SUBJECT: SPIRE CRYOGENIC INTERFACE THERMAL MATHEMATICAL MODEL (ITMM)

PREPARED BY: S. HEYS (RAL) **Date:** ………………

APPROVED BY: J. DELDERFIELD (RAL) **Date:** ……………….

B.SWINYARD (RAL) **Date:** ……………….

NOT APPROVED

DISTRIBUTION LIST

Institute	Holder	Issue/ Revision and Distribution Date							
		1.0							
		20/6/01							
RAL	Delderfield	x							
	Swinyard	x							
	Griffin	x							
	Parker								
	King								
	Smith								
QMW	Griffin	x							
	Hargrave								
ATC	Cunningham	x							
	Stobie								
MSSL	Winter	x							
CEA-SBT	Duband	x							
CEA-SAP	Cara								
	Auguères								
	Pinsard								
JPL	Bock								
	Lilienthal								
	Cafferty	x							
LAM	Pouliquen								
Can.	Taylor								
	Peterson								
ESA	Heske								
	Linder	x							
CESR	Pons								
IFSI	Giorgio								
	Orfei								
ALCATEL	Lund								

CHANGE RECORD

ISSUE	DATE	SECTION	CHANGE
1.0	20-06-01	-	New Document

ACRONYM LIST

BSM	Beam Steering Mechanism
DTMM	Detailed Thermal Mathematical Model
FPU	Focal Plane Units
HOB	Herschel Optical Bench
ITMM	Interface Thermal Mathematical Model
JFET	Junction Field Effect Transistor
L0	Herschel Temperature Level 0 (~1.8K)
L1	Herschel Temperature Level 1 (~4K)
L2	Herschel Temperature Level 2 (~10K)
SOB	SPIRE Optical Bench
SMEC	Spectrometer Mechanism
SPIRE	Spectral and Photometric Imaging Receiver
TBC	To Be Confirmed
TBD	To Be Defined

CONTENTS

1. SCOPE

This document defines the reduced node interface thermal mathematical model (ITMM) of the SPIRE instrument FPU. The ITMM is provided for incorporation into the Herschel Cryostat thermal model. This model is a simplified version of the detailed thermal model SPIRE14B.d. Updates to this model will be necessary as the SPIRE design iterates.

2. APPLICABLE DOCUMENTS

2.1. ESA Applicable Documents

ID	TITLE	NUMBER
AD 2.1.1	FIRST/Planck Instrument Interface Document Part B (IID-B) Instrument "SPIRE"	PT-SPIRE-02124. Issue-Rev. No. 0-4 15-MAY-00
AD 2.1.2	FIRST Simplified Optical Bench Thermal Model	Fax Ref: SCI-PT/FIN-08132 24-AUG-00
AD2.1.3	FIRST /Planck Instrument Interface Document IID-Part A	SCI-PT-IIDA-04624 Issue 1/0 01-SEPT-00

2.1: ESA Applicable Documents

2.2. Dornier Applicable Documents

ID	TITLE	NUMBER
AD 2.2.1	FIRST Instrument I/F Study Final Report	FIRST-GR-B0000.009. Issue 1 02-FEB-00

Table 2.2: Dornier Applicable Documents

2.3. RAL Applicable Documents

ID	TITLE	NUMBER
AD 2.3.1	SPIRE Thermal Transient Cases for Cryostat Study	SPIRE-RAL-NOT-xxx 14-DEC-99
AD 2.3.2	SPIRE Inputs For Cryostat and Instrument Thermal Modeling	RAL 15-MAY-00 -update
AD 2.3.3	SPIRE Thermal Configuration Control Document	SPIRE-RAL-PRJ-000560 Issue: D8 18-APR-01

Table 2.3: SPIRE Applicable Documents

3. INSTRUMENT THERMAL REQUIREMENTS

The thermal requirements of the SPIRE instrument are summarised below in Table 3.1.

PARAMETER	SPECIFICATION	REFERENCE
FPU Bulk Temperature	~4K	-
Cooler Interface Temperature	4K	-
Detector Module Interface Temperature	~1.8K	-
Detector temperature	T <310mK	AD2.3.7
300mK detector array stability*	670nK/√Hz between 0.03 and 25Hz.	AD2.7.7
1.8K stage stability*	9.1K/√Hz	AD2.7.7
4K stage stability*	5mK/√Hz	AD2.7.7
80K stage stability*	1mK/√Hz	AD2.7.7

* Drift Scanned/Extended Emission observing modes specify more stringent stabilities (see AD2.7.7). However these are not absolute requirements.

Table 3.1: SPIRE Instrument Thermal Requirements

4. INSTRUMENT THERMAL DESIGN OVERVIEW

The SPIRE FPU and JFET Boxes are mounted off the HERSCHEL Cryostat Optical Bench, surrounded by the HERSCHEL Instrument Shield. Four temperature stages on the FPU are used to achieve the 300mK detector temperature, with nominal temperatures of 10K, 4K, 1.8K and 300mK. Each stage below 10K is cooled via thermal straps to the Cryostat Vent Pipes or LHe Tank. Stringent specifications are placed on the allowable heat loads between these stages in order to maximise mission life and to guarantee the interface temperatures.

STAGE	SPIRE COMPONENTS	HEAT SINK
Level 2	JFET boxes	HERSCHEL Optical Bench
Level 1	SOB structure/ mechanisms / mirrors	HERSCHEL L1 Vent Pipes
Level 0	FPU detector boxes / dichroics / mirrors	HERSCHEL L0 LHe Tank
300mK	FPU detectors / cooler thermal link	SPIRE ^{3}He Sorption Cooler

Table 4.1: SPIRE Temperature Stages and Heat Sinks

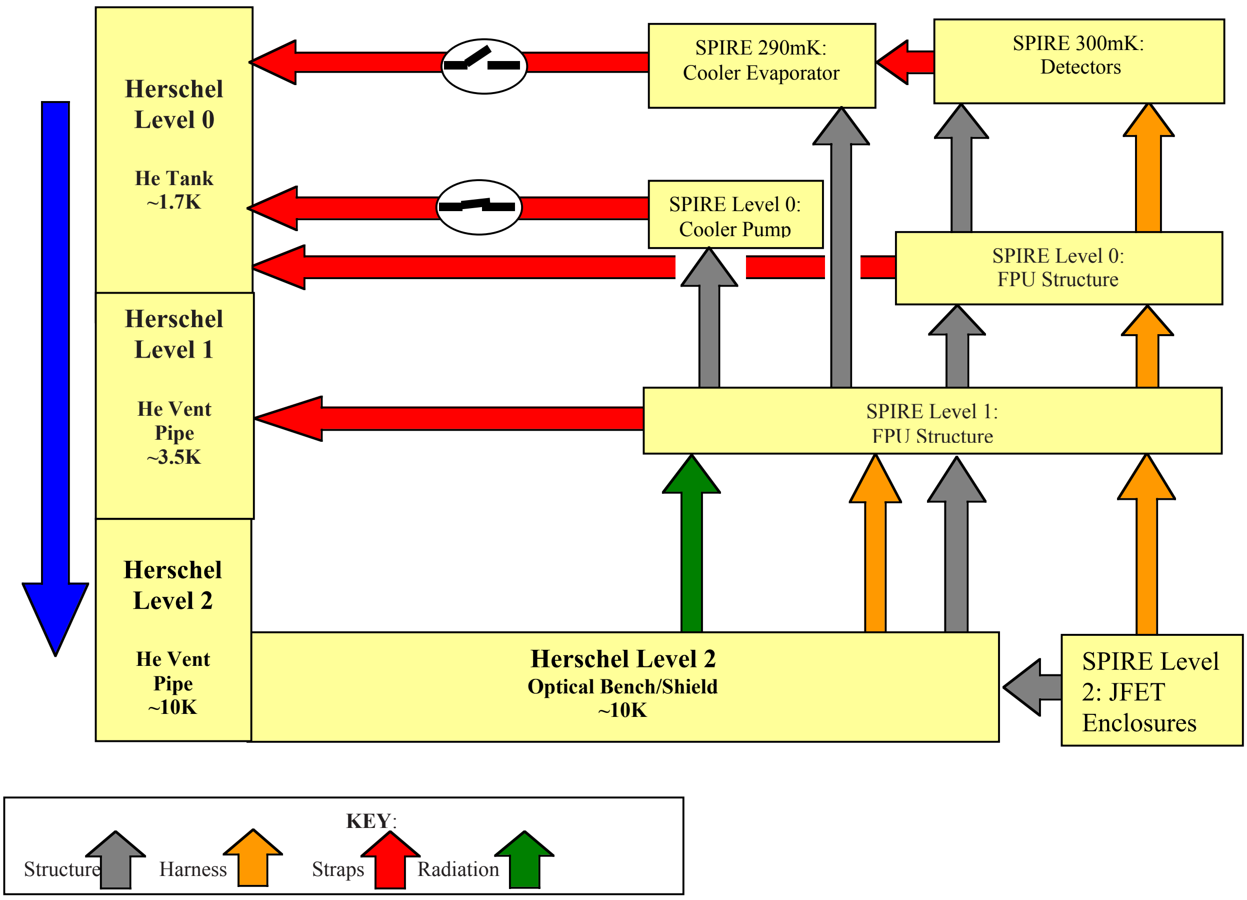


Figure 4.1: SPIRE Temperature Stages and Heat Sinks

5. NODAL BREAKDOWN

5.1. Herschel Boundary Nodes

NODE NUMBER	NODE NAME	LOCATION
1000	L2 Herschel Optical Bench	SPIRE side of foot joint
2000	L2 Herschel Instrument Shield	
3000	L1 Strap Interface - FPU	SPIRE side of strap attachment joint
4000	L0 Strap Interface – 1.8K Enclosures	SPIRE side of strap attachment joint
5000	L0 Strap Interface – Cooler Pump	SPIRE side of strap attachment joint
6000	L0 Strap Interface – Cooler Evaporator	SPIRE side of strap attachment joint

5.2. SPIRE Nodes

NODE NUMBER	NODE NAME	DESCRIPTION	LOCATION	MATERIAL	MASS
Level 2					
10	PHOTOMETER JFET ENCLOSURE		Hard mounted to HOB	Aluminium Alloy 6082	5.27
20	SPECTROMETER JFET ENCLOSURE		Hard mounted to HOB	Aluminium Alloy 6082	1.72
Level 1					
30	FPU OPTICAL BENCH	L1 SPIRE Optical Bench, Side Panels and optics	Mounted off HOB on insulating supports	Aluminium Alloy 6082	30
40	RF FILTER BOXES		Hard mounted to SOB	Aluminium Alloy 6082	1.465
50	BEAM STEERING MECHANISM	Mechanism	Hard mounted to SOB	Aluminium Alloy 6082	1.1
60	SMECm	Mechanism	Hard mounted to SOB	Aluminium Alloy 6082	1.3
70	PHOTOMETER CALIBRATOR	Calibration Source	Hard mounted to SOB	Aluminium Alloy 6082	0.03
80	SPECTROMETER CALIBRATOR	Calibration Source	Mounted to SOB on insulating suppports	Aluminium Alloy 6082	0.007
90	SHUTTER	Mechanism	Mounted on outer surface of FPU walls	Aluminium Alloy 6082	0.08
Level 0					
100	PHOTOMETER DETECTOR ENCLOSURE	L0 Enclosure housing Spectrometer Detector Modules	Mounted off SOB on insulating supports	Aluminium Alloy 6082	1.967
				Stainless Steel	0.114
				Invar	0.192
				Silicone	0.048
110	SPECTROMETER DETECTOR ENCLOSURE	L0 Enclosure housing Photometer Detector Modules	Mounted off SOB on insulating supports	Aluminium Alloy 6082	1.433
				Stainless Steel	0.076
				Invar	0.128
				Silicone	0.032
300mK					
120	PHOTOMETER DETECTORS	300mK Photometer Detectors and cooler strap	Mounted off Detector Enclosure on insulating supports	Invar	0.435
				Copper	0.804
130	SPECTROMETER DETECTORS	300mK Spectrometer Detectors and cooler strap	Mounted off Detector Enclosure on insulating supports	Invar	0.281
				Copper	0.318

Cooler					
160	COOLER PUMP		Mounted off SOB on insulating supports	Titanium	0.15
170	COOLER SHUNT		Suspended between evaporator and pump	Titanium	0.01
180	COOLER EVAP		Mounted off SOB on insulating supports	Titanium	0.084
190	COOLER PUMP HEAT SWITCH	Heat Switch to L0 Sink	Mounted off SOB on insulating supports	Titanium	0.037
200	COOLER EVAP HEAT SWITCH	Heat Switch to L0 Sink	Mounted off SOB on insulating supports	Titanium	0.037

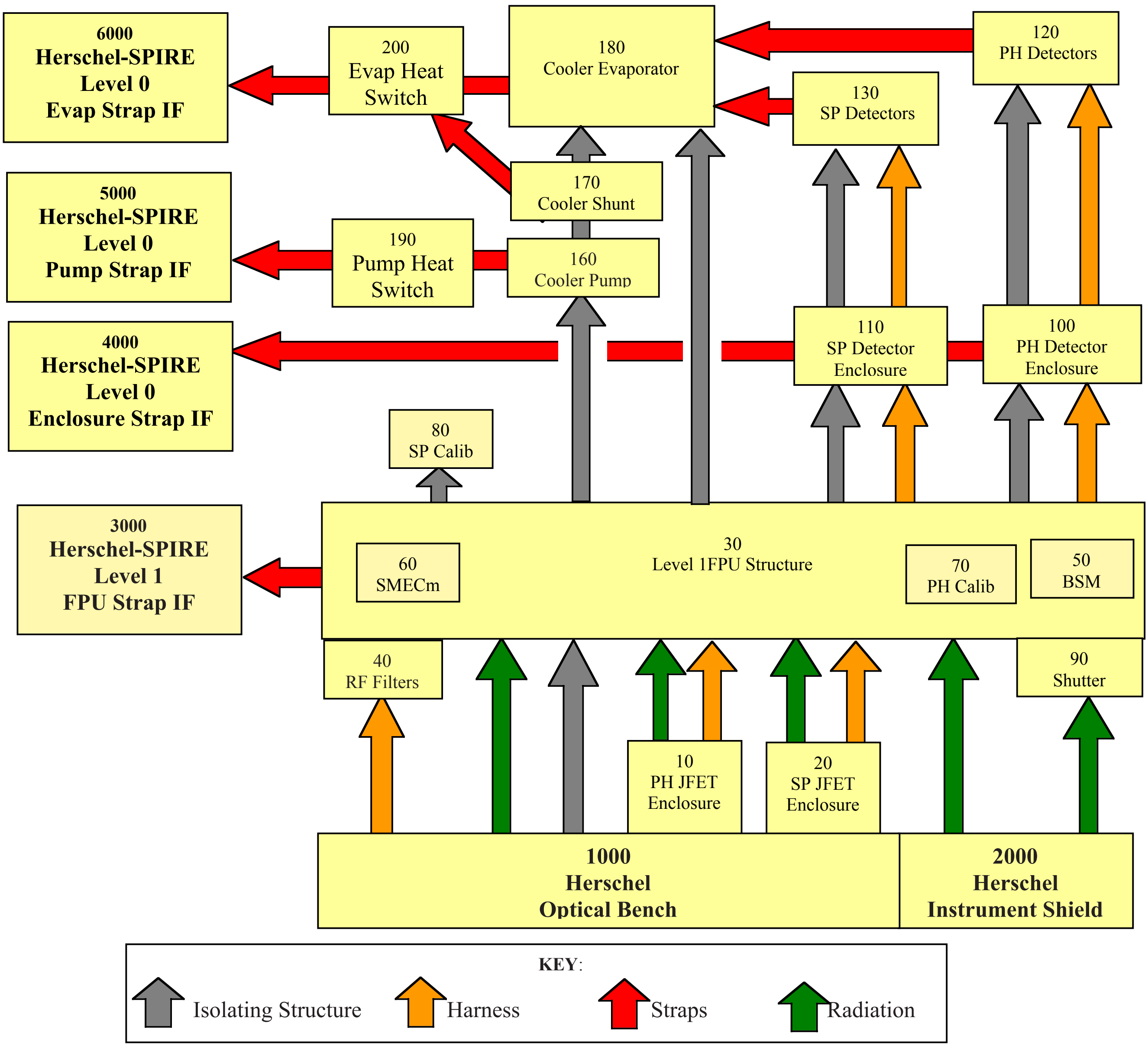


Figure 5.1: ITMM Node Locations

6. COUPLINGS

6.1. Herschel-SPIRE Interface Conductances

The harness from the SPIRE Warm Electronics to the JFET enclosures and FPU are sunk to the Herschel Optical Bench. This heat load on the HOB is not included in the SPIRE ITMM, since it is assumed to form part of the Cryostat TMM.

NODE I	NODE J	DESCRIPTION	MATERIAL	X-SECTION (m2)	LENGTH (m)
1000	10	JFET Bolted Interface	Al-Al	4 bolts	-
1000	20	JFET Bolted Interface	Al-Al	4 bolts	-
1000	30	FPU Support Feet	Stainless Steel	1.06E-04	0.04
1000	40	RF Filter Harness	Stainless Steel	0.000007222	0.2
			Brass	2.0096E-06	0.2
			Teflon	2.22E-04	0.2
3000	30	L1 Strap	Aluminium Alloy	0.001	0.1
4000	110	L0 Strap - Enclosures	Copper	2.00E-05	0.04
5000	190	L0 Strap – Cooler Pump	Copper	2.00E-05	0.111
6000	200	L0 Strap – Cooler Evaporator	Copper	4.00E-05	0.173

6.2. SPIRE Internal Conductances

NODE I	NODE J	DESCRIPTION	MATERIAL	X-SECTION (m2)	LENGTH (m)
10	30	Photometer JFET Harness	stainless steel	9.516E-06	0.1
			manganin	4.070E-06	0.1
			teflon	3.168E-05	0.1
20	30	Spectrometer JFET Harness	stainless steel	2.379E-06	0.1
			manganin	1.018E-06	0.1
			teflon	7.920E-06	0.1
30	40	RF Filters Hard Bolted to FPU	Al-Au-Al	4 bolts	-
30	50	Mechanism Hard Bolted to FPU	Al-Au-Al	4 bolts	-
30	60	Mechanism Hard Bolted to FPU	Al-Au-Al	4 bolts	-
30	80	Spec Calibrator Insulated Support	-	-	9.375E-05W/K
30	90	Mechanism Hard Bolted to FPU	Al-Au-Al	4 bolts	-
50	70	Calibrator within BSM	Al-Au-Al	4 bolts	-
30	100	Photometer Enclosure Supports + Detector Harness	Stainless Steel	3.797E-05	0.0275
			Manganin	4.070E-06	0.025
			Teflon	3.168E-05	0.025
30	110	Spectrometer Enclosure Supports + Detector Harness	Stainless Steel	3.012E-05	0.0275
			Manganin	1.018E-06	0.025
			Teflon	7.920E-06	0.025
100	110	Photometer-Spectrometer Enclosure Strap	Copper	2.00E-05	0.19
100	120	Photometer Detector Supports + Photometer 300mK Strap Busbar & Feedthrough	Kevlar	1.752E-05	0.02
100	120	Photometer Harness	Kapton	0.00001911	0.03
			Constantan	0.000000216	0.03
110	130	Spectrometer Detector Support + 300mK Strap Feedthrough	Kevlar	1.088E-05	0.020

110	130	Spectrometer Harness	Kapton	0.000003885	0.03
			Constantan	0.000000054	0.03
120	180	Cooler - Photometer Detector Strap	Copper	7.07E-06	0.541845
130	180	Cooler - Spectrometer Detector Strap	Copper	7.07E-06	0.210285
160	170	Cooler Pump to Shunt	Ti6Al4V	6.41E-06	0.038
170	180	Cooler Shunt to Evaporator	Ti6Al4V	6.41E-06	0.06
170	200	Internal Shunt strap	Copper	0.000005	0.05
180	200	Evaporator Heat Switch	ON = 3mW/K	-	-
			OFF = 0.28microW/K	-	-
190	160	Pump Heat Switch	ON = 16mW/K	-	-
			OFF = 6microW/K	-	-
190	30	Pump HS Support	Ti6Al4V	1.16E-05	0.027
200	30	Evaporator HS Support	Ti6Al4V	1.16E-05	0.027

6.3. Heat Switch Status

NODE I	NODE J	DESCRIPTION	MODE					
			Photometer	Spectrometer	Standby	Off	Cooler Recycle	Mode Change
180	200	Evaporator Heat Switch	OFF	OFF	OFF	OFF	see 7.2.2	OFF
190	160	Pump Heat Switch	ON	ON	ON	OFF	see 7.2.2	ON

6.4. Herschel-SPIRE Interface Radiative Couplings

	NODE I	NODE J	AREA J (m2)	IR-EMISSIVITY
HOB to FPU and JFETs	1000	10	0.014	0.1
	1000	20	0.012	0.1
	1000	30	0.69258094	0.1
Shield to FPU and JFETs	2000	10	0.1109	0.1
	2000	20	0.0766	0.1
	2000	30	0.94221	0.1
JFETs to FPU	10	30	0.02624553	0.1
	20	30	0.02624553	0.1
Shield to Shutter	2000	90	0.01	0.1

6.5. SPIRE Internal Radiative Couplings

	NODE I	NODE J	AREA J (m2)	IR-EMISSIVITY
JFETs to FPU	10	30	0.02624553	0.1
	20	30	0.02624553	0.1

7. POWER DISSIPATION

7.1. Steady-State Cases

NODE NUMBER	NODE NAME	MODE AVERAGE POWER (mW)			
		Photometer	**Spectrometer**	**Standby**	**Off**
10	PH. JFET	49.5	0.0	49.5	0.0
20	SP. JFET	0.0	14.1	0.0	0.0
50	BSM	4.0	1.0	0.0	0.0
60	SMECm	0.0	2.4	0.0	0.0
70	PH. CALIBRATOR	0.1	0.0	0.0	0.0
80	SP. CALIBRATOR	0.0	5.0	0.0	0.0
90	SHUTTER	0.0	0.0	0.0	0.0
160	PUMP	1.02	1.02	0.0	0.0
170	SHUNT	0.005	0.005	0.0	0.0
180	EVAP	0.0	0.0	0.0	0.0
190	PUMP HS	0.2	0.2	0.0	0.0
200	EVAP HS	0.0	0.0	0.0	0.0

7.2. Transient Cases

7.2.1. Operational Mode Change –Photometer to Spectrometer

During mode change analysis the status of the heat switches remains constant with the pump switch ON and evaporator switch OFF.

TIME (MM:SS)	NODE NUMBER	NODE NAME	STATUS	POWER DISSIPATION (mW)
00:00	10	PH. JFET	ON	49.5
00:00	160	PUMP	ON	1.02
00:00	170	SHUNT	ON	0.005
00:00	190	PUMP HS	ON	0.2
00:01	70	PH. CALIBRATOR	ON	2.0
10:00	70	PH. CALIBRATOR	OFF	0.0
10:01	10	PH. JFET	OFF	0.0
10:01	20	SP. JFET	ON	14.1
10:02	50	BSM	ON	1.0
10:02	80	SP. CALIBRATOR	ON (heating to 20K)*	5.0
-	80	SP. CALIBRATOR	ON (stabilising at 20K)*	2.0
10:32	60	SMECm	ON(scanning)	2.4**
14:32	60	SMECm	OFF	0.0

*Power of 5W applied until calibration source reaches 20K. Power then reduced to 2mW.
**2.4mW mean power. Fluctuation as shown in Figure 7.2.1.

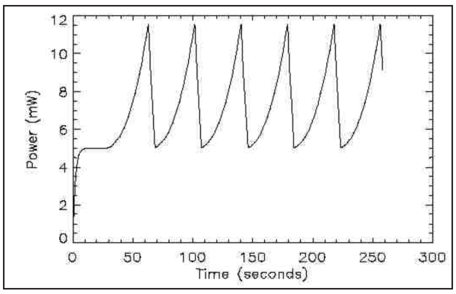


Figure 7.2.1: SMECm Power Fluctuation + 5mW Calibration Source Power

7.2.2. Cooler Recycling

During this analysis the Cooler Cold Tip is changed from a diffuse to a boundary node as recycling starts. After 55 minutes, when Cryopumping starts, the cooler is converted to a boundary node, whose temperature is reduced at a constant rate of 0.105K/min to 290mK.
Heat switch states and therefore input powers and conductance are switched during this analysis as shown.

TIME (H:MM:SS)	NODE NUMBER	NODE NAME	STATUS	POWER (mW)
0:00:00	10	PH. JFET	OFF	0.0
0:00:00	-	Mechanisms / Calibrators	OFF	0.0
0:00:00	-	COOLER	OFF	0.0
RECYCLE				
0:00:01	200 190	EVAP HS PUMP HS	ON OFF	0.2 0.0
0:00:02	160	PUMP	NET LOAD	142.1
	170	SHUNT	-	57.8
0:25:00	160	PUMP	NET LOAD	25.0
	170	SHUNT	NET LOAD	6.9
0:55:00	160	PUMP	OFF	0.0
	170	SHUNT	NET LOAD	0.0
COOLDOWN				
0:55:01	200 190	EVAP HS PUMP HS	OFF ON	0.0 0.2
0:55:02	180	EVAP	Cryopumping to 290mK @ 0.105K/min	0.0
0:55:02	160	PUMP	NET LOAD (until evap reaches 290mK).	17.07
OPERATION				
1:19:00	160	PUMP	NET LOAD	1.019
	170	SHUNT	NET LOAD	0.0054
1:30:00	10	PH. JFET	ON	49.5
1:40:00	70	PH. CALIBRATOR	ON	2.0
1:42:00	70	PH. CALIBRATOR	OFF	0.0
1:42:01	50	BSM	ON	4.0
2:12:00	50	BSM	OFF	0.0

8. ANALYSIS ASSUMPTIONS AND UNCERTAINTIES

The SPIRE ITMM is a reduced node version of the ESATAN SPIRE DTMM, SPIRE14b.d. All interface critical aspects of the instrument are incorporated into the ITMM, whilst more detailed information, such as temperature gradients across the SOB, detectors and straps, internal heat flows, cooler thermodynamic performance, etc are not included in significant detail. In addition the 300mK stage of the instrument is modelled at a basic level to ensure the accuracy of Level 0 interfaces, rather than to accurately predict the loads and temperatures at the detector stage. Therefore inaccuracies at this stage in the ITMM are expected and acceptable.

In order to compare the ITMM with the DTMM it is necessary to ensure that the same boundary conditions are used for the various cases. These boundary conditions are set by running the DTMM with the FIRST ITMM (AD2.1.2) and a mass flow rate set at a constant value of 2.30378mg/s (ref: ESATAN HERSCHEL_R output file, email M. Linder, 15-05-01). The resulting Herschel-SPIRE interface temperatures are used as input boundary temperatures for the SPIRE ITMM. The results of a comparison between DTMM and ITMM results are shown in Appendix A, and demonstrate a mean agreement in heat loads and temperatures of 98% for the four steady-state cases. Some inconsistencies are present due to the simplified level of the ITMM. However these are anticipated to have a negligible effect on the accuracy of the SPIRE FPU representation within the overall Herschel cryostat TMM.

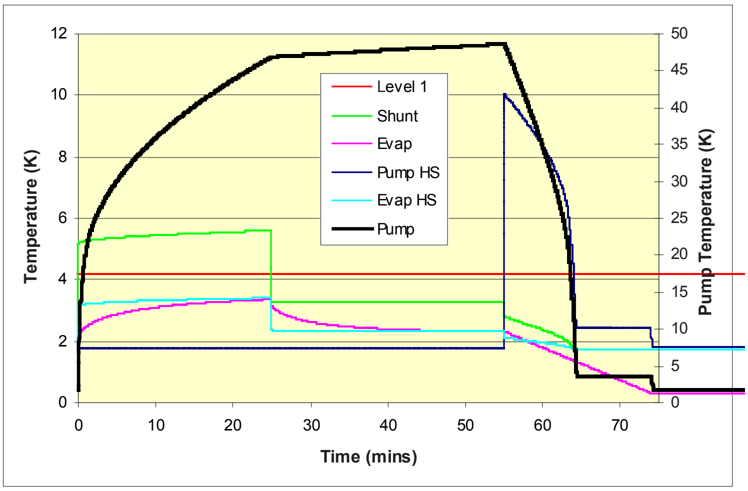
ANNEX A: COMPARISON OF ITMM AND DTMM RESULTS

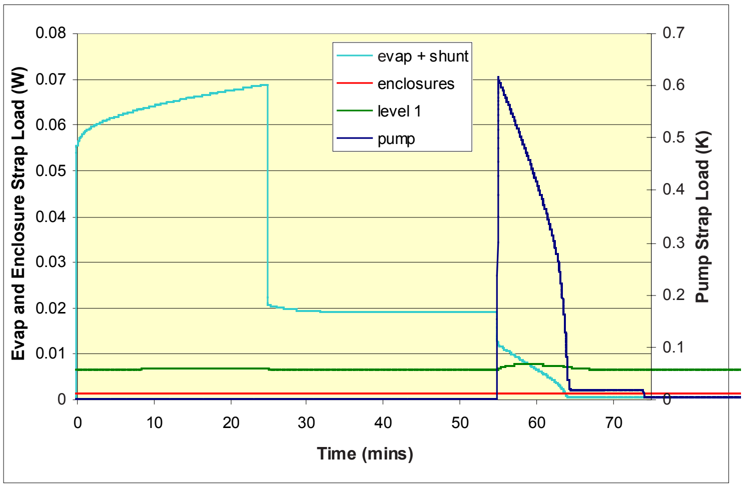
A1: Steady-State Results

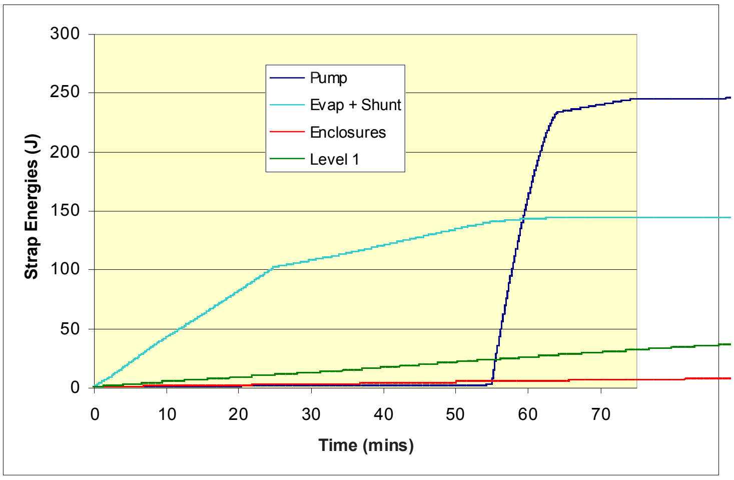
PARAMETER	DTMM NODE	ITMM NODE	MODE											
			PHOTOMETER			SPECTROMETER			STANDBY			OFF		
			ITMM	DTMM	(%)	ITMM	DTMM	(%)	ITMM	DTMM	(%)	ITMM	DTMM	(%)
			INTER01B	SPIRE 14B		INTER01B	SPIRE 14B		INTER01B	SPIRE 14B		INTER01B	SPIRE 14B	
Boundary Conditions:														
Mass Flow Rate (mg/s)				2.30378			2.30378			2.30378			2.30378	
H-S I/F Level 2 (K)	10000	1000		13.137			10.726			13.051			9.244	
H-S I/F Level 1 (K)	1330	3000		5.965			5.375			5.585			4.114	
H-S I/F Level 0 –encl (K)	6100	4000		1.812			1.786			1.795			1.745	
H-S I/F Level 0-pump (K)	6200	5000		1.763			1.759			1.718			1.709	
H-S I/F Level 0-evap (K)	6300	6000		1.713			1.711			1.712			1.706	
Temperatures:														
SPIRE Level 1 (K)	1600	30	6.080	6.15	0.989	5.483	5.552	0.988	5.683	5.751	0.988	4.169	4.209	0.990
SPIRE Level 0 (K)	2900	100	2.006	2.04797	0.979	1.938	1.970	0.984	1.961	1.998	0.981	1.823	1.837	0.992
SPIRE Detectors (K)	2950	120	0.317	0.3296	0.961	0.314	0.326	0.964	-	-	-	-	-	-
Loads:														
Cooler Evaporator (μW)			23.560	30.000	0.785	22.130	27.020	0.819	-	-	-	-	-	-
SPIRE Level 0 (mW)			5.606	5.671	0.989	4.558	4.676	0.975	3.748	3.810	0.984	1.790	1.819	0.984
SPIRE Level 0 – enclosure strap (mW)			3.234	3.271	0.989	2.477	2.498	0.991	2.729	2.767	0.986	1.257	1.278	0.983
SPIRE Level 0 – Pump strap (mW)			1.790	1.810	0.989	1.608	1.696	0.948	0.508	0.510	0.995	0.266	0.266	1.001
SPIRE Level 0 – evaporator strap (mW)			0.582	0.590	0.987	0.473	0.482	0.983	0.511	0.533	0.959	0.267	0.275	0.971
SPIRE Level 1 – Strap (mW)			18.194	18.240	0.997	15.732	15.790	0.996	14.619	14.722	0.993	6.334	6.501	0.974
SPIRE Level 2 (mW)			31.156	30.950	1.007	34.040	32.703	1.041	31.280	31.035	1.008	8.086	8.209	0.985
Mean Agreement*:					**0.987**			**0.987**			**0.987**			**0.985**

*Agreement does not include 300mK loads.

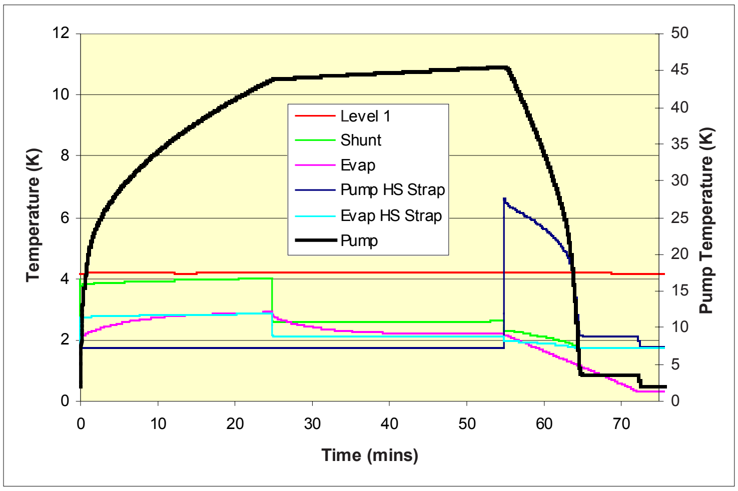
A2: ITMM Cooler Recycle Results

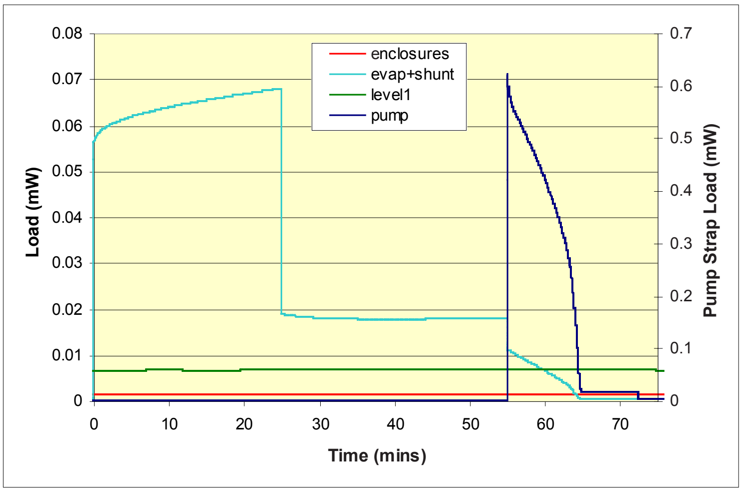


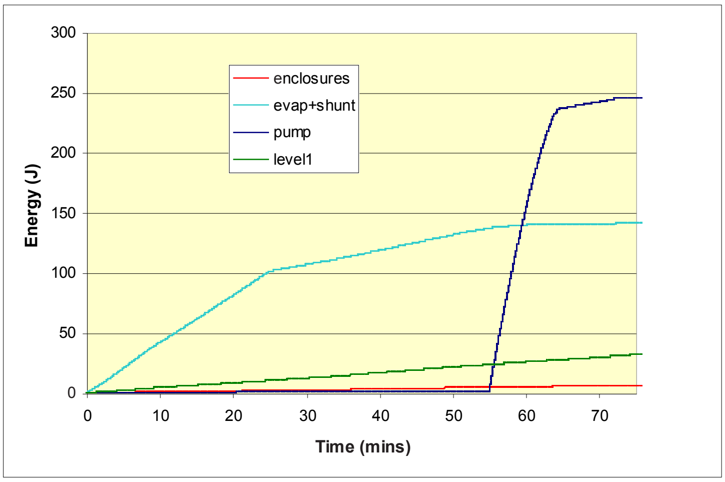




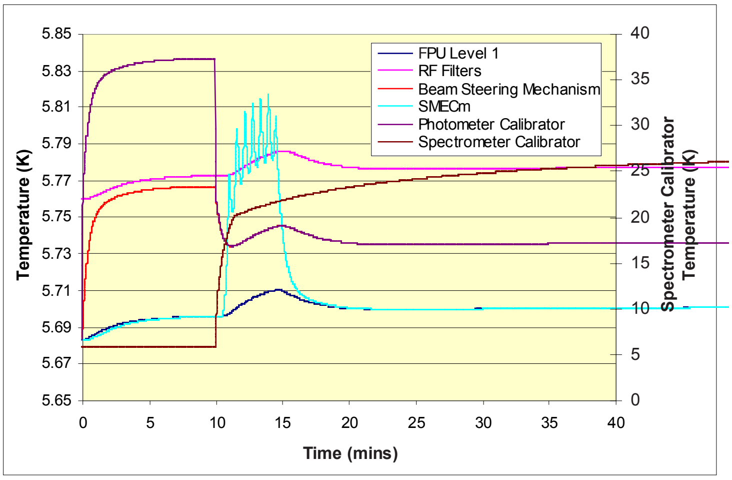
A3: DTMM Cooler Recycle Results

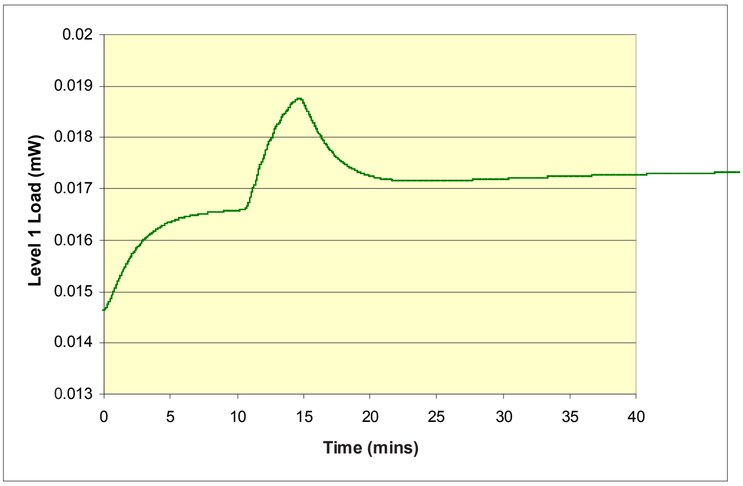


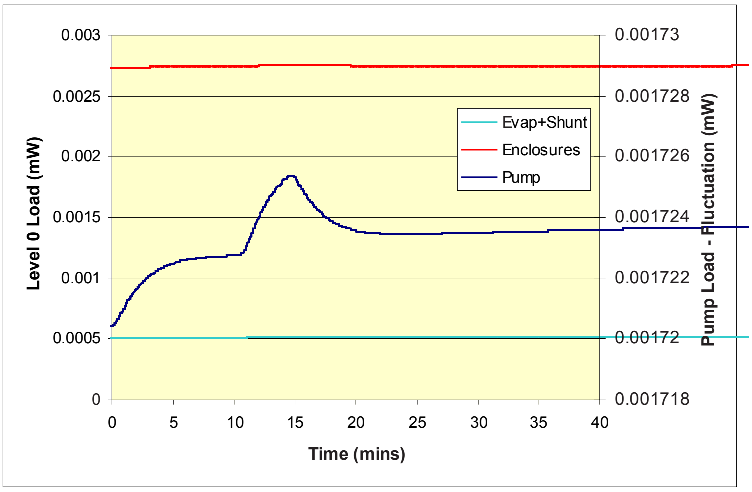


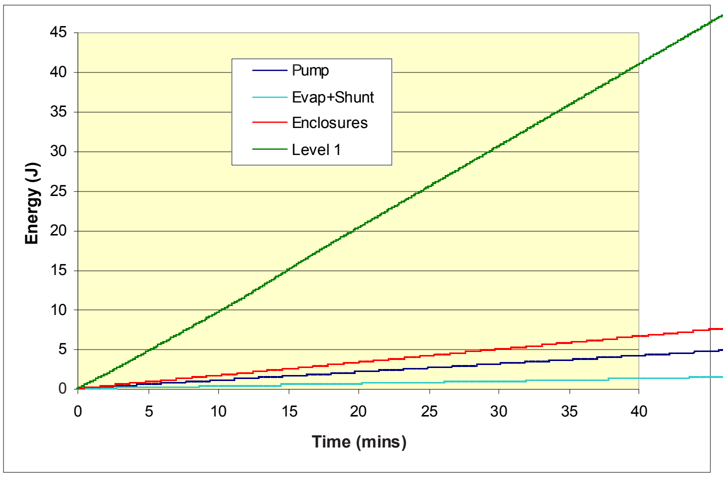


A4: ITMM Mode Change Results



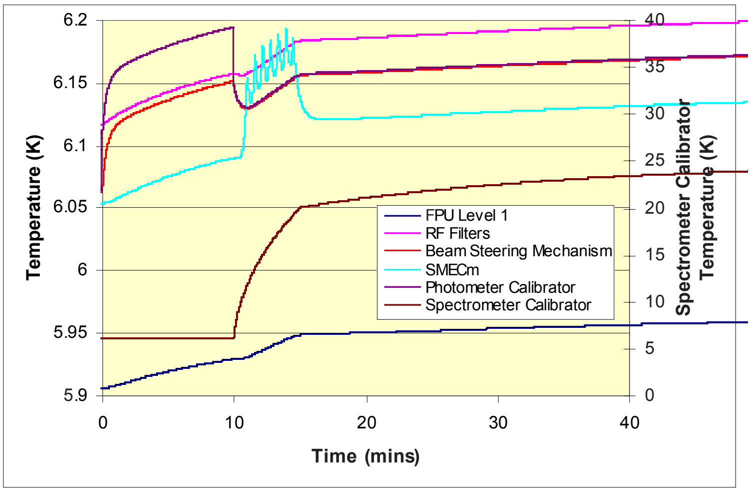


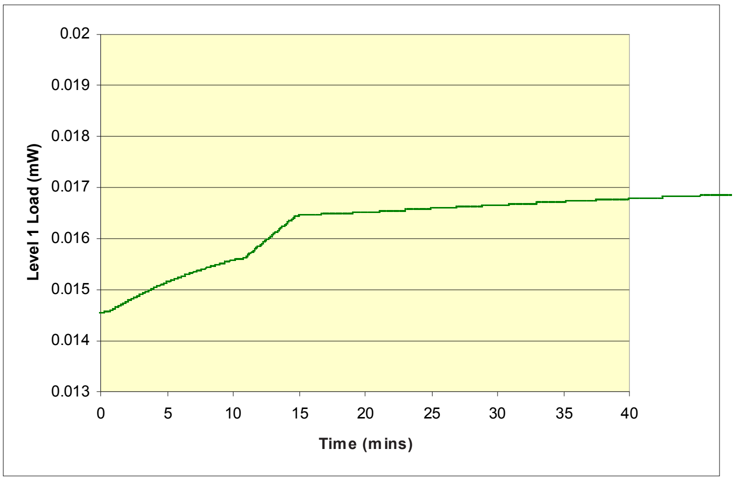


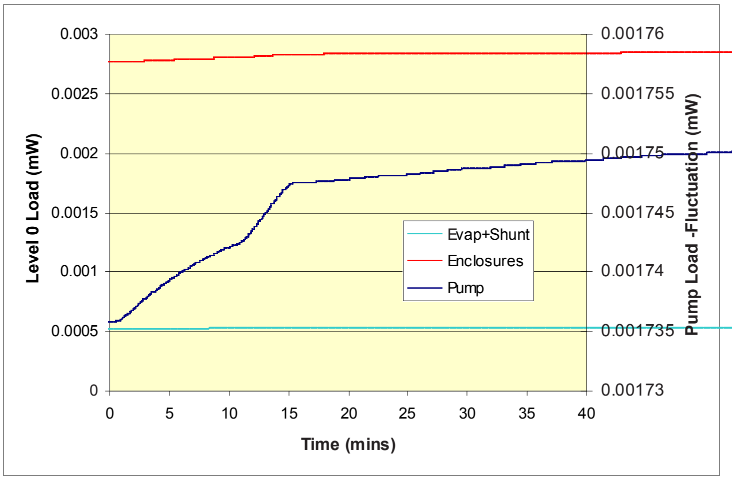


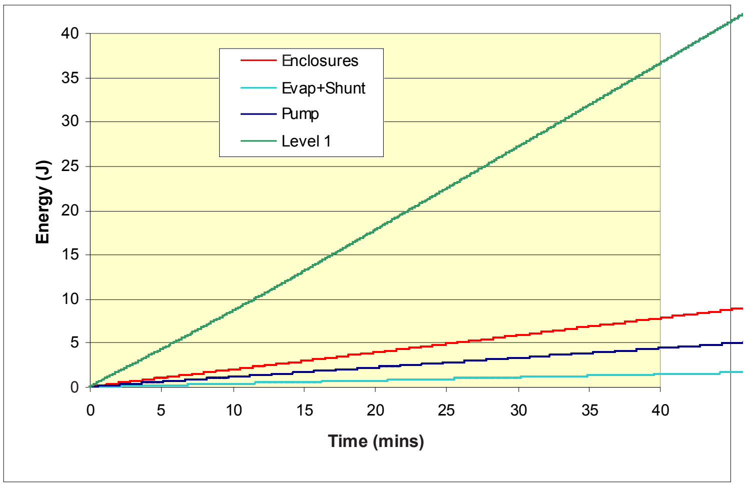
45
40
35
30
25
20
15
10
5
0
Energy (J)
Pump
Evap+Shunt
Enclosures
Level 1
0
5
10
15
20
25
30
35
40
Time (mins)

A5: DTMM Mode Change Results








Enclosures
Evap+Shunt
Pump
Level 1
Energy (J)
Time (mins)
0
5
10
15
20
25
30
35
40