SPIRE Science Verification Review

RAL

January 26, 27 2005

Thermal Performances

Document Number: SPIRE-RAL-REP-002557

Author
A. Goizel

Date
13/01/06

PREPARED BY:	A.S. GOIZEL	RAL	13/01/06	Signature Not Verified Digitally signed by Anne-Sophie Goizel Date: 2006.01.16 19:35:35 Z
CHECKED BY:	B. SHAUGHNESSY	RAL		Signature Not Verified Digitally signed by Bryan Shaughnessy Date: 2006.01.17 08:04:46 Z
APPROVED BY:	B. SWINYARD	RAL		

Acronyms

Acronym	Definition
AD	Applicable Document
BDA	Bolometer Detector Arrays
BSM	Beam Steering Mechanism
CBB	Cold Black Body
CQM	Cryogenic Qualification Model
DRCU	Digital Readout Control Unit
DTMM	Detailed Thermal Mathematical Model
EGSE	Electronic Ground Support Equipment
FM	Flight Model
FPU	Focal Plane Unit
FS	Flight Spare
HOB	Herschel Optical Bench
HeI	Helium I
HeII	Helium II
I/F	Interface
IIDB	Instrument Interface Document Part B
IRD	Instrument Requirement Document
JFET	Junction Field Effect Transistor
L0	Level-0
L1	Level-1
L2	Level-2
L3	Level-3
LN2	Liquid Nitrogen
MGSE	Mechanical Ground Support Equipment
PFM	Proto Flight Model
RD	Reference Document
SMEC	Spectrometer Mechanism
SOB	SPIRE Optical Bench
SPIRE	Spectral and Photometric Imaging Receiver
TBT	Thermal Balance Test
DTMM	Detailed Thermal Mathematical Model

Contents

List of Tables

1. Introduction and scope

1.1 Scope

The scope of this document is to report about:

- Thermal test results obtained during the CQM, FM and EQM test campaigns that are relevant to the in-flight instrument scientific performances,
- Any remaining/additional thermal tests required to complete the validation of the instrument thermal performances,
- Provide inputs for the system-level verification requirements.

1.2 Applicable Documents

AD	Title	Document Number
AD1	SPIRE CQM Thermal Balance Test Specification	SPIRE-RAL-DOC-002077 Draft 4.5
AD2	SPIRE CQM Thermal Balance Test Report	SPIRE-RAL-REP-002078 Issue 1
AD3	SPIRE PFM2 Thermal Balance Test Specification	SPIRE-RAL-DOC-002435 Issue 1
AD4	SPIRE PFM2 Thermal Balance Test Report	SPIRE-RAL-REP-002534 Issue 1
AD5	SPIRE Thermal Balance Test Sequence and Requirements For EQM Testing	SPIRE-RAL-NOT-002319 Issue 1
AD6	Subsystem Verification Matrix - SPIRE Thermal Hardware	Working Version 3.2
AD7	SPIRE 300-mK and Level-0 straps Subsystems Thermal Performances Assessment	SPIRE-RAL-NOTE-002129 Issue 1
AD8	SPIRE CQM2 Thermal Test Results Memo	SPIRE-RAL-MEM-002533 Issue 1
AD9	Analysis of SPIRE Thermal Performances with Hybrid FPU Supports	SPIRE-RAL-NOT-002551 Issue 1
AD10	SPIRE PFM3 Thermal Balance Test Specification	SPIRE-RAL-MEM-002563 To be written
AD11	Flight L0 Thermal Straps Test Report	Cardiff 15/11/05
AD12	Herschel Thermal Model Issue Email Object: RE: PFM Cryostat - SPIRE L1 Flexibles Thermal Conductance (TB Test in LSS)	05/12/05 Email from A. Hauser
AD13	Use of BSM during spectrometer mode Email Object: RE - PFM Power II	23/02/04 Email from D. Griffin

AD	Title	Document Number
AD14	BSM Power Dissipation Emails Object: PFM Power and PFM Powers II	10/02/04 Email from B. Swinyard
AD15	SMEC Power Dissipation Update Emails Object: SMEC Consumption	07/07/05 Email from B. Swinyard

Table 1-1 – Applicable Documents

1.3 Reference Documents

RD	Title	Document Number
RD1	Instrument Interface Document Part A	SCI-PT-IIDA-04624 3.3
RD2	Instrument Interface Document Part B - SPIRE Instrument	SCI-PT-IIDB/SPIRE-02124 Issue 3.2
RD3	SPIRE Instrument Requirement Document	SPIRE-RAL-PRJ-000034 Issue 1.3
RD4	SPIRE Cryogenic Thermal Design Requirements	SPIRE-RAL-PJR-002075 Issue 1

Table 1-2 - Reference Documents

2. List of requirements that the test programme was designed to evaluate

2.1 Overview

In order to meet its science goals, the SPIRE instrument has been designed to meet the following high-level requirements:

- A minimum cooler hold time of 46-hr,
- A maximum absolute detector temperature of 310mK.

Both requirements shall be met with SPIRE operating in the thermal environment described in Table 2-1.

In-Orbit Thermal Requirements [1]			
SPIRE FPU Thermal IF	Maximum I/F Temperature at Max Heat Load		Cooler State
	Requirements	Goals	
Level 0 – Detector Box	2 K @ 4 mW	1.71K @ 1 mW	Operating
Level 0 – Cooler Pump	2 K @ 2 mW	2 K @ 2 mW	Operating
	10 K @ 500 mW peak	10 K @ 500 mW	Recycling
Level 0 – Cooler Evaporator	1.85 K @ 15 mW	1.75 K @ 15 mW	Recycling
Level 1	5.5 K @ 15 mW	3.7 K @ 13 mW	Operating
Level 2	12 K @ no load	8 K @ no load	Operating
Level 3 – Photometer	15 K @ 50 mW	15 K @ 50 mW	Operating
Level 3 – Spectrometer	15 K @ 25 mW	15 K @ 25 mW	Operating
Instrument Shield	16 K	16 K	Operating

Table 2-1 – SPIRE High-Level Thermal Requirements

Subsystems and instrument level requirements have been derived from these high-level requirements and are summarised in the Instrument Requirement Document [RD3] and the SPIRE Cryogenic Thermal Design Requirements [RD4]. A SPIRE Thermal Hardware Verification Matrix [AD6] has been compiled to keep track of their verification method and status depending of the instrument model being tested. Table 2-2 in the following section provides a summary of the applicable instrument level thermal requirements. Please note that a definition of the acronyms used in the “Verification Method” and “Verification Model” columns is given in Table 2-3 in the following pages.

[1] *Assuming a ^{2}He tank temperature of 1.7 K.*

2.2 SPIRE Instrument Thermal Requirements

Requirement Name	Description	Requirement	Upper Link	Verfication Method	Verification Model
IRD-BSMP-R11	BSM Thermal Isolation	The BSM structure or mirror shall rise by no more than 1K from the nominal temperature of the surrounding after an hour of operation in any mode	IRD-OPTP-R08 IRD-OPTS-R09	D, A, ILTT, ILOP	PFM2, PFM3
IRD-BSMP-R12	BSM Cold Power Dissipation	The dissipation should be within specification given in RD15 - 3mW maximum mean power dissipation during 46hr operation.	IIDB-Sect 5.9.1	D, A, ILTT, ILPT, ILOP	SS, PFM3
IRD-CALP-R10	PCAL Thermal Isolation	The thermal conductance between the calibrator body and the SOB shall be >2mW/K	Created	D, A, ILTT	PFM2, PFM3
IRD-CALP-R12	PCAL Cold Power Dissipation	Shall be within the specification given in RD15 - 0.033mW maximum mean power dissipation during 46hr operation.	IIDB-Sect 5.9.1	D, A, ILTT, ILOP	SS, PFM2, PFM3
IRD-CALS-R09	SCAL Cold Power Dissipation	Shall be within the specification given in RD15 - 2mW maximum mean power dissipation during 46hr operation.	IIDB-Sect 5.9.1	D, A, ILTT, ILOP	SS, PFM3
IRD-CALS-R12	SCAL Thermal Isolation	The SCAL enclosure shall provide an attachment point for a thermal strap to avoid the SCAL to warm up its environment by more than 1K	Created	D, A, ILTT	SS, PFM3
IRD-CALS-R15	SCAL Thermometry	Thermometers shall be provided on the spectrometer calibrator as specified in section 3.5.12	Created	D, A, ILTT	PFM2, PFM3
IRD-CALS-R16	SCAL Time Response	Warmup Time: Stable nominal operating temperature to be reached in less than 30 min(reqt) 15 min (goal). Cooldown Time from nominal operating temperature to <10K: 3hr (reqt) 30 min (goal)	Created	D, A, ILTT, ILPT, ILOP	SS, PFM3
IRD-COOL-R01	Temperature at the detectors	The 3He cooler, in conjunction with the associated 300 mK architecture, shall maintain all bolometer detector assemblies at less than 310 mK – goal 300 mK	IRD-PHOT-R04 IRD-PHOT-R05 IRD-SPEC-R06 IRD-SPEC-R07	D, A, ILTT, ILPT	CQM2, PFM2, PFM3
IRD-COOL-R02	Operating temperature control	Desirable to vary the temperature of the detectors up to 320mK and below 300mK if permitted by thermal busbar.	Created	D, A, ILTT, ILPT, ILOP	PFM3
IRD-COOL-R03	Temperature drop across thermal link between detectors and evaporator cold tip	Maximum of 20mK (Goal = 10mK)	IRD-COOL-R01	D, A, ILTT	CQM2, PFM2, PFM3
IRD-COOL-R04	Temperature drift	Evaporator cold tip should drift by no more than 0.1mK/h under active control	IRD-PHOT-R05	D, A, ILTT	PFM2, PFM3

IRD-COOL-R05	Temperature fluctuations at the evaporator cold tip	10uK.Hz-1/2 in a 0.1-10 Hz band	IRD-PHOT-R04 IRD-PHOT-R05 IRD-SPEC-R06 IRD-SPEC-R07	D, A, ILTT, ILPT, ILOP	PFM2, PFM3
IRD-COOL-R07	Heat lift at evaporator cold tip	Minimum of 10uW at 290mK	Created	D, A, ILTT	SS
IRD-COOL-R08	Cooler Hold time	Minimum of 46 hrs	IIDA-Sect 5.13.2.5	D, A, ILTT	CQM2, PFM2, PFM3, EQM
IRD-COOL-R09	Cooler Recycle time	Maximum of 2 hours	IIDA-Sect 5.13.2.5	D, A, ILTT	CQM2, PFM2, PFM3, EQM
IRD-COOL-R11	Thermal Interface with Herschel cryostat	Cooler L0 Strap conductance Requirement of 150mW/K at 1.7K	Created	D, A	SS
IRD-COOL-R12	Parasitic thermal load onto He bath during cold operation	Pump L0 load in operation 2mW maximum	IIDB-Sect 5.7.1.3	D, A, ILTT	PFM2, PFM3
IRD-COOL-R13	Time averaged thermal load onto He bath for 48 hour cycle		IIDB-Sect 5.7.1.3	D, A, ILTT	SS
IRD-COOL-R18	Cooler Thermometers	Thermometers shall be provided on the cooler as necessary to monitor its behaviour and operation (see section 3.5.12). Absolute temperature measurement on evaporator cold tip shall be 1% (<3mK) with a resolution of 1mK.	Created	D, A, ILTT	CQM2, PFM2, PFM3
IRD-DETP-R13	300 mK thermal load	The thermal dissipation and parasitic load at 300mK shall be within the specification given in RD15	IRD-COOL-R08	D, A, ILTT, ILPT	CQM2, PFM2, PFM3
IRD-DETS-R14	300 mK thermal load	The thermal dissipation and parasitic load at 300mK shall be within the specification given in RD15	IRD-COOL-R08	D, A, ILTT, ILPT	CQM2, PFM2, PFM3
IRD-FTB-R05	JFET Cold Power Dissipation	The dissipation of the JFET amplifiers shall be heat sunk to the L3 cryostat stage and shall be within the specification given in RD15 - 42mW and 14mW maximum mean power dissipation during 46hr operation for PJFET and SJFET respectively.	IIDB-Sect 5.9.1	D, A, ILTT, ILPT, ILOP	SS, PFM2, PFM3
IRD-FTB-R11	JFET Thermal Isolation	The JFET structure shall be thermally isolated from the Herschel optical bench with specification given in RD15	IIDA-Sect 5.7.1.2	A,D,ILTT	CQM2

IRD-FTB-R12	L3 Thermal IF	The JFET structure shall be thermally connected to L3 via a strap with interface specification given in RD15	IIDB-Sect 5.7.1.3	D, A	
IRD-SMEC-R11	SMEC Cold Power Dissipation	The dissipation should be within specification given in RD15 - 3.2mW maximum mean power dissipation during 46hr operation.	IIDB-Sect 5.9.1	D, A, ILTT, ILPT, ILOP	SS, PFM3
IRD-SMEC-R13	SMEC Temperature Sensor	The SMEC shall provide thermometers as detailed in section 3.5.12.	Created	D, A, ILTT	CQM2, PFM2, PFM3
IRD-STRC-R05	Surface Finish of the Common Structure Cover	The inside and outside of the box shall have a finish with a low emissivity. At least e = 0.2. Some parts of the structure walls may be blackened as part of the straylight control.	RD15	D, A, I , ILTT	PFM2, EQM, PFM3
IRD-STRC-R07	Thermometry	The structure subsystem shall provide thermistors and associated wiring to allow the temperature of critical parts to be monitored during in-flight operations – see section 3.5.12	Created	D, A, ILTT	CQM2, PFM2, PFM3
IRD-STRC-R14	FPU Thermal Isolation	The conductance from the level 2 to level 1 stage shall be within the specification given in RD15.	Created	D, A, ILTT	PFM2, PFM3
IRD-STRC-R15	SOB Temperature	The SPIRE Optical Bench shall be connected to the L1 stage with a thermal conductance meeting the requirements in RD15	Created	D, A, ILTT	PFM3
IRD-STRP-R04	Surface Finish	The outside of the box shall have a finish with a low emissivity. At least e = 0.2. The inside of the box shall have a low reflectivity finish on all non-optical surfaces.	RD15	D, A, I	CQM2, PFM2, PFM3
IRD-STRP-R09	L0 Phot Thermal Isolation	The conductance along the photometer detector box mechanical support from L1 to L0 shall be within the specification set in RD15	Created	D, A, ILTT	PFM2, PFM3
IRD-STRP-R10	Photometer Box Temperature	The photometer box shall be connected to the spectrometer box with a strap meeting the conductance requirements in RD15 - 0.05W/K at 1.7K	Created	D, A, ILTT	CQM2, PFM2, PFM3
IRD-STRS-R04	Surface Finish	The outside of the box shall have a finish with a low emissivity. At least e = 0.2. The inside of the box shall have a low reflectivity finish on all non-optical surfaces.	RD15	D, A, I	CQM2, PFM2, PFM3
IRD-STRS-R08	L0 Spectr Thermal Isolation	The conductance along the spectrometer detector box mechanical support from L1 to L0 shall be within the specification set in RD15	Created	D, A, ILTT	PFM2, PFM3
IRD-STRS-R09	Spectrometer Box Temperature	The spectrometer box shall be connected to the cryostat L0 stage with a strap meeting the conductance requirements in RD15 - 0.15W/K at 1.7K.	Created	D, A, ILTT	SS

Table 2-2 – SPIRE Instrument Thermal Requirements Summary [AD6]

Note: RD15 is the above table refers to the "SPIRE Cryogenic Thermal Design Requirements" document [RD4] in this document.

Verification Method	D	Design
	A	Analysis
	I	Inspection
	ILTT	Instrument Level Thermal Tests
	ILPT	Instrument Level Performance Tests
	ILCFT	Instrument Level Cold Functional Test
	ILOT	Instrument Level Operations Tests
Verification Model	SS	Subsystem Level
	SC	Spacecraft Level
	CQM1	First CQM Test Campaign
	CQM2	Second CQM Test Campaign
	PFM2	Second PFM Test Campaign
	PFM3	Third PFM Test Campaign
	EQM	EQM Test Campaign

Table 2-3 – Acronyms used for Verification Matrix

3. Test results and conclusions

3.1 List of tests carried out and tests still to be done

The following section summarises the tests that have been carried out at instrument level, including a brief summary of the test outcome and conclusion for each test campaign. A final section provides an overview of the test remaining to be done in order to complete the verification of the instrument thermal performances.

3.1.1 List of tests carried out during the CQM/PFM/EQM Test Campaigns

Test Name	Description	CQM2	PFM2	EQM
Temperature Sensors Characterisation	Characterise the temperature measurement errors of the flight and EGSE temperature sensors.	**X**	**X**	**-**
Cooler Pump Characterisation	Characterise the MGSE L0 pump strap conductance and establish the relation between the pump temperature and its internal power dissipation. The later will be used for future correlation to estimate the total cooler load based on the pump temperature.	**X**	**X**	**X**
Level-0 Detector Strap Characterisation	Characterise the MGSE L0 detector strap conductance and evaluate the heat load flowing on the strap.	**X**	**-**	**-**
Level-1 Characterisation	Characterise the MGSE L1 strap conductance and evaluate the heat load flowing on the strap.	**-**	**X**	**-**
JFET Isolation Characterisation	This test assesses the level of isolation of the JFET CFRP supports.	**X**	**-**	**-**
Cooler Recycling	The operation profile of the cooler during recycling is assessed during this test.	**X**	**X**	**X**
Cooler Hold Time Characterisation	This test assesses the instrument hold time performance for a given thermal environment. This test was carried out as part of the thermal balance tests below.	**X**	**X**	**X**
Thermal Balance Test 1 OFF Mode	Test with nominal thermal environment - calibration cryostat temperature stages maintained at ~1.7K and ~4K and instrument in OFF mode.	**X**	**X**	**-**
Thermal Balance Test 2 Cold Case	Test with nominal thermal environment - calibration cryostat temperature stages maintained at ~1.7K and ~4K.	**X**	**X**	**-**
Thermal Balance Test 3 Hot Case	Test with a warmer thermal environment (as worst case) with the calibration cryostat temperature stages maintained at ~2K and 4K to 5.5K.	**X** **2K/4K**	**X** **2K/5.5K**	**-**

Table 3-1 – List of tests carried out during the CQM/PFM/EQM Test Campaigns

3.1.1.1 CQM Test Campaign Summary [AD1]

All thermal tests were carried out successfully but inconsistencies were detected in some of the temperature sensors data. Specific tests were carried out during the CQM2 test campaign to check whether sensor self-heating could be the reason for these erroneous data but the results remained unsatisfactory. Further analysis was carried out to identify others possible causes for these inconsistencies [AD8] and specific tests were defined to help characterise any error present in the flight and EGSE temperature sensors as part of the following PFM test campaign. Correlation of the CQM test data with the thermal model was found difficult but the preliminary observations provided important information about the instrument thermal performances. These are summarised below:

- During the CQM1 test campaign, large temperature drops (about 0.3K) were observed at both the photometer and spectrometer enclosures L0 straps interfaces. As a result, both the thermal interfaces and the interbox L0 strap were modified, on time to be tested as part of the CQM2 test campaign. The temperature drops were successfully reduced to about 0.05K for the nominal thermal environment (1.7K/4K).

- The cooler cold tip and PLW detector temperatures were measured during the CQM2 test campaign for the nominal thermal environment (1.7K/4K) and the five detectors connected to the 300mK busbar (of which, four were STM BDAs). A 35mK temperature drop was observed along the 300-mK busbar, well in excess of the maximum 20mK specified (and 10mK as a goal). Corrective measures were taken and a higher purity copper was used for the flight 300-mK busbar.

- Two thermal balance test cases were run, from which the cooler total load and hold time could be estimated, as summarised in the table below. It is important to note that the following restrictions were applicable to these preliminary measurements:

    - While the parasitic loads from the cooler and the 300mK busbar were flight representative, four of the BDA were STM.

    - The CQM cooler was slightly undercharged.

    - MGSE L0 straps (non-flight representative) were used to recycle the cooler as the flight one would not fit inside the calibration cryostat.

Thermal Test Cases	Nominal Case	Hot Case
Thermal Environment during Recycling	1.7K/4K	1.7K/4K
Thermal Environment during Operation	1.7K/4K	2K/4K
Temperature of Evaporator at end of condensation phase	~2K	~2K
FPU Temperature at L1 IF	4.39K	4.39K
Average L0 Enclosures Temperature	1.76K	1.98K
Estimated Evaporator Average Load	24-26uW	36-40uW
Cooler Hold Time	49 hr	36 hr
Cooler cold tip Temperature	277mK	286mK
PLW Detector Temperature	310mK	350mK

Table 3-2 – Instrument Level Performances during CQM2 Test Campaign

A specific test was carried out to characterise the overall conductance of the PJFET isolation supports. These test data could not be used for thermal correlation however because of inconsistencies present in some of the temperature sensor readings. Now that these inconsistencies are fully understood and characterised [AD4], the test data from the CQM2 test campaign can now be used again.

3.1.1.2 PFM2 Test Campaign Summary [AD3]

All tests were carried out successfully during the PFM2 test campaign with the exception of the "L0 Detector Strap Characterisation" test. The EGSE heater required for this test was found to be in open circuit following cooldown.

A characterisation test was carried out on the flight prime/redundant and EGSE temperature sensors and as a result, the sources of inconsistencies observed during the previous CQM test campaigns are now well understood. DC Offset and self-heating errors has even been quantified for some of the flight sensors allowing some thermal test data from CQM2 test campaign to be used again for the thermal model correlation (after accounting for the errors).

Additional observations could be made about the instrument thermal performances as part of this test campaign, these are summarised below:

- The L0 interbox strap performances remained good. A further reduction of the temperature drop at the boxes interfaces could be observed (from 0.05K to <0.02K) following the change from stainless steel isolation supports to CFRP supports. This means that the two boxes are now isothermal within about 10mK.
- The new 300mK busbar (made of higher purity copper) was used for this test campaign and the temperature drop along the 300mK strap was successfully reduced from 35mK (measured during the CQM campaign) to about 10mK for the nominal thermal environment of 1.7K/4K, which is well within the 20mK requirement. Please note that the flight cooler and all five flight detectors were used this time and that these performances represent the instrument in-flight capability for this specific thermal environment.
- Two thermal balance test cases were run from which the cooler total load and hold time could be estimated, as summarised in the table below.
- The measured cooler hold time for the nominal 1.7K/4K thermal environment was about 50h25min which is within the required 46 hr. Please note however that the L0 straps were not flight representative. Further analysis is required that will compare the conductance of these MGSE L0 straps with the measured flight ones to estimate the in-flight performances of the instrument. A "hot" case was also run to provide a second data point for the correlation of the test data with the instrument thermal model.
- The following instrument operational heat loads were measured for both the cold and hot cases:
    - Heat load flowing on the L0 pump strap,
    - Heat load flowing on the L1 strap. This heat load will be correlated in order to estimate how much heat load is coming from the calibration cryostat cryo-harnesses and radiation. As these are not representative of the Herschel flight cryostat, the current value does not allow a proper verification of the instrument L1 operational load.

Thermal Test Cases	Nominal Case	Hot Case
Thermal Environment during Recycling	1.7K/4K	2K/5K
Thermal Environment during Operation	1.7K/4K	2K/5K
Evaporator Temperature at end of condensation phase	~2.1K	~2.1K
Pump Temperature at end of condensation phase	~41.7K	~43.4K
FPU Temperature at L1 IF	4.3K	4.8K
Average L0 Enclosures Temperature	1.72K	1.95K
Estimated Evaporator Average Load	26-29uW	30-33uW
Cooler Hold Time	50h25min	34h30min
Cooler cold tip Temperature	288.5mK	294.9mK
PLW Detector Temperature	283mK	-
PMW Detector Temperature	303.7mK	-
PSW Detector Temperature	293.3mK	-
SLW Detector Temperature	299.9mK	341.5mK (*)
SSW Detector Temperature	299.5mK	341.5mK (*)

Table 3-3 – Instrument Level Performances during PFM2 Test Campaign

(*) The cooler cold tip was at 301.9mK at the time the detectors temperature was measured.

Note: The measured temperature for the PLW detector appears to be cooler that the evaporator cold tip itself. This is not possible and further analysis is required to understand where this inconsistency is coming from.

3.1.1.3 EQM Test Campaign Summary

The main goal of the EQM level-testing was to assess the impact of instrument operational modes on its L1 thermal stability and hence on its overall thermal performances (in terms of cooler hold time and absolute detector temperatures). This test could not be carried out as the mass flow rate of the EQM cryostat L1 ventline was too different from the one that can be expected in the flight cryostat. Thermal balance testing was difficult as the stability requirements were hard to achieve in the EQM cryostat. This test however was an opportunity to check any potential anomalies of the instrument performances at system level. The following anomalies were observed:

- Inconsistencies present in some of the instrument temperature sensors reading – this problem had already been encountered at instrument test level during the CQM2 test campaign and is now understood ([AD8], [AD4]).
- Some observations suggested that the instrument L1 temperature may be strongly linked to the cryostat cryo-cover temperature. The reasons for this behaviour still require to be clarified.

3.1.2 List of tests still to be done

The thermal tests defined in the Table 3-4 are required to complete the instrument level verification of the instrument thermal performances.

Test Name	Description	Applicable Requirement	Priority	Possible Mitigation
Cooler Pump characterisation	This test will ensure that the instrument thermal performances have not degraded following the cold vibration testing done at CSL.	All	High	-
Thermal Balance Test Nominal and Hot Case	This test will ensure that the instrument thermal performances have not degraded following the cold vibration testing done at CSL.	All	High	These tests can be run at week-end to save time and only the nominal case could be run.
L1 Strap Characterisation	This test will characterise the change in L1 heat load following the change of the L1 cone support from CFRP to Stainless Steel as well as the L1 glued interface which was not present during the PFM2 test campaign.	IRD-STRC-R14 IRD-STRC-R15	High	-
PTC Operation	This test will assess the impact of the PTC operation on the cooler total load and detector temperature stability.	IRD-COOL-R02 IRD-COOL-R04 IRD-COOL-R05	High	-
Mechanisms and Calibration Sources Operation	This test will assess the impact of mechanisms operation on the instrument L1 interface temperature and stability, as well as confirm the instrument L1 heat load for all operational modes. This test will also allow to check for any overall mechanisms temperature increase for all operational modes.	IRD-BSMP-R11 IRD-BSMP-R12 IRD-CALP-R12 IRD-CALS-R09 IRD-CALS-R12 IRD-CALS-R16 IRD-SMEC-R11	High	-

Test Name	Description	Applicable Requirement	Priority	Possible Mitigation
Cooler Recycling in Close-Loop	This test will allow the tuning of the PID parameter that will be used to maintain the pump temperature at 45K during the cooler recycling.	None	Medium	The efficiency of the cooler recycling could be further improved by implementing this.
L0 Detector Strap Heat Load	Characterisation of the heat load on L0 detector box strap.	IRD-STRS-R09	Medium	Could probably be done by correlation with the thermal model.
Photometer Detector Temperature	This test would measure the temperature of the photometer detector for L0 enclosures held at ~2K test.	-	Medium	This test has been carried out with the spectrometer detectors during PFM2.
Flight Temperature Sensors Characterisation	Some of the flight sensors could not be checked out for DC offset and self-heating errors.	IRD-STRC-R07 IRD-CALS-R15 IRD-SMEC-R13 IRD-COOL-R18	Low	Might not be required if the sensor accuracy is adequate for commissioning.

Table 3-4 - List of tests still to be done [AD10]

3.2 Subsystem requirements tested at instrument level and their verification status

Requirement Name	Description	Requirement	Measured Value	Comments
IRD-BSMP-R11	BSM Thermal Isolation	The BSM structure or mirror shall rise by no more than 1K from the nominal temperature of the surrounding after an hour of operation in any mode	0.06K	No significant warm-up found but has not been done for all operations modes.
IRD-BSMP-R12	BSM Cold Power Dissipation	The dissipation should be within specification given in RD15 - 3mW maximum mean power dissipation during 46hr operation.	Current estimation is 3.47mW	In excess by 0.47mW.
IRD-CALP-R10	PCAL Thermal Isolation	The thermal conductance between the calibrator body and the SOB shall be >2mW/K	TBC	Will be checked by analysis using the correlated SPIRE thermal model.
IRD-CALP-R12	PCAL Cold Power Dissipation	Shall be within the specification given in RD15 - 0.033mW maximum mean power dissipation during 46hr operation.	2.91mW dissipated for standard PCAL flash during PFM2 ILT, 0.0527mW	In excess by 0.0197mW.
IRD-CALS-R09	SCAL Cold Power Dissipation	Shall be within the specification given in RD15 - 2mW maximum mean power dissipation during 46hr operation.	Current estimation is 2.3mW	In excess by 0.3mW
IRD-CALS-R12	SCAL Thermal Isolation	The SCAL enclosure shall provide an attachment point for a thermal strap to avoid the SCAL to warm up its environment by more than 1K	TBC	
IRD-CALS-R15	SCAL Thermometry	Thermometers shall be provided on the spectrometer calibrator as specified in section 3.5.12	**Self-Heating:** SCAL = 2.6mK SCAL2 = 13.9mK SCAL4 = 17.9mK **DC Offset:** SCAL2 = 4mK SCAL4 = -5.3mK	Prime sensors checked for self-heating, DC offset and calibration errors.
IRD-CALS-R16	SCAL Time Response	Warmup Time: Stable nominal operating temperature to be reached in less than 30 min(reqt) 15 min (goal). Cooldown Time from nominal operating temperature to <10K: 3hr (reqt) 30 min (goal)	TBC	
IRD-COOL-R03	Temperature drop across thermal link between detectors and evaporator cold tip	Maximum of 20mK (Goal = 10mK)	PLW = -5.5mK PMW = 15.2mK PSW = 4.8mK SLW = 11.5mK SSW = 11.1mK	All within requirement for the nominal thermal environment of 1.7K/4K. Note: data for PLW does not look consistent.
IRD-COOL-R04	Temperature drift	Evaporator cold tip should drift by no more than 0.1mK/h under active control	N/A	Not tested yet.
IRD-COOL-R07	Heat lift at evaporator cold tip	Minimum of 10uW at 290mK	Exact value TBC	In specification.
IRD-COOL-R11	Thermal Interface with Herschel cryostat	Cooler L0 Strap conductance Requirement of 150mW/K at 1.7K	Evap strap ~130mW/K at 1.7K (out of specification) Pump strap ~203mW/K at 1.7K (within specification)	Measured at unit level as the strap don't fit in the RAL calibration cryostat. Measurements and test setup to be verified as part of a second test at unit level.
IRD-COOL-R18	Cooler Thermometers	Thermometers shall be provided on the cooler as necessary to monitor its behaviour and operation (see section 3.5.12). Absolute temperature measurement on evaporator cold tip shall be 1% (<3mK) with a resolution of 1mK.	Some of the prime and redundant flight sensors have been checked for self-heating, DC offset and calibration errors when possible.	Please see PFM Thermal Test Report SPIRE-RAL-REP-002534-PFM2 for more details. Please note that the accuracy of the evaporator temperature at 300mK could not be checked.

Requirement Name	Description	Requirement	Measured Value	Comments
IRD-FTB-R05	JFET Cold Power Dissipation	The dissipation of the JFET amplifiers shall be heat sunk to the L3 cryostat stage and shall be within the specification given in RD15 - 42mW and 14mW maximum mean power dissipation during 46hr operation for PJFET and SJFET respectively.	Current estimation is 50.82mW for PJFET and 21.38mW for SJFET has been measured at unit level.	These values includes a +/-5% error bar. They are both exceeding the allocated 42 and 14mW power dissipation.
IRD-FTB-R11	JFET Thermal Isolation	The JFET structure shall be thermally isolated from the Herschel optical bench with specification given in RD15	TBC	Has been tested at instrument level. Awaits thermal model correlation.
IRD-FTB-R12	L3 Thermal IF	The JFET structure shall be thermally connected to L3 via a strap with interface specification given in RD15	N/A	Cannot be tested in the RAL calibration cryostat as there is no L3 temperature stage. Will be estimated by analysis with the Herschel thermal model following the SPIRE thermal model correlation.
IRD-SMEC-R11	SMEC Cold Power Dissipation	The dissipation should be within specification given in RD15 - 3.2mW maximum mean power dissipation during 46hr operation.	Current estimation is 3.735mW	In excess by 0.535mW
IRD-SMEC-R13	SMEC Temperature Sensor	The SMEC shall provide thermometers as detailed in section 3.5.12.	N/A	These sensors could not be checked for self-heating, DC offset and calibration errors.
IRD-STRC-R05	Surface Finish of the Common Structure Cover	The inside and outside of the box shall have a finish with a low emissivity. At least e = 0.2. Some parts of the structure walls may be blackened as part of the straylight control.	TBC	The L1 heat load has been measured at instrument level. Awaits thermal model correlation to determine radiation load.
IRD-STRC-R07	Thermometry	The structure subsystem shall provide thermistors and associated wiring to allow the temperature of critical parts to be monitored during in-flight operations – see section 3.5.12	Some of the prime and redundant flight sensors have been checked for self-heating, DC offset and calibration errors whenever possible.	Please see PFM Thermal Test Report SPIRE-RAL-REP-002534-PFM2 for more details. Please note that the accuracy of the evaporator temperature at 300mK could not be checked.
IRD-STRC-R14	FPU Thermal Isolation	The conductance from the level 2 to level 1 stage shall be within the specification given in RD15.	TBC	The L1 heat load has been measured at instrument level. Awaits thermal model correlation to determine L1 isolation supports load. Please note however that the L1 CFRP cone has since been changed to SST following cold vibration failure.
IRD-STRC-R15	SOB Temperature	The SPIRE Optical Bench shall be connected to the L1 stage with a thermal conductance meeting the requirements in RD15	TBC	L1 glue joint was not implemented on PFM2, to be tested during PFM3 test campaign
IRD-STRP-R04	Surface Finish	The outside of the box shall have a finish with a low emissivity. At least e = 0.2. The inside of the box shall have a low reflectivity finish on all non-optical surfaces.	N/A	Visual inspection.
IRD-STRP-R09	L0 Phot Thermal Isolation	The conductance along the photometer detector box mechanical support from L1 to L0 shall be within the specification set in RD15	TBC	Awaits thermal model correlation.
IRD-STRP-R10	Photometer Box Temperature	The photometer box shall be connected to the spectrometer box with a strap meeting the conductance requirements in RD15 - 0.05W/K at 1.7K	TBC	Awaits thermal model correlation.
IRD-STRS-R04	Surface Finish	The outside of the box shall have a finish with a low emissivity. At least e = 0.2. The inside of the box shall have a low reflectivity finish on all non-optical surfaces.	N/A	Visual inspection.

Requirement Name	Description	Requirement	Measured Value	Comments
IRD-STRS-R08	L0 Spectr Thermal Isolation	The conductance along the spectrometer detector box mechanical support from L1 to L0 shall be within the specification set in RD15	TBC	Awaits thermal model correlation.
IRD-STRS-R09	Spectrometer Box Temperature	The spectrometer box shall be connected to the cryostat L0 stage with a strap meeting the conductance requirements in RD15 - 0.15W/K at 1.7K.	Enclosure strap ~237 mW/K at 1.7K (within specification)	Measured at unit level as the strap don't fit in the RAL calibration cryostat. Measurements and test setup to be verified following a second unit level test.

Table 3-5 - Subsystem requirements tested at instrument level Verification Matrix

3.3 Instrument-level requirements and their verification status.

Requirement Name	Description	Requirement	Measured Value	Comments
IRD-COOL-R01	Temperature at the detectors	The 3He cooler, in conjunction with the associated 300 mK architecture, shall maintain all bolometer detector assemblies at less than 310 mK – goal 300 mK	PLW = 283mK PMW = 303.7mK PSW = 293.3mK SLW = 299.9mK SSW = 299.5mK For evaporator base temperature of ~288.5mK	All within requirement for the nominal thermal environment of 1.7K/4K. Only one detector exceeding the goal temperature. Note: data for PLW is inconsistent.
IRD-COOL-R02	Operating temperature control	Desirable to vary the temperature of the detectors up to 320mK and below 300mK if permitted by thermal busbar.	N/A	Not tested yet.
IRD-COOL-R05	Temperature fluctuations at the evaporator cold tip	10uK.Hz-1/2 in a 0.1-10 Hz band	N/A	Cannot be tested in the RAL calibration cryostat as the stability of the L1 temperature stage is not representatif.
IRD-COOL-R08	Cooler Hold time	Minimum of 46 hrs	50h25min	Within requirement, for the nominal thermal environment of 1.7K/4K. Evaporator Temperature at end of condensation was 2.1K and pump temperature was 41.7K at start of cryo-pumping.
IRD-COOL-R09	Cooler Recycle time	Maximum of 2 hours	Less than 2 hrs	In specification but the cooler L0 straps were not flight representative.
IRD-COOL-R12	Parasitic thermal load onto He bath during cold operation	Pump L0 load in operation 2mW maximum	~ 1.8mW	Within requirement, for the nominal thermal environment of 1.7K/4K. This result is based on a preliminary analysis and will be confirmed following the thermal model correlation.
IRD-COOL-R13	Time averaged thermal load onto He bath for 48 hour cycle		TBC	Will be checked by analysis using the correlated SPIRE thermal model.
IRD-DETP-R13	300 mK thermal load	The thermal dissipation and parasitic load at 300mK shall be within the specification given in RD15	The total cooler load has been estimated to be between 26-29uW. 12-14uW should be accounted for the cooler parasitic load, which gives a total 300mK system load ranging between 12-17uW (including 300mK busbar parasitic loads).	Within requirement, for the nominal thermal environment of 1.7K/4K. This result is based on a preliminary analysis and will be confirmed following the thermal model correlation. Note: the requirement on the cooler total load is 30uW, 15uW for all detectors and 2uW for 300mK busbar and 12uW for the cooler parasitic.
IRD-DETS-R14	300 mK thermal load	The thermal dissipation and parasitic load at 300mK shall be within the specification given in RD15	See IRD-DETP-R13 for more details.	Within requirement, for the nominal thermal environment of 1.7K/4K. This result is based on a preliminary analysis and will be confirmed following the thermal model correlation.

Table 3-6 - Instrument-level requirements Verification Matrix

4. Open issues and anomalies

4.1 Open Issues

4.1.1 SPIRE Thermal Model Correlation

The instrument main system thermal performances have been verified and validated during the PFM2 test campaign for the nominal 1.7K/4K thermal environment with the exception of:

- The stability requirement at the evaporator cold tip (IRD-COOL-R05),
- Impact of PTC use on cooler hold time (IRD-COOL-R02) and (IRD-COOL-R04).

To maximise the chances of Herschel providing the required 1.7K/4K thermal environment, a number of unit level requirements must be met. Some have already been validated through direct observations of the instrument performances during the instrument level testing (such as the L0 interbox strap and characterisation of the L0 pump strap heat load), but some remained to the validated as part of the thermal model correlation, such as:

- Instrument L1 isolation support conductance (IRD-STRC-R14) and L1 isolation joint conductance (IRD-STRC-R15) - hence, the total L1 heat load and interface temperature.
- JFET isolation supports conductances (IRD-FTB-R11).

In addition, the instrument L1 cone support has recently been changed from CFRP back to stainless steel following a cold vibration failure. The impact of this change will have to be assessed as part of the PFM3 instrument level test campaign.

The correlation of the SPIRE thermal model is expected to be completed by mid-February 2006 the latest. Preliminary results of the correlation will be part of the Science Verification Review presentation material if available then.

4.1.2 L0 FM strap confirmation of test results

While the flight L0 straps could not be used as part of the instrument level testing[2], their thermal conductance has been measured at unit level. The test results [AD11] currently show that both the pump and enclosure L0 straps are within the specification while the evaporator strap is 14% under the specification (130mW/K measured versus 150mW/K required). In addition, it was suggested that this unit level testing should be performed again to confirm the current numbers as issues with the test setup had been encountered in the past. This test remained to be done to date.

It is important to note that the cooler performances (in terms of recycling time and efficiency) will be fully validated once the MGSE L0 evaporator strap conductance is known (as part of the thermal model correlation) and only if the flight L0 evaporator strap conductance is equal or exceeding the MGSE one.

4.1.3 Instrument Operational Mode Scenarios and Thermal Stability

An update of the instrument power dissipation budgets is presented in appendix 6 for the worse instrument operating mode. A 0.5mW total mechanism increase has been estimated for the photometer mode while a 1.5mW increase has been estimated for the spectrometer mode. The following points should be noted however:

- These cases are worse cases – it is unlikely that the instrument will operate the BSM in the chop-jiggle mode or the SMEC R1000 mode for the whole 46hr period for example.
- An increase in L1 heat load could degrade the instrument performance if as a result, the Herschel L1 interface temperature increases too much.
- The results from the thermal model correlation will provide an additional insight as to how much margin is currently available for the total L1 heat load.

It is important that in the near future, more realistic instrument operational mode scenarios be devised and used as an input to the thermal model (after correlation) in order to analyse the impact of mechanism operation on the instrument thermal stability and overall performances.

4.2 Anomalies

Errors in the instrument temperature readings as large as 90mK have been quantified. Their cause is now well understood but cannot be corrected for at this stage as it would require to change the way the sensors are readout by the flight electronics (change from DC excitation voltage to an AC excitation voltage) [AD4].

Some inconsistency was found with the PLW BDA detector temperature reading and the cooler cold tip one. The cause of this anomaly is not yet understood also the measured error was within 5mK.

Results from the EQM testing suggested that the instrument L1 temperature may be strongly linked to the EQM cryostat cryo-cover temperature. The reasons for this behaviour still require to be clarified.

---

[2] *As they would not fit inside the calibration cryostat.*

5. Recommendations for further data analysis and test

5.1 Further Analysis

The correlation of the instrument level test data with the thermal model is underway and currently has the highest priority. Once an acceptable level of agreement has been reached between the thermal model and the test data, new flight prediction thermal analyses with the Herschel cryostat thermal model will be required. These analyses should include some transient analyses to investigate the thermal stability performances of the instrument for the various operational modes. Please note that a new issue of the Herschel thermal model is not expected before end of February 2006 so Issue 4 will be used in the meantime [AD12]. Finally, a new SPIRE Interface Thermal Model should be created (based on the correlated SPIRE detailed thermal model) and should be delivered to Astrium for future analyses at spacecraft level.

5.2 Further Testing

Additional instrument level testing has been defined in section 3.1.2. Table 5-1 below provides recommendations about further testing of the instrument as part of the Herschel Thermal Vacuum Testing.

Test Name	Description
SPIRE Thermal Stability	This test would assess the thermal stability performance of the instrument for all flight operation scenarios in photometer and spectrometer mode.

Table 5-1 – Suggestions for SPIRE Testing at Spacecraft Level

6. Appendices

6.1.1 Instrument Power Dissipation Budgets

Mechanism/Calibration Sources/JFET	Allocated Budgets [RD15]	Dissipation Measured at Unit Level		Comment
PCAL	33uW	52.7uW	Standard PCAL Flash (~2.91mW for ~30 sec every hour)	Maximum mean power dissipation during 46hr operation.
SCAL	2mW	2.3mW		Maximum mean power dissipation during 46hr operation.
BSM Photometer Mode	3mW	3.47mW		Maximum mean power dissipation during 46hr operation. Assumption: the worse case operational mode is used for the whole 46hr period (POF3: Chop-Jiggle Mapping).
BSM Spectrometer Mode	0.2mW	0.8mW		Maximum mean power dissipation during 46hr operation.
SMEC Actuator	2.6mW	2.1mW		Maximum mean power dissipation during 46hr operation. Assumption: the worse case operational mode is used for the whole 46hr period (R1000).
SMEC Encoder	0.5mW	1.523mW		Maximum mean power dissipation during 46hr operation.
SMEC LVDT	0.1mW	0.112mW		Maximum mean power dissipation during 46hr operation.
Total L1 Dissipation Budget Photometer Mode	3.033mW	3.523mW		In excess of 0.49mW.
Total L1 Dissipation Budget Spectrometer Mode	5.4mW	6.85mW		In excess of 1.45mW.
PJFET	42mW	50.82mW		Maximum power dissipation during 46hr operation.
SJFET	14mW	21.38mW		Maximum power dissipation during 46hr operation.

Table 6-1 – SPIRE Power Dissipation Budgets {AD13], [AD14], [AD15].