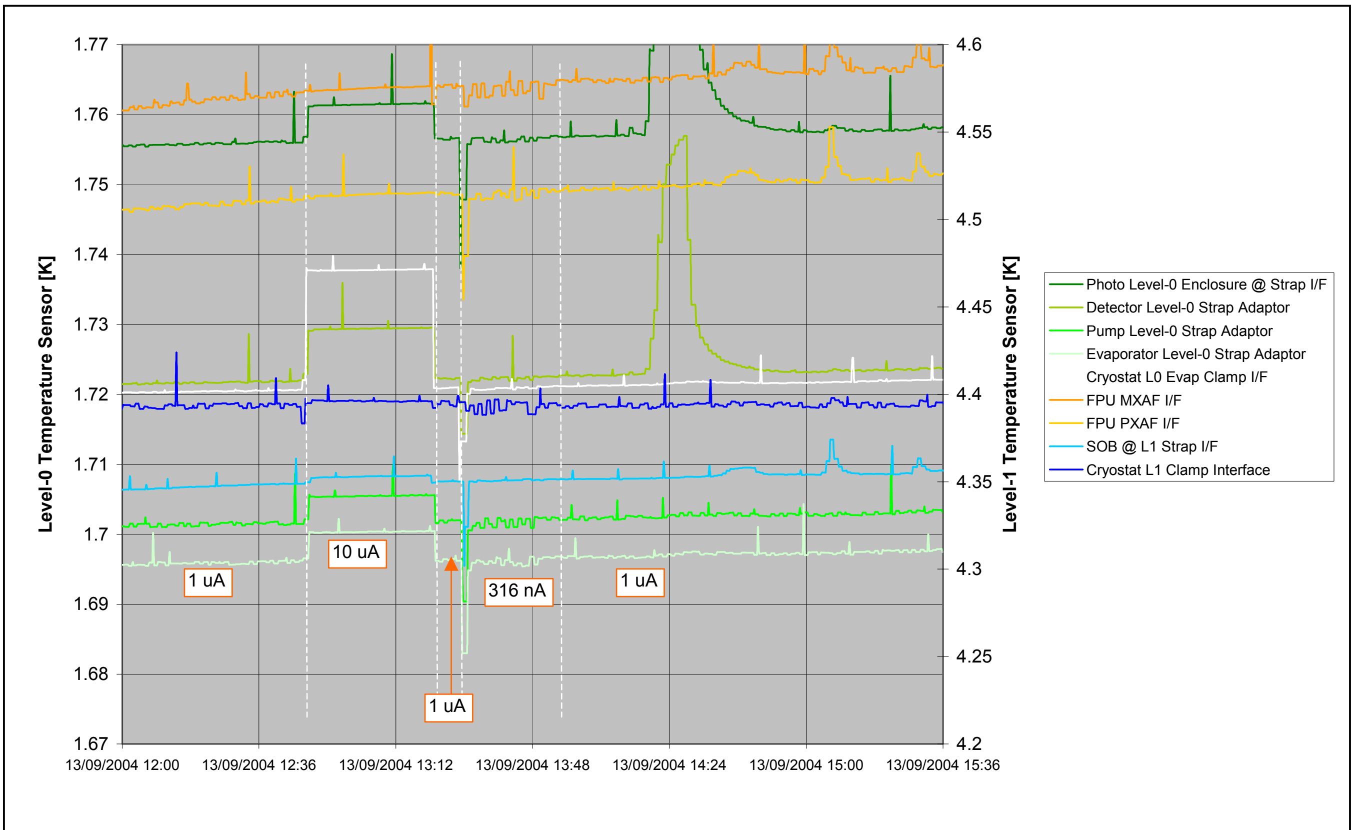

Figure 5.2.1-1 – EGSE Temperature Sensors Self-Heating Characterisation

Excitation Current On AC bridge	1uA			10uA			Calculations				
Sensors	Temp [K]	Resistance [ohm]	Power Qsh0 [W]	Temp [K]	Resistance [ohm]	Power Qsh1 [W]	DeltaTsh[6] [mK]	Sensor G [K/W]	Calculated DeltaTsh For 1uA [mK]	Predicted Harness Parasitic [uW]	Additional Predicted DeltaTsh from Parasitic [mK]
T_PL0_3	1.760	1065.0	1.06E-09	1.771	1062.0	1.06E-07	11.5	109387	0.12	0.249	27.2
T_L0_DSTR	1.727	1348.9	1.35E-09	1.734	1343.2	1.34E-07	6.7	50385	0.07	0.334	16.8
T_L0_PSTR	1.707	695.2	6.95E-10	1.711	694.0	6.94E-08	4	58217	0.04	0.334	19.5
T_L0_ESTR	1.701	776.1	7.76E-10	1.705	774.6	7.75E-08	4	52162	0.04	0.201	10.5
T_FPU_PXAF	4.516	487.3	4.87E-10	4.520	487.0	4.87E-08	4	82970	0.04	0.009	0.8
T_FPU_MXAF	4.572	419.1	4.19E-10	4.578	418.8	4.19E-08	6	144715	0.06	0.031	4.5
T_SOB_L1STR	4.349	4313.7	4.31E-09	4.353	4310.2	4.31E-07	4	9374	0.04	0.006	0.1
4K Vessel Top	6.258	424.4	4.24E-10	6.282	423.3	4.23E-08	24	572729	0.24	n/a	n/a
4K Vessel Bottom	4.272	587.4	5.87E-10	4.267	588.1	5.88E-08	-5	-85876	-0.05	n/a	n/a
FPU L1 Strap	4.395	446.3	4.46E-10	4.396	446.2	4.46E-08	1	22635	0.01	n/a	n/a
1.7K Vessel Bottom	1.741	484.3	4.84E-10	1.745	583.7	5.84E-08	4	69106	0.03	n/a	n/a
FPU Evap Strap IF	1.721	2589.2	2.59E-09	1.739	2558.5	2.56E-07	18	71073	0.18	n/a	n/a
1.7K Vessel Top	1.756	1127.4	1.13E-09	1.762	1123.5	1.12E-07	6.4	57542	0.06	n/a	n/a

Table 5-4 - Thermal Sensors Self-Heating Characterisation

[6] *Measured Temperature sensors increase from 1 to 10 uA excitation current.*

5.2.1.2 Results Discussion

In Table 5-4, the sensor interface resistance in K/W has been calculated using Equation 1 below:

$$G^{-1} = [(Qsh1 - Qsh0) / DeltaTsh]^{-1} \quad (1)$$

Where:

G	Sensor Interface Resistance K/W
Qsh1	Sensor Power Dissipation for a 10 uA excitation current
Qsh0	Sensor Power Dissipation for a 1 uA excitation current
DeltaTsh	Measured Temperature sensors increase from 1 to 10 uA excitation current.

Figure 5.2.1-2 provides an overview and trends for the various temperature sensor interface resistance at a given temperature. One can see that for cernox sensor mounted with a CU package at ~1.7K, the interface resistance ranges from 50000 to 110000 K/W.

Note: Some of the CU packages have been bolted on studs, which have been glued onto the instrument structure.

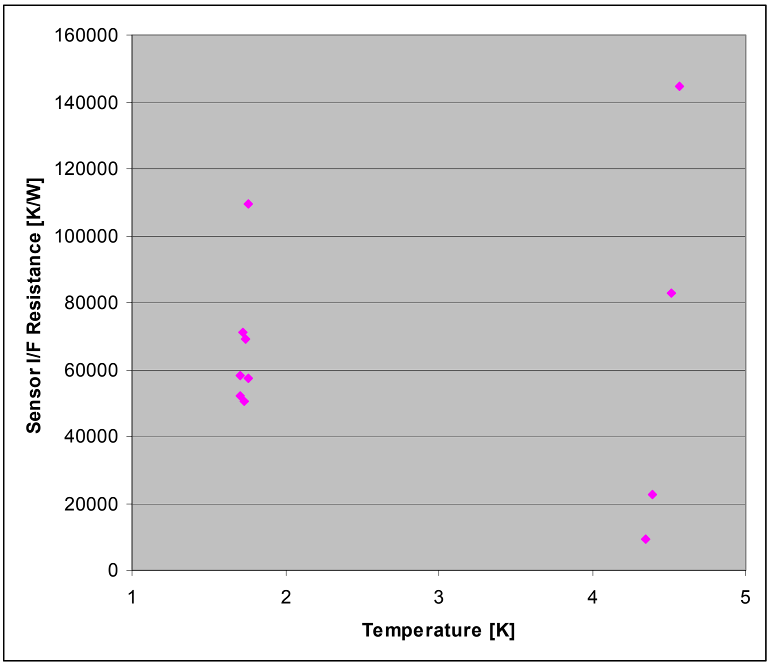

Figure 5.2.1-2 – SPIRE Temperature Sensors Interface Resistance Trends

Once the sensors interface conductance is known, the temperature offset which would be introduced by the 1uA excitation current and the additional parasitic from the sensor harness can be evaluated.

Table 5-5 below summarises the self-heating error that we can expect on the L0 EGSE sensors, while Table 5-6 describes the difference in error that one can expect on the EGSE and the flight sensors.

		Measured Temperature	Calculated Self-Heating For 1uA	Predicted Self-Heating From Parasitic	Total Predicted Self-Heating Error
		[K]	[mK]	[mK]	[mK]
L0 Photometer Enclosure at Interbox strap Interface	T_PL0_3	1.760	0.12	27.2	~27
L0 Enclosure Strap at adaptor	T_L0_DSTR	1.727	0.07	16.8	~17
L0 Pump Strap at adaptor	T_L0_PSTR	1.707	0.04	19.5	~20
L0 Evaporator Strap at adaptor	T_L0_ESTR	1.701	0.04	10.5	~11
L0 Evaporator Cryostat Clamp Interface	FPU EVAP Strap IF	1.721	0.18	unknown	Unknown

Table 5-5 - Summary of the Self-Heating Error on the EGSE Sensors

Error	***EGSE***	***Flight***
Electronics: Voltage and current accuracy	Constant Error See Lakeshore Spec	Constant Error See SCU QM1 test report
Current Excitation	Constant at 1uA	Variable with constant 10mV voltage
Self-heating	Variable Error Known	Variable Error Unknown
EMF Error	Current reversal is used Error cancelled	DC current excitation Assumed Constant offset at a given operation temperature
Calibration	Constant Offset	Constant Offset
Data Interpolation	Chebychev Best Fit and limited Error	Linear Variable Error estimated between 0 up to +5 mK
Harness Parasitic	Known but Variable Error	Unknown Variable Error

Table 5-6 - Source of errors in both the EGSE and flight sensors

Note: Constant errors are at a given temperature.

The OFF case can be used to validate the previous predictions on sensors self-heating. Figure 5.2.1-3 below describes the temperature at the various place of the L0 stage of the SPIRE instrument when in OFF mode.

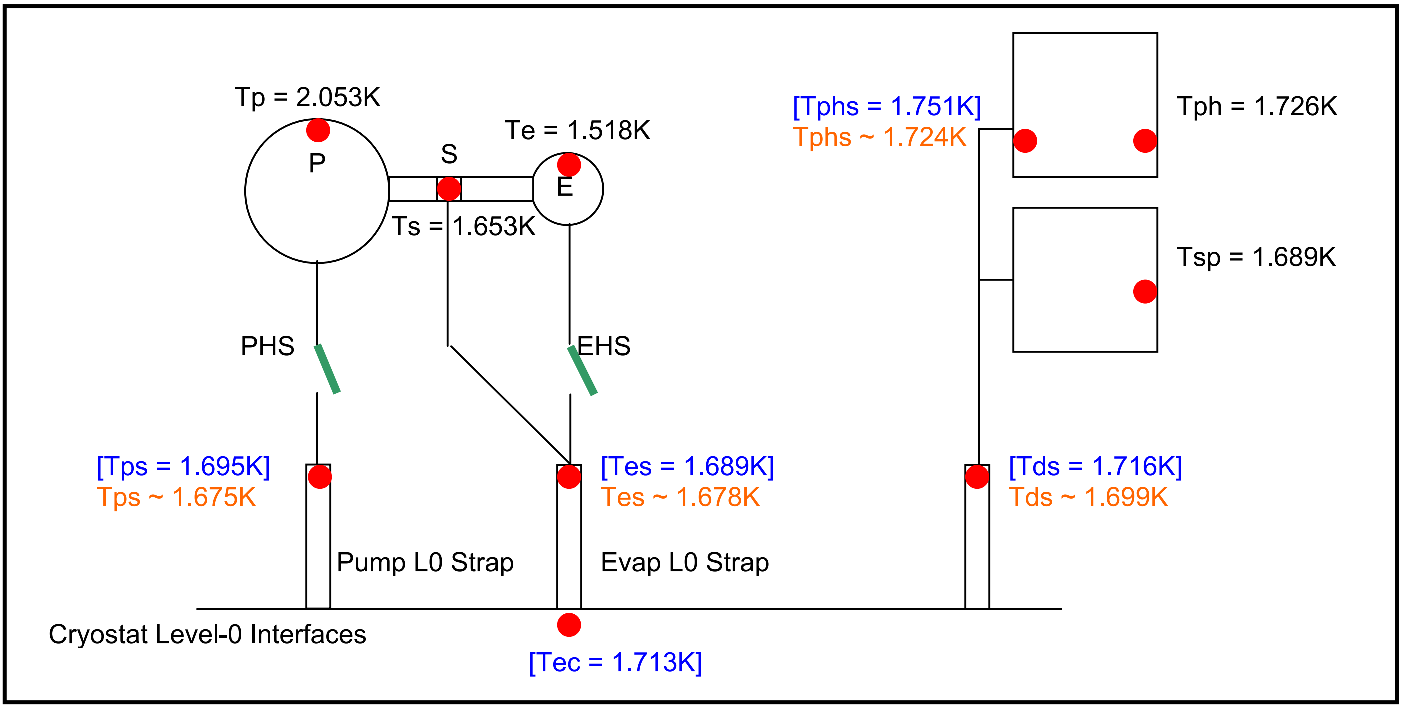

Figure 5.2.1-3 – L0 Stage Temperature during OFF Case

Legend:

P	Pump
S	Shunt
E	Evaporator
PHS	Pump Heat Switch
EHS	Evaporator Heat Switch
Tp	Pump Temperature
Ts	Shunt Temperature
Te	Evaporator Temperature
Tps	Pump Strap Temperature
Tes	Evaporator Strap Temperature
Tds	L0 Enclosure Strap Temperature
Tec	L0 Evaporator Cryostat Interface Temperature
Tph	L0 photometer Enclosure temperature at PWL Interface
Tphs	L0 photometer Enclosure temperature at Interbox Strap Interface
Tsp	L0 Spectrometer Enclosure temperature at A-Frame Interface

- The Blue temperatures have been measured with the EGSE sensors connected on the AC Bridge.
- Black Temperatures readings come from the flight sensors.
- The orange data are predicted temperature for the EGSE sensors when the self-heating error is removed.

Observations:

- The cooler shunt is isolated from everything with the exception of the evaporator strap to which it is thermally coupled. One would expect the shunt temperature to be at the same temperature as the L0 evaporator strap but it isn't and there is a 21mK difference. This might suggest that the self-heating on the sensor on the evaporator strap is larger than predicted.

- In OFF mode, the cooler heat switches are open and the pump and evaporator L0 straps are therefore isolated and only thermally coupled to the cryostat L0 stage. Although the L0 evaporator strap is connected to the shunt, it is expected that the load on both straps is very small. One can therefore expect that both straps be at the L0 cryostat interface temperature. Although the straps appear to run at the same temperature, as indicated by the corrected readings, the L0 cryostat interface is again reading warmer temperatures. It is suspected that a calibration error might be the reason for this offset in that case.

- After correction, the sensor reading at the L0 photometer enclosure strap interface appears more appropriate.

- The temperature at the L0 enclosure strap adaptor however still seems to read warmer temperature than the L0 spectrometer enclosure by about 10mK, which again might suggest that the self-heating has been under-estimated. One can observe as well that the temperature at the L0 enclosure strap adaptor runs warmer than at the pump and evaporator L0 strap adaptor. This however would be expected, as the L0 enclosure strap would see a large load from the L0 enclosures.

		Calculated Self-Heating For 1uA	Calculated Self-Heating From Parasitic	Additional Measured Error	Total Estimated Error
		[mK]	*[mK]*	*[mK]*	*[mK]*
L0 Photometer Enclosure at Interbox strap Interface	T_PL0_3	0.12	27.2	~0	~27
L0 Enclosure Strap at adaptor	T_L0_DSTR	0.07	16.8	~10	~27
L0 Pump Strap at adaptor	T_L0_PSTR	0.04	19.5	~25	~45
L0 Evaporator Strap at adaptor	T_L0_ESTR	0.04	10.5	~25	~35
L0 Evaporator Cryostat Clamp Interface	FPU EVAP Strap IF	0.18	unknown	~60	~60

Table 5-7 - Summary of sensors possible Self-Heating

In view of the correlation exercise with the mathematical thermal model, the following points should be kept in mind:

- Accurate absolute temperature is only required when correlating the 300-mK system parasitic load for a given L0 enclosure temperatures.

- As described in the next sections, most of the time, we are more interested in the relative accuracy rather than the absolute accuracy (i.e. pump characterisation and L0 interbox strap characterisation). This means that a constant error in the temperatures readings (such as calibration errors) would not compromise the correlation. Errors introduced by sensors self-heating however vary with temperature, meaning that the relative accuracy between two sensors would also vary with temperature, introducing some uncertainties in the correlation exercise.

- The cryostat L0 seems to be running at temperature slightly lower than 1.7K and possibly around 1.65K.

<u>Additional Observations:</u>

Gradient on SOB haven't change with respect to the first test campaign, which seems to indicate that the cryostat L1 temperature hasn't changed (despite the indication of the sensor on the cryostat L1 clamp interface).

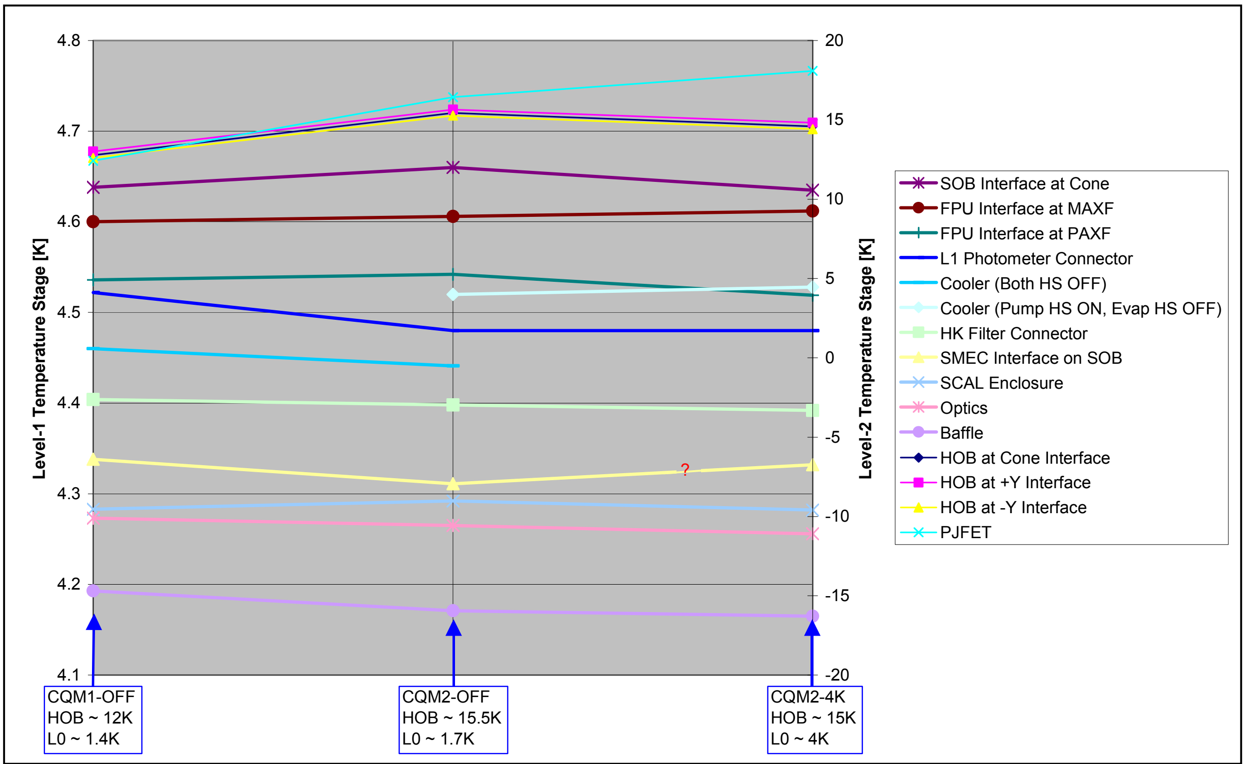

Figure 5.2.1-4 – Temperature Gradient on the SOB

5.2.2 Cooler Testing

5.2.2.1 Pump Performances Characterisation

5.2.2.1.1 Test Background

A pump characterisation test has been carried out to provide an indication of the cooler performance as well as a tool to estimate the total evaporator load when in operation at the sub-K temperature.

When the cooler is in operation, helium in the evaporator is being evaporated and absorbed by charcoal in the pump. This adsorption process releases heat and warms the pump up. The amount of heat released in the pump is proportional to the total load seen by the evaporator as described in Equation 2. The factor varies between 45 up to 50 depending on the amount of helium already contained in the pump [RD5].

$$Qads = [45\text{-}50] \times Qevap \qquad (2)$$

Where:

Qads Heat of Adsorption in mW
Qevap Total evaporator load in mW

By plotting the temperature of the Pump Tp versus a known applied load on the pump Qp (using the pump heater), the slope "m" of the resulting curve can then be used to predict the load on the pump for a given increase in pump temperature as described in Equation 3. The amount of load on the evaporator can be estimated using Equation 2.

$$Qp = (Tp - Tp0) \times m \qquad (3)$$

Where:

Tp0 No load pump temperature in K
Tp Temperature of pump for a given pump load Qp in K
Qp Load applied on the pump in mW
m Ratio of Pump Temperature Increase to Pump applied load in mW/K

A test has therefore been carried out during which the pump heater was set to a known power dissipation (from 15mW up to 75mW) and the temperature of the pump was recorded once stable. Figure 5.2.2-1 on next page describes the cooler set-up in normal operation. Figure 5.2.2-2 describes the cooler setup used during the pump characterisation testing. In this case, the evaporator had previously been discharged to ensure that the pump would not see any adsorption load due to the 300-mK system charge on the evaporator i.e. the increase in pump temperature would only be caused by the pump heater load.

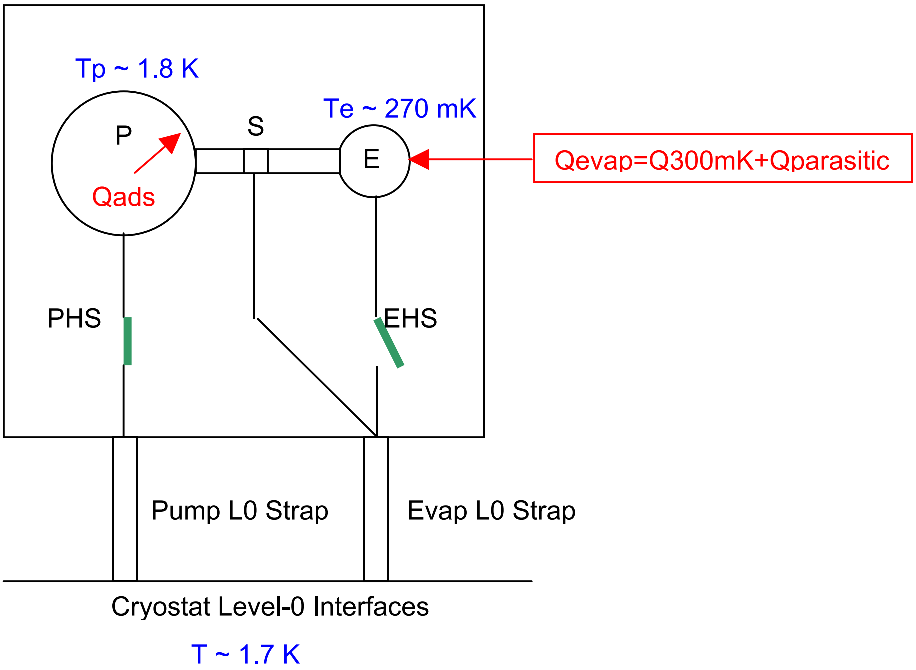

Figure 5.2.2-1 – Schematic of Cooler In Operation [Eq2]

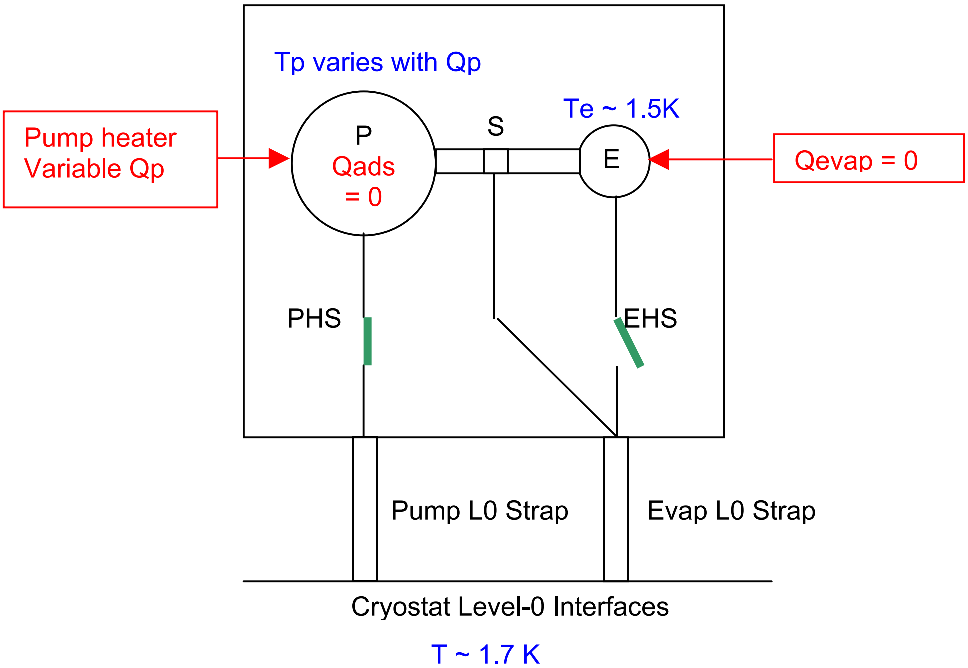

Figure 5.2.2-2 - Schematic of Test Set-up for Pump Characterisation [Eq3]

5.2.2.1.2 Test Results

Table 5-8 summarises the setup of the pump heater during the pump characterisation test.

Q Pump Tested	Command Sent	Calculated Current	Voltage from Housekeeping	Actual Q Pump	T Pump Recorded
[mW]	*[Hex]*	*[A]*	*[V]*	*[mW]*	*[K]*
0	0	-0.00002254	0	0	1.708
15	1F8	0.00610267	2.451	14.96	2.660
30	2C8	0.00863054	3.466	29.91	3.386
45	368	0.01057505	4.25	44.94	4.033
75	465	0.01364981	5.481	74.81	5.161

Table 5-8 – Pump Characterisation Test Heater Setup

Figure 5.2.2-3 on next page gives an overview of the pump temperature profile during the characterisation test. Although a test had initially been attempted with a pump heater power dissipation of 60mW, the manostat made the stabilisation of the L0 cryostat interface temperatures very difficult and it was therefore decided to carry on with a lower heater power dissipation.

Figure 5.2.2-4 on next page gives an overview of the cryostat L2 shield and Instrument FPU/SOB temperature profiles during the pump characterisation test. An overall FPU/SOB small increase in temperature (0.04K) has been observed when starting the test with the pump heater power dissipation set to 75mW, with the exception of the temperature sensor at the cryostat L1 interface which remained constant at all time. A reduction in the overall cryostat L2 stage temperature has been observed for the whole duration of the test, which can be explained by the important load applied to L0 Helium pot during the test, and therefore, an increased cryostat overall mass flow rate.

From these results, one can deduce the following information about the pump performances:

- The pump temperature when not subjected to any load or "no load" pump temperature Tp0,
- The pump temperature rate of change versus pump internal power dissipation [K/mW].

The "no load" pump temperature was measured for a given L0 Helium bath temperature and for a given set of L0 straps. Although the strap will not change during the test campaign, any change in the L0 bath temperature will offset the pump temperature with respect to the reference "no load" pump temperature. Although the L0 Helium Bath temperature isn't readily available, the temperature read out at the cryostat L0 clamp interface for the L0 evaporator strap can be used as an indication of the L0 bath temperature variations (see Figure 5.2.2-5 for more information on the location of the sensor).

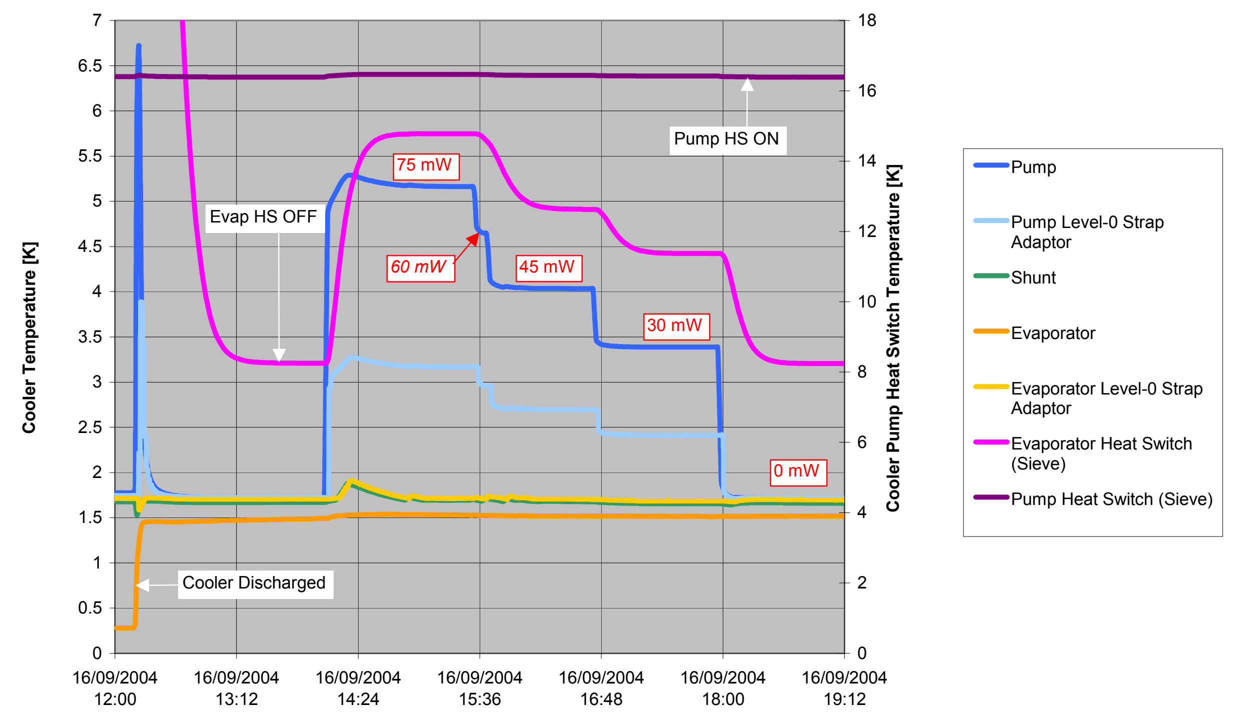

Figure 5.2.2-3 – Temperature Profiles during Pump Characterisation Test

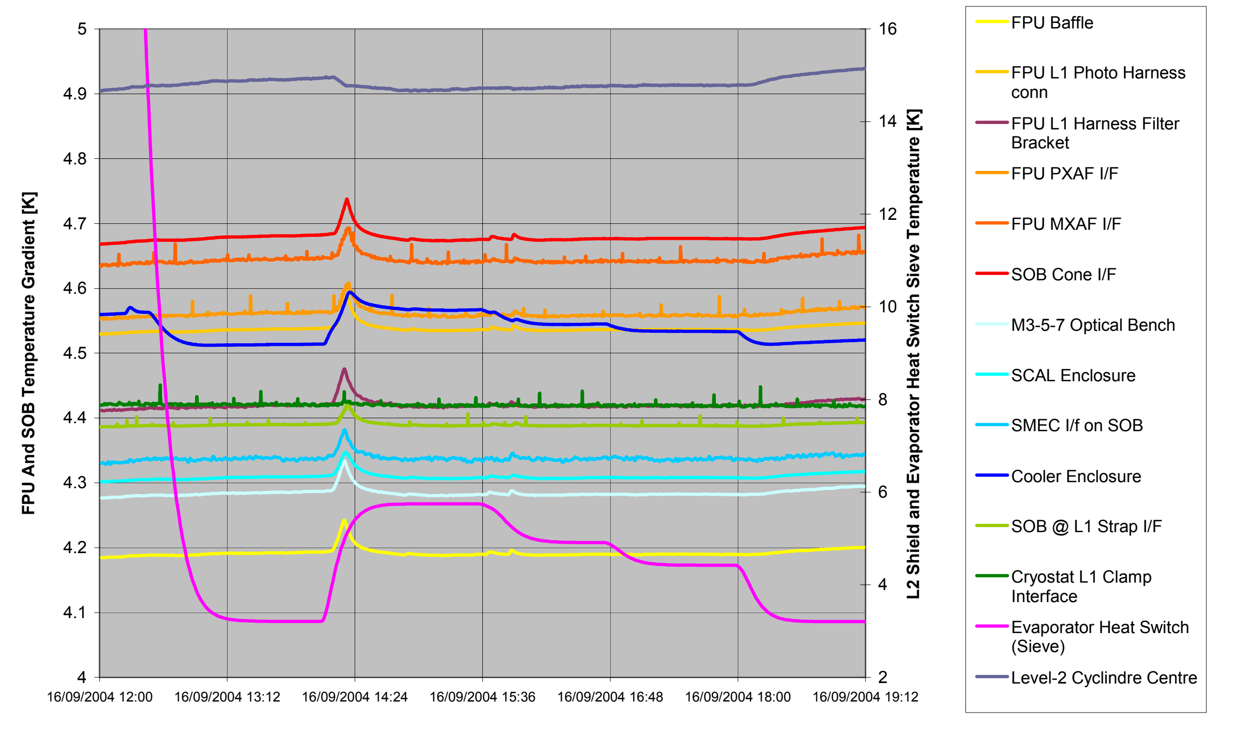

Figure 5.2.2-4 - Temperature Profiles during Pump Characterisation Test

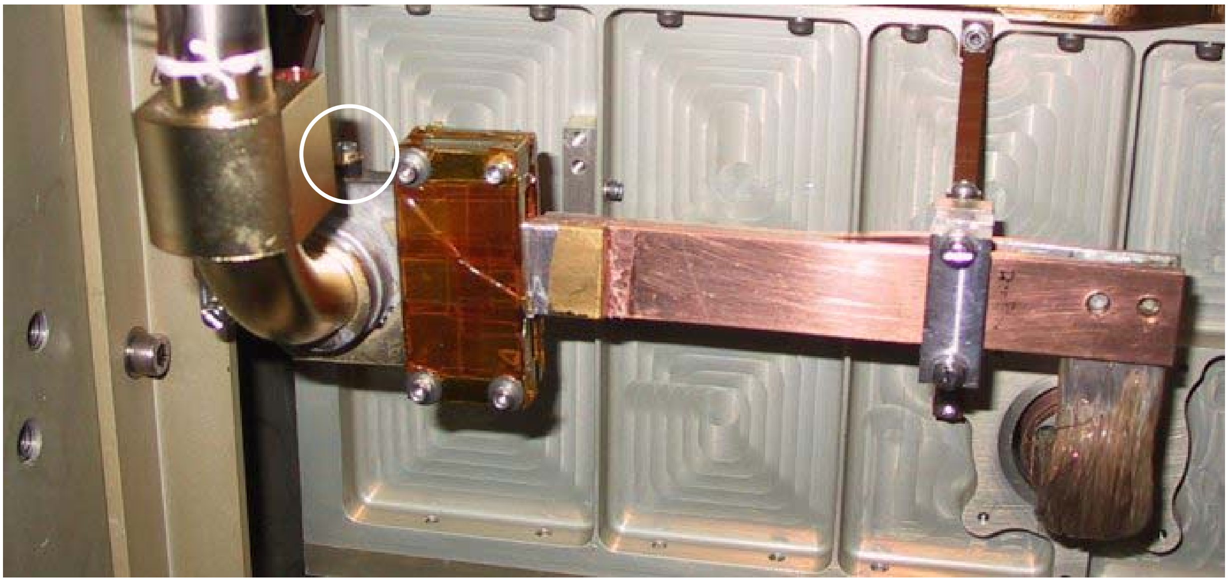

Figure 5.2.2-5 – Temperature sensor mounted on the Level-0 Cryostat Evaporator Clamp Interface

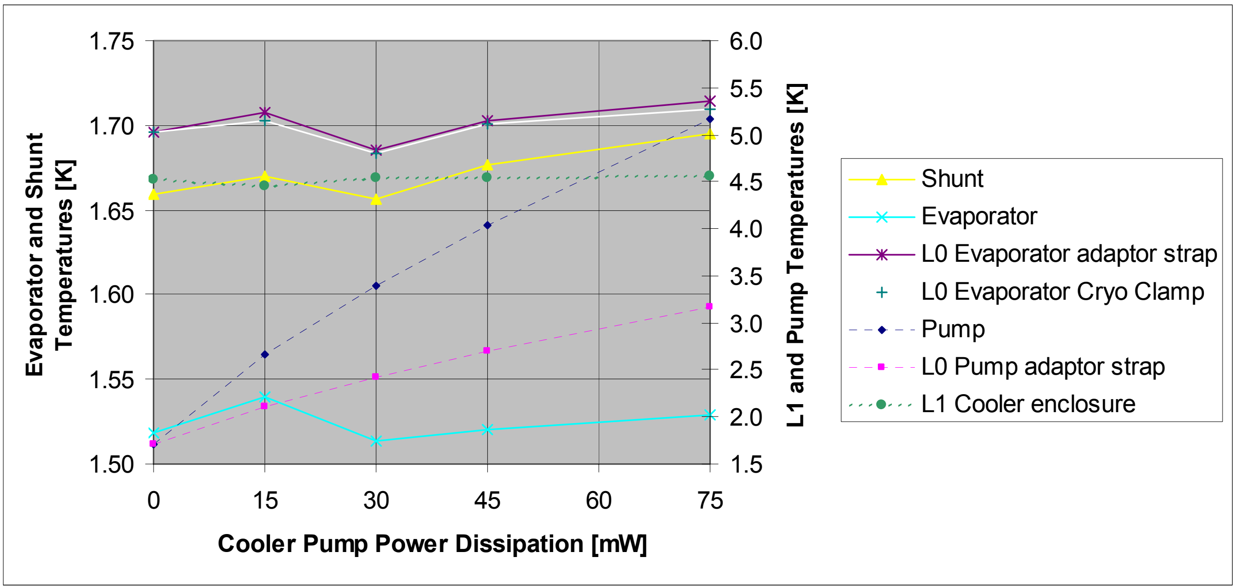

Figure 5.2.2-6 - Temperature Profiles during Pump Characterisation Test

Figure 5.2.2-6 provides a snapshot of the L0 stage temperature profiles during the pump characterisation test. It can be seen that the pump and its strap temperature increases as the power applied on the pump increases.

The others temperatures profiles (shunt, evaporator, evaporator strap and cryostat L0 evaporator clamp interface) provide an indication of the L0 bath temperature variations. This change in L0 bath temperature has been accounted for (as an offset) when calculating the pump temperature variation versus pump load, as described in Table 5-9.

5.2.2.1.3 Results Discussion

Q Pump Heater	Pump Increase In Temperature	L0 Bath Temperature Variation	Corrected Pump Delta T For Variation in L0 Bath
[mW]	*[K]*	*[K]*	*[K]*
Baseline: 0	0	0	0
14.96	0.952	0.007	0.944
29.91	1.678	-0.013	1.691
44.94	2.324	0.005	2.320
74.81	3.453	0.014	3.438

Table 5-9 – Pump Temperature Increase versus Pump Heater Power Dissipation

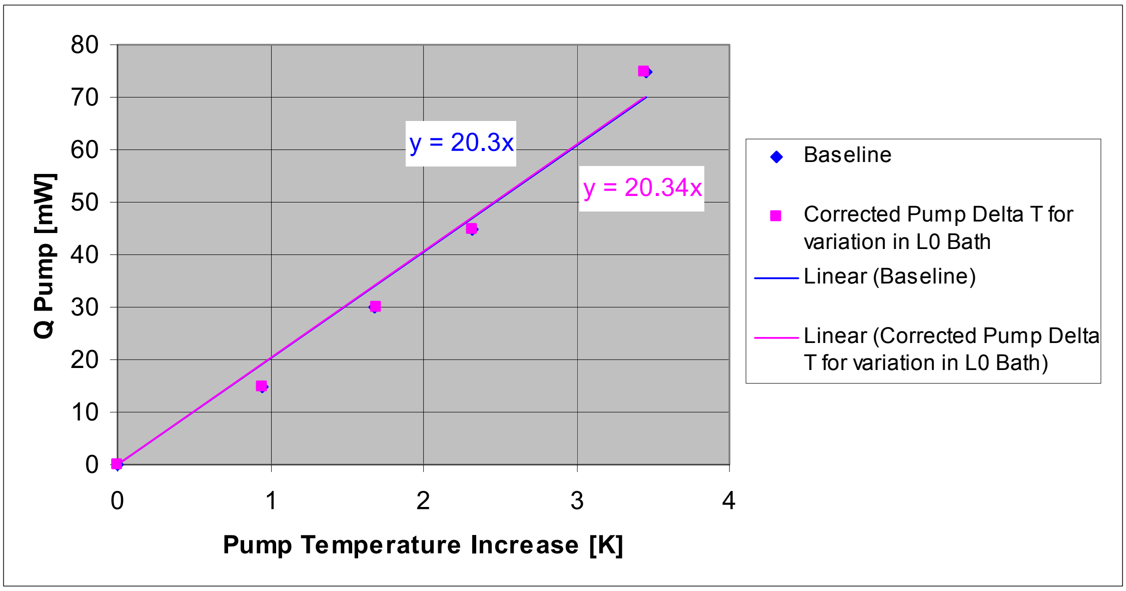

Figure 5.2.2-7 - Pump Temperature Increase versus Pump Heater Power Dissipation

From Figure 5.2.2-7, the following information can be deduced:

- The slope of the curve shows that for each 1K increase in pump temperature, the pump must be subjected to an internal power dissipation of 20.34 mW.
- The temperature of the pump when not subjected to any load or "no load pump temperature" Tp0 is 1.708K.

Equation 4 can then be used to predict the pump adsorption load as well as the evaporator total load:

$$Qads\ [mW] = (Tp\ [K] - 1.708) \times 20.34 \quad (4)$$

$$Qevap\_min\ [mW] = Qads\ [mW] / 50$$

$$Qevap\_max\ [mW] = Qads\ [mW] / 45$$

Because the temperature of the pump is the information that will be used to estimate the performance of the system, it is important to be aware of the possible source of errors, which may be present in the temperature sensor reading. Table 5-10 provides an insight of the estimated self-heating error that could be expected on the pump temperature sensor at a given temperature, as well as the error it would introduce in the estimation of the 300-mK parasitic load.

Cooler Pump Sensor	CX-1030	X14909

Pump Sensor Resistance at 1.8K		Sensor I/F Resistance[1]	Excitation Current[2]	Self-Heating Error[3]	Pump Power Error[4]	Evap Load Error Min[4]	Evap Load Error Max[4]
[ohms]		*[K/W]*	*[uA]*	*[mK]*	*[mW]*	*[uW]*	*[uW]*
3000	1.7	110000	3.33	3.7	0.075	1	2
3000	1.7	50000	3.33	1.7	0.034	1	1
2796	1.8	70000	3.58	2.5	0.051	1	1
2396	2.0	70000	4.17	2.9	0.059	1	1
1424	3.0	70000	7.02	4.9	0.100	2	2
1043	4.0	20000	9.59	1.9	0.039	1	1
843	5.0	10000	11.86	1.2	0.024	0	1

Table 5-10 – Pump Temperature Sensor Excitation Current and Self-Heating Error

Note1: The self-heating calculation performed at 1.7K uses the minimum and maximum sensor interface resistance measured and described in Figure 5.2.1-2.
The self-heating calculations for the others temperatures use values for sensor interface resistance recommended for CU packages by Lakeshore.

Note2: The flight electronics uses a 10mV voltage-controlled variable current source to drive the flight temperature sensors. No current reversal is available but it is assumed that the error introduced by the emf is constant over the 1.7K – 5K temperature range.

Note3: The sensor self-heating error can be estimated using Equation 1.

Note4: Based on Equation 4:

- Pump Load Estimation Error = Pump Temperature Self-heating Error x 20.34
- Evaporator Load Estimation Error Min = Pump Load Estimation Error / 50
- Evaporator Load Estimation Error Max = Pump Load Estimation Error / 45

Table 5-10 shows that the maximum variation in self-heating error between 1.7K and 5K is in the order of 5mK. This error is less than the sensor minimum resolution and has therefore been found acceptable.

5.2.2.2 Pump Heat Switch Performances Testing

The cooler heat switches actuation has been qualified with a heater power dissipation of 0.8 mW. When in operation, it is preferable to limit the heat being dissipated to the Herschel cryostat Level-0 stage and therefore it is anticipated that the power on the pump heat switch could be reduced to 0.4mW once actuated in ON mode and stable.

A test has been carried out to evaluate the impact that such a power reduction would have on the pump heat switch performance and as a result, on the cooler cold tip temperature. Figure 5.2.2-8 and Figure 5.2.2-9 provide an insight of the cooler performances once the power of the pump heat switch heater is reduced from 0.8mW to 0.4mW. It can be observed that following the reduction in power, the pump temperature increases from 1.78K to 2.21K and that the resulting increase in evaporator cold tip temperature is less than 1mK.

The pump characterisation test performed during the first CQM test campaign also gives an indication of the cooler cold tip temperature variation versus pump temperature variation, as described in Figure 4.2.2-4.

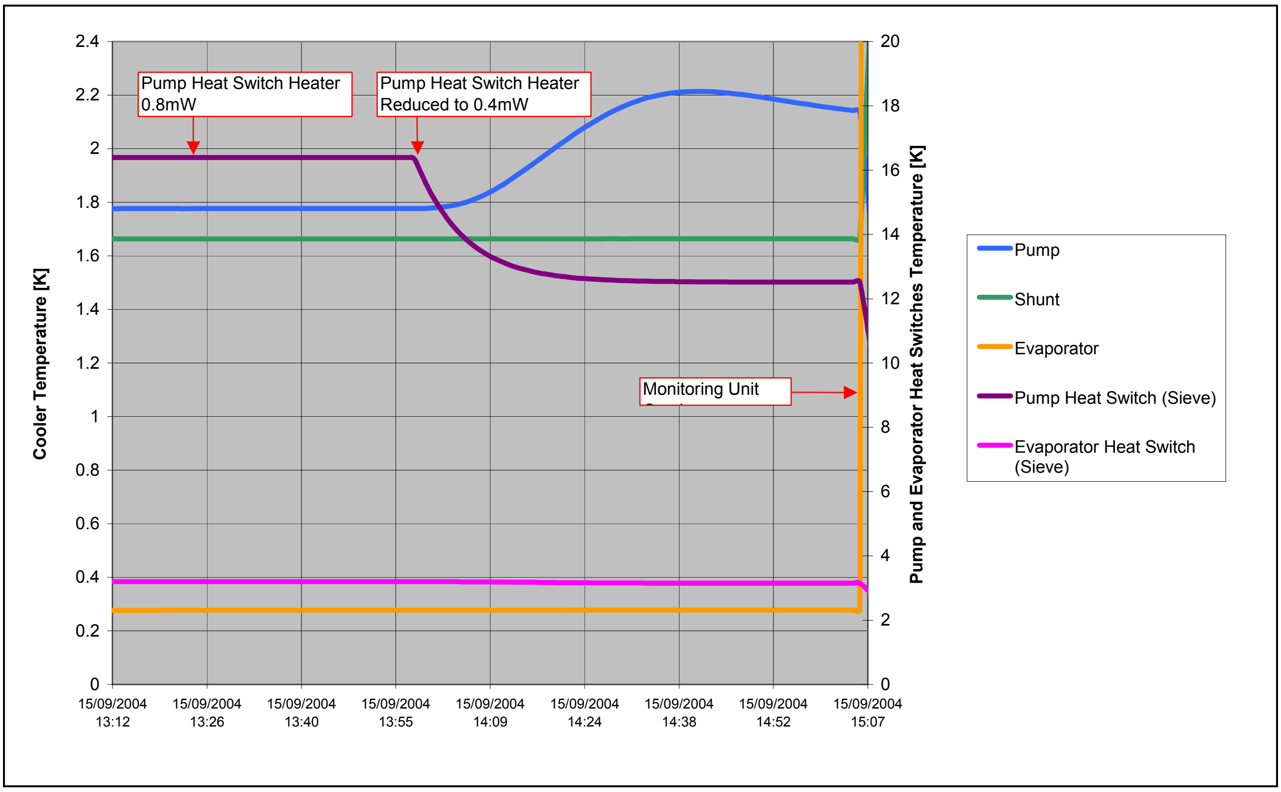

Figure 5.2.2-8 – Pump Heat Switch Operation Characterisation

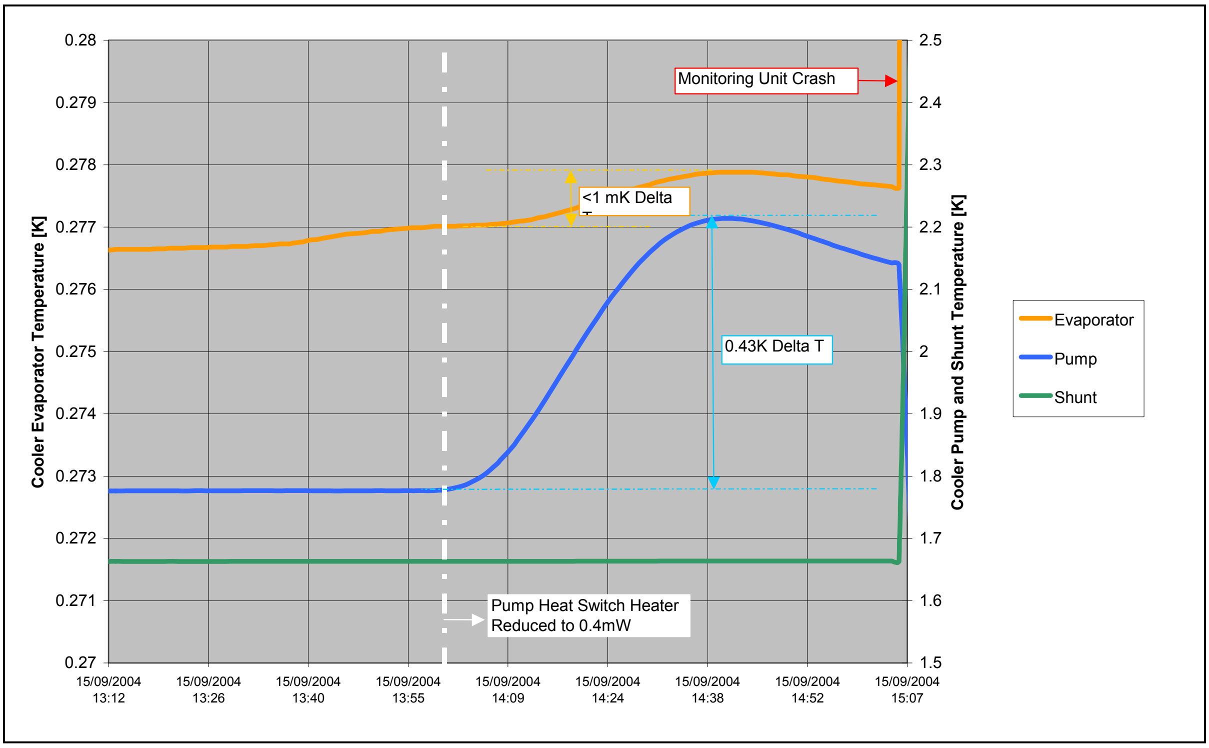

Figure 5.2.2-9 - Pump Heat Switch Operation Characterisation

5.2.2.3 Cooler Temperature Profiles in Recycling Mode

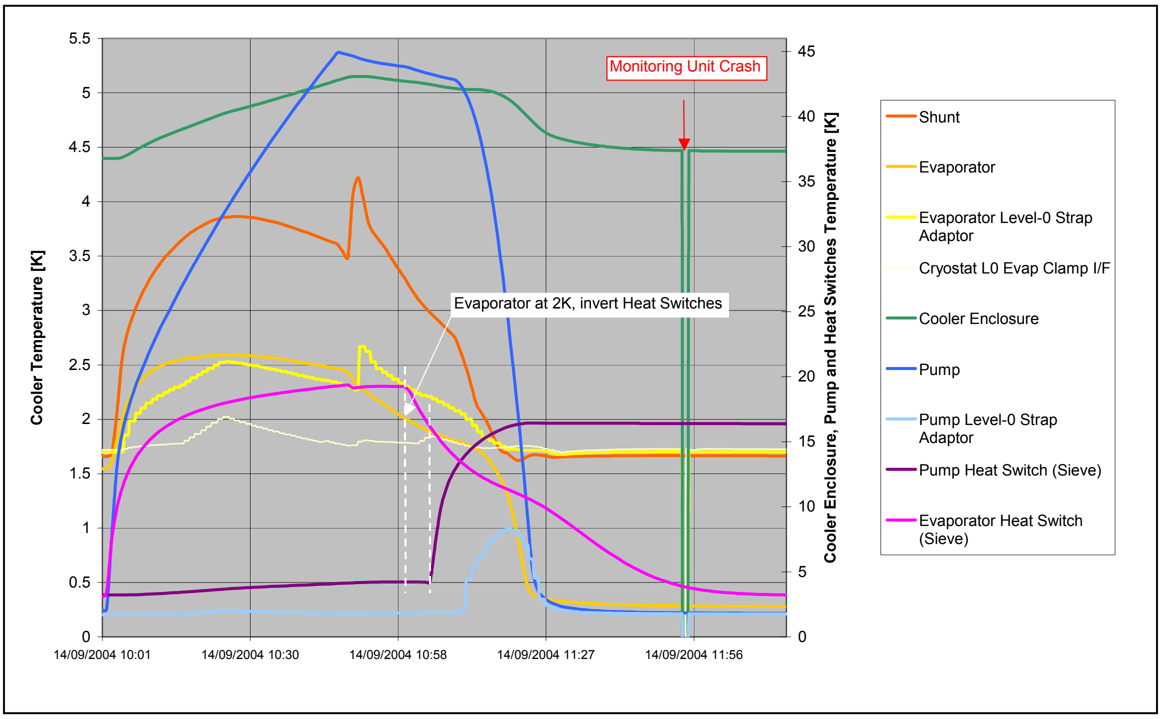

Figure 5.2.2-10 – Cooler Temperature Profile During Recycling

In order to have consistent data for the correlation of the thermal model, all cooler recyclings have been performed in a similar way and a script was written to help with the cooler operation. Identical criteria were used to drive the switching sequence of the heat switches, as described below:

- Reduce the pump heater power to 40mW as soon as the pump has reached 45K,
- Set the evaporator heat switch OFF as soon as the evaporator has reached 2K,
- Wait for the evaporator heat switch temperature to be below 16K to actuate the pump heat switch in ON mode.

5.2.3 Photometer JFET Thermal Characterisation

This test provided thermal data for the correlation of the F-harness, which connects the PJFET to the instrument FPU, as well as the JFET isolation supports. This test will help getting a better understanding of the implication the temperature of the JFET has on the instrument L1 load.

Because the load through the F-harness is expected to be small, it has been decided that the PJFET wouldn't be thermally connected to the cryostat shield. In this configuration, the PJFET chassis, which is, now isolated from the HOB and shield would warm up and produce larger temperature gradient between the chassis, the HOB and the FPU. This approach will greatly improve the accuracy with which the future correlation will be done.

For this test, the Photometer JFET was in OFF mode, meaning that its CQM PLW modules were turned OFF and were therefore dissipating no energy. The heaters on the STM modules have then been used to set the total power dissipation of the PJFET to 20 mW and finally 40 mW. The OFF mode thermal balance case provides the baseline for the 0mW power dissipation case.

Note1: There wasn't any 4-wire measurement that could be done during these tests to check the actual power dissipated within the module.

Note2: The Spectrometer JFET has been left in-operation and doesn't take part to this test.

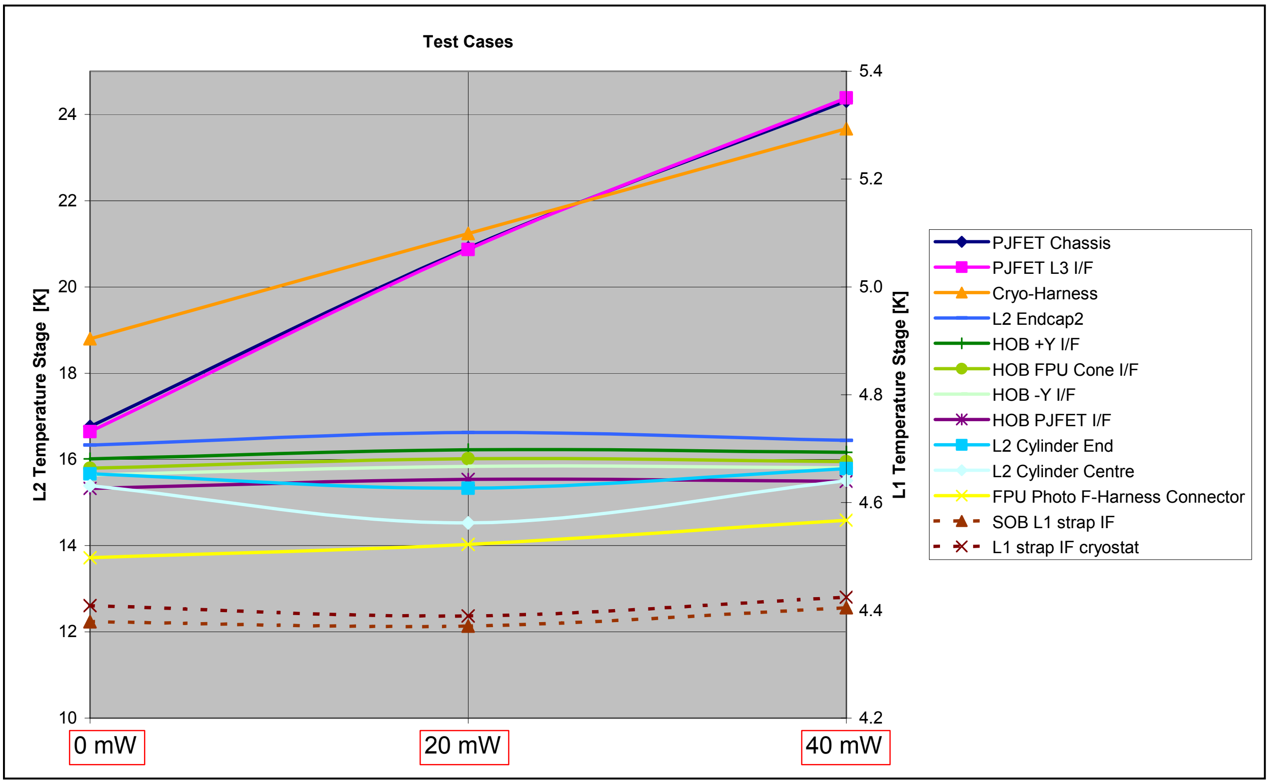

Figure 5.2.3-1 – Photometer JFET Temperature Profiles During Thermal Characterisation Test

Power Dissipation	***0 mW***	***20 mW***	***40mW***
Vss	***0***	***-1.5V***	***-3.157V***
Decimal	***0***	***77***	***161***
Hexadecimal	***0***	***4C***	***A1***
		Temperatures	
PJFET Chassis	16.76	20.90	24.31
PJFET L3 I/F	16.64	20.87	24.38
Cryo-Harness	18.79	21.24	23.67
FPU Photo F-Harness Connector	4.50	4.52	4.57
HOB PJFET I/F	15.33	15.54	15.49
HOB FPU Cone I/F	15.79	16.01	15.95
HOB +Y I/F	16.01	16.22	16.17
HOB -Y I/F	15.64	15.84	15.81
L2 Endcap2	16.33	16.62	16.44
L2 Cylinder Centre	15.39	14.53	15.51
L2 Cylinder End	15.67	15.33	15.79
SOB L1 strap IF	4.38	4.37	4.40
L1 strap IF cryostat	4.41	4.39	4.42

Table 5-11 – Photometer JFET Temperature Profiles During Thermal Characterisation Test

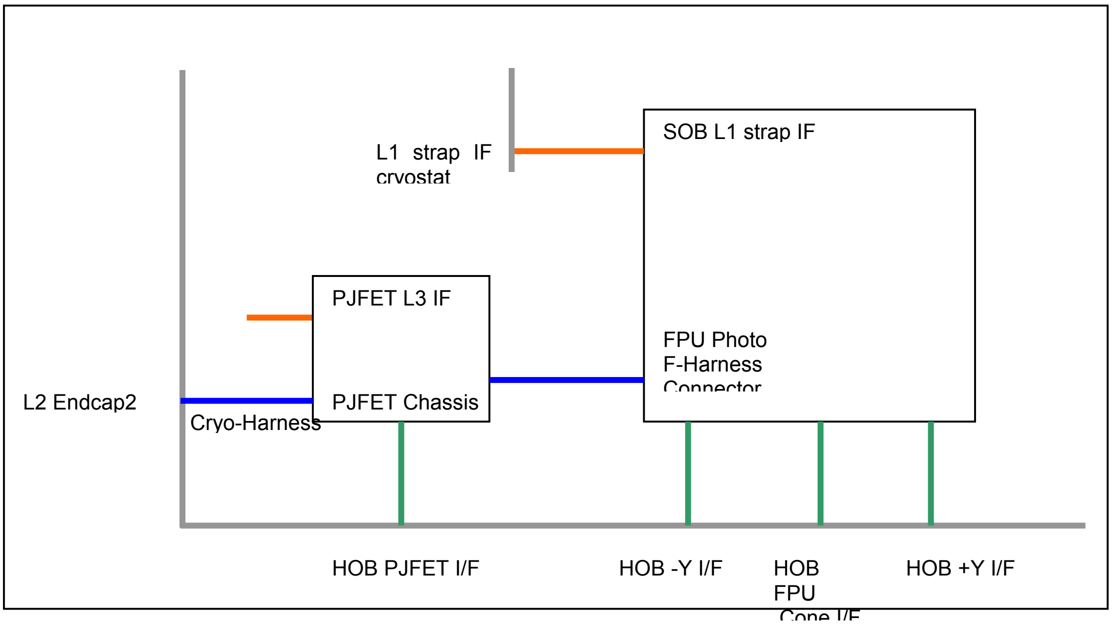

Figure 5.2.3-2 – Sensor Location Description

Harness
Thermal Straps
Isolating Supports

5.2.4 Level-0 Interbox Strap Characterisation

5.2.4.1 Test Background

Following the first test campaign, an improvement of the overall thermal conductance of the interbox strap was required. A temporary heater was fitted on the L0 photometer enclosure during the second test campaign that would help estimating the new interbox strap conductance. Figure 5.2.4-1 describes the setup used for this test.

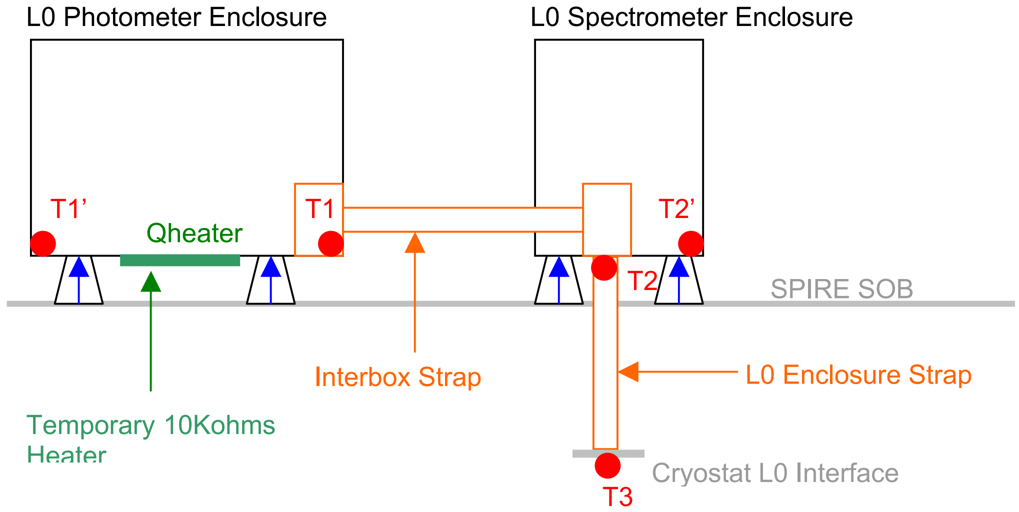

Figure 5.2.4-1 – Interbox Characterisation test setup

Temperature Sensor
Enclosure Parasitic Heat Load Qparasitic through supports and harnesses

Note: The heater was glued on Kapton tape which was then fitted on the photometer enclosure. This approach had the advantage that the heater could be removed at later stage.

The following calculations provide a first estimation of the interbox strap performances:

$$Q\_parasitic + Q\_heater = G\_interbox\_strap \times (T2' - T1)$$

Where:

Q_parasitic	Parasitic load going from the SOB into the photometer enclosure and flowing on the interbox strap,
Q_heater	Power being dissipated in the heater,
G_interbox_strap	Interbox strap overall conductance,
T1 and T2'	Temperatures described in Figure 5.2.4-1.

5.2.4.2 Test Results

Table 5-12 summarises the setup of the heater mounted on the L0 photometer enclosure during the interbox strap characterisation test.

Required Dissipation	Commanded Current	Measured Voltage	Actual Dissipated Power
[mW]	*[mA]*	*[V]*	*[mW]*
0	0	0	0
5	0.7	6.95	4.865
10	1	9.9	9.9

Table 5-12 – Heater Test Setup for L0 Enclosure Characterisation

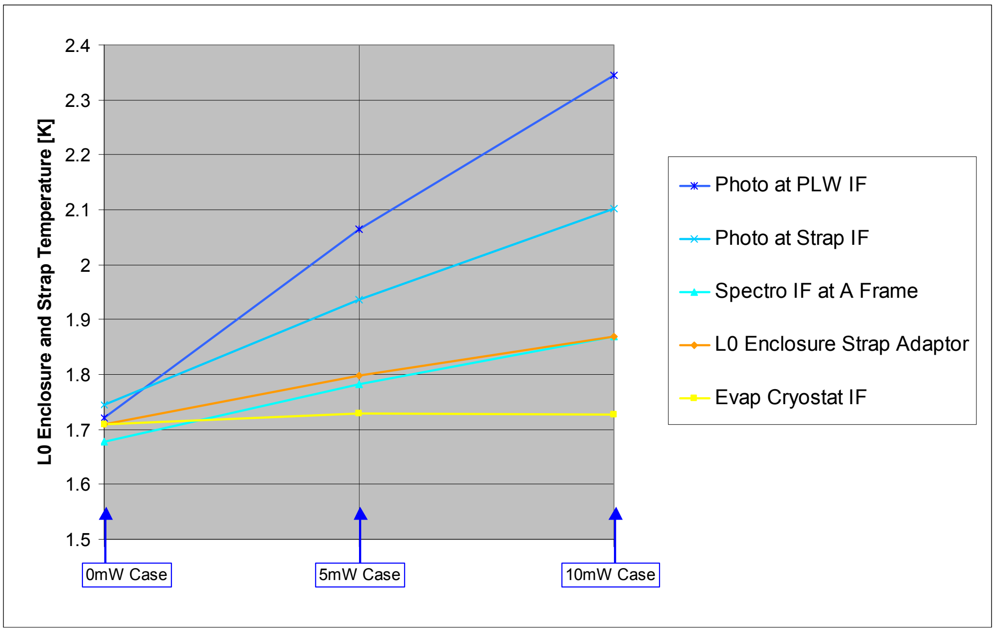

Figure 5.2.4-2 – Interbox L0 Strap Characterisation Test – Temperature Profile

Temperature Sensors	Figure 5.2.4-1	0 mW Case	5 mW Case	10mW Case
Evaporator Cryostat L0 IF	T3	1.7098	1.728	1.726
L0 Enclosure Strap Adaptor	T2	1.7098	1.798	1.87
Spectro IF at A Frame	T2’	1.677	1.782	1.87
Photo at Strap IF	T1	1.745	1.937	2.101
Photo at PLW IF	T1’	1.721	2.065	2.344

Table 5-13 - Interbox L0 Strap Characterisation Test – Results

5.2.4.3 Test Discussion

5.2.4.3.1 Thermal Performances of the L0 interbox strap

Figure 5.2.4-2 on previous page shows some discrepancies between the various temperatures readings on the L0 stage of the instrument. The 10mW test case has been used to estimate the thermal performances of the new interbox strap as:

- The gradient and heat flowing along the strap is larger, therefore providing more accurate data despite the errors observed on the temperature sensor readings,
- The error introduced by the sensor lead parasitic load should be lower as the L0 enclosures run warmer.

Because the sensor at the spectrometer strap interface wasn't working, the temperature from the second sensor on the spectrometer box has been used based on the assumptions that the gradient within the spectrometer box is relatively small.

Table 5-14 below describes the data used for the evaluation of the interbox strap conductance. The performance of the strap has then been estimated for various amount of the photometer parasitic load (through supports and F-harness) as described in Table 5-15.

L0 photometer Enclosure at Strap IF[7]	T1	2.074K
L0 Spectrometer L0 enclosure at A Frame IF	T2'	1.87K
Average Interbox strap Temperature	-	1.972K
Temperature Drop	-	0.204K
Heater Dissipated Power	-	9.9 mW

Table 5-14 – L0 Interbox Strap Characterisation Inputs

Qphoto_parasitic at 2K	G interbox	+/-10% Error on gradient Temperature readings
mW	W/K	W/K
0.5	0.051	0.0051
1.0	0.054	0.0054
1.5	0.056	0.0056
2.0	0.059	0.0059

Table 5-15 – L0 Interbox Strap Performance Predictions

From Table 5-15, one can make the following observations:

- Depending on the parasitic load that is flowing into the photometer enclosure at 2K, the interbox strap conductance has been estimated to be between 0.05W/K and 0.06W/K for an average strap temperature of 1.97K.
- A +/-10% error can be applied on those predictions to account for the possible error on the temperature readings.

[7] The temperature reading has been corrected with the predicted self-heating error. This represents the worst-case scenario as the self-heating of the sensor would be less at 2K than as measured at 1.7K.

- A 0.055W/K overall conductance has been predicted in this configuration but for a strap average temperature of 1.7K.
- The correlation with the thermal model will confirm the amount of parasitic load that was flowing along the strap at the time of the test and the actual strap performance will therefore be known.

5.2.4.3.2 300-mK Stage Thermal Performances

The L0 interbox strap characterisation test also provided an interesting set of data that helped to gain a better understanding of the 300-mK system parasitic load for a given L0 enclosures temperatures. The following inputs have been used for this preliminary analysis:

Pump Temperature for no Load [K]	1.708
L0 Cryostat Evaporator IF Reference Temperature [K]	1.720
Pump Characterisation Slope [mW/K]	20.34
Cooler Adsorption Heat Factor	45-50

Table 5-16 – Inputs to 300-mK Subsystem Performances Analysis

Table 5-17 below, Figure 5.2.4-3 and Figure 5.2.4-4 on next pages describes the temperature and estimated heat load profiles for the 300mK subsystem for different L0 enclosure temperatures.

L0 Photometer Enclosure Heater Dissipation [mW]	0	5	10
L0 Cryostat Evaporator IF Temperature [K]	1.728	1.727	1.727
L0 Bath Temperature Variation wrt to reference Temperature [K]	-0.015	-0.017	-0.016
T pump [K]	1.766	1.781	1.797
T pump [K] - Correction for He L0 Bath Variation	1.758	1.774	1.790
Delta T [K]	0.058	0.072	0.089
Estimated Pump Load [mW]	1.180	1.468	1.809
Max Total Evaporator Load [uW] – Factor 45	26	33	40
Min Total Evaporator Load [uW] – Factor 50	24	29	36
L0 Photometer Enclosure Temperature at Strap IF [K]	1.764	1.938	2.101
Evaporator Temperature [mK]	277	282	286
PLW Detector Temperature [mK]	310	330	350
Temperature Drop along 300-mK Busbar [mK]	33	45	64

Table 5-17 – Analysis of the 300-mK Subsystem Thermal Performances

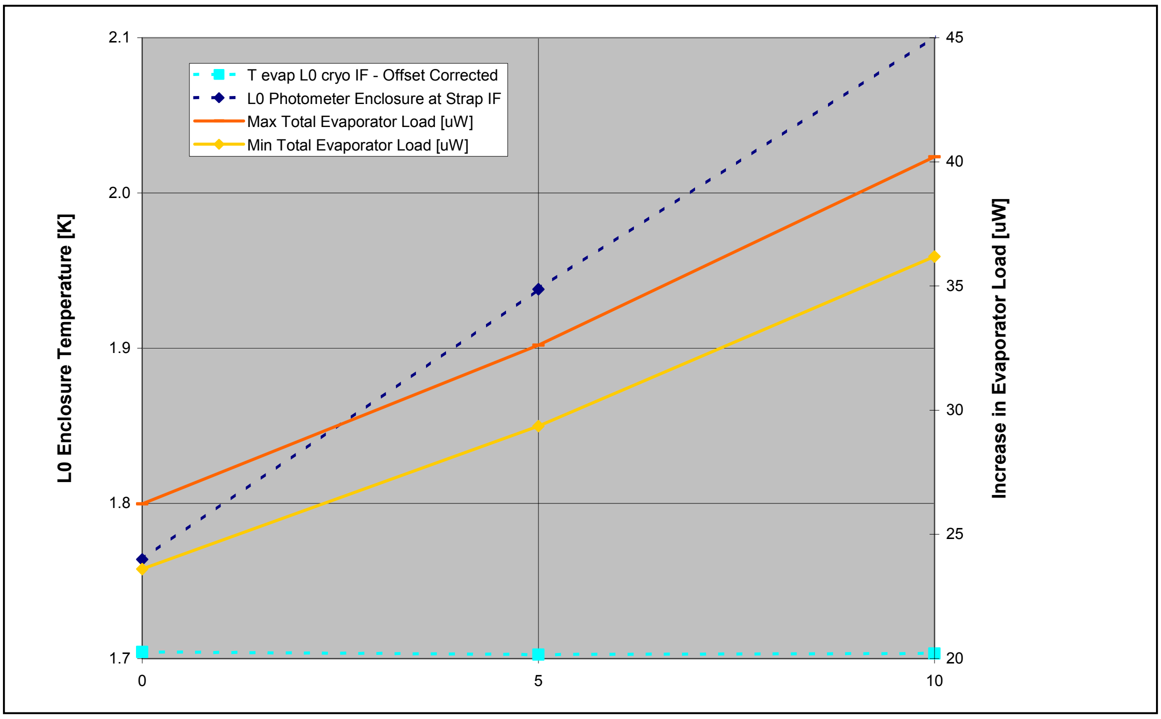

Figure 5.2.4-3 - Analysis of the 300-mK Subsystem Thermal Performances

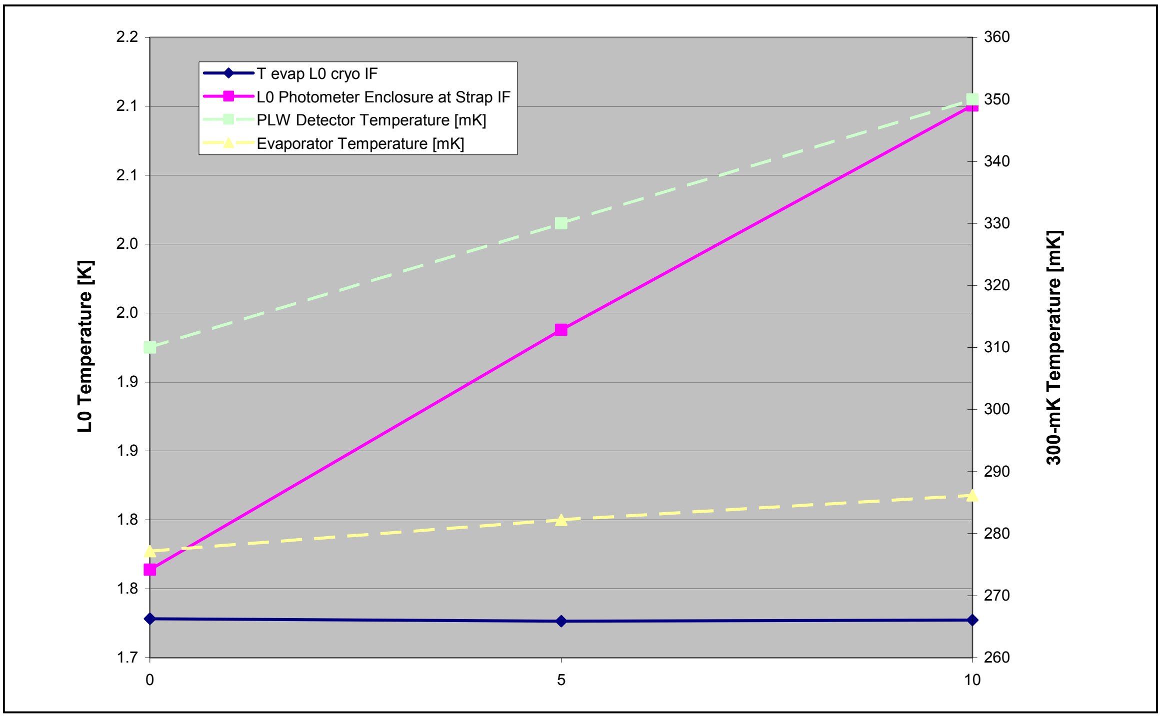

Figure 5.2.4-4 - Analysis of the 300-mK Subsystem Thermal Performances

As the heater dissipation on the L0 photometer enclosure increases, the L0 enclosure temperatures increase as well. An AC load curve has been performed for each case to obtain the temperature of the PLW BDA detector. The pump temperature has then been use to obtain an initial estimation of the total load on the evaporator cold tip as the L0 enclosure temperatures increase. From Figure 5.2.4-3 and Figure 5.2.4-4, the following initial observations can be made:

- For a L0 enclosure temperature close to 1.75K, the total estimated load on the cooler cold tip ranges between 24-26 uW,
- For a L0 enclosure temperature close to 1.9K, the total estimated load on the cooler cold tip ranges between 29-33 uW,
- For a L0 enclosure temperature close to 2.1K, the total estimated load on the cooler cold tip ranges between 36-40 uW.

As the L0 enclosure temperatures increase, one can see that, as a result of the increase in parasitic load flowing along the 300-mK strap:

- The cold tip temperature increases from 277mK to 286mK,
- The temperature drop along the 300-mK Busbar increases from 33mK to 64mK.

This test confirms again that the current performances of the 300-mK Busbar isn't satisfactory and that it needs improving in order to reduce the temperature drop to a maximum of 10mK.

5.2.5 Thermal Balance Test Cases

The thermal balance test cases have been defined to provide a set of temperatures that will be used to correlate the thermal mathematical model against the real thermal performances of the instrument as well as to validate the thermal design of the instrument.

Three cases have been carried out:

- An OFF mode during which the instrument is non-operating and the cooler has been discharged. This mode is important as it represents the load the instrument will apply on the Herschel cryostat for the 2/3 of the mission [AD9],

- Photometer Mode – Cold Case: This mode represents the instrument power dissipation when in photometer mode; with a Cryostat L0 interface temperature at 1.7K [AD9].

- Photometer Mode – Hot Case: This mode represents the instrument power dissipation when in photometer mode; with a Cryostat L0 interface temperature at 2K [AD9].

For all cases, the following applies:

- The temperature rate of changes are compliant with the steady-state criterion defined in AD5,

- All temperatures are within the expected range of temperatures. The only exception is for the PLW BDA detector temperature, which confirms the need for an improvement of the 300-mK Busbar overall thermal conductance.

In addition for both photometer cases (cold and hot), an insight about the instrument overall performances in terms of cooler cold tip temperature and hold time has been obtained. The cooler had initially been recycled as described in section 5.2.2.3 with a cryostat L0 interface temperature at 1.7K in both cases. The L0 cryostat interface temperature has then been increased to 2K for the hot photometer case. The advantage that this approach offers is that the amount of helium available in the evaporator at the beginning of each operation period should be similar. The difference in measured hold time for both cases is therefore only caused by the variation of in average load on the evaporator cold tip during operation.

5.2.5.1 OFF mode

	Name	Rate of change [*]	Temperature
	-	mK/hr	K
300mK	PLW Detector Temperature	n/a	n/a
L0	Evaporator	-0.301	1.517
	Evap HS	-0.898	3.079
	L0 Evaporator adaptor strap	-0.298	1.686
	L0 Evaporator at Cryostat IF	-0.293	1.710
	Shunt	-0.278	1.650
	Pump	3.009	2.048
	Pump HS	-0.979	3.248
	L0 Pump adaptor strap	-0.338	1.692
	L0 photometer Enc at PLW IF	-0.330	1.748
	L0 photometer Enc at strap IF	-0.327	1.724
	L0spectrometer Enc at A-f IF	-0.301	1.680
	L0 detector Enc strap adaptor	-0.313	1.712
L1	L1 Cooler enclosure	-1.554	4.455
	L1 photo conn harness	-1.971	4.497
	L1 HK filter harness	-1.916	4.414
	SOB L1 strap IF	-1.130	4.379
	Cryostat L1 Strap IF	1.366	4.409
	T_FPU_PXAF	-2.076	4.560
	T_FPU_MXAF	-2.464	4.629
	T_SOB_CONE	-2.644	4.684
	T_SUB_1	-1.893	4.282
	T_BAF_1	-1.767	4.187
	T_BSMS_1	-1.537	4.033
	T_SCST_1	-1.649	4.306
	T_SCL4_1	-1.862	4.557
	T_SCL2_1	-2.224	4.557
	T_BSMM_1	n/a	n/a
	T_FTSM_1	-1.691	4.463
	T_FTSS_1	-1.513	4.322
L2/L3	T_PJFS_CHAS	-38.585	16.762
	T_SJFS_CHAS	-40.232	15.682
	L2 Cylinder End [L3 strap of SJFET]	-42.727	15.666
	Cylinder Centre	-39.944	15.392
	Cylinder End Cap [Cryo-harness Heat Sink]	-41.422	16.333
	FSJFP L3 I/F (L3 strap side)	-39.540	16.641
	FSJFS L3 I/F (L3 strap side)	n/a	n/a
	FSJFP-HOB I/F (HOB side)	-42.124	15.329
	FPU Cone Foot I/F (HOB side)	-40.082	15.794
	FPU +Y Foot I/F (HOB side)	-39.861	16.009
	FPU -Y Foot I/F (HOB side)	-40.967	15.640
	FSJFS-HOB I/F (HOB side)	-40.548	15.407
	Harness Sink WE-Ph JFET(L2 Shield Side)	-39.568	18.795

[*] Achieved over a 9 hours period.

5.2.5.2 Photometer Mode – Cold Case

	Name	Rate of change [*]	Temperature
	-	mK/hr	K
300mK	PLW Detector Temperature	n/a	n/a
L0	Evaporator	-0.118	0.279
	Evap HS	-0.791	3.201
	L0 Evaporator adaptor strap	-0.067	1.700
	L0 Evaporator at Cryostat IF	-0.070	1.725
	Shunt	-0.066	1.663
	Pump	-0.151	1.778
	Pump HS	0.125	16.391
	L0 Pump adaptor strap	-0.169	1.744
	L0 photometer Enc at PLW IF	-0.156	1.739
	L0 photometer Enc at strap IF	-0.147	1.763
	L0spectrometer Enc at A-f IF	-0.119	1.694
	L0 detector Enc strap adaptor	-0.111	1.728
L1	L1 Cooler enclosure	-1.507	4.514
	L1 photo conn harness	-1.845	4.534
	L1 HK filter harness	-1.619	4.426
	SOB L1 strap IF	-0.995	4.388
	Cryostat L1 Strap IF	-0.250	4.414
	T_FPU_PXAF	-1.837	4.568
	T_FPU_MXAF	-2.004	4.649
	T_SOB_CONE	-2.273	4.689
	T_SUB_1	-7.912	4.291
	T_BAF_1	-1.596	4.197
	T_BSMS_1	-1.345	4.041
	T_SCST_1	-1.543	4.313
	T_SCL4_1	-1.375	4.568
	T_SCL2_1	-1.613	4.568
	T_BSMM_1	n/a	n/a
	T_FTSM_1	-1.545	4.476
	T_FTSS_1	-1.461	4.341
L2/L3	T_PJFS_CHAS	-38.512	22.555
	T_SJFS_CHAS	-31.479	15.508
	L2 Cylinder End [L3 strap of SJFET]	-116.915	16.133
	Cylinder Centre	-31.711	15.198
	Cylinder End Cap [Cryo-harness Heat Sink]	53.188	15.460
	FSJFP L3 I/F (L3 strap side)	-39.536	22.552
	FSJFS L3 I/F (L3 strap side)	n/a	n/a
	FSJFP-HOB I/F (HOB side)	-32.996	15.172
	FPU Cone Foot I/F (HOB side)	-31.687	15.645
	FPU +Y Foot I/F (HOB side)	-31.334	15.864
	FPU -Y Foot I/F (HOB side)	-32.794	15.492
	FSJFS-HOB I/F (HOB side)	-31.796	15.261
	Harness Sink WE-Ph JFET(L2 Shield Side)	-45.278	22.482

[*] Achieved over a 8 hours period.

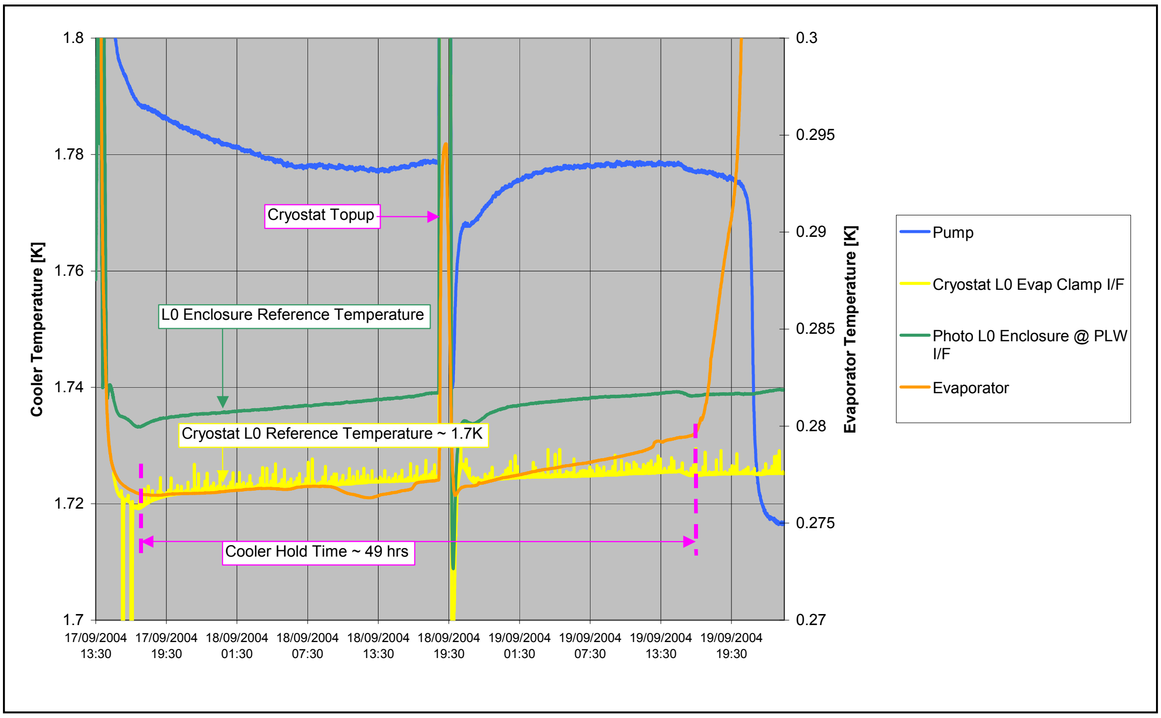

Figure 5.2.5-1 – Photometer Cold Thermal Balance Test

The cooler hold time has been measured to be about 49 hrs in photometer mode with a L0 cryostat interface temperature of 1.7K.

5.2.5.3 Photometer Mode – Hot Case

	Name	Rate of change [*]	Temperature
	-	mK/hr	K
300mK	PLW Detector Temperature	n/a	n/a
L0	Evaporator	-0.128	0.285
	Evap HS	-0.672	3.272
	L0 Evaporator adaptor strap	-0.138	1.931
	L0 Evaporator at Cryostat IF	0.010	1.956
	Shunt	-0.055	1.882
	Pump	0.125	2.008
	Pump HS	-0.375	16.402
	L0 Pump adaptor strap	-0.103	1.958
	L0 photometer Enc at PLW IF	-0.175	1.936
	L0 photometer Enc at strap IF	-0.283	1.982
	L0spectrometer Enc at A-f IF	-0.117	1.898
	L0 detector Enc strap adaptor	-0.062	1.952
L1	L1 Cooler enclosure	-1.231	4.516
	L1 photo conn harness	-1.550	4.534
	L1 HK filter harness	-1.270	4.429
	SOB L1 strap IF	-0.780	4.388
	Cryostat L1 Strap IF	-1.748	4.417
	T_FPU_PXAF	-1.537	4.554
	T_FPU_MXAF	-1.950	4.666
	T_SOB_CONE	-1.875	4.691
	T_SUB_1	-1.427	4.295
	T_BAF_1	-1.187	4.199
	T_BSMS_1	-1.265	4.044
	T_SCST_1	-1.265	4.315
	T_SCL4_1	-1.750	4.577
	T_SCL2_1	-0.850	4.575
	T_BSMM_1	n/a	n/a
	T_FTSM_1	-1.337	4.480
	T_FTSS_1	0.700	4.348
L2/L3	T_PJFS_CHAS	-34.475	22.521
	T_SJFS_CHAS	-26.050	15.575
	L2 Cylinder End [L3 strap of SJFET]	-23.725	15.518
	Cylinder Centre	-22.154	15.250
	Cylinder End Cap [Cryo-harness Heat Sink]	-24.350	16.193
	FSJFP L3 I/F (L3 strap side)	-35.200	22.519
	FSJFS L3 I/F (L3 strap side)	n/a	n/a
	FSJFP-HOB I/F (HOB side)	-26.022	15.240
	FPU Cone Foot I/F (HOB side)	-25.262	15.714
	FPU +Y Foot I/F (HOB side)	-25.400	15.928
	FPU -Y Foot I/F (HOB side)	-26.413	15.560
	FSJFS-HOB I/F (HOB side)	-26.137	15.329
	Harness Sink WE-Ph JFET(L2 Shield Side)	-43.817	22.449

[*] Achieved over a 4 hours period

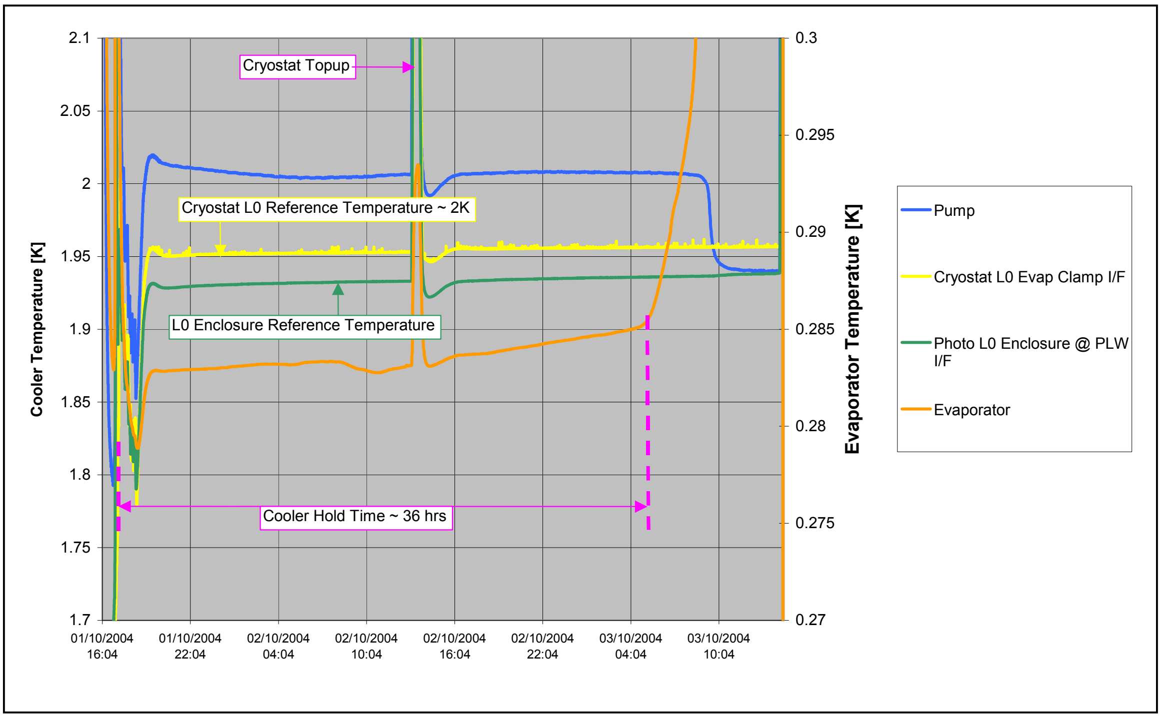

Figure 5.2.5-2 - Photometer Cold Thermal Balance Test

The cooler hold time has been measured to be about 36 hrs in photometer mode with a L0 cryostat interface temperature of 2K.

Note: Some EGSE temperatures sensors were disconnected from the 370 AC Bridge and connected back to a 218 Lakeshore Unit. The applicable sensors are defined below [AD11]:

- T_L0_PSTR sensor mounted at the pump L0 strap adaptor,
- T_FPU_PAXF sensor mounted at the A-frame interface on the FPU,
- T_FPU_MAXF sensor mounted at the A-frame interface on the FPU,
- T_SOB_L1STR sensor mounted at the L1 strap interface on the SOB.

5.3 Conclusion

5.3.1 SPIRE CQM2 Thermal Performances Overview

The following general performances have been obtained with SPIRE during the CQM2 test campaign:

Nominal Interface temperatures	
L2 HOB and Shroud	15K
L1 Cryostat Interface	4.12K
L0 Cryostat Interface	~1.7K
Overall instrument temperatures	
SOB temperature Range	4.3-4.5K
L0 photometer enclosure	<1.75K
L0 spectrometer enclosure	<1.75K
Evaporator Cold tip	277mK
PLW BDA Temperature	310 mK

Table 5-18 – SPIRE Overall Performances during CQM1 Test Campaign

One can notice that despite the fact that the L2 temperature stage was running warmer for this test (as to optimise the cryostat hold time), the L1 temperature stage remained unchanged. Therefore no correlation between the variations in the L1 stage temperature and the SPIRE Level-1 loads can be made.

5.3.1.1 Cooler and 300-mK System Performances Observations

The cooler ran again very well and with five detectors connected this time (one flight like and four STM).

- Its evaporator cold tip was seating at 277mK and a 49 hrs hold time has been experienced for a L0 cryostat interface temperature running at ~1.7K,
- Its evaporator cold tip was seating at 285mK and a 36 hrs hold time has been experienced for a L0 cryostat interface temperature running at ~2K,
- There was no time to re-design the Busbar between the first and second test campaign, therefore the temperature drop remains unsatisfactory and ranges between 30mK and 60mK depending on the L0 cryostat interface temperature,
- A local warn up of 0.7K at the cooler enclosure has been measured when the pump heater is turned ON,
- The evaporator heat switch still takes up to an hour to switch ON,
- Sieve temperature increased up to 20K in some instance. Future analysis will have to check what would be the impact of this radiation load on the cooler components.

- Some temperature drift has also been observed at the evaporator cold tip. The impact of such a drift need to be analysed in more detailed and will be used as an inputs for the PTC control algorithm.

5.3.1.2 L0 Enclosures Observations

During the first thermal balance test campaign, significant temperature drops were observed at the interfaces between the L0 enclosures, the interbox strap and the L0 enclosure strap. These straps interfaces have been reviewed and changed for larger glued area that should help reducing the resistance of the electrically isolating joints. The strap cross section has also been increase by a factor 3 and a 5 nines purity copper has been used for the interbox strap.

Following this change, the following improvement in performances has been measured:

- The maximum temperature drop between the photometer and the spectrometer L0 enclosures is about 0.044K (when measured between the two enclosure flight sensors) versus 0.24K in the first test campaign, representing a factor 5.45 improvement of the interbox strap conductance.

5.3.2 SPIRE CQM2 – Recommendations for PFM Test Campaign

Temperature sensors on the cryostat interfaces have again been found defective, despite the rewiring of some of the non-working sensors already found during the first test campaign. Those sensors are very important for the correlation exercise and more work is required in this area.

The use of the AC bridge to monitore the EGSE sensors has been a great improvement. However, sensor self-heating still appear to take place in some places, indicating that more work is required to ensure that the leads of all sensors at the Level-0 stage mainly, will be heat sunk as appropriate in future test campaigns.

The use of a temporary heater on L0 photometer enclosure has proven to be really successful and if possible, should be implemented again for the FPM test campaigns.

Appendix A

Converting data logged with the Lakeshore 218 unit:

- Set Excel to calculate dates using the 1904-year baseline,
- Use the following expression to obtain the correct date and time: timestamp / (24*3600)
- Use Cernox and TVO calibration curves and check that the resistance readings remain within the range of calibration.

Converting data logged with the instrument on-board software:

- Convert raw data to signed data (if count>32767, then count = count-65536 else count = count),
- Use signed data sheet as input to the Matlab subroutine,
- Use calib03.xls spreadsheet as a calibration curves input (file must be present in folder),
- Interpolate data,
- Set Excel to calculate dates using the 1904-year baseline,
- Use the following expression to obtain the correct date and time: (timestamp / (24*3600))+19724.

Appendix B

R heater = 402 ohms applicable to both heat switches heater and the sorption pump heater.

Sorption Pump Heater control

Current Command = (Ia + 2.254x10-5) / 1.21532x10-5

Sorption Pump HS Heater control

Current Command = (Ia + 2.05x10-6) / 3.9353x10-7

Sorption Evaporator HS Heater control

Current Command = (Ia + 2.44x10-6) / 3.9357x10-7

Appendix C – CQM1 Temperature Predictions [AD10]

SPIRE Cooler TEMPERATURES

Evaporator Cold Tip	0.280 K

SPIRE DETECTORS TEMPERATURES

photo_LW_detector1 2750	0.311 K
photo_LW_Feedhorn	0.301 K
photo_LW_Strap	0.300 K
Internal T drop	0.011 K
photo_MW_detector2 2850	1.983 K
photo_SW_detector3 2950	2.052 K
spect_LW_detector1 3750	1.764 K
spect_SW_detector2 3850	1.764 K

SPIRE BUSBAR TEMPERATURES

cooler_photo_strap_flang	0.284 K
photo_busbar_feedthru	0.285 K
photo_busbar_cold	0.286 K
photo_busbar	0.288 K
photo_busbar	0.288 K
photo_busbar	0.291 K
photo_busbar_warm	0.291 K
Busbar T drop	0.020 K

SPIRE L0 ENCLOSURES TEMPERATURES

photo_L0_box_px[2400]	1.914 K
photo_L0_box_mid[2410]	1.966 K
photo_L0_box_mx[2420]	2.024 K
spect_L0_box_px[3400]	1.765 K
spect_L0_box_mx[3410]	1.749 K

SPIRE COOLER TEMPERATURES

Cooler L1	4.314 K
Cooler Pump	1.832 K
HS Pump Cold	1.808 K
HS Pump Base	1.726 K
Cooler Shunt	1.704 K
Cooler Evaporator	0.280 K
HS Evap Cold	0.280 K
HS Evap Base	1.704 K

SPIRE MECHANISM TEMPERATURES

photo_calibrator	4.749 K and QI =	0.033 mW
photo_bsm	4.745 K and QI =	0.200 mW
spect_SMECm_base	4.818 K and QI =	0.000 mW
spect_SMECm_actuator	4.899 K and QI =	2.600 mW
spect_SMECm_LVDT	4.822 K and QI =	0.100 mW
spect_SMECm_encoder	4.834 K and QI =	0.500 mW
SCAL_enclosure	4.844 K and QI =	1.500 mW
SCAL_disc01	4.844 K and QI =	0.000 mW
SCAL_disc02	4.844 K and QI =	0.000 mW
SCAL_disc03	4.844 K and QI =	0.000 mW
SCAL_disc04	4.844 K and QI =	0.000 mW
photo_JFET_mem1	10.005 K and QI =	0.000 mW
spect_JFET_mem1	151.147 K and QI =	4.700 mW

SPIRE INTERFACE TEMPERATURES

PJFET_L3 IF	10.003 K
SJFET_L3 IF	10.635 K
L1_Cryo-Harness SIF	4.777 K
L1_Cryo-Harness PIF	4.786 K
L1_HK-Harness IF	4.835 K
L1_strap_IF1	4.336 K
L0 Enc IF	1.749 K
L0 Pump IF	1.726 K
L0 Evap IF	1.704 K

CALIB CRYO INTERFACES TEMPERATURES

HOB - 1001	10.195 K
HOB - 1002	10.201 K
HOB - 1003	10.193 K
HOB - 1004	10.218 K
HOB - 1005	10.212 K
HOB - 1006	10.227 K
HOB - 1007	10.200 K
HOB - 1008	10.205 K
HOB - 1009	10.201 K
LN2 Shield	77.000 K
L2 Shield	10.000 K
L1 IF	4.200 K
L0 IF	1.700 K

Heat Fluxes for SPIRE Cooler

Photo 300mK	5.663 uW
Spectro 300mK	0.000 uW
L1 Parasitics	1.826 uW
Shunt Parasitics	7.182 uW
Heat Switch Parasitics	2.958 uW
Total Cooler Load	17.629 uW

Heat Fluxes for SPIRE 300mK System

PLW Kevlar Parasitic	2.103 uW for L0 Encl Temp at	1.914 K
PLW Harness Parasitic	1.078 uW	
PMW Kevlar Parasitic	0.000 uW for L0 Encl Temp at	1.966 K
PMW Harness Parasitic	0.000 uW	
PSW Kevlar Parasitic	0.000 uW for L0 Encl Temp at	2.024 K
PSW Harness Parasitic	0.000 uW	
Busbar Supports Parasitic	0.784 uW for L0 Encl Temp at	1.914 K
Busbar Supports Parasitic	0.784 uW for L0 Encl Temp at	1.914 K
Busbar FeedThru Parasitic	0.913 uW for L0 Encl Temp at	2.024 K
Total Photo 300mK Load	5.663 uW	
Balance on photo 300mK	0.000 uW	

SLW Kevlar Parasitic	0.014 uW for L0 Encl Temp at	1.765 K
SLW Harness Parasitic	0.002 uW	
SSW Kevlar Parasitic	-0.013 uW for L0 Encl Temp at	1.749 K
SSW Harness Parasitic	-0.003 uW	
Spectro FeedThru Parasitic	0.001 uW for L0 Encl Temp at	1.765 K
Total Spectro 300mK Load	0.000 uW	
Balance on Spectro 300mK	0.000 uW	

Heat Fluxes for SPIRE Level 0 - Enclosure

L0 Photometer Enc Foot Supports	1.487 mW
L0 Harn Parasitic for PLW	0.063 mW
L0 Harn Parasitic for PMW	0.125 mW
L0 Harn Parasitic for PSW	0.219 mW
Load into Photo 300mK System	0.006 mW
Load into L0 Spectrometer Enc	1.888 mW
Balance on L0 Photometer Enc	0.000 mW

L0 Spectrometer Enclosure Foot Supp	0.493 mW
L0 Harn Parasitic for SLW	0.032 mW
L0 Harn Parasitic for SSW	0.061 mW
Load into Spectro 300mK System	0.000 mW
L0 Enc Strap Standoffs	0.099 mW
Balance on L0 Spectrometer Enc	0.000 mW

L0 Enclosure Strap Load 2.573 mW for IF Temp at

Heat Fluxes for SPIRE Level 0 - Pump

Pump Supports	0.002 mW
Initial Pump Dissipation	1.400 mW
Pump Heat Switch Dissipation	0.400 mW
Pump Heat Switch Support Parasitic	0.216 mW
Pump Heat Switch Harness Parasitic	0.005 mW
Additional Pump Dissipation	-0.519 mW
L0 Pump Strap Standoffs	0.099 mW
Balance on L0 pump Strap Load	0.000 mW
Balance on Pump Dissipation	0.000 mW

L0 Pump Strap Load 1.603 mW for IF Temp at

Heat Fluxes for SPIRE Level 0 - Evaporator

Evap Heat Switch Dissipation	0.000 mW
Evap Heat Switch Support Parasitic	0.217 mW
Evap Heat Switch Harness Parasitic	0.005 mW
Evap Heat Switch Shunt Strap load	-0.001 mW
Evap Heat Switch leak to evap	-0.003 mW
L0 Evap Strap Standoffs	0.100 mW
Balance on L0 evap Strap Load	0.000 mW

L0 Evap Strap Load 0.317 mW for IF Temp at

Heat Fluxes for SPIRE Level 1

Harness Load from PJFET	0.919 mW
Harness Load from SJFET	0.237 mW
L1 Foot Supports	8.885 mW
L1 Housekeeping Harness	2.566 mW
Total Radiation Load	7.130 mW
PCAL Dissipation	0.033 mW
BSM Dissipation	0.200 mW
SMEc Actuator Dissipation	2.600 mW
SMEc LDVT Dissipation	0.100 mW
SMEc Encoder Dissipation	0.500 mW
SCAL Dissipation	1.500 mW
Aperture Filter Dissipation	0.015 mW
HK IF Dissipation	0.000 mW
Total Mechanisms Dissipation	4.948 mW
Leak to L0 via Supports (pump+HS)	-0.439 mW
Leak to L0 via Harness (shunt+HS)	-0.013 mW
Leak to L0 straps	-0.298 mW
Leak to L0 Detector Boxes	-2.480 mW
Balance on L1	0.000 mW

L1 Strap1 Load 21.456 mW for IF Temp at 4.200 K
Total L1 Load 21.456 mW

Heat Fluxes for SPIRE Level 3

PJFET Harness Load to FPU	-0.919 mW	
PJFET Harness Load to HOB	-0.002 mW	
PJFET Foot Supports to HOB	0.379 mW	
PJFET Strap Load	-0.131 mW for IF Temp at	10.000 K
PJFET Radiation Load	0.674 mW	
PJFET Dissipation Load	0.000 mW	
PJFET Harness Dissip Load	0.000 mW	
Balance on PJFET	0.000 mW	
SJFET Harness Load to FPU	-0.237 mW	
SJFET Harness Load to HOB	-0.115 mW	
SJFET Foot Supports to HOB	-0.934 mW	
SJFET Strap Load	-12.958 mW for IF Temp at	10.000 K
SJFET Radiation Load	0.144 mW	
SJFET Dissipation Load	14.100 mW	
SJFET Harness Dissip Load	0.000 mW	
Balance on SJFET	0.000 mW	

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