# SPIRE PFM

# THERMAL PERFORMANCE
# FLIGHT PREDICTIONS

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# CHANGE RECORD

| Issue | Date | Section | Change |
|---|---|---|---|
| Draft A | 06/03/06 | - | New Document. |
| Issue 1 | 08/03/06 | - | First Issue |

# 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 |
| HCSS | Herschel Common Science System |
| HeI | Helium I |
| HeII | Helium II |
| HOB | Herschel Optical Bench |
| I/F | Interface |
| IIDB | Instrument Interface Document Part B |
| IRD | Instrument Requirement Document |
| ILT | Instrument Level Testing |
| 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 |
| SCU | Subsystem Control Unit |
| SOB | SPIRE Optical Bench |
| SPIRE | Spectral and Photometric Imaging Receiver |
| TBT | Thermal Balance Test |

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# 1 INTRODUCTION

## 1.1 Scope

This technical note presents the results of the SPIRE Proto Flight Model (PFM) thermal flight performances prediction analysis. These predictions have been based on thermal performances measured during the instrument level PFM2 test campaign at RAL on September 2005.

## 1.2 Documents

### *1.2.1 Applicable Documents*

| ID | Title | Number |
|---|---|---|
| AD1 | SPIRE Thermal Design Requirements | SPIRE-RAL-PJR-002075<br>Issue 1<br>13/01/06 |
| AD2 | SPIRE Instrument Interface Document Part B (IIDB) | SPIRE-ESA-DOC-000275<br>01-Mar-04<br>Issue 3.2 |

*Table 1-1- Applicable Documents*

### *1.2.2 Reference Documents*

| ID | Title | Number |
|---|---|---|
| RD1 | SPIRE & PACS Sorption Cooler<br>SPIRE CQM Test Report | HSO-SBT-RP-085<br>Issue 1<br>13/08/2003 |
| RD2 | SPIRE & PACS Sorption Cooler<br>Heat Switch [1-10] Tests Report | HSO-SBT-RP-107<br>Issue 1<br>03/11/02004 |
| RD3 | SPIRE Sorption Cooler<br>FM1 Tests Report | HSO-SBT-RP-118<br>Issue 1<br>15/11/2004 |
| RD4 | SPIRE PFM2 Thermal Test Report | SPIRE-RAL-REP-002534<br>Issue 1<br>06/03/06 |
| RD5 | Adsorption de L'Helium 4 Par le Charbon Actif<br>Colloque International Vide et Froid, SFITV, Grenoble. | P. Roubeau<br>1969 |
| RD6 | PACS Sorption Cooler<br>FM2 Tests Report | HSO-SBT-RP-123<br>Issue 1<br>17/08/2005 |
| RD7 | Flight L0 Thermal Straps Test Report | Cardiff<br>15/11/05 |

*Table 1-2 - Reference Documents*

# 2 ANALYSIS METHODOLOGY

## 2.1 Background

The thermal performances of SPIRE have been measured as part of the PFM2 thermal balance test campaign for a nominal 1.7K/4K thermal environment. In this configuration, the instrument cooler hold time and its detectors absolute temperatures both met their design requirement as described in Table 2.1.

| 1.7K / 4K Thermal Environment | Requirements [AD1] | Measured during PFM2 |
|---|---|---|
| Cooler Hold Time | > 46 hr | 50 hr 25 m |
| Detector Temperature | < 310mK | All < 304mK |

*Table 2-1 – SPIRE Thermal Performance Requirements [AD1]*

This 1.7K/4K environment corresponds to the “goal” interface temperatures of the Herschel cryostat. The Herschel “requirement” interface temperatures however are different from the “goal” and represent the hottest thermal environment SPIRE is likely to experience during the mission. It is therefore of interest to predict how the SPIRE thermal performances will be affected by this worst case scenario. To this end, a flight performance prediction analysis has been carried out, the methodology used and results obtained will be discussed in the following sections.

## 2.2 Methodology

### *2.2.1 Cooler Thermal Model Validation*

The instrument cooler hold time performance depends on two important parameters:

- The total operational heat load on the evaporator for a given thermal environment,
- The evaporator temperature of condensation at the start of the cooler cryo-pumping phase.

In order to obtain accurate flight predictions based on these parameters, it is important that the thermal model of the cooler is as accurate and representative as possible of the flight cooler. The first stage of this analysis was therefore to correlate the predicted thermal performances of the cooler thermal model with performances of the cooler measured at unit level and during the PFM2 test campaign.

### *2.2.2 Herschel Thermal Environment – Interface Temperatures Predictions*

Table 2-2 describes the agreed interface temperatures of SPIRE with the Herschel cryostat.

| ***SPIRE Thermal Interface*** | ***Requirement Interface Temperatures*** | ***Goal Interface Temperatures*** |
|---|---|---|
| Level-0 (L0) Detector Box | 2 K for 4 mW | 1.71K for 1mW |
| Level-0 (L0) Cooler Pump | 2 K for 2mW | 2 K for 2mW |
| Level-0 (L0) Cooler Evaporator | 1.85K for 15mW | 1.75K for 15mW |
| Level-1 (L1) | 5.5 K for 15mW | 3.7K for 15mW |
| Level-2 (L2) | 12K | 12K |
| Level-3 (L3) Photometer | 15 K for 50mW | 15 K for 50mW |
| Level-3 (L3) Spectrometer | 15 K for 25mW | 15 K for 25mW |

*Table 2-2 – Herschel Cryostat Interface Temperatures [AD2]*

As it can be seen from the table, the Herschel thermal interface temperatures have been defined as a function of SPIRE's operational heat loads. Some of these heat loads have been measured during the PFM2 test campaign at RAL and will be used as an input to this analysis to define the worst case interface temperature that can be expected in flight.

# 3 ANALYSIS RESULTS

## 3.1 Cooler Thermal Model Validation

### *3.1.1 Overview*

As part of the cooler thermal model validation, the following activities have been carried out:

- Validation of the assumptions used for the cooler hold time calculations:

Assuming the evaporator total load and temperature of condensation are well known, it is important to ensure that correct assumptions are used to then estimate the cooler hold time. The cooler hold time has been measured in known conditions and for different loads as part of the unit test level. These test results have been used as test cases to verify and validate the approach used to predict the cooler hold time, based on the evaporator total load and temperature of condensation.

- Validation of the cooler thermal model parasitic heat loads:

The cooler parasitic loads have been measured at unit level for two different thermal environments. These test results have been used as test cases to verify and validate the cooler thermal model.

- Validation of the cooler additional 300mK heat loads:

In addition to its own parasitic loads, the cooler is subjected to an additional heat load from the 300-mK subsystem, which consists of five detectors and two busbars suspended from the L0 temperature stage on Kevlar strings. This additional load has been characterised as part of the instrument PFM2 test campaign and will be used to verify and validate the thermal modelling of the 300mK system.

The following uncertainties are applicable to the cooler performances [RD3]:

- The cooler Helium charge has been estimated to be 6.3L at +/-5%,
- A 6.3L helium charge has been assumed for the theoretical predictions,
- When the cooler runs out of helium, there is not sharp temperature rise and thus it will be assumed that the cooler has run out of helium as soon as its evaporator temperature has risen by 1%,
- A +/-3.3% correlation was achieved during the characterisation tests of the flight cooler hold time at unit level.

Based on this, the following observations could be made:

- When comparing the hold time performance predicted by the cooler thermal model with the one measured as part of the instrument level testing, one should expected a similar level of agreement as the one experienced at unit level testing (+/-3.3%).
- This +/-3.3% uncertainty in cooler hold time can be translated into a cooler total load uncertainty of +/- 1uW (based on a 30uW total cooler load which is the current cooler baseline [AD1]).

Table 3-1 summarises the correlation performance criteria which have been used as a reference in the following analyses. Please note also that the correlation factor will be obtained by dividing the performance predicted with the thermal model by the one measured during testing.

| | **Good Correlation Factor** | **Comments** |
|---|---|---|
| Cooler Hold Time [hr] | ≤ +/- 3.3% | Similar correlation factor as for the unit level testing. |
| Cooler Total Load [uW] | ≤ +/- 1 uW | Based on a 30uW total cooler load. |

*Table 3-1 – SPIRE Cooler Performance Correlation Criteria*

### *3.1.2 Cooler Hold Time – Validation*

The following parameters are taken into account when estimating the cooler hold time with the thermal model:

- Cooler initial Helium3 charge: 6.3L,
- Evaporator total operational heat load,
- Evaporator temperature of condensation,
- Condensation efficiency based on the evaporator temperature at the end of the condensation phase,
- Cryo-pumping efficiency based on the evaporator temperatures at the end of both the condensation and the cryo-pumping phase,
- Latent heat of evaporation based on the evaporator cold base temperature.

Note: Please note that the pump temperature is assumed to be at 45K to match the test done at cooler unit level.

Table 3-2 describes the cooler hold times measured at unit level for different test cases and the hold time predicted by the thermal model for the same evaporator total load and temperature of condensation.

| | **Units** | **Case1** | **Case2** | **Case1-2** | **Case2-2** | **Case 3** |
|---|---|---|---|---|---|---|
| **L1 / L0 Thermal Environment** | **[K]** | **1.6K / 1.8K** | | | | **1.7K / 4K** |
| Evaporator Parasitic Load | [uW] | 6.87 | 6.87 | 6.87 | 6.87 | 11.30 |
| Evaporator Applied Load | [uW] | 200.00 | 30.00 | 200.00 | 30.00 | 10.00 |
| Evaporator Total Load | [uW] | 206.87 | 36.87 | 206.87 | 36.87 | 21.30 |
| Temperature of Evaporator at End of Condensation | [K] | 2.15 | 2.15 | 2.1 | 2.1 | 2.1 |
| Temperature of Pump at End of Condensation | [K] | 45 | 45 | 45 | 45 | 45 |
| Measured Hold Time at Unit Level | [hr] | 7.07 | 39.63 | 7.08 | 40.45 | 69.08 |
| Estimated Hold Time with TMM | [hr] | 7.16 | 38.34 | 7.30 | 39.10 | 67.01 |
| Agreement | [%] | -1.3 | 3.3 | -3.1 | 3.3 | 3.0 |

*Table 3-2- Measured versus Predicted Cooler Hold Time for Unit Level Testing*

One can see that the model agrees with the measured data to within +/-3% which is an acceptable level of correlation.

### *3.1.3 Evaporator Parasitic Loads - Validation*

#### 3.1.3.1 Kevlar Parasitic Load

The Kevlar contribution to the cooler total parasitic load was measured for the PACS CQM unit [RD1] for a varying L1 thermal environment. The only difference between the PACS and the SPIRE cooler is the diameter of the Kevlar cords. PACS uses a 0.5mm cord diameter versus 0.29mm for SPIRE. Test data from the PACS cooler unit level test have therefore been used to validate the cooler thermal model. Table 3.3 describes the Kevlar parasitic loads predicted by the thermal model for the SPIRE cooler operating in two different L1 environments, 2K and 4K respectively. Based on these predictions, the Kevlar parasitics of the PACS cooler can be determined by applying a 2.97 factor (to replicate the increase in the Kevlar cords cross section from a 0.29mm to a 0.5mm diameter). When compared with the test data from the PACS CQM unit, one can see that the thermal model predictions for the Kevlar parasitics agree with the PACS test data to within 0.2 uW which is an acceptable level of correlation.

| **Thermal Environment 300mK / L1** | **SPIRE Kevlar Parasitic Load** | **PACS Kevlar Parasitic Load** |
|---|---|---|
| 0.28K / 2K | 0.32 uW | 0.95 uW |
| 0.28K / 4K | 1.534uW | 4.555 uW |
| Predicted increase in Kevlar Parasitic Load for L1 varying from 2K to 4K | 1.214 uW | 3.605 uW |
| Measured increase in Kevlar Parasitic Load for L1 varying from 2K to 4K | - | 3.4 uW |
| Agreement | - | 0.2 uW = + 6 % |

*Table 3-3 – SPIRE Cooler Model Prediction of Kevlar Parasitic Loads*

#### 3.1.3.2 Heat Switch Parasitic Load

The parasitic load from the evaporator heat switch is also another contributor to the cooler total parasitic load. The SPIRE evaporator heat switch OFF conductance was measured at unit level for the flight cooler and for a 1.6K thermal environment as described in Table 3.4 [RD2].

| **Evaporator Heat Switch OFF Conductance** | **SPIRE FM** | **Comments** |
|---|---|---|
| Applied Heater Load | 4.7 uW | - |
| Measured Temperature Increase | 0.833 K | - |
| OFF Conductance | $5.64 \times 10^{-6}$ W/K | At 1.6K |

*Table 3-4 – Measured Evaporator Heat Switch OFF Conductance at 1.6K*

This conductance was checked with the thermal model for the evaporator heat switch in OFF state and running at 1.6K.

Table 3-5 describes the predicted conductance versus the measured one and shows that the predicted data is currently underestimated by 27.5%.

| Heat Switch Held At 1.6K | OFF Conductance |
|---|---|
| Measured during FM Unit Level Test | 5.64x10$^{-6}$ W/K |
| Predicted with Thermal Model | 4.09 x10$^{-6}$ W/K |
| Agreement | -27.5 % |

*Table 3-5 – Evaporator Heat Switch OFF Conductance*

Based on this, the OFF conductance of the evaporator heat switch has been adjusted by a factor 1.3795 in the thermal model.

#### 3.1.3.3 Cooler Total Parasitic Loads

The SPIRE flight cooler total parasitic loads have been measured at unit level for two thermal environments, 1.6K/1.8K and 1.7K/4K respectively [RD3]. Table 3.6 shows the cooler total parasitic load predicted with the thermal model versus the ones measured at unit level.

| L0 / L1 Thermal Environments | 1.6K / 1.8K | | 1.7K / 4K | | Correlation Factor |
|---|---|---|---|---|---|
| | Measured | Predicted | Measured | Predicted | |
| L1 Kevlar Parasitic [uW] | - | 0.24 | - | 1.534 | 1 |
| Shunt Parasitic [uW] | - | 4.906 | - | 5.738 | 1.3795 |
| Heat Switch [uW] | - | 3.472 | - | 4.061 | 0.8 |
| Total Parasitic [uW] | 6.9 | 8.618 | 11.3 | 11.33 | - |
| Agreement | + 24.9% | | + 0.3% | | - |

*Table 3-6 – Correlated Cooler TMM Predictions versus Cooler Performances measured at Unit Level*

Note: A 1.3795 correlation factor was applied on the evaporator heat switch OFF conductance in order to match the unit level test result (see previous section). No test data were available to cross check the parasitic load from the shunt titanium tube. A 0.8 factor was applied to the shunt tube conductance to match the total parasitic load measured at unit level for the 1.7K/4K test case.

Table 3-6 shows that while the correlated model is in good agreement with the measured performances for the 1.7K/4K environment, higher discrepancies have been noted for the 1.6K/1.8K case. These are probably linked to higher uncertainties in the data used for the titanium thermal conductivity for the 0.2K-0.3K range i.e. the titanium thermal conductivity has been assumed constant within this range.

Note: Lionel Duband’s theoretical model predicted a total parasitic load of 8.5uW for the 1.6K/1.8K test case [RD3]. This value is within 1.3% of the data predicted by the thermal model and therefore in good agreement again despite the discrepancy with the actual measured value.

### *3.1.4 Evaporator Additional 300mK Loads - Validation*

The cooler total load consists of the evaporator own parasitic loads plus the load coming from the 300mK subsystem (five detectors and two busbars). The cooler total load has been characterised as part of the PFM2 ILT test campaign (using the pump characterisation test) for the 1.7K/4K thermal environment [RD5]. Results from the pump test are summarised in Table 3.7.

| **Thermal Environment** | **Parameters** | **Comments** |
|---|---|---|
| Shunt/Evaporator L0 Interface | 1.701K | - |
| L0 Photometer Enclosure Strap Interface | 1.715K | - |
| L0 Spectrometer Enclosure Strap Interface | 1.711K | - |
| L1 Enclosure | 4.375K | 4.275K at the L1 Thermal Interface plus 0.1K to the cooler L1 enclosure. |
| **Pump Characterisation Test** | **Parameters** | **Comments** |
| Pump Temperature | 1.868 K | - |
| Estimated Pump Adsorption Load (Qads) | ~ 1.21mW | Qads = (1.868-1.73) x 8.78 |
| Estimated Total Evaporator Load | 26.9uW | Using a 45 amplification factor [RD3] |

*Table 3-7 – Cooler Total Load Characterized for the 1.7K/4K Environment during PFM2 ILT*

A comparison of the measured cooler total heat load and the one predicted with the cooler thermal model is given in Table 3-8.

| **L0 / L1 Thermal Environment** | **1.7K / 4K** | |
|---|---|---|
| | **Measured** | **Predicted** |
| Photometer 300mK System [uW] | - | 12.53 |
| Spectrometer 300mK System [uW] | - | 5.07 |
| L1 Kevlar Parasitic [uW] | - | 1.89 |
| Shunt Parasitic [uW] | - | 5.76 |
| Heat Switch Parasitic [uW] | - | 4.08 |
| Total Cooler Load [uW] | 26.9 | 29.33 |
| Agreement | + 9% | |

*Table 3-8 –Cooler Total Load Predictions versus Measured Load during PFM2 ILT*

A 9% agreement on the cooler total load was not satisfactory so further analysis was carried out to try understand where this discrepancy might be coming from. The first step was to verify that the measured cooler total load was sensible for the measured cooler hold time. Table 3.9 summarises the parameters applicable to the measured cooler hold time and Figure 3-1 describes the cooler temperature profiles during the recycling.

| | **Parameters** | **Comments** |
|---|---|---|
| Evaporator Temperature at end of condensation | 1.86K / 2.1K | Here a range is given because of uncertainties in the test setup. |
| Pump temperature at end of condensation | 41.6K | Versus 45K at Unit Level |
| Measured Hold Time | 50 hr 25 min | - |
| Cooler Cold Base Temperature | 288.5mK | - |

*Table 3-9 – Cooler Hold Time Performances during PFM2 ILT*

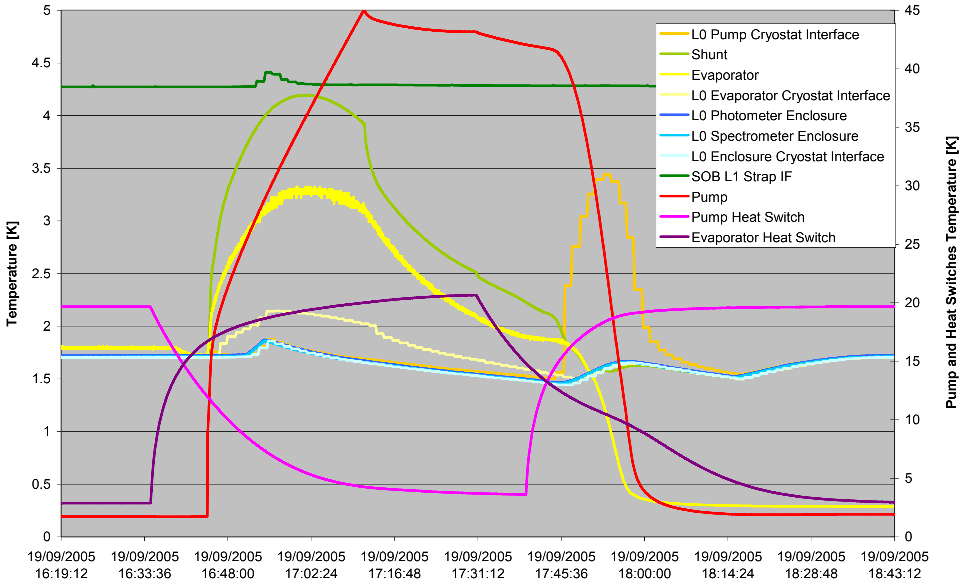

*Figure 3-1 Cooler Recycling Profile during PFM2 ILT*

The L0 interface temperature of the calibration cryostat was slightly varying during the cooler recycling and the pump temperature had been left unregulated. In order to define which temperature the evaporator was at the end of the condensation phase, the cooler adsorption curve was plotted as a function of the pump and evaporator temperatures for the end of the condensation period, as described in Figure 3-2 [RD5].

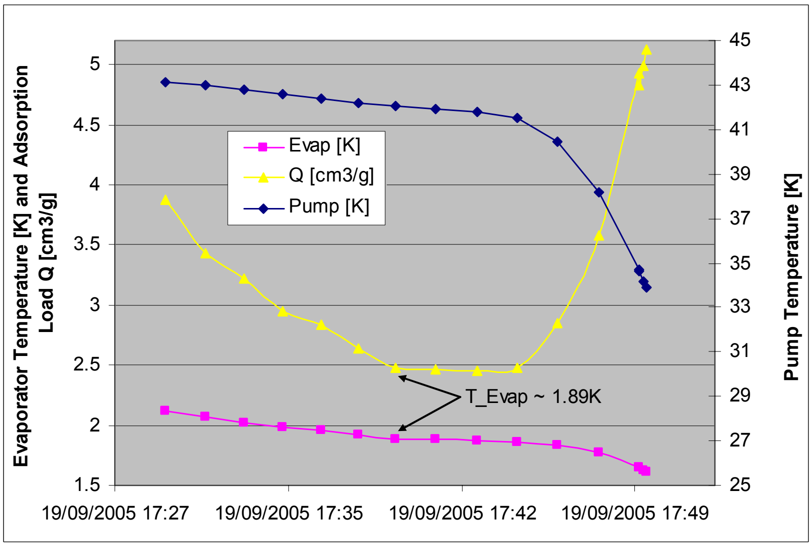

*Figure 3-2 – Adsorption Rate as a function of Evaporator and Pump Temperature*

One can see that the adsorption Q is still decreasing after 17:35, meaning the evaporator was still condensing. From 17:39 however, Q stabilises and the temperature of the evaporator at that time was used as the temperature of end of condensation ~ 1.89K. Using this parameter, the expected load on the cooler for the measured hold time could be checked as described in Table 3-10. This analysis shows that there is also a mismatch between the cooler total load calculated from the "pump characterisation test" and the total load expected based on the measured hold time and recycling conditions.

| | |
|---|---|
| Hold Time [hr] | 50.42 |
| Temperature of Condensation [K] | 1.89 |
| Expected Total Evaporator Load [uW] | 30.65 |
| Measured Total Evaporator Load [uW] | 26.9 |
| Agreement | + 13.9% |

*Table 3-10- Predicted Total Cooler Load based on Measured Hold Time*

Overall it appears that the cooler total load when calculated based on the pump characterisation test is underestimated by 9% to 14%. This means that new ways of assessing the cooler total load should be considered for the PFM3 ILT test campaign. When comparing the cooler total load predicted from the measured hold time with the one predicted with the thermal model (Table 3-11), a better agreement was found, with the thermal model currently under-estimating the cooler total load by 1.32uW.

| | |
|---|---|
| Total Evaporator Load Expected based on Measured hold time | 30.65 uW |
| Total Evaporator Load Predicted with Thermal Model | 29.33 uW |
| Agreement | - 4.3% |

*Table 3-11 - Cooler Total Load Predicted from Measured Hold Time and from the Thermal Model*

As mentioned previously, the pump was unregulated during the cooler recycling and its temperature had reached 41.6K when the cryo-pumping phase started (versus 45K during all tests at unit level). Some testing with the PACS FM cooler suggested that there is a 1%/1K relation between the cooler hold time and the temperature of the pump during recycling i.e. a reduction of 1K in the pump temperature from 45K reduces the cooler hold time by 1% [RD6]. With this in mind, the cooler total load predicted from the measured hold time was adjusted to account for the fact that the pump was not at 45K and compared again with the one predicted with the thermal model, as described in Table 3-12.

| | | |
|---|---|---|
| Measured Hold Time | [hr] | 50.42 |
| Pump Temperature at End of Condensation Phase | [K] | 41.6K |
| Expected Reduction of Hold Time | [%] | 3.4K<br>=> 3.4% |
| Predicted Hold Time with Pump at 45K | [hr] | 52.19 |
| Temperature of Condensation | [K] | 1.89 |
| Expected Cooler Total Load based on effective hold time. | [uW] | 29.62 |
| Predicted Cooler Total Load with Thermal Model. | [uW] | 29.33 |
| Agreement | [%] | - 1% |

*Table 3-12 - Predicted Total Cooler Load based on Measured Hold Time*

This analysis suggests that the expected total cooler load (based on the hold time measured during the PFM2 test campaign) is in good agreement with the load predicted by the thermal model for a similar thermal environment.

### *3.1.5 Cooler Thermal Model Validation - Conclusions*

It was demonstrated in the previous sections that:

- The cooler parasitic loads predicted by the thermal model are in good agreement with the cooler performances measured at unit level,
- The additional 300mK heat load predicted by the thermal model is also in good agreement with test data from the ILT PFM2 test campaign,
- The pump characterisation test appears to underestimate the cooler total load by 9% and a new way of assessing the cooler total load should be considered for the PFM3 ILT test campaign.

This analysis completes the validation of the cooler thermal model.

## 3.2 Herschel Thermal Environment – Interface Temperatures Predictions

### *3.2.1 Overview*

As mentioned in section 2.2.2, the Herschel interface temperatures during the mission will depend on SPIRE owns operational heat loads. Some of these loads have been characterised as part of the ILT PFM2 test campaign and will be used to define the worst case thermal environment the instrument is likely to experience during the mission. As the evaporator temperature of condensation, the L1 and L0 temperature stages of the instrument are the main drivers for the cooler hold time, they will be investigated in more details in the following sections.

### *3.2.2 Evaporator - Temperature of Condensation*

The evaporator temperature of condensation during recycling is driven by the following parameters:

- Herschel L0 Evaporator interface temperature,
- Temperature drop along the SPIRE L0 evaporator strap,
- Temperature drop internal to the cooler.

The heat load flowing on the instrument evaporator strap at the end of the condensation phase has been measured during unit test level with the flight cooler and is about 15mW. For this heat load, the worst case interface temperature agreed at the Herschel L0 evaporator interface is 1.85K (1.75K as a goal).

The conductance of the SPIRE L0 evaporator strap has been measured at unit level and is about 0.125W/K at 1.7K [RD7]. It is important to note that this measurement includes the spacecraft interface but not the evaporator heat switch interface. According to the Herschel Thermal Model (Issue 4), the spacecraft interface conductance should be ~2.4W/K at 1.7K. This means that the evaporator strap conductance (excluding interface at heat switch) should be ~0.132W/K at 1.7K. This leads to a 0.114K temperature drop along the strap for a 15mW heat load.

Finally, the temperature drop internal to the cooler (and including the interface conductance at the evaporator heat switch) has been measured during the CQM2 test campaign and is ~0.23K at 1.7K.

Table 3-13 summarises the range of temperatures that can be expected at the evaporator towards the end of a recycling condensation phase during the mission:

| | **Requirement / Goal** |
|---|---|
| Herschel L0 Evaporator Interface Temperature | 1.85K / 1.75K |
| Temperature Drop along L0 Evaporator strap | 0.114K |
| Temperature Drop Internal to Cooler | 0.23K |
| Temperature of Evaporator at end of condensation | 2.2K / 2.1K |

*Table 3-13 – Predicted Evaporator Temperature of Condensation*

### 3.2.3 L1 Temperature

As described in Table 2-2, the L1 interface temperature will be about 5.5K for a 15mW operational load (3.7K as a goal). The Instrument L1 heat load has been characterised during the PFM2 test campaign and further correlation with the thermal model is required to define the parasitic load through the L1 supports. A recent change in the material of one of these supports will also have to be evaluated as part of the PFM3 ILT test campaign. In addition, the SPIRE L1 operational load is also highly dependent on others parameters such as:

- The thermal environment in the Herschel cryostat (HOB temperature and radiation load),
- The parasitic load from the Herschel housekeeping cryo-harness.

For the purpose of this study, it is assumed that the SPIRE L1 operational heat load is equal to the required 15mW. Based on this, Table 3-14 summarises the thermal interface temperatures that can be expected during the mission.

| | **Requirement / Goal** |
|---|---|
| Herschel L1 Interface Temperature | 5.5K / 3.7K |

*Table 3-14 - Predicted L1 Interface Temperature*

### 3.2.4 L0 Enclosures Temperature

As described in Table 2-2, the temperature at the Herschel L0 Detector interface has been defined for a given instrument operational heat load at this interface. This heat load has been characterised under various conditions as part of the CQM2 and PFM2 test campaign. A summary of the method used to estimate this load is presented hereafter.

The interbox strap conductance was characterised during the ILT CQM2 test campaign using an EGSE heater on the L0 photometer enclosure. This test could not be repeated during the PFM2 test campaign as the EGSE heater failed during cool down. The test from the CQM2 test campaign will therefore be used as an input to this analysis. The temperature drop between the temperature sensor on the L0 photometer box (at the interbox strap interface) and the sensor on the MGSE L0 enclosure strap (on the adaptor) was monitored for different heater power dissipation as described in Table 3-15.

| **Heater Dissipation** | **0mW** | **5 mW** | **10mW** |
|---|---|---|---|
| Temperature at the Photometer Box (at Strap IF) | 1.764K | 1.938K | 2.100K |
| Temperature at the L0 MGSE Detector Strap (on Adaptor) | 1.728K | 1.799K | 1.869K |
| Temperature Gradient | 0.0359K | 0.1395K | 0.231K |

*Table 3-15 – Temperature Drop between Photometer Enclosure and MGSE Strap Adaptor during the CQM2 ILT*

Table 3-16 and Figure 3-3 on the following page describe the characterisation of the L0 interbox strap conductance using a linear curve fit through the test data presented in Table 3-15.

| Average Temperature | Qh [mW] | Delta [K] | G [mW/K] |
|---|---|---|---|
| 1.746 | 0 | 0.0359 | 54.5 |
| 1.868 | 4.865 | 0.1395 | 48.3 |
| 1.985 | 9.9 | 0.231 | 50.6 |

*Table 3-16- SPIRE CQM2 L0 Interbox Strap Conductance Characterisation*

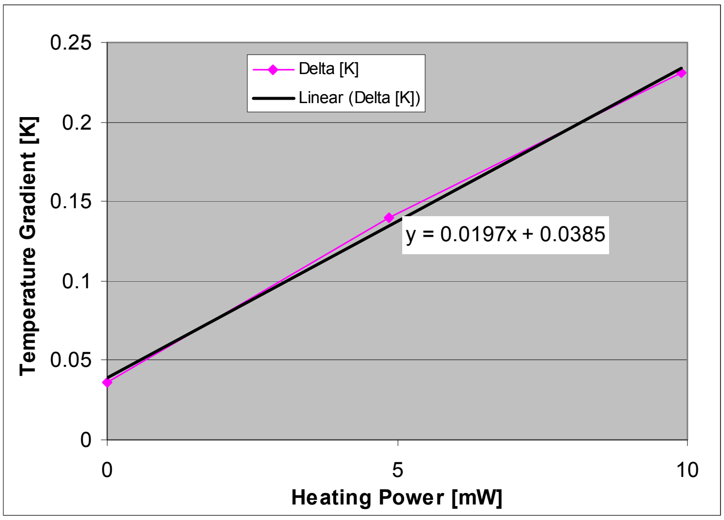

*Figure 3-3 - SPIRE CQM2 L0 Interbox Strap Conductance Characterisation*

The interbox strap for the PFM2 model has been made from the same batch of material as for the CQM2 and the temperature sensors have been fitted at the same locations. The temperature drop between the photometer enclosure and the L0 strap adaptor has therefore been measured again as part of the PFM2 test campaign as described in Table 3-17.

| | |
|---|---|
| Temperature at the Photometer Box (at Strap IF) | 1.715K |
| Temperature at the L0 MGSE Detector Strap (on Adaptor) | 1.707K |
| Temperature Gradient | 0.008K |

*Table 3-17 – L0 Interbox Strap Temperature Drop to MGSE Adaptor Strap for PFM2*

The worst case L0 interbox strap conductance estimated from the CQM2 characterisation test was used to estimate the heat load flowing on the L0 detector strap:

0.008K x 0.055W/K = 0.44mW for a 1.7K/4.3K thermal environment

In addition, an additional heat load of 0.241mW has been predicted with the thermal model coming from the L0 detector strap own Torlon supports off the L1 temperature stage. A total of 0.68mW is therefore currently predicted at the L0 detector strap interface for a 1.7K/4.3K thermal environment. For a L1 interface temperature of 5.5K, this load would increase by a factor 1.462 ([5.5-1.7] / [4.3-1.7]), leading to an overall heat load of 0.994 mW at the L0 detector strap interface for a 1.7K/5.5K thermal environment.

For the purpose of this study, it is assumed that the SPIRE L0 detector strap operational heat load will be equal to 1mW for the worst case thermal environment. Based on this, Table 3-16 summarises the thermal interface temperatures that can be expected during the mission at the SPIRE L0 detector strap interface.

| | Requirement | Goal |
|---|---|---|
| Interface Definition in IIDB | 2K for 4mW with HeII Base Temperature of 1.7K | 1.71K for 1mW with HeII Base Temperature of 1.7K |
| Herschel L0 Detector Strap Interface Temperature | 1.775K | 1.71K |

*Table 3-18 - Predicted L0 Detector Strap Interface Temperature*

### *3.2.5 HERSCHEL Thermal Environment – Summary*

Table 3-19 summarises the interface temperatures which should be used in order to predict SPIRE flight thermal performances.

| | Requirements | Goals |
|---|---|---|
| L0 Evaporator Interface Temperature | 1.75K | 1.85K |
| Expected Evaporator Temperature at the end of condensation phase | 2.2K | 2.1K |
| L0 Detector Interface Temperature [*] | 1.775K | 1.71K |
| Expected L0 spectrometer Enclosure Strap Interface Temperature | 1.787K | 1.718K |
| Expected L0 Photometer Enclosure Strap Interface Temperature | 1.795K | 1.722K |
| L1 Temperature [**] | 5.5K | 3.7K |

*Table 3-19 –Expected Herschel Thermal Interface Temperatures - Summary*

[*] This interface temperature was transformed into an interface temperature at each L0 enclosures based on the 1mW maximum heat load and on the measured L0 Detector strap performance (0.26W/K at 1.7K excluding the interface at the spectrometer enclosure [RD7]).

[**] A maximum 0.1K temperature gradient has been measured between the cooler L1 enclosure and the L1 thermal interface. This has been accounted for in the analysis.

## 3.3 SPIRE PFM2 Flight Thermal Performance Predictions

### *3.3.1 Herschel "Goal" Interface Temperatures Predictions*

Table 3-20 summarises the predicted thermal performance of SPIRE from the test data measured during the ILT PFM2 test campaign to the expected interface temperatures based on the IIDB goal interface temperatures.

| | **PFM2** | **Case 1** | **Case 2** | **Case 3** | **Goals** |
|---|---|---|---|---|---|
| Pump Temperature at the end of condensation | 41.6K | 41.6K | **45K** | 45K | 45K |
| Evaporator Temperature at the end of condensation | 1.89K | **2.1K** | 2.1K | 2.1K | 2.1K |
| L0 Enclosures Interface Temperature Cryostat | 1.702K | 1.702K | 1.702K | 1.710K | 1.710K |
| L0 Detector Strap Adaptor | 1.707K | 1.707K | 1.707K | 1.714K | 1.714K |
| Temperature at the Spectrometer Box (at Strap IF) | 1.711K | 1.711K | 1.711K | **1.718K** | 1.718K |
| Temperature at the Photometer Box (at Strap IF) | 1.715K | 1.715K | 1.715K | **1.722K** | 1.722K |
| L1 I/F Temperature | 4.275K | 4.275K | 4.275K | 4.275K | **3.7K** |
| Delta T between TSOB and Cooler L1 enclosure | 0.1K | 0.1K | 0.1K | 0.1K | 0.1K |
| Cooler L1 Enclosure | 4.375K | 4.375K | 4.375K | 4.375K | 3.8K |
| Total Cooler Load | 29.32uW | 29.32uW | 29.32uW | 29.59uW | 29 uW |
| Cooler Hold Time | 50.92 hr | 47.49 hr | 49.16 hr | 48.72 hr | 49.71 hr |

*Table 3-20 – SPIRE Flight Thermal Performance Predictions for the Goals Interface Temperatures*

### *3.3.2 Herschel “Requirement” Interface Temperatures Predictions*

Table 3-21 summarises the predicted thermal performance of SPIRE from the goal predicted performances to the expected interface temperatures based on the IIDB requirement interface temperatures.

| | **Case 4** | **Case 5** | **Requirements** |
|---|---|---|---|
| Pump Temperature at the end of condensation | 45K | 45K | 45K |
| Evaporator Temperature at the end of condensation | **2.2K** | 2.2K | 2.2K |
| L0 Enclosures Interface Temperature Cryostat | 1.710K | 1.710K | 1.775K |
| L0 Detector Strap Adaptor | 1.714K | 1.714K | 1.779K |
| Temperature at the Spectrometer Box (at Strap IF) | 1.718K | 1.722K | **1.787K** |
| Temperature at the Photometer Box (at Strap IF) | 1.722K | 1.730K | **1.795K** |
| L1 I/F Temperature | 4.275K | 5.5K | 5.5K |
| Delta T between TSOB and Cooler L1 enclosure | 0.1K | 0.1K | 0.1K |
| Cooler L1 Enclosure | 4.375K | **5.6K** | 5.6K |
| Total Cooler Load | 29.59uW | 31.43uW | 32.85uW |
| Cooler Hold Time | 46.81 hr | 44 hr | 42.16 hr |

*Table 3-21 – SPIRE Flight Thermal Performance Predictions for the Requirement Interface Temperatures*

# 4 CONCLUSION

This analysis shows that:

- SPIRE currently meets its 46hr hold time requirement in the Herschel “goal” thermal environment and even exceeds it by 3.71 hr.
- SPIRE does not currently meet its 46hr hold time requirement in the Herschel “requirement” thermal environment and is short of 3.84 hr.

It is important to note that:

- This analysis assumes that the SPIRE L1 operational heat load will not exceed 15mW. This will be confirmed by correlation of the PFM3 test campaign results with the thermal model.
- Any additional load from the Photometer Thermal Control (PTC) has not been accounted for.