SPIRE & PACS Sorption cooler evaporator heat flow & temperature requirement

Date: March 2003 SPIRE-RAL-NOT-001579
May 2003 revised in blue from some Lionel inputs

Scope:

Since appointment of the HERSCHEL/Planck Industrial Contractors negotiations have been ongoing to redefine Spire's thermal interface. Some engineering design has progressed but requirements have not been firm because of the need to converge instrument and satellite thermal computations; only realistic modelling can provide a framework secure enough for all parties to agree the impact of thermal engineering designs. Spire's thermal requirements on HERSCHEL are sufficiently demanding that it's not possible just to write down a thermal interface specification that both sides would be happy to sign up to; there are no comfortable working margins. On the other hand, we should strive to find an overall solution that does not require the use of project level contingency, such as higher He mass flow rate.

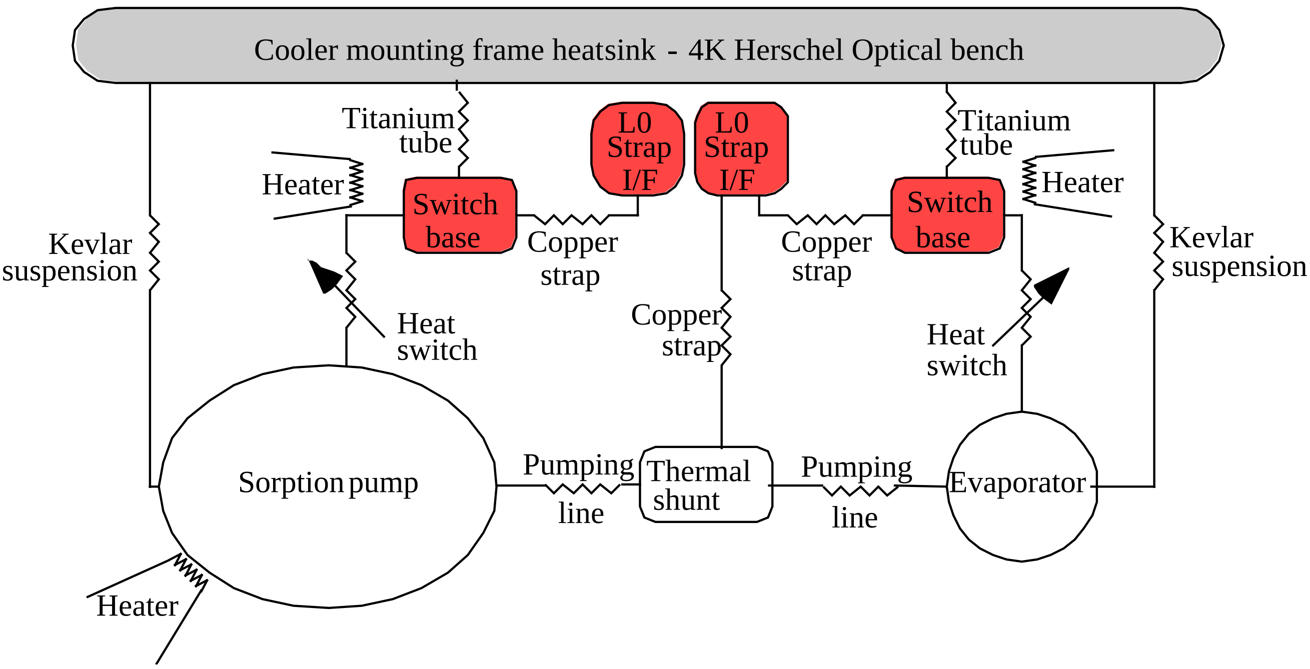
As thermal computation convergence now draws to completion, and as both sides have considered certain hardware designs, we are come back to defining Spire's thermal interface. As of Friday 21st March, computations were running without oscillations but Spire computations give results for L2 that still differ by 2.5K from Herschel's.

Spire's thermal interface must be correct and clear because for the industrial party it will be a firm price contract baseline and for the instrument team/ESA it will be a large factor in determining the science return from Spire.

There are many subtleties about Spire's thermal accommodation in the CVV, not least because transients during recyling pose significantly different requirements to normal "cold" cooler operation, and these transients are more difficult to thermally model. So this note includes more background about cooler operation than would be appropriate in the IID-B specification. Of particular interest are the required conductances of the SPIRE & PACS L0 straps (this means end-to-end from cooler to He, not just any one party's contribution to the straps' impedances). The matter arises again now because the fulfilling of this particular requirement has comparatively recently been highlighted within the Herschel cryostat design process.

Cooler Background.

The sorption cooler configuration is as follows:



The cooler has been through its Detailed Design Review (DDR) for Spire, monitored by ESA, all its parts are made, and its specification is frozen. In particular, the cooler is supplied to documents number HSO-SBT-SP-001 issue 3.3 (Requirements) and HSO-SBT-ICD-012 issue 1.3 (Interfaces) as per said DDR.

About this HSO-SBT-SP-001 says:
"The sorption cooler will be mounted off a 4 K plate (level 1) and 1.7 K (level 0) thermal paths will be provided for the heat switches and thermal shunt for the operation of the cooler. The radiative environment will be 4 K."

Regarding the Interfaces, HSO-SBT-ICD-012 says:

	Operating Mode	*Regeneration: Condensation*	*Regeneration: Cooldown*	*Operating: Low temperature*
Sorption pump heat switch	*Max.temperature*	N/A	10 K	5 K
	Max. heat flow	10 mW	1 W	2 mW depending on load
Evaporator heat switch	*Max.temperature*	2.8K	2K	2K
	Max. heat flow	50mW	15mW	1mW

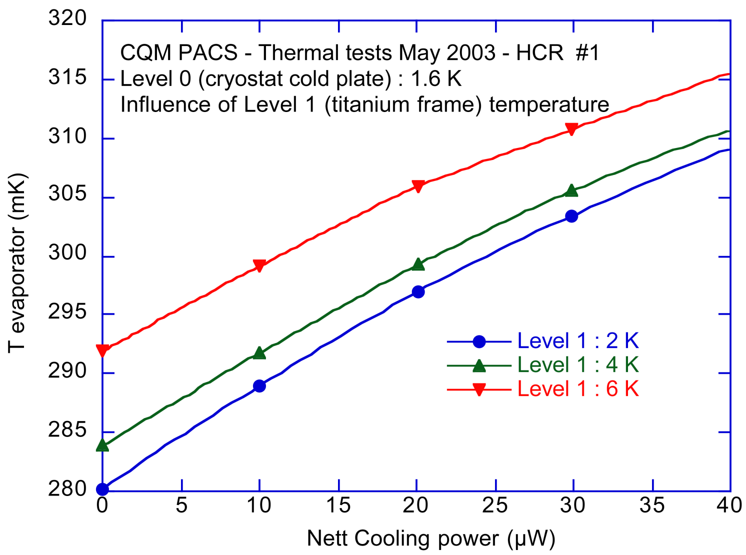
Note that these interface conditions need "unpacking". For instance 1Watt at 10K implies a strap conductance end-to-end of (1000)/(10-1.7)=120mW/K, which is a much higher than even the same document's recommended conductance for the pump strap.

There is also CEA's TNS2 on changing from 4 to 6 litres of ^{3}He at STP.

Cooler Operating Mode.

This is the mode in which the cooler will operate at low detector temperature for 46 hours observing time in each 48 hour cycle. It is to first order a stable state, excepting the decay of thermal transients across the instrument remaining from recycling decay, and possibly ones from elsewhere on the HOB as the previously operated instrument cools.

Taking a typical operating point, the pump will achieve 304mK at its evaporator cold tip when lifting 21.4μW nett (33.3μW gross). In more detail the 6 litre unit's performance is:

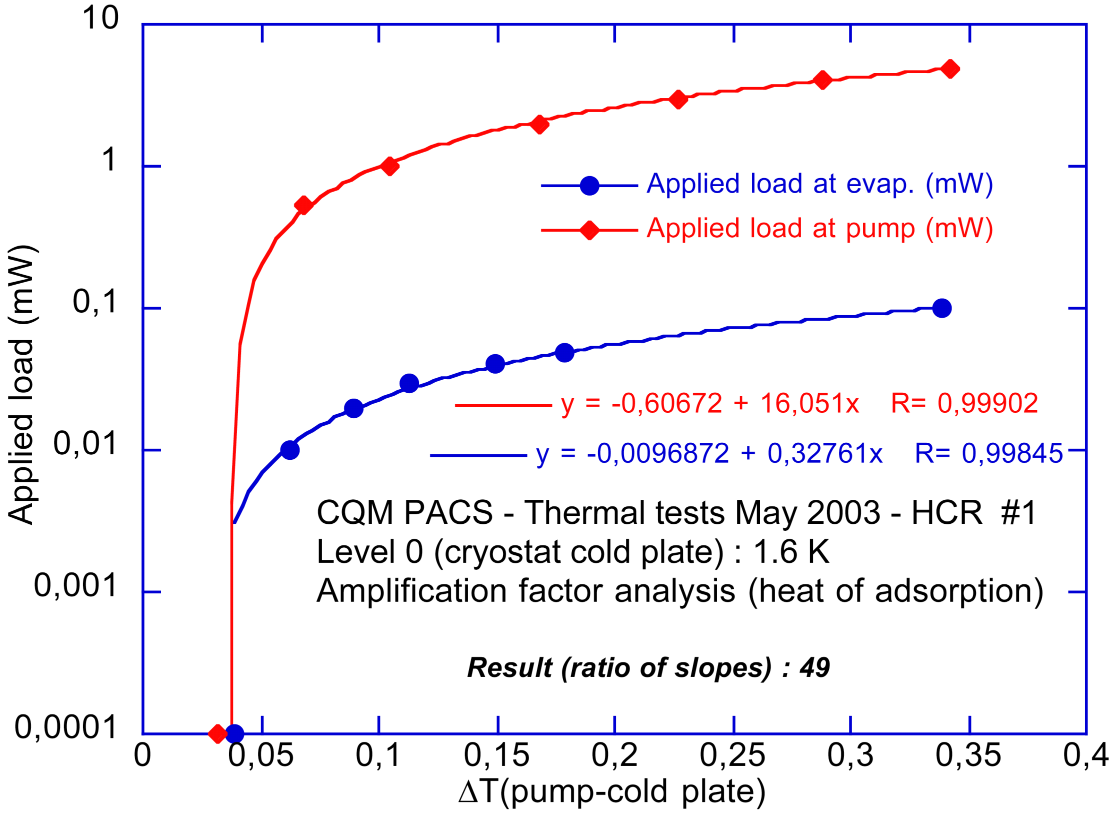


As expected, these all become one gross cooling curve assuming parasitics of 12μW at 2K, 16μW at 4K and 23μW at 6K. Since we know that hold-time has a sensitivity of about 1 hour/μW, this just shows the need to keep L1 low. Note that for SPIRE these parasitics will be reduced to maybe 75%of the above powers because of the thinner Kevlar one end.

Spire has 3 and a half L0 straps! There are three external interfaces, the two cooler ones shown above and one to the detector boxes. The "half" I refer to is an internal link between the photometer and spectrometer detector boxes.

In operating mode only the sorption pump sieve heat-switch heater is on. For the 4 litre unit some 200μW raised the switch sieve to ~14K, heated from the L1 side of the isolated switch. On 6 litre units these values are 300μW and 18K respectively.

In this normal operating mode, L0 strap heatflows are of course dominated by sorption cooler thermodynamic loads, both nett load and parasitic from L1. Whenever helium gets adsorbed, heat is released and there is an amplification factor between the load at the evaporator and the resulting load at the pump. An example analysis is displayed in the following curves.



A ratio of 46-49 is typical, and so this PACS cooler is pumping as it should.

With Spire's design, the maximum powers in the detector box strap, the cooler pump strap and the cooler evaporator strap are estimated as 5mW, 2mW and 1mW respectively. Were the strap conductances to the 1.7K ^{4}Helium liquid surface to be the specified 50mW/K, 50mW/K and 100mW/K respectively, the cooler interface temperatures would be 1.8K, 1.74K and 1.71K respectively. Two observations should be made:

a. these steady state heat flows are definitely on the high side for operating mode and hence estimating HeII hold-time, but operating mode is not the most demanding case for the interface. Therefore the operating mode cooler interface temperatures need not be quite this low, but these interface temperatures occur anyway as a result of the straps needing to work for other cases.
b. The sorption coolers are characterised and specified in a CEA Dewar in which the specified L0 end-to-end strap conductances are probably achieved. Moving away from this would call into doubt **all** existing measured cooler performance data. There are some measurements requested in SPIRE-RAL-NOT-001588 to address moving away from the cooler's operating conditions in its specification document mentioned above, and we now (end May 2003) have results which answer some of the questions but not the vital one concerning higher impedance L0 straps.

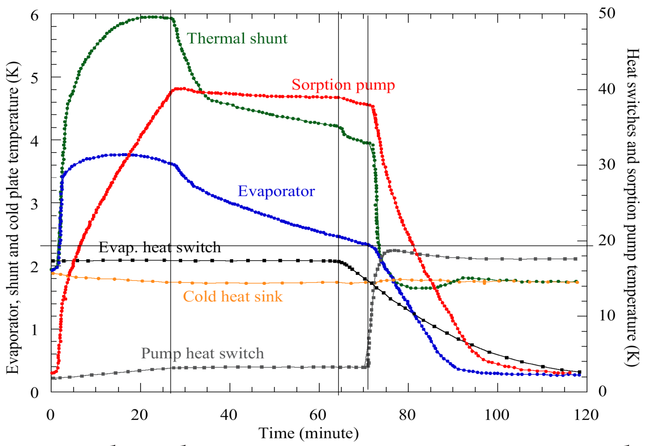
Cooler Re-Cycling/Regenerating Mode.

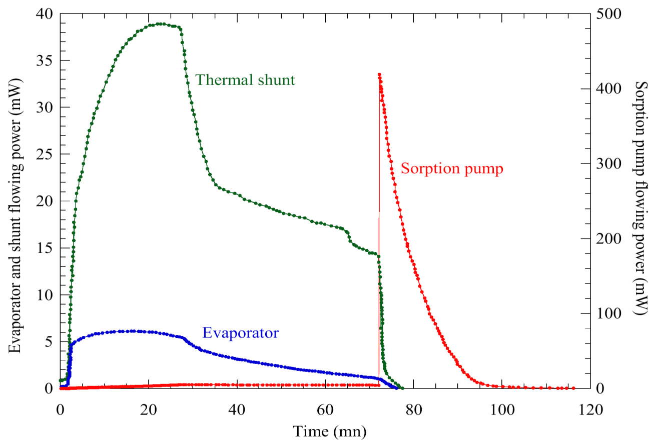
SPIRE IID-B section 7.5.1.1 presently shows Lionel's indicative measurements of temperature & heat flows on the 4 litre prototype Sorption cooler as shown below:-

a. 65 minutes "condensation" with the sorption pump heater on (taking the first 27mins with ~200mW to reach 40K and ~25mW for the remainder to maintain this temperature). Also the evaporator heat switch is on taking 200μW and running at about 17.8K. The shunt goes up to about 6K partway through this process driven by gas enthalpy plus heat conducted along the tube from the pump (it has to go above 3K to avoid it condensing the gas!). The shunt stops the evaporator going above 3.8K. As the enthalpy load falls off because the gas has all moved into the evaporator, the shunt and the evaporator cool.

b. Then the evaporator heatswitch sieve heater is turned off, and the heatsink starts to cool slowly. For about 7 minutes neither heatswitch sieve heater is on. However the the evaporator continues to cool and by the end of this time has reached to 2.35K, which is a little higher than optimum.

c. Finally 50minutes are taken to "cool down" again, for the sorption pump to reach <2K. The pump heatswitch on with about 200μW and runs at about 18K; for some reason it initially overshoots in temperature slightly.



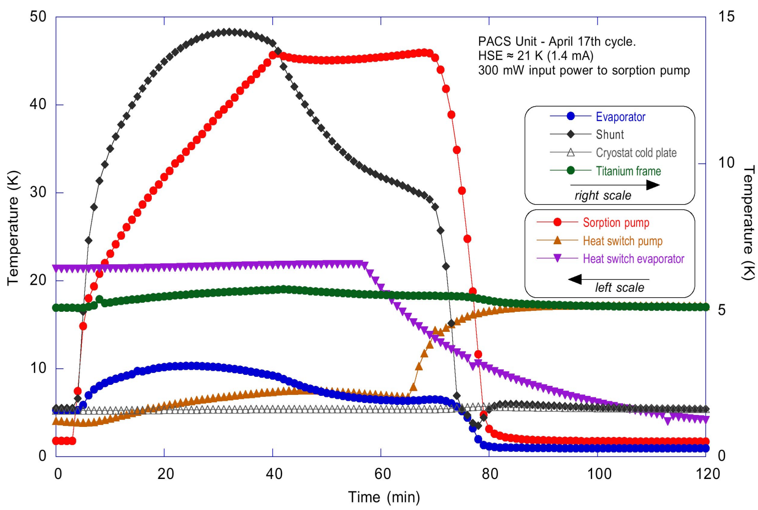


I note that these plots start at time=0 with the evaporator heatswitch on and the pump heatswitch off, which is not as per normal operating mode, i.e. there has already been non-radiometric operating time before the graph starts.

During the recycling process, >80% of the enthalpy of the hot gas should be removed via the heat shunt block around the tube between the cooler's pump and evaporator.

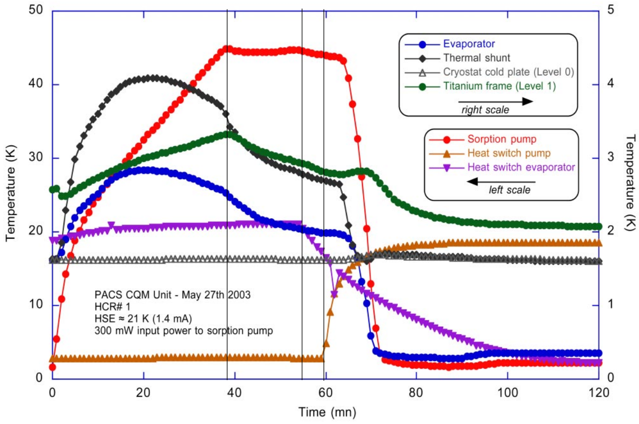
In the above curves, the integrated energy at the spire/Herschel L0 I/Fs sums to 202(267) Joules for the pump, 105(137) for the shunt, and 16(15) for the evaporator, where the bracketed values apply to an earlier run of the same cooler.

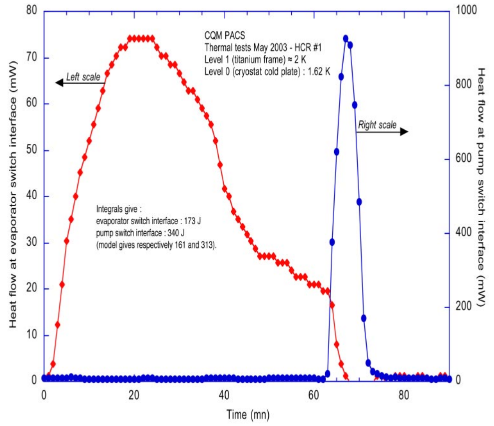
Now consider the 6 litre unit, and first a run on 17th April which had some problems:



There are some intentional changes from the 4 litre unit's operation. The heatpump needs to go to 45K not 40K to achieve good recycling: 38 minutes at 300mW are used to achieve this transient. To maximise conductivity, the evaporator heatswitch is run at 300μW and reaches a little over 21K. However the shunt goes above 14K which indicates that its strap has too poor a conductivity, in this case within the cooler.

So SBT changed to a better shunt and 27th May's results are much better with the shunt and evaporator exhibiting nice temperature profiles as follows, although the titanium L1 frame is at 2K and the L0 1.62K which are never conditions relevant to Spire:

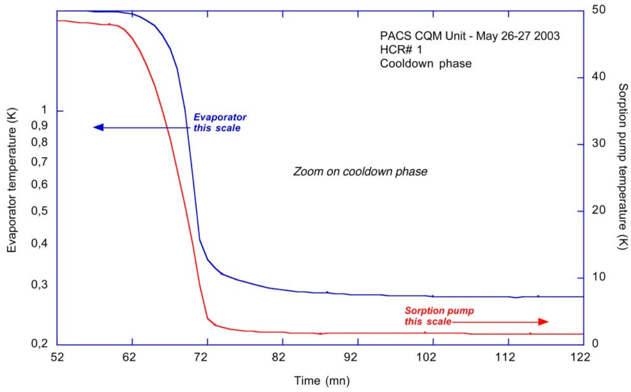




The heatshunt now only goes up to about 4.1K, but this adequately exceeds 3K.

I've distorted these plots to nearly match the scales of the 4litre curves. It should be noted that the recycle timings are slightly different. The "condensation" with the sorption pump heater on is only 55minutes and not 65. The evaporator heatswitch still takes the full 120mins to come back to equilibrium.

Lionel considers the last period to merit a detailed plot of evaporator and pump temperatures



I've taken the liberty of normalising the time axis.

We see that with the system used for test, and probably in flight also, the cooler's titanium frame alters temperature during re-cycling.

The integrated energy values from the heatflow power curves of 340 and 173 Joules seem to fit the expected 4 to 6 litre scaling.

Note that all the data given here apply when this cooler is run with substantial conductance laboratory straps straight to the outer surface of a ^{4}HeII cryostat. The cooler chassis was fixed all along one side (PACS style). Also none of these data have the thermal capacity of the Spire BDAs and cold plumbing connected to the evaporator, which must affect matters somewhat!

Just to state the obvious first of all, these heat flows are MUCH higher than during cooler operating mode. The 400mW spike on the pump strap has increased to nearer 900mW. Maybe the switch was operated faster in the 6 litre test than the 4 litre one, although this would not seem to be case looking at the heatswitch temperature profile,. In any case, Spire needs to be told a command sequence to operate this switch slowly, not just that it should be so operated! Also the high loadings on the shunt/evaporator are quite long-term states not just transients. The broad peak of combined total loading from evaporator and shunt has increased from 45mW to 75mW.

To understand some wider trade-offs, if the heat shunt and evaporator strap could take the load as a high flow-rate of warm ^{3}He leaves the pump, we could heat the pump with some 600mW to 45K very quickly, keep it there for just a few minutes, turn off and let everything cool down again, which would achieve a very energy efficient regeneration. In practise, even with the good conductivity as specified, the strap impedance both limits the initial power that can be applied and causes us to wait an appreciable time before the evaporator comes back down to ~2K, the point at which "cool down" can be commenced. Achieving a strictly 2 hour regeneration may be compromised if end-to-end strap thermal impedances are too high, but this would be much more acceptable than not operating on a 48 hour cycle because of regenerating inefficiently.

Given that the quoted operating conditions are achieved and that the pump is heated to 45K to achieve 95% condensation efficiency (see TNS2), over a 48 hour cycle, including the two in recycling mode, ~~some 711 Joules total would flow down the L0 straps, i.e. an average of 4.1mW.~~ These values need confirming.

In practise the whole system must be able to cope with the recycling heat pulses, e.g. their arrival must be over a sufficient area at the cryostat's He surface that it does not induce unwetting. There is also a limit as to how fast one wants to recycle a cooler because all of its components must be qualified with margin to withstand the number of such thermal "shocks".

However generally speaking the faster the whole regeneration process the better, both in terms of the minimising the total single recycle energy and in terms of the fraction of time available for science.

Evaporator Strap

For the 4litre unit, the energy to be transported via the Evaporator itself is expected to be 40 Joules with the profile shown, peaking at 45mW during the process. Thus the total energy through this strap is maybe 150 Joules, but this is not the difficult bit

The <2K evaporator temperature requirement is so that most of the ^{3}He is condensed in the evaporator at the end of the regeneration process. ! Although the <u>evaporator</u> power drops to <2mW at the end of the condensation phase, as Anne-Sophie emphasised at the last interface meeting, there is still 15-25mW from the heat shunt coming down the evaporator strap. Taking a worst case 27mW and 1.7K ^{4}Helium liquid surface, 75mW/K gives a temperature of 2.06K, a slight **negative** margin. Because there are unavoidable impedances within the cooler, its heatswitch and at its interface, in order to achieve a conductivity of 75mW/K from the evaporator itself to the Herschel ^{4}Helium liquid surface, Spire has specified a total strap impedance between the cooler interface and the Herschel helium liquid surface of 100mW/K.

Pump strap

The requirements related to the pump strap are unchanged (w.r.t. what is already in Spire's IID-B) duration of pump cooling period: 1560s, energy 350J, triangular profile peaks up at 420mW near the start of regeneration cooling phase, Tstrap interface must be <10K at this point. A strap with 50mW/K end-to end conductance gives a temperature of 10.1K at the pump interface if the helium surface temperature is 1.7K, again a slight **negative** margin

The 27th May 6 litre cooler regeneration cycle has some 900mW flowing at t=68 minutes when the pump is at 25K. Simplistically this suggests 36mW/K which, because of impedances internal to the cooler, seems consistent with 50mW/K strap end-to-end, but this is TBC.

Discussion.

Alcatel's proposed way forward:

After agreement on these data (SPIRE requested to confirm), we proposed that the temperature & heat flow requirements are included in a table as proposed by Astrium in the SPIRE interface meeting H-P-ASPI-MN-2748, via re-writing of SPIRE ECR 09. (Now agreed to be ECR 9 for general info. and ECR 10 for specific agreed numerical flight values).

SPIRE has a power profile included in the transient timeline of their Thermal model. This needs to be dynamically adjusted so the pump follows the operating cycle described above, at least initially depending on environmental condition. It is recommended that a physically representative model of the cooler should be implemented by SPIRE & PACS.

SPIRE shall also include in its Instrument verification and ILT a validation of the cooler recycling (particularly confirmation of the duration of condensation & pump cooling phases), to which small margins would then need to be applied for flight operations.

RAL's response:

To re-emphasise, all the cooler heatflows and energy estimates need reconfirming for the 6 litre cooler, particularly if margins are small. ~~As of today there are no 6litre cooler measured performance data.~~ We now have initial 6 litre results under unrepresentative conditions. We either need this data set measured over a range of operating conditions or a well correlated with a more adaptable way of really computing the recycling.

To clarify, Spire has a semi-empirical thermodynamic thermal model for normal operational mode that links pump power to cold end load. However, Spire has a recycling mode "model" which is not a full thermodynamic representation of the sorption process as regards the temperature between its ends, timelags, etc., but rather it splices the one set of energy data shown herein into the surrounding thermal model elements, with integrated energies correlated to 10%. PACS has essentially no cooler model at all for recycling. There will be a separate technical note circulated giving more information about the cooler sub-system modelling and suggested developments of it.

The Alcatel text makes no mention of the value of overall strap conductances; these parameters as being pivotal to the engineering design , which then need evolving to fix the point along each strap at which the Spire to Herschel interface is situated. Some tables in the IID-B (flight and test conditions separated as appropriate) are indeed the agreed way to formalise I/F requirements. However, we should not delude ourselves with patch-ups at this stage of the project; Spire project resource is already at risk because this matter is very much lagging behind our hardware procurement. So we need good figures to go in the tables before we finalise them. For instance without characterising the 6litre we would sign up to the figures herein, and their derivatives, but anything worse could only be via significant modelling and measurement of its effects….for which there seems to be neither time nor resources.

I'm very happy to explore the proposed way forward, but I will not sign-off on IID-B thermal interface updates until we have a set of analysed performances corresponding to outline designs on both sides of the interface to which all parties are happy to deliver. The first stage of getting RAL and Astrium computations to yield good agreement for a defined situation seemed to be almost within our grasp (some ~8months after starting).

I repeat my proposal that I made to Astrium months ago that there are three non-trivial elements to the L0 straps: getting the "coolth" geometrically close to the cooler; providing Ohmic isolation; providing mechanical compliance to avoid exceeding the cooler I/F's 50Newton applied force specification. These elements are thermally in series, and so for the most demanding 100mW/K strap I proposed three equal allocations of 300mW/K, of which it must be said Herschel has the most straightforward one and Spire the two more awkward!

Spire's baseline is that we have a very full programme of work to achieve the project even if the Herschel contractor provides us the cooling capabilities we previously negotiated with ESA. I think Spire has already demonstrated a high level of flexibility and it will continue to be our inclination to look for every design solution to make this experiment work well, but let's share the effort/pain.

JD
23/3/03

Draft IID-B table for completion after negotiations:

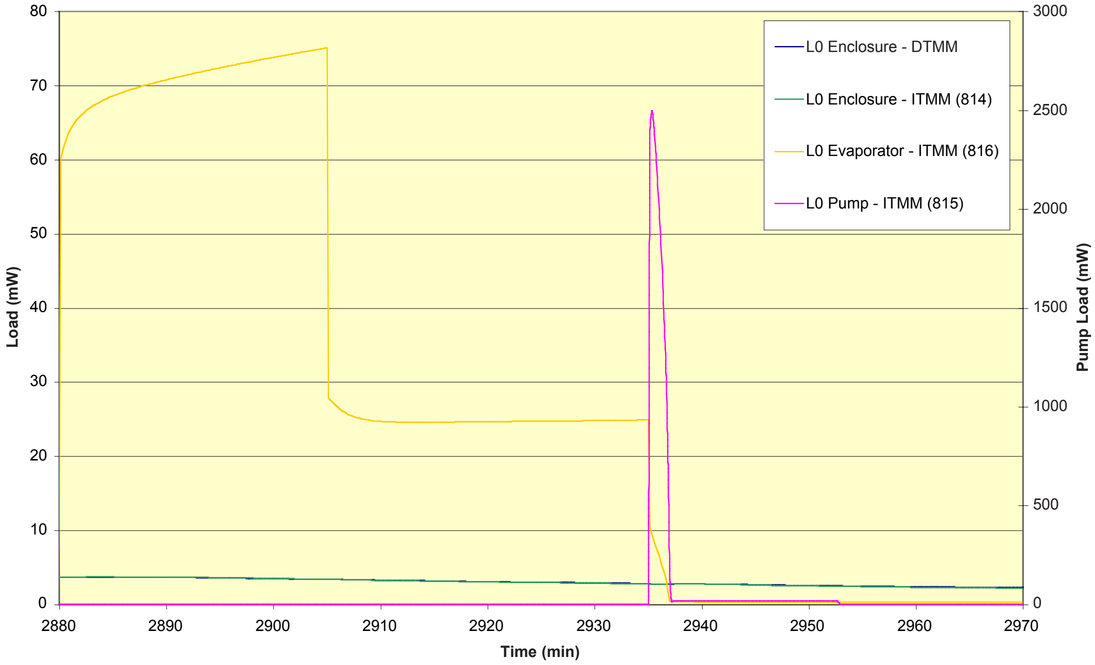
SPIRE FPU thermal I/F		In-Orbit (cycle 48h assumed)					
		Operation 46h		Recycling Cooler 2h		Not in use 48hrs	
		Max Temp*	Max average Heat load	Max Temp*	Max. Heat load	Max Temp*	Max. Heat load
L0	SPIRE Detector enclosures	1.8 K	5 mW	1.8K	5mW		
	SPIRE Cooler Pump strap	1.8 K	2 mW	10 K	420mW		
	SPIRE Cooler Evaporator strap	1.8 K	1 mW	2 K	30mW for strap design		
L1	SPIRE L1 (two straps)	4.5 K	13 mW	5.5 K	13 mW		
L2	SPIRE L2 (HOB / FPU legs)	10K	TBD	10.K	TBD-		
L3	SPIRE L3 (HSJFP, HSJFS/strap)	14K	50 mW	14K	50 mW		

*These temperatures need refining as Spire/Herschel interface position is optimised. For the cooler the present temperatures apply at the heatswitch interface, NOT the Spire/Herschel interface.

Note that there needs to be another similar table in the IID-B ground test section to cover non-flight operations.

ANNEX:

For information, this shows what RAL's basic cooler cycling model does even at present. The error of stating that RAL is missing half the cooler energy is resolved by this and the data elsewhere in this note.



Evaporator strap load during recycling in orange.
Pump strap load during recycling in pink.

Estimated energy on evaporator strap during recycling:

Phase	*Average load (mW)*	*Duration (sec)*	*Energy (J)*
Condensation Pump heated up to 40-45K Qheater = 200mW	70	25x60 = 1500	105
Condensation Pump maintained at 40-45K Qheater = 25mW	25	30x60 =1800	45
Cryo-pumping	10/2 =5	2.5x60 = 150	0.75
Total	**-**	**57.5x60 = 3450** *+ recovery time*	**150.75**
Energy estimated from 4 litres test results data			121
Expected energy scaled for 6litres cooler from 4 litres test results data			121 x 1.5 = **181.5**
Ratio			**83%**

Estimated energy on pump strap during recycling:

Phase	*Average load (W)*	*Duration (sec)*	*Energy (J)*
Cryo-pumping	2.5/2 =1.25	2.5x60 = 150	187.5
Energy estimated from 4 litres test results data (will be identical for 6 litres)			202
Ratio			**92.8%**