SPIRE Cooler Performance Degradation

During PFM3 Testing

THERMAL ENGINEERING GROUP				
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SPIRE PROJECT				
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1. Introduction

Degraded cooler performance was detected during recyclings completed as part of the PFM3 test campaign. A NCR [RD1] was raised to trace this issue and analysis has since been on-going to try establish the most likely cause for this degradation. This technical note summarises the results of analyses completed to date.

2. Reference Documents

ID	Title	Number
RD1	NCR - Cooler Thermal Interfaces	HR-SP-RAL-NCR-150 24/05/06
RD2	Cooler Recycling Systematic Analysis.xls	13/07/06

Table 1 – Reference Documents

3. Background

During the PFM3 test campaign, the cooler recycling temperature profiles appeared to run warmer than usual (i.e. in comparison with data from the PFM2 test campaign) and to take longer to cooldown. Both observations suggest that the cooler is not as well coupled to the L0 temperature stage as it uses to be. A preliminary analysis of the profiles was carried out during a telecon with Lionel Duband and several possible causes were identified and discussed. Conclusions from this discussion were recorded in the NCR150 and a degraded joint conductance between the cooler heat switches and the L0 GSE straps was thought to be the most likely cause for this change in cooler behaviour. Because of the limited number of temperature sensors inside the cooler, it was not possible to rule out a possible internal degradation of the heat switches and/or cooler straps. Given that this is critical to the instrument flight performance, it was decided that further analysis should be carried out to try rule out as many options as possible. The following analysis has been completed and is summarised hereafter:

- Systematic check of the cooler temperature gradients during all recyclings performed during PFM3 and confirms whether there are any signs of degradation.

- Systematic check of all the cooler hold times measured during PFM3 and confirms whether there are any signs of degradation. This analysis could not be done easily for reasons explained in later section.

4. Systematic Analysis of the Cooler Gradients during Recycling

In this analysis, the temperature gradients between the evaporator as well as shunt and the top of the L0 strap have been tabulated for the several recyclings performed during PFM2 and PFM3 and at various but specific times during the recycling. The specific times used for comparison purpose are as follows:

- Start of cooler recycling – when pump heater is turned ON,
- Peak condensation – when maximum shunt and evaporator temperatures are recorded,
- Peak pump – when pump reaches 45K and heater turned down,
- End of condensation – when evaporator heat switch is turned OFF,
- Low operation phase – when evaporator reaches 295mK.

Table 2 summarises the data gathered for two PFM2 recyclings and five PFM3 recycling (including the first one '1' and the last one '17' of the PFM3 test campaign).

	PFM2	PFM2	PFM3	PFM3	PFM3	PFM3	PFM3
Date	**19/09/2005**	**26/09/2005**	**08/05/2006**	**10/05/2006**	**12/05/2006**	**15/05/2006**	**23/06/2006**
Recyclings	**#1**		**1**	**2**	**#1**	**3**	**17**
Time 1 - Start Recycling (Pump Q ON)	**16:44:28**	**10:36:02**	**15:33:57**	**19:59:43**	**17:13:13**	**13:26:37**	**08:32:12**
Pump 1	1.753	1.772	5.064	2.015	1.962	9.644	2.346
Pump HS 1	11.982	11.941	3.034	15.072	10.647	3.022	11.915
Evap HS 1	16.707	16.706	8.849	13.741	19.699	7.155	16.590
Shunt 1	1.716	1.732	1.714	1.661	1.899	1.785	1.707
Evap 1	1.717	1.743	2.699	0.411	1.940	1.804	1.736
L0 Evap Adapt 1 1	1.708	1.724	1.699	1.711	1.886	1.715	1.692
L0 Evap Adapt 2 1	1.704	1.720	1.697	1.709	1.881	1.709	1.689
L0 Detect Adapt 2 1	1.704	1.719	1.698	1.710	1.880	1.708	1.690
Time 2 - Peak Condensation	**17:00:58**	**10:53:04**	**15:54:00**	**20:23:51**	**17:32:45**	**13:44:53**	**08:50:12**
Pump 2	35.417	35.793	38.610	39.613	38.339	37.300	36.963
Pump HS 2	5.577	5.436	3.490	5.003	4.702	3.394	5.182
Evap HS 2	19.305	19.358	19.302	19.751	20.143	19.058	19.640
Shunt 2	4.193	4.174	4.434	4.432	4.441	4.404	4.388
Evap	3.282	3.302	3.772	3.772	3.827	3.666	3.640
L0 Evap Adapt 1 2	2.576	2.536	2.539	2.604	2.545	2.401	2.378
L0 Evap Adapt 2 2	2.125	2.069	2.113	2.203	2.118	1.941	1.923
L0 Detect Adapt 2 2	1.764	1.677	1.888	2.003	1.892	1.663	1.649
Shunt / Strap Gradient	1.617	1.638	1.895	1.828	1.896	2.003	2.010
Evap / Strap Gradient	0.705	0.766	1.232	1.168	1.282	1.265	1.261
Time 3 - Peak Pump (400mW OFF)	**17:11:36**	**11:03:18**	**16:02:07**	**20:29:46**	**17:40:43**	**13:53:24**	**08:59:03**
Pump 3	45.095	45.026	45.972	45.103	44.997	45.090	45.063
Pump HS 3	4.265	4.223	3.731	4.465	4.186	3.622	4.260
Evap HS 3	20.010	20.031	20.077	20.165	20.465	19.985	20.257
Shunt 3	3.918	3.891	4.268	4.312	4.138	4.227	4.202
Evap 3	3.096	3.096	3.640	3.666	3.640	3.519	3.519
L0 Evap Adapt 1 3	2.463	2.434	2.541	2.624	2.509	2.389	2.319
L0 Evap Adapt 2 3	2.023	1.991	2.159	2.250	2.105	1.921	1.829
L0 Detect Adapt 2 3	1.653	1.605	1.959	2.070	1.893	1.637	1.508
Shunt / Strap Gradient	1.455	1.457	1.727	1.687	1.629	1.838	1.883
Evap / Strap Gradient	0.633	0.662	1.099	1.042	1.131	1.130	1.200
Time 4 - End Cond (HS OFF)	**17:30:57**	**11:26:17**	**16:46:40**	**21:38:54**	**18:37:47**	**14:39:33**	**09:37:27**
Pump 4	43.133	43.035	44.347	44.862	44.929	43.699	45.024
Pump HS 4	3.713	3.649	3.646	3.683	3.761	3.624	3.674
Evap HS 4	20.638	19.991	21.017	21.050	20.985	21.005	21.111
Shunt 4	2.505	2.371	2.400	2.426	2.616	2.399	2.392
Evap 4	2.098	1.975	1.995	2.026	2.313	2.013	2.006
L0 Evap Adapt 1 4	1.866	1.787	1.634	1.758	2.035	1.703	1.642
L0 Evap Adapt 2 4	1.686	1.622	1.475	1.633	1.933	1.567	1.476
L0 Detect Adapt 2 4	1.531	1.477	1.369	1.569	1.884	1.487	1.367
Shunt / Strap Gradient	0.639	0.584	0.766	0.668	0.581	0.696	0.750
Evap / Strap Gradient	0.233	0.188	0.361	0.268	0.278	0.310	0.364
Time 5 - Low Phase (295mK)	**18:15:35**	**12:07:22**	**17:32:57**	**22:23:34**	**19:37:57**	**15:25:15**	**10:20:30**
Pump 5	1.917	1.940	1.996	1.978	2.075	2.002	1.822
Pump HS 5	19.588	19.582	19.340	19.327	19.386	19.325	17.687
Evap HS 5	4.708	4.882	4.553	4.908	3.393	4.610	5.616
Shunt 5	1.512	1.546	1.707	1.661	1.844	1.709	1.361
Evap 5	0.295	0.295	0.295	0.295	0.295	0.295	0.295
L0 Evap Adapt 1 5	1.509	1.506	1.694	1.644	1.869	1.694	1.364
L0 Evap Adapt 2 5	1.508	1.507	1.693	1.643	1.865	1.693	1.361
L0 Detect Adapt 2 5	1.510	1.510	1.694	1.645	1.864	1.695	1.366
Shunt / Strap Gradient	0.002	0.040	0.013	0.017	-0.025	0.014	-0.004
Evap / Strap Gradient	-1.214	-1.211	-1.399	-1.349	-1.574	-1.399	-1.069

Table 2 - Systematic Analysis of the cooler gradients during Recyclings

Note: The temperature gradient between the evaporator and the shunt remains unchanged for all recycling for the end of condensation case.

The temperature gradients were plotted for all recyclings versus the temperature of the L0 stage as described in Figure 1 (here for the peak condensation case). This analysis allowed to identify three important aspects of the cooler behaviour during recycling:

- The gradient experienced during recycling are varying slightly depending on the temperature of the L0 stage i.e. the colder the L0, the larger the gradient as the conductance of the interfaces and materials decreases with temperature.
- The gradients appears to vary linearly with temperature for a given test campaign and allows in a way to confirm that the cooler performance has been consistent throughout the given test campaign.
- The degradation of the cooler performance has been confirmed and could be estimated more precisely as summarised in the table 3 below:

Temperature Gradient [K]	**PFM2**	**PFM3**	**Ratio**
Recycling ID	**2**	**3**	**-**
Shunt / Strap	1.638	2.003	1.223
Evap / Strap	0.766	1.265	1.651

Table 3 – Cooler Gradients Degradation during Peak Condensation Period with L0 stage at about 1.67K

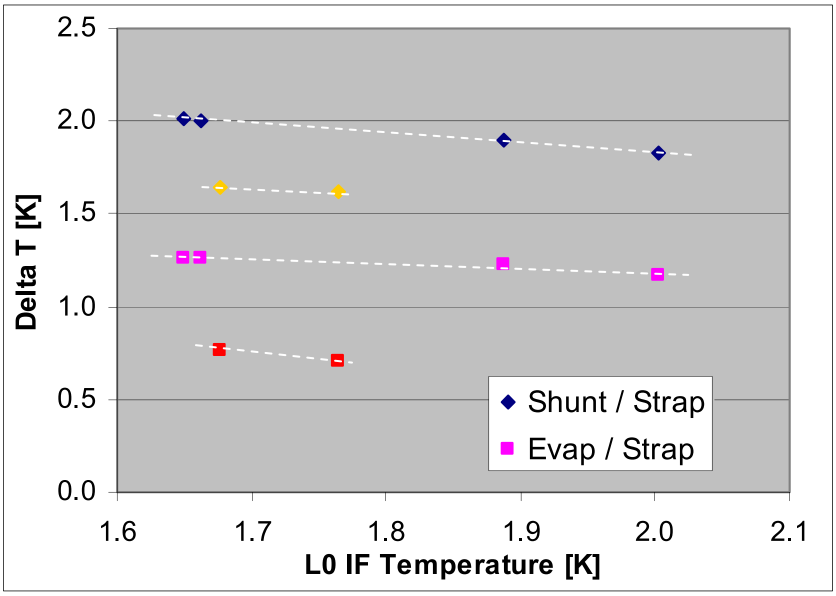


Figure 1 – Cooler Temperature Gradient during Recycling at the peak condensation Time

Note: The orange and red data points are for the PFM2 shunt/strap and evap/strap gradients respectively while the blue and pink data points are for the PFM3 shunt/strap and evap/strap gradients.

Based on this observation, further analysis was carried out using a thermal mathematical model of the cooler. The cooler model has been tuned to generate temperature profiles during recycling similar to the ones obtained during the unit level testing of the flight cooler. The assumptions and limitations of this analysis are discussed in more details in the following section.

5. Assumptions/Limitation of Cooler Thermal Modelling

- The cooler condensation load has been characterised at unit level and was used as an input to the thermal model to simulate the thermodynamic behaviour of the cooler during the condensation phase. The following curve fits were used to simulate the condensation load inside the cooler. This assumes that the condensation load doesn't change much from one recycling to the other, which is probably acceptable as the pump has always been warmed-up in the same way and from a discharged cooler in all the cases investigated here.

Note: The parasitic load coming from the pump at 45K was removed from the measured load.

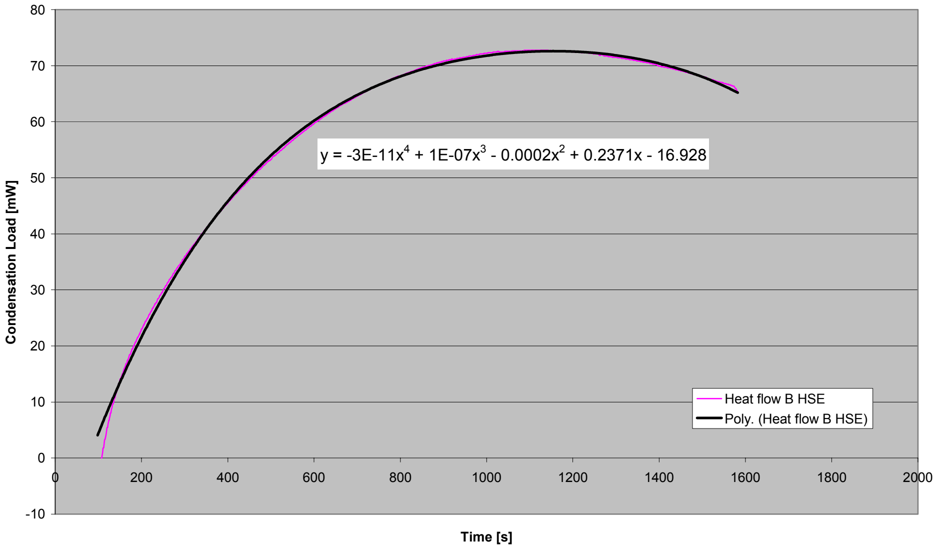


Figure 2-a – Cooler condensation load curve fits from 0 to 1860 sec

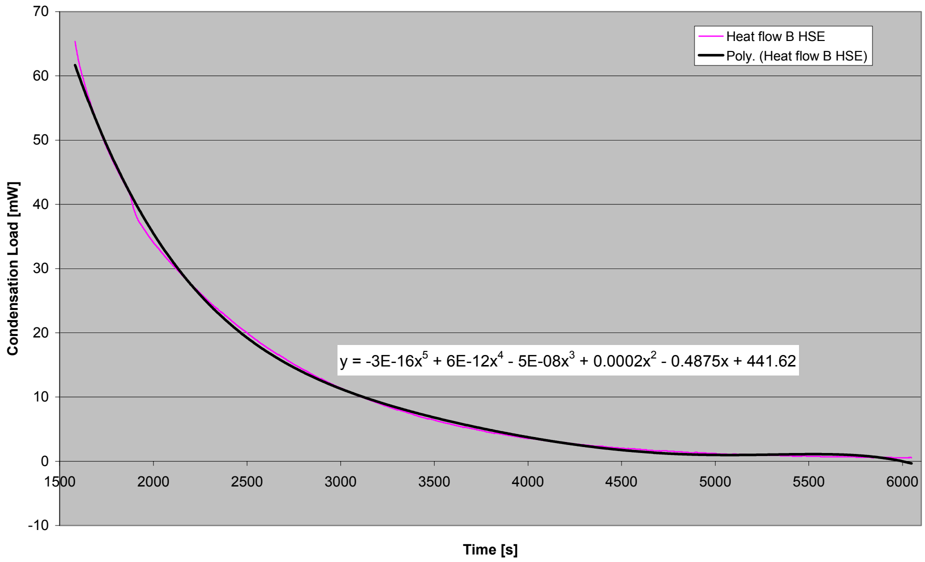


Figure 2-b – Cooler condensation load curve fits from 1860 sec to 5900 sec

- It was assumed that 83% of the condensation load was taken by the shunt strap and the remaining 17% by the evaporator strap.

- A factor 1.15 was added to the evaporator internal strap conductance to obtain a good correlation of the thermal model with test data from the PFM2 test campaign (for the PFM2 recycling #1 described in Table 1). The temperature correlation is described in Table 4 below at the peak condensation time.

Temperature [K]	PFM2	TMM	Delta
shunt	4.194	4.195	0.001
evap	3.281	3.284	0.003
L0 strap top	2.574	2.573	0.001
L0 strap bottom	2.132	2.132	0.000
L0 detector	1.784	1.784	0.000
Energy [J]	**Unit Level**	**TMM**	**Ratio**
Evap Strap	25.5	22	0.86
Pump Strap	234	225	0.96

Table 4 – Transient Correlation of thermal model with PFM2 recycling test data

Once an acceptable correlation was obtained, the cooler thermal model was run in transient for various heat switches and bolted interface degraded conductances to try obtain the performance measured during the PFM3 test campaign. The following observations could be made:

- A degraded 'heat switch / strap' interface conductance affects both the shunt and the evaporator temperatures in a similar way so it does not explain in itself why we observe a larger degradation on the evaporator strap (x1.65) than on the shunt strap (x1.22).

The following other possibilities remain:

- The evaporator heat switch ON conductance has somehow degraded,
- The evaporator internal strap conductance has degraded (if not braids, bolted interfaces).

Another educated guess:

Until now, it was assumed that the condensation heat load breakdown between the shunt and the evaporator straps was similar for PFM2 and PFM3. Because of the warmer temperatures experienced during PFM3 at the shunt however it could be that more condensation is now taking place at the evaporator than before.

Should this be the case, then a 0.3 degradation of the 'heat switch / strap' interface conductance followed by a shift of the condensation load breakdown from 0.83/0.17 for PFM2 to 0.78/0.22 for PFM3 would suffice for the thermal model to correlate with the PFM3 test data.

Note: a similar correlation could probably be obtained by degrading the shunt and evaporator internal straps. Despite this analysis, there is still no way to tell whether the evaporator heat switch has been degraded but the previous explication if acceptable, would explain why a different shift has been observed on both the shunt and the evaporator.

6. Systematic Analysis of the cooler hold time throughout the PFM3 test campaign

This analysis has proven difficult for the following reasons:

- The cooler has not always been left to run out as there was a need to optimise the time at which recyclings could be done,
- The cryostat manostat has been left opened in some cases after the recycling meaning that the instrument L0 stage could be as cold as 1.4K, thus making the comparison quite difficult.
- Some issues experienced with the calibration cryostat meant that the L0 stage was running out of helium overnight preventing again any easy comparison.

During the first PFM3 recycling, a minimum cooler hold time of 50 h 16 min was recorded for a 1.8K-2K condensation temperature and in the nominal 1.7K/4.3K thermal environment. This is very similar to the one measured during the PFM2 thermal test case where a 50 h 25 min hold time was recorded for similar conditions. This allows to confirm that no major degradation of the cooler has been experienced once in low temperature operation phase. Plots of the cooler PFM2 and PFM3 recyclings and thermal environment are given in appendix 9 for information.

Note: the heat switch ON conductance would not have any impact on the cooler hold time unless it restricts the temperature of the evaporator at the end of the condensation phase.

7. Additional Analysis – Change in Pump Temperature during Recycling

Changes in the pump L0 strap temperatures during the cryo-pumping phase have also been observed during the PFM3 test campaign. A pump characterisation test (5mW test case) did not show any degradation of the heat switch and/or strap conductance when compared to data from the PFM2 test campaign however.

When comparing the temperature drop between the pump and the top of the L0 strap as well as the gradient along the L0 strap during the peak of the cryo-pumping phase, the following observations could be made:

- The temperature drop along the L0 strap has decreased by about 0.82, suggesting that the peak load has decreased by about 18%.
- The temperature drop between the pump and the top of the L0 strap has increased by about 1.23,
- Despite this change, the pump seems to take about as long to cooldown down as during PFM2.

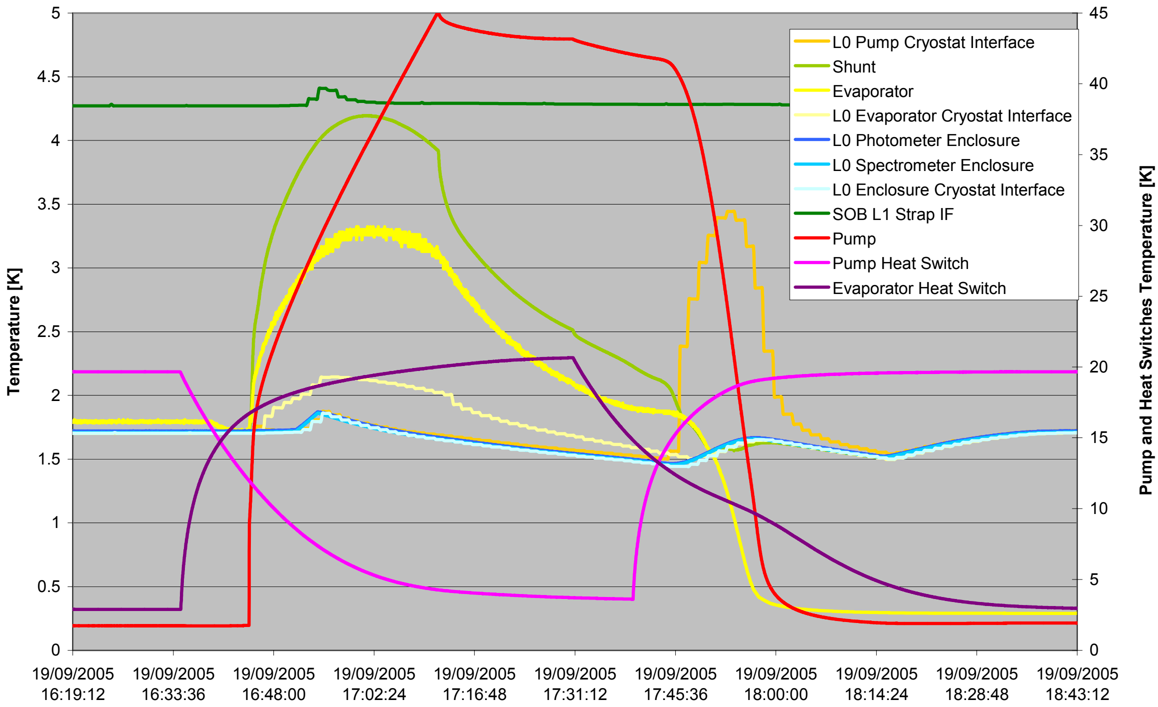
Note: this is an approximation as the gradients were difficult to check because of the way the AC bridge works (i.e. the temperature update rate is only every 1-2 min which means that the data we have might actually miss the maximum L0 pump strap temperature peak during cryo-pumping).

It is important to note that during cryo-pumping, the peak heat load can be as high as 1W. Therefore, a ~20% reduction in strap temperature gradient could easily be caused by a degraded interface conductance between the heat switch and the GSE strap i.e. when such heat load are experienced, it doesn't mean that the most limiting components is actually at the origin of it. Assuming that the peak heat load is 0.5W, the heat switch conductance is in the order of 0.035W/K and the strap/heat switch bolted interface is about 0.4K, a degradation factor of 4 on the bolted interface would suffice to obtain the measured pump gradients. This in itself isn't unlikely.

8. Preliminary Conclusions

It seems likely that the interface between the heat switches and the L0 GSE straps is at the origin of the degraded cooler performances experienced during PFM3.

9. Appendix



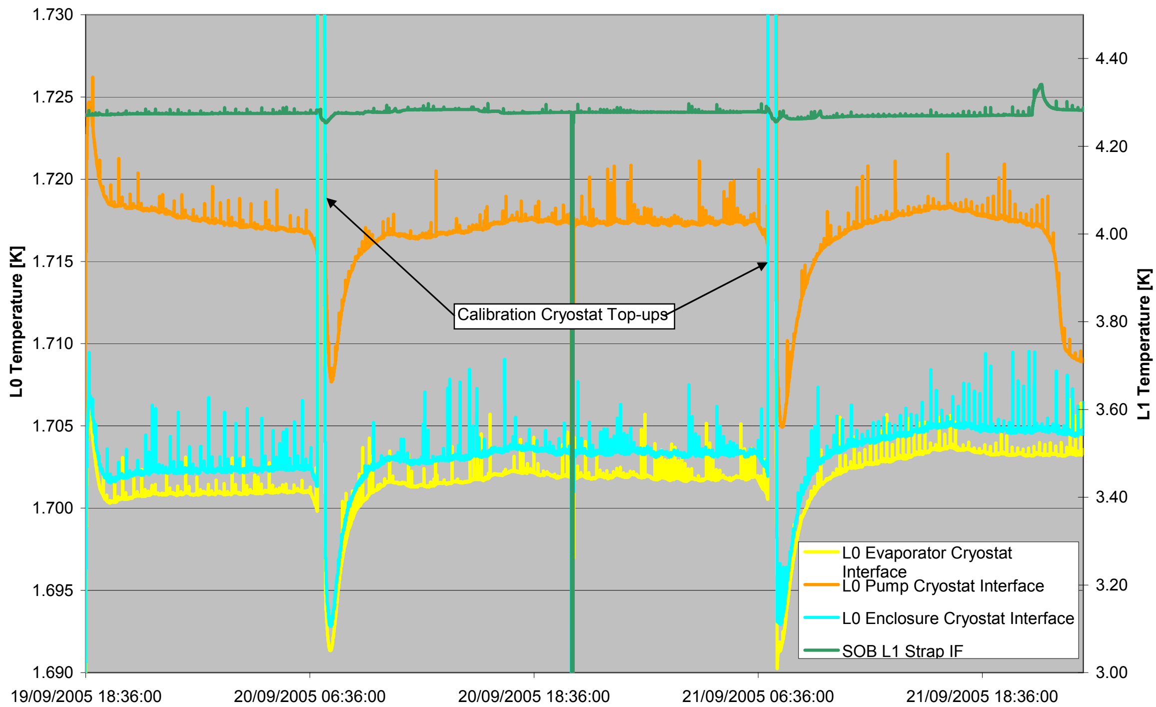
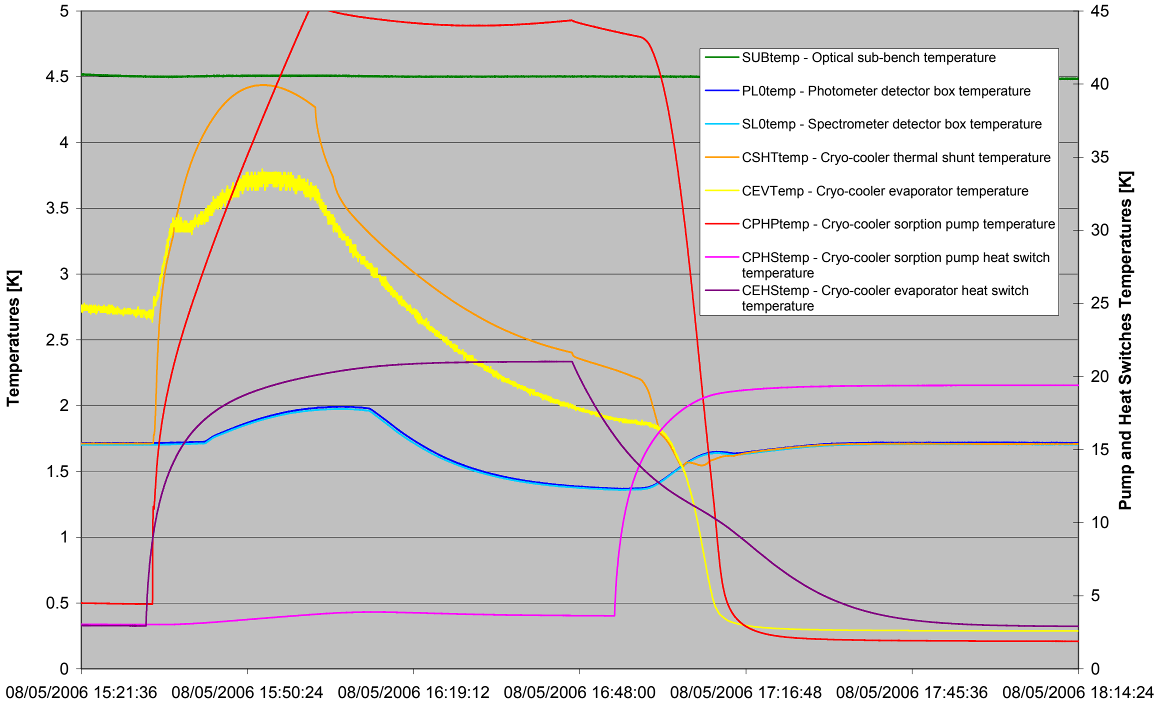


Figure 3 - Thermal Environment during PFM2 Nominal Thermal Test Case
Hold time: 50h25mn for an Evaporator Condensation Temperature of 1.89K



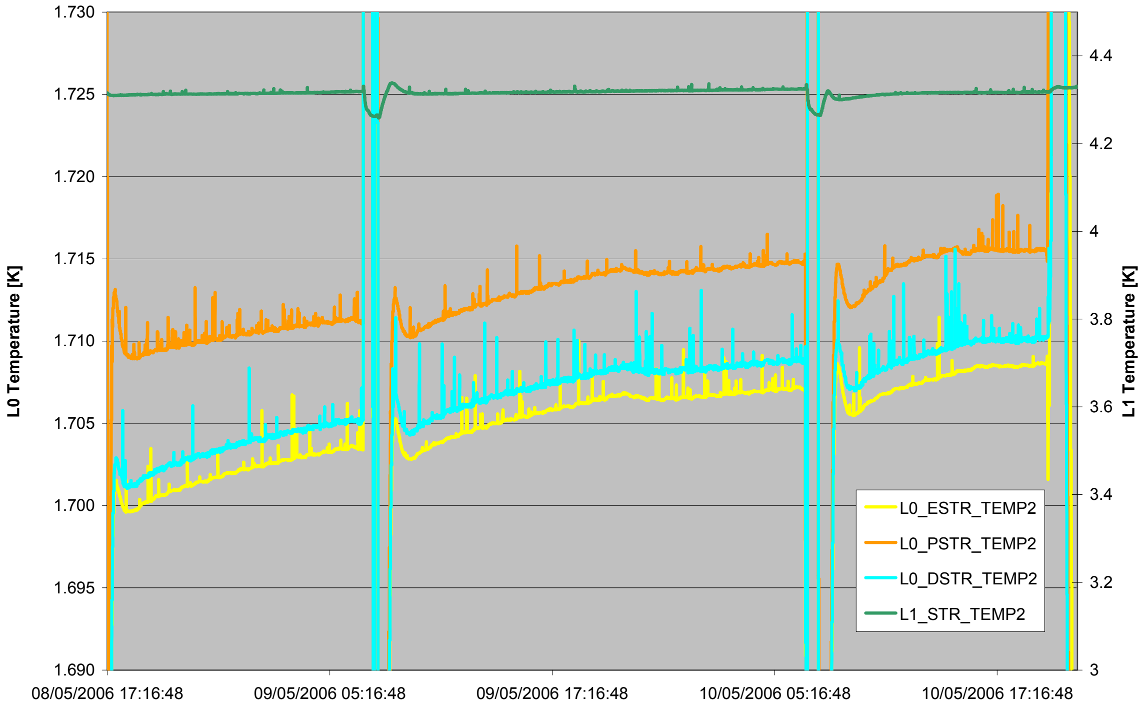


Figure 4 - Thermal Environment during PFM3 Nominal Thermal Test Case
Hold time: 50h16mn (as a minimum as next cooler recycling started before the cooler fully ran out)
For an Evaporator Condensation Temperature between 1.8K-2K