SUBJECT: THERMAL CONFIGURATION CONTROL DOCUMENT

PREPEARED BY: S. HEYS…………………………………… **Date:** ………………

APPROVED BY: J. DELDERFIELD…………………….. **Date:** ……………….

APPROVED BY: B.SWINYARD……………………………. **Date:** ……………….

CHANGE RECORD

ISSUE	DATE	SECTION	CHANGE
D1	03-11-00	-	New Document
D2	22-11-00	All Table 6.2.1 Table 6.1.3 Table 6.1.3 Table 6.2.1 Table 6.3.1 Table 6.3.3 8.5 Table 9.2	Sections rearranged. Cone support dimensions updated JFET enclosures attached with 4 bolts not 8. L2 straps included 10K to 4K harness updated Detector harness changed from W/mm per wire to W/mm per 12ax. Cu-Au-Cu on L0 straps changed to Cu-Ap-Cu. Constant Helium Mass Flow Rate Mirror Drive OFF at 14:32

CONTENTS

1. SCOPE

This document describes the overall SPIRE thermal mathematical model, consisting of the FPU and its components, the JFET Boxes, and the FIRST Cryostat interface model. A breakdown of all the significant input parameters and assumptions is provided. This document should be updated regularly as the instrument design iterates. Any modifications made to the SPIRE TMM should be referenced to this document.

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	Change To Requirements on the Cooler and Thermal Strap	e-mail B.Swinyard 07-APR-00
AD 2.3.3	Conceptual Design For the 300mK Thermal Strap	SPIRE-RAL-MOM-xxx 25-APR-00
AD 2.3.4	SPIRE Inputs For Cryostat and Instrument Thermal Modeling	RAL 15-MAY-00 -update
AD 2.3.5	SPIRE FPU TMM Specification	S.Heys 30-MAY-00
AD 2.3.6	SPIRE Radiative Heat Loads	e-mail, A.Richards, 09-JUN-00
AD 2.3.7	Change To Requirements/Spec on the Cooler and Thermal Strap	e-mail B.Swinyard 04-JUL-00
AD2.3.8	Thermal Summit QMW 25/26 Sept 00	SPIRE-RAL-MOM-000516

Table 2.3: SPIRE Applicable Documents

2.4. MSSL Applicable Documents

ID	TITLE	NUMBER
AD 2.4.1	PROVISIONAL SPIRE (FIRST) Interface Drawing	A1 5264 300 Issue 5 21-MAR-00

AD 2.4.2	Here It Is	e-mail B.Winter 13-JUN-00
AD 2.4.3	Structure-Optics ICD	Spire ICD 1.1/1.2 Issue 1 B.Winter 13-JUN-00
AD2.4.4	FIRST/SPIRE A Frame Analysis	e-mail B.Winter 12-JUL-00
AD 2.4.5	Thermal Conductance SP1 Analysis and 6082 Data	e-mail B.Winter 23-SEPT-00
AD 2.4.6	SPIRE Cold Strap Lengths	J.Coker 02-OCT-00
AD2.4.7	Re: SPIRE - Thermal Assumptions	e-mail B.Winter 11-OCT-00
AD2.4.8	Structure-Mass	Issue 0.11 B.Winter 14-JUN-00
AD2.4.9	Re: FPU Cone Support	e-mail B.Winter 22-NOV-00

Table 2.4: SPIRE MSSL Applicable Documents

2.5. QMW Applicable Documents

ID	TITLE	NUMBER
AD 2.5.1	The SPIRE Instrument For FIRST	SPIRE Meeting Munich -vue graphs 29-MAR-00
AD 2.5.2	SPIRE A Bolometer Instrument For FIRST	Proposal Submitted to ESA FEB-98

Table 2.5: SPIRE QMW Applicable Documents

2.6. CEA Applicable Documents

ID	TITLE	NUMBER
AD 2.6.1	Preliminary Comments	e-mail L.Duband 7-JUN-00
AD 2.6.2	Cryogenic Sorption Cooler – Detailed Design of Engineering Models – Test Plan	TN/SBT/SC/99-04 Iss 0 Rev 0 L.Duband 22-JUN-00
AD 2.6.3	Cryogenic Sorption Cooler –Technical Requirements for the Engineering Models and Related Preliminary Design	SBT/CT/99-02
AD 2.6.4	Cryogenic Sorption Cooler ESA Contract: 12942/98/NL/PA	Presentation 07-SEPT-00
AD 2.6.5	Straps	e-mail L.Duband 27-SEPT 00
AD2.6.6	Frigio 3 He - Ensemble	QM Drawing 29/04/99
AD2.6.7	A Thermal Switch For Use At Liquid Helium Temperatures In Space-Borne Cryogenic Systems	L.Duband Cryocoolers 8 1995

Table 2.6: SPIRE CEA Applicable Documents

2.7. JPL Applicable Documents

ID	TITLE	NUMBER

AD 2.7.1	Array Design	SPIRE Technology Downselect Meeting JPL vue graphs 01-FEB-00
AD 2.7.2	Spire Thermal Model	e-mail T.Cafferty 13-JUN-00
AD 2.7.3	Thermal Properties	e-mail T.Cafferty 04-AUG-00
AD 2.7.4	Re:More FPU Thermal Information	e-mail T.Cafferty 12-AUG-00
AD2.7.5	FPU Thermal Properties Summary	T.Cafferty 11-JUL-00
AD2.7.6	Mass.xls	Sept-00

Table 2.7: SPIRE JPL Applicable Documents

2.8. Miscellaneous Applicable Documents

ID	TITLE	NUMBER
AD 2.8.1	Properties of Aluminium and Aluminium Alloys	Touloukian Y.S.
AD 2.8.2	Properties of Materials at Low Temperatures (Phase A). A compendium.	Johnson V.J. Pergamon 1961
AD 2.8.3	RAL Thermal Database	
AD 2.8.4	Planck TMM	
AD2.8.5	Thermal Conductance of Gold Plated Metallic Contacts At Liquid Helium Temperatures	Peter Kittel
AD2.8.6	Thermal Conductance of Pressed Metallic Contacts Augmented With Indium Foil Or Apeizon Grease At Liquid Helium Temperatures	Salerno and Kittel
AD2.8.7	Thermal Conductance of Augmented Pressed Metallic Contacts At Liquid Helium Temperatures	Salerno, Kittel and Spivak

Table 2.8: Miscellaneous Applicable Documents

3. INTRODUCTION

A detailed thermal mathematical model of the SPIRE instrument has been created in ESATAN v.8.4.2. Input parameters for this model originate from various sources, as referenced in Section 2. The thermal model and all input parameters are to be maintained under configuration control, with this document and the TMM updated only as any design changes or material properties modifications are approved.
The primary aim of the TMM is to provide information on the thermal performance of the SPIRE FPU as follows:

- The steady-state temperatures of the various components within the FPU, when under nominal conditions for each mode of operation.
- Stabilisation time required after change of operating mode from Photometer to Spectrometer.
- The effect of transients (e.g. cooler recycling) on on the ultimate stability of the 300mK detector stage.
- The time required for the instrument parts to reach their nominal operating temperatures after launch.
- Provide input to thermal design through analysis of proposed design modifications.
- Provide information on FIRST interface temperatures and heat loads through incorporation of FIRST Cryostat reduced node model in SPIRE TMM.
- Hence demonstrate that SPIRE meets thermal interface requirements (max heat loads to L0, L1 and L2).

4. INSTRUMENT THERMAL REQUIREMENTS

The thermal requirements of the SPIRE instrument are summarised below in Table 4.1.

Parameter	Specification	Reference
FPU Bulk Temperature	~4K	-
Cooler Interface Temperature	~4K	-
Detector Module Interface Temperature	~1.8K	-
Detector temperature	T <310mK	AD 2.3.7
Detector array stability	150nK/√Hz between 0.03 and 25Hz.	-
Heat leak to FPU from FIRST Optical Bench	6mW for delta T = 11-4.2 = 6.8K	AD 2.3.4
Conductive heat leaks down 1.8K box supports	1mW for delta T = 4.2 - 1.7 = 2.5K	AD 2.3.4
Total heat leak down the Photometer and Spectrometer 300mK strap supports	1.0µW	AD 2.3.3
Parasitic heat leak on 300mK detector stage	<1.6µW per array <8µW total	AD 2.3.3
Cooler heat lift	10µW (at 290mK evaporator temperature)	AD 2.3.7
Temperature difference between cooler cold tip and detector arrays	< 20mK	AD 2.3.7
Temperature gradient along compliant links from bus bars to Cooler or detectors	2mK/link	AD 2.3.7

Table 4.1: SPIRE Instrument Thermal Requirements

5. INSTRUMENT THERMAL DESIGN OVERVIEW

5.1. Overview

The SPIRE FPU and JFET Boxes are mounted off the FIRST Cryostat 10K Optical Bench, surrounded by the FIRST Instrument Shield at approximately 10K. The instrument has four temperature stages at approximately 10K, 4K, 1.8K and 300mK. Each stage is cooled via direct mounting to the FIRST Optical Bench, or 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 as shown in Table 5.1. It is anticipated that the actual interface temperatures will be significantly lower than those shown.

SPIRE Stage	SPIRE Components	Heat Sink	Heat Sink Temperature at SPIRE Interface	Maximum Average Heat Lift	Reference
10K	JFET boxes	FIRST Optical Bench FIRST L2 Vent Pipes	<15K	50mW	AD2.1.3
4K	SOB structure/ mechanisms / mirrors	FIRST L1 Vent Pipes	<6K	25mW	AD2.1.3
1.8K	FPU detector boxes / dichroics / mirrors	FIRST L0 LHe Tank	<2K	10mW	AD2.1.3
0.3K	FPU detectors / cooler thermal link	SPIRE ^3He Sorption Cooler	<290mK	10μW	AD2.3.7

Table 5.1: SPIRE Temperature Stages and Heat Sinks

5.2. FPU 10K Stage

The Photometer and Spectrometer JFET chips are located in two separate enclosures. These boxes are hard mounted to the 10K FIRST Optical Bench, which acts as a heat sink for the dissipated electronics power. In addition a thermal strap to the FIRST L2 sink is attached to each enclosure. The enclosures are linked to the FIRST Shield 1 (at ~35K) via a harness.

5.3. FPU 4K Stage

The SPIRE FPU 4K Structure consists of an Aluminium Alloy 6082 Optical Bench with the Spectrometer and Photometer Assemblies mounted on opposite sides. Aluminium Alloy 6082 walls surround each assembly and are hard bolted to the Optical Bench. The 4K SOB is the mechanical interface for the mirrors, mechanisms and cooler. These components are hard bolted to the SOB. The key thermal design features of the 4K stage are as follows:

- FPU mounted off the 10K FOB using three stainless steel isolating mounts.
- SOB attached to the FIRST L1Vent Line (at approximately 4K) via a copper thermal strap.
- Low conductance stainless steel harness from 10K stage JFET boxes.

5.4. FPU 1.8K Stage

The five detectors require conductive and radiative interfaces at approximately 1.8K. This is achieved by housing the detectors in enclosures mounted off the SOB and cooled to 1.8K via the L0 sink. Separate enclosures are used for the Photometer and Spectrometer detectors. The key thermal design features of these enclosures are as follows:

- Boxes mounted from the 4K SOB on three insulating stainless steel blades.
- Low conductance stainless steel harness from 4K Stage.
- Boxes cooled via a thermal strap from FIRST L0. This strap runs from the Cryostat through a light tight feed through in the FPU 4K wall to the Spectrometer 2K Box wall and then onto the Photometer 2K Box wall.
- Detectors hard mounted to enclosure walls via 1.8K flange.

5.5. FPU 300mK Assembly

5.5.1. Detectors

The detector feedhorns, bolometer arrays and filters require to be held at <310mK. The key thermal design features used to achieve this are as follows:

- 300mK stage supported off 1.8K detector flange using 3000denier Kevlar thread.
- Low conductance Kapton and Constantan harnessing between the 300mK and the 1.8K stages.
- Copper straps from detectors to cooler cold tip at 290mK.

5.5.2. Cooler to Detector Thermal Straps

The Photometer and Spectrometer 300mK detector stages are coupled via two separate thermal straps to the cooler cold finger. These straps are manufactured from high purity copper and are supported on Kevlar threads from the 1.8K enclosure walls. The straps pass through light tight feedthrus at the point where they enter the 1.8K enclosure.

5.6. Helium Cooler

- The Cooler structure is hard mounted to the FPU 4K SOB.
- Kevlar threads are used to isolate the evaporator, pump and shunt from the Cooler 4K Stage.
- The pump and evaporator are linked to the FIRST L0 sink via heat switches and copper straps.
- The pump heat switch is ON during normal operations.
- The evaporator heat switch is OFF during normal operations.
- Recycling is carried out every 48 hours and should be completed in less than 2 hours.
- During recycling the evaporator heat switch is ON and the pump heat switch is OFF. The pump is heated to 40K for approximately 1 hour before the pump heater is switched OFF and the heat switch states are reversed. The pump then cools back to 1.8K, whilst the evaporator cools to <290mK. Separate straps are therefore necessary to prevent large increases in evaporator temperature, as the hot pump is re-connected to the Cryostat after recycling.

5.7. Mechanisms

TBD

6. HEAT LOAD AND TEMPERATURE GRADIENT BUDGETS

6.1. Level 2 Stage

6.1.1. Level 2 Heat Load

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Heat Load Budget
FIRST Shield 1	Photometer JFET Box	Harness	6.76E-6mm2 14.25E-6mm2 171E-6mm2	1.2m	Brass Stainless PTFE	-	-	AD2.2.1	2mW (TBC)
FIRST Shield 1	Spectrometer JFET Box	Harness	2.02E-6mm2 4.26E-6mm2 51.1E-6mm2	1.2m	Brass Stainless PTFE	-	-	AD2.2.1	2mW (TBC)
MAXIMUM AVERAGE HEAT LOAD TO SPIRE L2:									**4mW (TBC)**

6.1.2. Level 2 Average Power Dissipation

Component	Reference	Heat Load Budget	
		Photometer Mode	**Spectrometer Mode**
Photometer JFET Box	AD2.3.8	49.5mW	0.0mW (TBC)
Spectrometer JFET Box	AD2.3.8	0.0mW (TBC)	14.1mW
MAXIMUM AVERAGE POWER DISSIPATION AT SPIRE L2:		**49.5mW (TBC)**	**14.1mW (TBC)**

6.1.3. Level 2 Heat Sink

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	IID-A Heat Load Budget
Photometer JFET Enclosure	FIRST Optical Bench	Bolted	-	-	-	*Al-Al	4 bolts	AD2.1.3	(TBD)
Photometer JFET Enclosure	FIRST L2 Vent Pipes	10K Strap	-	-	-	0.07W/K @10K	-	*	(TBD)
Spectrometer JFET Enclosure	FIRST Optical Bench	Bolted	-	-	-	*Al-Al	4 bolts	AD2.1.3	(TBD
Spectrometer JFET Enclosure	FIRST L2 Vent Pipes	10K Strap	-	-	-	0.07W/K @10K -	-	*	(TBD)
MAXIMUM AVERAGE HEAT LOAD BUDGET TO FIRST L2:									**50mW**

*Assumed

6.2. Level 1 Stage

6.2.1. Level 1 Heat Load

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Heat Load Budget
FIRST Optical Bench	FPU 4K Stage	Cone Foot	2mmx2mm x 8 spokes = 32mm2	21mm	Stainless Steel	-	-	AD2.4.9	6mW (TBC)
FIRST Optical Bench	FPU 4K Stage	2 A-Frame Feet	2 x 22.5mm2 = 45mm2	35mm	Stainless Steel	-	-	AD2.4.4	
Photometer JFET Box	FPU 4K Stage	Harness	58-off 12-ax cables**	150mm	Stainless Steel	-	-	AD2.3.4 / AD2.3.8	0.5mW (TBC)
Spectrometer JFET Box	FPU 4K Stage	Harness	17-off 12-ax cables**	150mm	Stainless Steel	-	-	AD2.3.4 / AD2.3.8	0.5mW (TBC)
MAXIMUM AVERAGE HEAT LOAD TO SPIRE L1:									**7.0mW (TBC)**

**Heat Flow per 12ax (W/mm) = 3.1E-06 ($T_H^{2.19}$-$T_C^{2.19}$)

6.2.2. Level 1 Average Power Dissipation

Component	Reference	Power Budget	
		Photometer Mode	**Spectrometer Mode**
Photometer Calibrator	AD2.3.1	1.5mW	0.0mW
Spectrometer Calibrator	AD2.3.1	0.0mW	5.0mW
Beam Steering Mechanism	AD2.3.1	2.6mW	0.0mW
Spectrometer Mirror Drive	AD2.3.1	0.0mW	2.4mW
MAXIMUM AVERAGE POWER DISSIPATION AT SPIRE L1:		**4.1mW**	**7.4mW**

6.2.3. Level 1 Heat Sink

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	IID-A Heat Load Budget
FPU Wall	FIRST L1 Vent Pipes	4K Strap	20mm x 1mm = 20mm2	300mm	'ISO' Copper	*Cu-Au-Cu (both ends)	4.7x1.4 = 6.58cm2	AD2.1.2 / AD2.2.1	25mW
MAXIMUM AVERAGE HEAT LOAD BUDGET TO FIRST L1:									**25mW**

*Assumed

6.3. Level 0 Stage

6.3.1. Level 0 Heat Load

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Heat Load Budget
4K SOB	2K Box Strap	4K Feedthru	8 threads x 0.3mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.020mW
4K SOB	Cooler Evaporator Strap	4K Feedthru	8 threads x 0.3mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.020mW
4K SOB	Cooler Pump Strap	4K Feedthru	8 threads x 0.3mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.020mW
4K SOB	Phot. 2K Box	3 Blade Supports	3 x 10mm2 = 30mm2	30mm	Stainless Steel	-	-	AD2.3.4	0.600mW
4K SOB	Spec. 2K Box	3 Blade Supports	3 x 10mm2 = 30mm2	30mm	Stainless Steel	-	-	AD2.3.4	0.400mW
4K SOB	Phot. LW Detector 1.8K	Detector Harness	**9-off 12-ax cables	80mm	Stainless Steel	-	-	AD2.7.4	0.100mW
4K SOB	Phot. MW Detector 1.8K	Detector Harness	**19-off 12-ax cables	80mm	Stainless Steel	-	-	AD2.3.8 / AD2.7.4	
4K SOB	Phot. SW Detector 1.8K	Detector Harness	**30-off 12-ax cables	80mm	Stainless Steel	-	-	AD2.3.8 / AD2.7.4	
4K SOB	Spec. LW Detector 1.8K	Detector Harness	**7-off 12-ax cables	80mm	Stainless Steel	-	-	AD2.3.8 / AD2.7.4	
4K SOB	Spec. SW Detector 1.8K	Detector Harness	**11-off 12-ax cables	80mm	Stainless Steel	-	-	AD2.3.8 / AD2.7.4	
4K Cooler	1.8K Cooler	Cooler Heat Leaks							0.150mW (TBC)
MAXIMUM AVERAGE HEAT LOAD TO SPIRE L0:									**1.310mW (TBC)**

**Heat Flow per 12ax (W/mm) = 3.1E-06 ($T_H^{2.19}$-$T_C^{2.19}$)

6.3.2. Level 0 Average Power Dissipation

Component	Reference	Power Budget
Cooler Heat Switch		0.2mW
Cooler Pump Heater		200mW for 30mins every 48 hours = 2.08mW 25mW for 30mins every 48 hours = 0.26mW
MAXIMUM AVERAGE POWER DISSIPATION AT SPIRE L0:		**2.54mW (TBC)**

6.3.3. Level 0 Heat Sink

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	IID-A Heat Load Budget
FPU 4K Feedthru	FIRST L0	1.8K Enclosures Strap	20mm x 1mm = 20mm2	*350mm	UHP Copper	*Cu-Ap-Cu (both ends)	4.7x1.4 = 6.58cm2	AD2.2.1	5mW
FPU 4K Feedthru	FIRST L0	Cooler Pump Strap	20mm x 1mm = 20mm2	*350mm	UHP Copper	*Cu-Ap-Cu (both ends)	4.7x1.4 = 6.58cm2	AD2.2.1/ AD2.6.5	5mW
FPU 4K Feedthru	FIRST L0	Cooler Evaporator Strap	20mm x 2mm = 40mm2	*350mm	UHP Copper	*Cu-Ap-Cu (both ends)	4.7x1.4 = 6.58cm2	AD2.2.1/ AD2.6.5	
MAXIMUM AVERAGE HEAT LOAD BUDGET TO FIRST L0:									**10mW**

6.4. 300mK Stage

6.4.1. 300mK Heat Load

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Heat Load Budget
1.8K Box	300mK Phot. Busbar	Busbar Support	2 threads x 0.3mm2 x 4 attachment points = 2.4mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.50µW (TBC)
1.8K Box	300mK Phot. Feedthru	2K Feedthru Support	8 threads x 0.015mm2 = 1.2mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.25µW (TBC)
1.8K Box	300mK Spec. Feedthru	2K Feedthru Support	8 threads x 0.015mm2 = 1.2mm2	20mm	Kevlar 49 Thread	-	-	AD2.4.7	0.25µW (TBC)
1.8K Detector	300mK Detector	5 Detector Supports	5 x 16 threads x 0.3mm2 = 24mm2	25mm	Kevlar 49 Thread	-	-	AD2.7.2	4.0µW
1.8K Detectors	300mK Detectors	Harness	14mm2 0.275mm2	30mm	Kapton Constantan	-	-	AD2.7.4	4.0µW
MAXIMUM AVERAGE HEAT LOAD TO SPIRE 300mK STAGE									**9.0mW (TBC)**

6.4.2. 300mK Average Power Dissipation

Component	Reference	Power Budget
Temperature Control Heaters	*	1.0µW (TBC)
MAXIMUM AVERAGE POWER DISSIPATION AT SPIRE 300mK STAGE		**1.0mW (TBC)**

*Assumption

6.4.3. 300mK Heat Sink

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Heat Load Budget
300mK Assembly	Cooler Cold Tip	*See Tables 6.5.1 and 6.5.2 for breakdown of 300mK Thermal Strap Couplings*							10μW
MAXIMUM HEAT LOAD BUDGET TO SPIRE ^{3}HeCOOLER									**10mW**

6.5. Cooler - Detectors Thermal Strap Temperature Gradients

6.5.1. Photometer Strap

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Max Temperature Drop
Cover	Feedhorn	Contact Interface	-	-	-	In-Ap-In	0.4 cm^2	AD2.7.4	3.0mK
Feedhorn	300mK Flange	Internal Strap	Diameter 1mm = 0.78mm2	60mm	UHP Copper	Cu-ap-In	2.7 cm^2	AD2.7.4	3.0mK
LW Flange MW Flange SW Flange	Busbar	Detector Strap	Diameter 2.5mm = 4.91mm2	60mm 113mm 53mm	UHP Copper	*Cu-Ap-Cu	$2\pi R$ x 0.6 = 0.47cm^2	AD2.4.5 / AD2.7.4	2.5mK
Phot. Busbar	Phot. Feedthru	Busbar	Diameter 3mm = 12.57mm2	288mm	UHP Copper	*Cu-Ap-Cu	$2\pi R$ x 0.6 = 0.57cm^2	AD2.4.5	3.5mK
Phot. Feedthru	Phot. Feedthru Flange	2K Box Feedthru	Diameter 5mm = 12.57mm2	50mm	UHP Copper	*Cu-Ap-Cu	*1cm2	AD2.4.5	3.0mK
Phot. Feedthru Flange	Cooler Evaporator	Cooler Strap	Diameter 2mm = 3.14mm2	130mm	UHP Copper	*Cu-Ap-Cu	*1cm2	AD2.4.5 / AD2.3.3	5.0mK
MAXIMUM TEMPERATURE DROP FROM COOLER TO DETECTOR									**20mK**

6.5.2. Spectrometer Strap

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference	Max Temperature Drop
Cover	Feedhorn	Contact Interface	-	-	-	In-Ap-In	0.4 cm^2	AD2.7.4	3.0mK
Feedhorn	300mK Flange	Internal Strap	Diameter 1mm = 0.78mm2	60mm	UHP Copper	Cu-ap-In	2.7 cm^2	AD2.7.4	3.0mK
LW Flange SW Flange	Busbar	Detector Strap	Diameter 2.5mm = 4.91mm2	54mm 54mm	UHP Copper	*Cu-Ap-Cu	1cm^2	AD2.4.5 / AD2.7.4	1.0mK
Spec. Feedthru	Spec. Feedthru Flange	2K Box Feedthru	Diameter 5mm = 12.57mm2	40mm	UHP Copper	*Cu-Ap-Cu	*1cm2	AD2.4.5	1.5mK
Spec. Feedthru Flange	Cooler Evaporator	Cooler Strap	Diameter 2mm = 3.14mm2	210mm	UHP Copper	*Cu-Ap-Cu	*1cm2	AD2.4.5 / AD2.3.3	3.5mK
MAXIMUM TEMPERATURE DROP FROM COOLER TO DETECTOR									**12mK**

*Assumption

6.6. Sub-System Conductive Couplings

6.6.1. Cooler Internal Conductive Couplings

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference
4K Flange	Pump	Kevlar Supports	2.4mm^2	27mm	Kevlar Thread	-	-	*
4K Flange	Evaporator	Kevlar Supports	2.4mm^2	54mm	Kevlar Thread	-	-	AD2.6.2
Pump	Shunt	Pipe	OD = 10.4mm ID = 10mm	45mm	Ti6Al4V	-	-	AD2.6.2
Shunt	Evaporator	Pipe	OD = 10.4mm ID = 10mm	110mm	Ti6Al4V	-	-	AD2.6.2
4K Flange	Pump HS	HS Support	OD = 7.2mm ID = 7.0mm	50mm	Ti6Al4V	-	-	AD2.6.2
4K Flange	Evaporator HS	HS Support	OD = 7.2mm ID = 7.0mm	50mm	Ti6Al4V	-	-	AD2.6.2
Evaporator HS	Shunt	Strap	10mm^2	50mm	Cu	Cu-Ap-Cu	2cm^2	*
Evaporator	Evaporator HS	HS ON HS OFF	--	-	-	3mW/K 0.28µW/K	-	AD2.6.2
Pump	Pump HS	HS ON HS OFF	-	-	-	16mW/K 6µW/K	-	AD2.6.2

*Assumption

6.6.2. Detector Internal Conductive Couplings

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference
2K Flange	Top Ring	Kevlar Supports	8 threads x 0.3 cm^2 = 2.4 mm^2	25mm	Kevlar 49 Thread	-	-	AD2.7.2
2K Flange	Bottom Ring	Kevlar Supports	8 threads x 0.3 cm^2 = 2.4 mm^2	25mm	Kevlar 49 Thread	-	-	AD2.7.2
Top Ring	Spacer	Spacer	33mm^2	15.25mm	Invar	In-Ap-In	0.66cm^2	AD2.7.4
Bottom Ring	Spacer	Spacer	33mm^2	15.25mm	Invar	In-Ap-In	0.66cm^2	AD2.7.4
Bottom Ring	Cover		-	-	-	In-Ap-In	5.7 cm^2	AD2.7.4
Feedhorn	Cover		-	-	-	In-Ap-In	0.4 cm^2	AD2.7.4
Feedhorn	Strap Flange	Internal Strap	1mm dia	60mm	UHP Copper	Cu-Ap-In	2.7 cm^2	AD2.7.4
Top Ring	Strap Flange	-	-	-	-	Cu-Ap-In	1 cm^2	AD2.7.4

*Assumption

6.6.3. Mechanism Interface Couplings

From	To	Description	XSection	Length	Material	Interface Type	Contact Area	Reference
Spectrometer Calibrator	4K Optical Bench	Mounting	-	-	-	Al-Au-Al	4 x1cm^2	*
Photometer Calibrator	4K Optical Bench	Mounting	-	-	-	Al-Au-Al	4 x1cm^2	*
Spectrometer Mechansim	4K Optical Bench	Mounting	-	-	-	Al-Au-Al	4 x1cm^2	*
Photometer Beam Steering Mechanism	4K Optical Bench	Mounting	-	-	-	Al-Au-Al	4 x1cm^2	*

*Assumption

7. COMPONENT POWER DISSIPATION

The power dissipations for the various components are given in Table 7.1 below.

Component	Peak Power (mW)	Mean Power (mW)	Comments	Reference
Photometer Cold Read-Out Electronics	49.5	49.5	ON constantly in Photometer Mode	AD2.3.8
Spectrometer Cold Read-Out Electronics	14.1	14.1	ON constantly in Spectrometer Mode	AD2.3.8
Cooler Pump Heat Switch	0.2	0.2	On constantly when cooler ON	AD2.3.8
Cooler Heater	 200 25	 200 25	ON during cooler recycling: 0mins- 30mins 30mins-60mins	AD2.3.8
Photometer Calibrator	2.0*	1.5**	ON for 10 minute intervals during Photometer Mode.	*AD2.3.1
Spectrometer Calibrator	5.0	5.0	ON in Spectrometer Mode	AD2.3.1
Beam Steering Mechanism	4.0*	2.6**	ON in Photometer Mode	*AD2.3.1
Spectrometer Mirror Drive	6.5	2.4	ON (cycling) during Spectrometer Mode (see Figure 11)	AD2.3.1

**Values calculated to give total steady-state powers as stated in AD2.3.4

Table 7.1: Component Power Dissipation

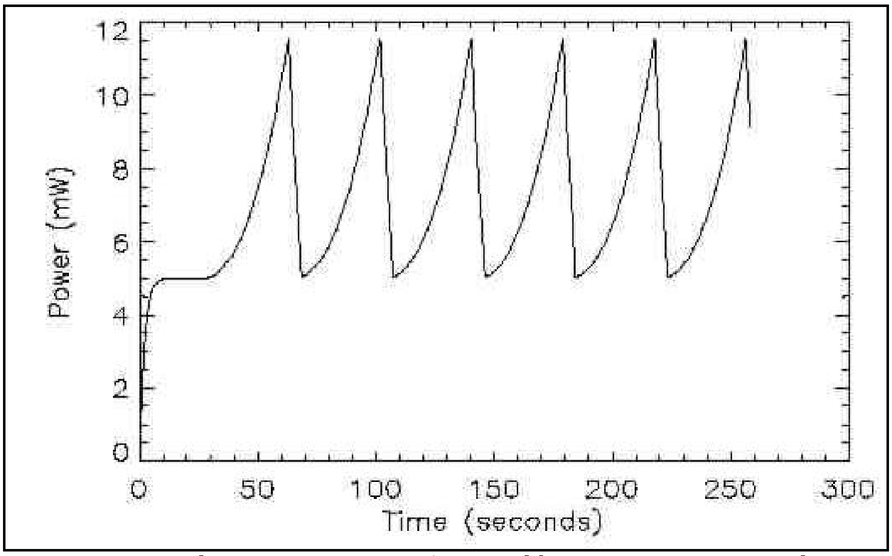


Figure 7.1: Spectrometer Mode Power Dissipation (5mW calibration source + mirror drive power)

8. THERMAL MATHEMATICAL MODEL

8.1. NODAL BREAKDOWN

The SPIRE thermal model consists of 138 diffuse nodes representing the SPIRE FPU, a single diffuse node for each of the two JFET Boxes, a single boundary node to represent the Cooler Cold Tip and four boundary nodes to represent the FIRST Cryostat. A full nodal breakdown of the TMM can be found in Appendix A.

8.1.1. 10K Enclosures

The two JFET boxes are each represented by single diffuse nodes, hard mounted to the FIRST Optical Bench. The harnesses between the JFET boxes and the Spacecraft are sunk to the FIRST Shield 1 temperature. Straps to the FIRST L2 sink have an assumed conductance of 0.07W/K at 10K.

8.1.2. 4K FPU Structure

The FPU structure is discretised along all axes in order to show temperature gradients through the instrument. A total of 10 nodes are used to represent the walls of the Spectrometer and Photometer and 16 nodes for the Optical Bench.

The FPU structure is mounted from the FIRST Optical Bench node on a single cone foot and two A-frame feet. Due to the non-uniform cross sectional area of the Cone Foot and the variation in conductivity across the foot with temperature, the cone is discretised into 10 nodes to improve the accuracy of the TMM. The A-Frames have a constant cross section and are therefore modelled as a simple conductive coupling between the FIRST Optical Bench and the FPU.

8.1.3. Mechanisms and Calibration Sources

The mechanisms and calibration sources are modelled very simply, due to lack of detailed information on their design. A single node is used to represent each component, with an associated power dissipation and heat capacity. The components are assumed to be hard mounted to the structure with gold coated aluminium to aluminium interfaces. The conductance across this interface is varied according to temperature.

8.1.4. Mirrors

Each mirror is modelled as a single node with an associated heat capacity. The mirrors are hard mounted to the structure via gold-coated aluminium to aluminium interfaces. The conductances across these interfaces are varied according to temperature.

8.1.5. 1.8K Enclosures

The photometer and spectrometer 1.8K enclosure walls are discretised into 3 nodes and 2 nodes respectively. Baffles and mirrors within the boxes are modelled as separate nodes, as are the detectors.

8.1.6. 300mK Assembly

The photometer and spectrometer thermal links from the cooler cold tip to the detector 300mK stages are modelled in order to show the critical temperature drops along these link. Figure 6.6 shows the nodal breakdown of the complete 300mK system.

8.1.7. Detectors

The detector model is a simplified version of the reduced node detector model provided by JPL (AD2.7.2). Each detector is discretised into 7 nodes as shown in Figure 6.6.

8.1.8. Cooler

The Cooler model is based on the nodal breakdown provided by L.Duband (AD2.6.1). A total of 6 nodes are used to represent the cooler as shown in Figure 6.6.

8.1.9. Straps

Straps to the L0,L1 and L2 sinks are modelled as shown in Figures 6.9.1 to 6.9.4.

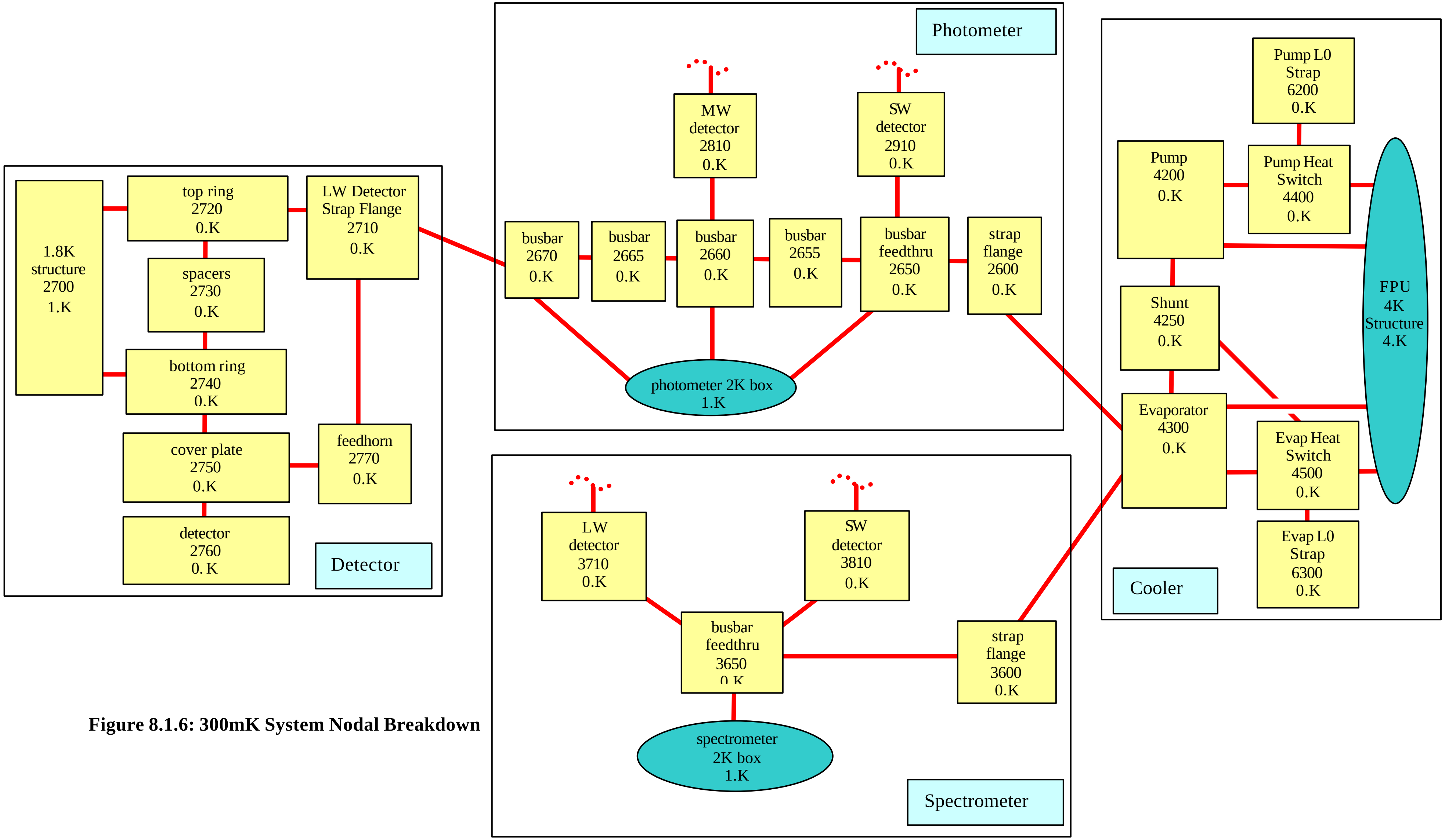


Figure 8.1.6: 300mK System Nodal Breakdown

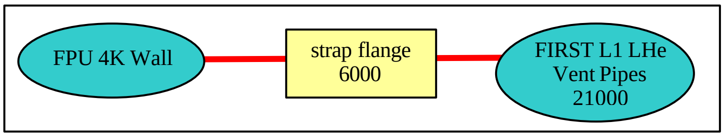


Figure 8.1.9.1: L1 Strap Node Breakdown

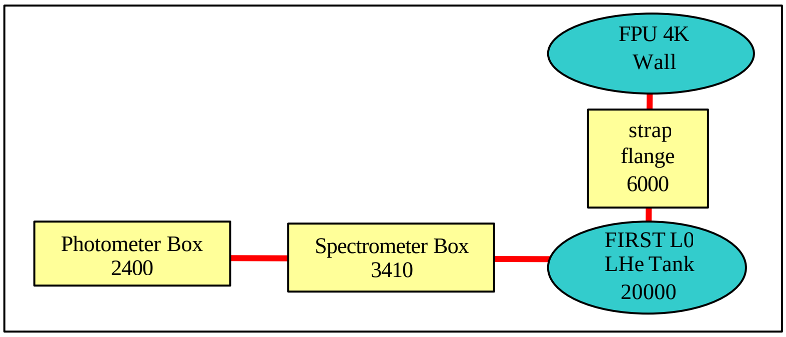


Figure 8.1.9.2:L0 2K Box Strap Node Breakdown

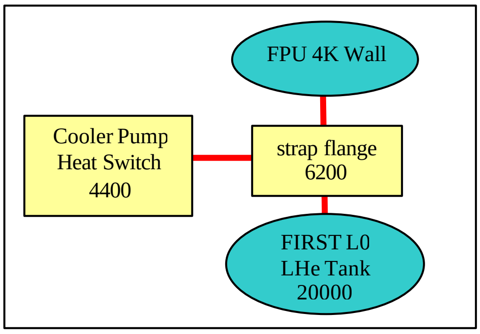


Figure 8.1.9.3: L0 Cooler Pump Strap Node Breakdown

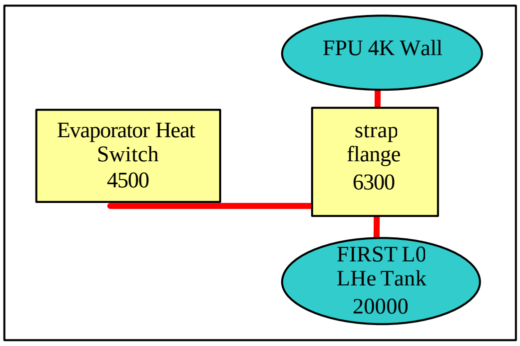


Figure 8.1.9.4: L0 Cooler Evaporator Strap Node Breakdown

8.2. Conductive Couplings

8.2.1. Definitions

The assumptions used for the definition of all critical conductive couplings are given in Section 7.

8.2.2. Thermal Conductivity

The thermal conductivity vs temperature relationships assumed for the various materials are given in Appendix B. The integrated thermal conductivity is used in couplings linking components at different temperature stages, in order that changes in conductivity with temperature are accounted for in the analysis.
The most critical conductivity value is for copper, since changes in purity and application can significantly alter the conductivity. Two grades of copper are therefore assumed:

-'Ultra High Purity Copper' for the L0 straps, the 300mK links and the detector internals. This material exhibits a conductivity of 767W/mK at 2K. This is in close agreement with the value of 800W/mK at 2K given in AD2.2.1 for the L0 strap copper.
-A lower purity copper is assumed for the L1 straps. The material used has a conductivity of 138W/mK at 2K, which is in close agreement with the value of 140W/mK given in AD2.2.1 for the L0 strap copper.

These values will be updated following conductivity tests on the actual copper grade and configurations specified in the final design.

8.2.3. Joint Interface Conductance

All significant joint interface conductances are accounted for in the TMM. The conductance values assumed are varied with temperature and are dependant on the materials being joined and on the interface. All critical interfaces in the 300mK Assembly are assumed to have interface conductances similar to that shown in Appendix D for Apeizon Grease interfaces. This is also the assumption for the L0 Straps. All other joints are assumed to have conductances similar to those shown for gold coated surfaces.

8.3. Radiative Couplings

Radiative couplings between the SPIRE instrument's external walls and the FIRST Cryostat are calculated by hand. The assumed emissivities and view factors are given in Table 8.3 below. Internal radiative loads have been shown to be insignificant due to the low temperatures involved.

Surface i	Surface j	Emissivity i	Emissivity j	View Factor	Reference
FPU external side walls	FIRST Instrument Shield	0.10	0.10	*0.5	AD2.3.4
FPU external side walls	FIRST Optical Bench	0.10	0.10	*0.5	AD2.3.4
FPU external base	FIRST Instrument Shield	0.10	0.10	*0.0	AD2.3.4
FPU external base	FIRST Optical Bench	0.10	0.10	*1.0	AD2.3.4
JFET Boxes	FIRST Optical Bench	0.10	0.10	*0.5	AD2.3.4
JFET Boxes	FIRST Instrument Shield	0.10	0.10	*0.5	AD2.3.4

*Approximation

Table 8.3: Radiative Exchange Coupling Parameters

8.4. Heat Capacities

8.4.1. Specific Heat Capacity

The assumed specific heat capacity vs temperature relationships for the various materials used within the TMM are shown in Appendix C.

8.4.2. Masses

The masses assumed for all SPIRE components are shown in Table 8.4.2. Nodes representing the FIRST ITMM have boundary nodes with zero associated thermal mass. Their rate of change of temperature is restricted within the TMM as described in Section 8.5.

Sub-System	Component	Temp (K)	No. Off	Mass (kg)	Material	Reference
4K Structure	Optical Bench	4	1	7.102	Al 6082	AD2.4.8
4K Structure Photometer Cover	back panel	4	1	0.539	Al 6082	AD2.4.8
	base plate	4	1	1.229	Al 6082	AD2.4.8
	front panel	4	1	0.709	Al 6082	AD2.4.8
	top cover	4	1	0.787	Al 6082	AD2.4.8
	top rear cove	4	1	0.434	Al 6082	AD2.4.8
	outer panel	4	1	3.597	Al 6082	AD2.4.8
4K Structure Spectrometer Cover	back panel	4	1	0.407	Al 6082	AD2.4.8
	base plate	4	1	1.000	Al 6082	AD2.4.8
	front panel	4	1	0.577	Al 6082	AD2.4.8
	top cover	4	1	0.638	Al 6082	AD2.4.8
	top rear cover	4	1	0.409	Al 6082	AD2.4.8
	outer panel	4	1	3.184	Al 6082	AD2.4.8
4K Structure Mounting	A-frame	4	2	0.115	Al 6082	AD2.4.4
	Cone	4	1	0.150	Al 6082	Assumption
4K Structure Photometer mounts and clamps	CM3, CM5, CM7 – mount	4	1	0.650	Al 6082	AD2.4.8
	PM6, SM6 – mount	4	1	0.120	Al 6082	AD2.4.8
	PM9 – mount	2	1	0.010	Al 6082	AD2.4.8
	PM10 – mount	2	1	0.010	Al 6082	AD2.4.8
	PM11 –mount	2	1	0.010	Al 6082	AD2.4.8
	dichroic clamp + mount	2	2	0.100	Al 6082	AD2.4.8
4K Structure Spectrometer	beam splitter mount + clamp	4	2	0.100	Al 6082	AD2.4.8

mounts and clamps						
	SM7 – mount	4	1	0.115	Al 6082	AD2.4.8
	SM8/11 –mount	4	4	0.096	Al 6082	AD2.4.8
	SM9/10 – mount	4	2	0.144	Al 6082	AD2.4.8
	SM12 –mount	2	2	0.010	Al 6082	AD2.4.8
4K Structure Bulkhead/mirror mounts/baffles	M6 bulkhead/baffle	4	1	0.352	Al 6082	AD2.4.8
	PM8 bulkhead/baffle	4	1	0.212	Al 6082	AD2.4.8
	intermediate bulkhead/baffle	4	1	0.105	Al 6082	AD2.4.8
	lower bulkhead/baffle	4	1	0.180	Al 6082	AD2.4.8
	entry baffle	*4*	*1*	*0.500*	*Al 6082*	*AD2.4.8*
Mirrors Photometer	CM3		1	0.183	Al 6082	AD2.4.3
	CM5		1	0.360	Al 6082	AD2.4.3
	PM6		1	0.027	Al 6082	AD2.4.3
	PM7		1	0.300	Al 6082	AD2.4.3
	PM8		1	0.056	Al 6082	AD2.4.3
	PM9		1	0.223	Al 6082	AD2.4.3
	PM10		1	0.065	Al 6082	AD2.4.3
	PM11		1	0.060	Al 6082	AD2.4.3
Mirrors Spectrometer	SM6		1	0.029	Al 6082	AD2.4.3
	SM7		1	0.044	Al 6082	AD2.4.3
	SM8		2	0.056	Al 6082	AD2.4.3
	SM9		2	0.037	Al 6082	AD2.4.3
	SM10		2	0.056	Al 6082	AD2.4.3
	SM11		2	0.097	Al 6082	AD2.4.3
	SM12		2	0.025	Al 6082	AD2.4.3
Mechanisms	Beam Steering Mechanism	4	1	1.000	Aluminium	Assumed
	Spectrometer Mechanism	4	1	0.500	Aluminium	Assumed
Calibration Sources	Photometer	4	1	0.100	Aluminium	Assumed
	Spectrometer	4	1	0.500	Aluminium	Assumed
2K Structure	2K Photometer Box	2	1	1.575	Al 6082	AD2.4.8
	2K Spectrometer Box	2	1	1.096	Al 6082	AD2.4.8

Detectors Common	2K Structure	2	5 5 5 5	0.044 0.038 0.064 0.016	Al St. Steel Invar Silicon	AD2.7.6
	Top Ring	0.3	5	0.049	Invar	AD2.7.6
	Spacer	0.3	5	0.0184	Invar	AD2.7.6
	Bottom Ring	0.3	5	0.029	Invar	AD2.7.6
Detectors Photometer LW	Detector Cover	0.3	1	0.031	Invar	AD2.7.6
	Detector Strap	0.3	1	0.007	Copper	AD2.7.6
	Feedhorn	0.3	1	0.314	Copper	AD2.7.6
Detectors Photometer MW	Detector Cover	0.3	1	0.058	Invar	AD2.7.6
	Detector Strap	0.3	1	0.005	Copper	AD2.7.6
	Feedhorn	0.3	1	0.247	Copper	AD2.7.6
Detectors Photometer SW	Detector Cover	0.3	1	0.058	Invar	AD2.7.6
	Detector Strap	0.3	1	0.005	Copper	AD2.7.6
	Feedhorn	0.3	1	0.190	Copper	AD2.7.6
Detectors Spectrometer LW	Detector Cover	0.3	1	0.031	Invar	AD2.7.6
	Detector Strap	0.3	1	0.007	Copper	AD2.7.6
	Feedhorn	0.3	1	0.165	Copper	AD2.7.6
Detectors Spectrometer SW	Detector Cover	0.3	1	0.058	Invar	AD2.7.6
	Detector Strap	0.3	1	0.005	Copper	AD2.7.6
	Feedhorn	0.3	1	0.118	Copper	AD2.7.6
Cooler	4K Structure	4	1	0.151	Titanium	AD2.6.6
	Pump	2	1	0.254	Titanium	AD2.6.6
	Shunt	2	1	0.0085	Stainless Steel	AD2.6.6
	Evaporator	0.3	1	0.236	Titanium	AD2.6.6
	Pump Heat Switch	2	1	0.050	Titanium	AD2.6.7
	Evaporator heat Switch	2	1	0.050	Titanium	AD2.6.7
300mK Link	Photometer Busbar	0.3	1	0.018	Copper	calculated
	Photometer 2K Feedthru	0.3	1	0.009	Copper	calculated
	Spectrometer 2K Feedthru	0.3	1	0.007	Copper	calculated

JFET Boxes	Photometer	10	1	1.250	Aluminium	AD2.1.6
	Spectrometer	10	1	1.250	Aluminium	AD2.1.6
Straps	L1	4	1	0.054	Copper	calculated
	L0 – 2K Box	2	1	0.104	Copper	calculated
	L0-Pump	2	1	0.083	Copper	calculated
	L0-Evaporator	2	1	0.187	Copper	calculated

Table 8.4.2: SPIRE - Assumed Mass Breakdown

8.5. FIRST Interface Thermal Model

The FIRST interface nodes (L0, L1 and L2 sinks, FOB, FIRST Instrument Shield and FIRST Shield 1) are set as boundary nodes, whose temperatures are varied according to the SPIRE loads. The functions which are used to calculate these interface temperatures are as given in AD2.1.2.

During transient analysis the rates of change of these boundary temperatures are restricted to prevent model instability, since the FIRST ITMM itself has no inherent thermal mass. This rate restriction is achieved by maintaining a constant Helium mass flow rate (as stated in AD2.1.3) and restricting the rate of change of boundary temperatures, as shown in Table 8.5.

Parameter	**Max Rate of Change**
Helium Mass Flow Rate	0 mg/s
FIRST Shield 1 Temperature	0.1 K/s
L2 (Optical Bench) Temperature	0.1 K/s
L1 (Vent Pipe)Temperature	0.1 K/s
L0 (LHe Tank) Temperature	1.7K - constant
FIRST Instrument Shield	10K - constant

Table 8.5: FIRST Cryostat Parameter Rate of Change Restrictions

9. ANALYSIS CASE DEFINITIONS

9.1. Steady-State Cases

Component	Node No.	POWER (mW)		Reference
		Photometer Operation	Spectrometer Operation	
Photometer Cold Read-Out Electronics	5000	49.5	0.0	AD2.3.8
Spectrometer Cold Read-Out Electronics	5500	0.0	14.1	AD2.3.8
TOTAL L2 (JFET) Dissipation	**-**	**49.5**	**14.1**	**-**
Cooler Pump Heat Switch (mean)	4400	0.2	0.2	AD2.3.8
Cooler Heater	4200	0.0	0.0	-
Photometer Calibrator	2090	1.5	0.0	*AD2.3.1 / AD2.3.4
Spectrometer Calibrator	3250	0.0	5.0	AD2.3.1
Beam Steering Mechanism	2100	2.6	0.0	*AD2.3.1 / AD2.3.4
Spectrometer Mirror Drive	3200	0.0	2.4	AD2.3.1
TOTAL L1 (FPU) Dissipation	**-**	**4.3**	**7.6**	**-**

Table 9.1: Steady-State Case Definition

9.2. Operational Mode Change – Spectrometer to Photometer

Analysis is performed to predict the time taken for the FPU temperature to stabilise after a change in the mode of operation.

Time (mm:ss)	Sub-System	Node No.	Status	Power Dissipation (mW)
00:00	Ph. Cold Read-Out Electronics	5000	ON	49.5
00:01	Photometer Calibrator	2090	ON	2.0
10:00	Photometer Calibrator	2090	OFF	0.0
10:01	Ph. Cold Read-Out Electronics	5000	OFF	0.0
10:01	Sp. Cold Read Out Electronics	5500	ON	14.1
10:02	Spectrometer Calibrator	3250	ON (stabilising)	5.0
10:32	Spectrometer Calibrator	3250	ON	5.0
10:32	Mirror Drive	3200	ON(scanning)	2.4
14:32	Mirror Drive	3200	OFF	0.0
14:32	Spectrometer Calibrator	3250	ON*	5.0

Status and Powers: ref. AD2.3.1
*Spectrometer remains ON: ref. AD2.3.8

Table 9.2: Operational Mode Change Case Definition

9.3. Cooler Recycling

Analysis is performed to predict the level of disturbance caused to FPU temperatures during Cooler Recycling, and the time taken to stabilise after re-cycling.
During this analysis the Cooler Cold Tip is changed from a diffuse to a boundary node as recycling starts. After 1 hour, when Cryopumping starts, the cooler is converted to a boundary node, whose temperature is reduced at a constant rate to 0.3K. The cooling rate assumed is based on cooler test results given in AD2.6.4.

Time (h:mm:ss)	Sub-System	Node No.	Status	Power (mW)	Reference
0:00:00	Ph. Cold Read-Out Electronics	5000	OFF	0	AD2.3.1
0:00:00	Mechanisms / Calibrators	-	OFF	0	AD2.3.1
0:00:00	Cooler	4300	OFF	0	AD2.3.1
0:00:01	Cooler Evap HS Cooler Pump HS	4500 4400	ON OFF	0.2 0	AD2.3.1
0:00:02	Cooler Heater	4200	ON	200	AD2.3.8
0:25:00	Cooler Heater	4200	ON	25	AD2.3.8
0:55:00	Cooler Heater	4200	OFF	0	AD2.3.8
0:55:01	Cooler Evap HS Cooler Pump HS	4500 4200	OFF ON	0 0.2	AD2.3.1
0:55:02 to 1:30:00	Cooler / Detectors	4300	Cryopumping to 290mK @ constant rate	0	AD2.6.4
1:30:00	Ph. Cold Read Out Electronics	5000	ON	49.5	AD2.3.1
1:40:00	Photometer Calibrator	2090	ON	2	AD2.3.1
1:42:00	Photometer Calibrator	2090	OFF	0	AD2.3.1
1:42:01	Beam Steering Mechanism	2100	ON	4	AD2.3.1
2:12:00	Beam Steering Mechanism	2100	OFF	0	AD2.3.1

Table 9.3: Cooler Recycling Case Definition

APPENDIX A: NODE LISTING

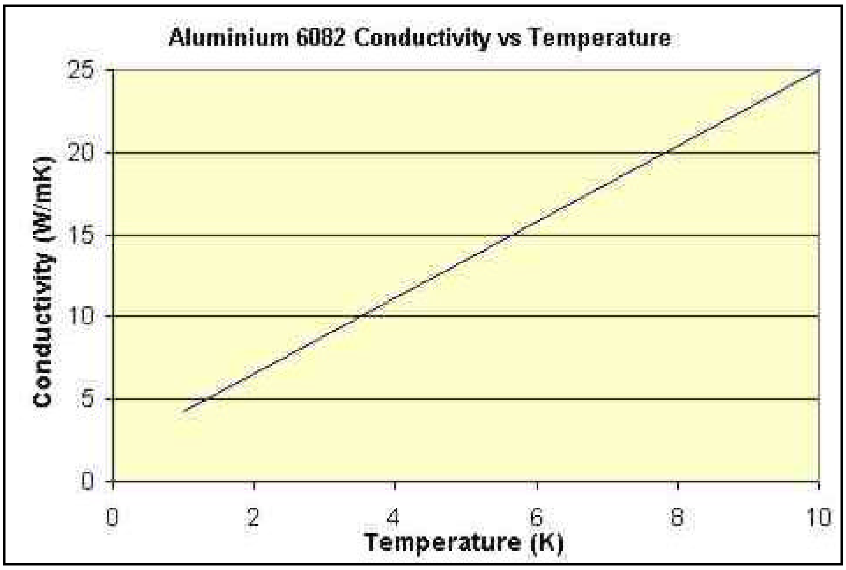
Node No.	Node Name	Node Type	Temperature Stage (K)	Material
CONE FOOT				
1	spire_cone_foot1	D	10	Stainless Steel
2	spire_cone_foot2	D	0	Stainless Steel
3	spire_cone_foot3	D	0	Stainless Steel
4	spire_cone_foot4	D	0	Stainless Steel
5	spire_cone_foot5	D	0	Stainless Steel
6	spire_cone_foot6	D	0	Stainless Steel
7	spire_cone_foot7	D	0	Stainless Steel
8	spire_cone_foot8	D	0	Stainless Steel
9	spire_cone_foot9	D	0	Stainless Steel
10	spire_cone_foot10	D	4	Stainless Steel
FPU OPTICAL BENCH				
1000	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1010	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1020	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1030	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1100	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1110	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1120	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1130	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1200	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1210	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1220	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1230	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1300	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1310	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1320	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
1330	spire_4k_optical_bench	D	4	Aluminium Alloy 6082
FPU 4K WALLS				
1500	spire_4k_spect_base	D	4	Aluminium Alloy 6082
1510	spire_4k_spect_top	D	4	Aluminium Alloy 6082
1520	spire_4k_spect_+z	D	4	Aluminium Alloy 6082
1530	spire_4k_spect_-z	D	4	Aluminium Alloy 6082
1540	spire_4k_spect_+y	D	4	Aluminium Alloy 6082
1600	spire_4k_photo_base	D	4	Aluminium Alloy 6082
1610	spire_4k_photo_top	D	4	Aluminium Alloy 6082
1620	spire_4k_photo_+z	D	4	Aluminium Alloy 6082
1630	spire_4k_photo_-z	D	4	Aluminium Alloy 6082

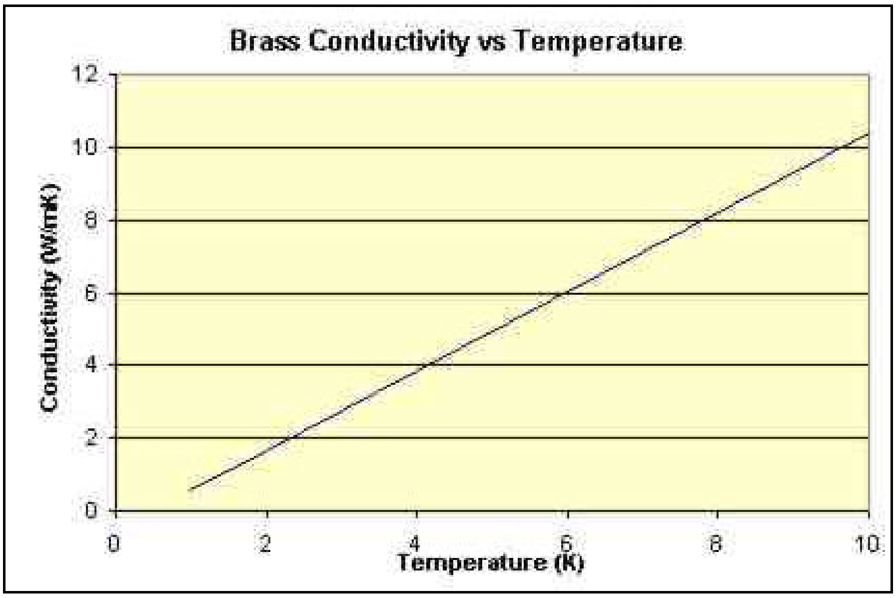
1640	spire_4k_photo_+y	D	4	Aluminium Alloy 6082
1700	spire_4k_connector panel	D	4	Aluminium Alloy 6082
1800	spire_4k_aperture_filter	D	4	-
PHOTOMETER 4K STAGE				
2000	photo_3_mirror_mount	D	4	Aluminium Alloy 6082
2030	photo_mirror3	D	4	Aluminium Alloy 6082
2040	photo_mirror4	D	4	Aluminium Alloy 6082
2050	photo_mirror5	D	4	Aluminium Alloy 6082
2060	photo_mirror6	D	4	Aluminium Alloy 6082
2070	photo_mirror7	D	4	Aluminium Alloy 6082
2080	photo_mirror8	D	4	Aluminium Alloy 6082
2090	photo_calibrator	D	4	Aluminium Alloy 6082
2100	photo_beam_steering_ mechanism	D	4	Aluminium Alloy 6082
2150	photo_4K_baffle	D	4	Aluminium Alloy 6082
2160	photo_4K_baffle	D	4	Aluminium Alloy 6082
2170	photo_4K_baffle	D	4	Aluminium Alloy 6082
2180	photo_4K_baffle	D	4	Aluminium Alloy 6082
PHOTOMETER 2K STAGE				
2400	photo_2k_box_px	D	2	Aluminium Alloy 6082
2410	photo_2k_box_mid	D	2	Aluminium Alloy 6082
2420	photo_2k_box_mx	D	2	Aluminium Alloy 6082
2450	photo_2k_baffle	D	2	Aluminium Alloy 6082
2500	photo_2k_dichroic1	D	2	Aluminium Alloy 6082
2510	photo_2k_dichroic2	D	2	Aluminium Alloy 6082
2520	photo2k__mirror9	D	2	Aluminium Alloy 6082
2530	photo2k__mirror10	D	2	Aluminium Alloy 6082
2540	photo2k__mirror11	D	2	Aluminium Alloy 6082
PHOTOMETER 0.3K COLD LINK				
2600	cooler_photo_strap	D	0.3	Copper (UHP)
2620	photo_spect_strap	D	0.3	Copper (UHP)
2650	photo_300mK_busbar_cold	D	0.3	Copper (UHP)
2655	photo_300mK_busbar	D	0.3	Copper (UHP)
2660	photo_300mK_busbar	D	0.3	Copper (UHP)
2665	photo_300mK_busbar	D	0.3	Copper (UHP)
2670	photo_300mK_busbar_warm	D	0.3	Copper (UHP)
PHOTOMETER DETECTORS				
2700	photo_detector1_2k	D	2	Aluminium Alloy 6082
2710	photo_detector1_strap	D	0.3	Copper (UHP)
2720	photo_detector1_top_ring	D	0.3	Invar
2730	photo_detector1_spacers	D	0.3	Invar
2740	photo_detector1_bot_ring	D	0.3	Invar
2750	photo_detector1_cover	D	0.3	Invar

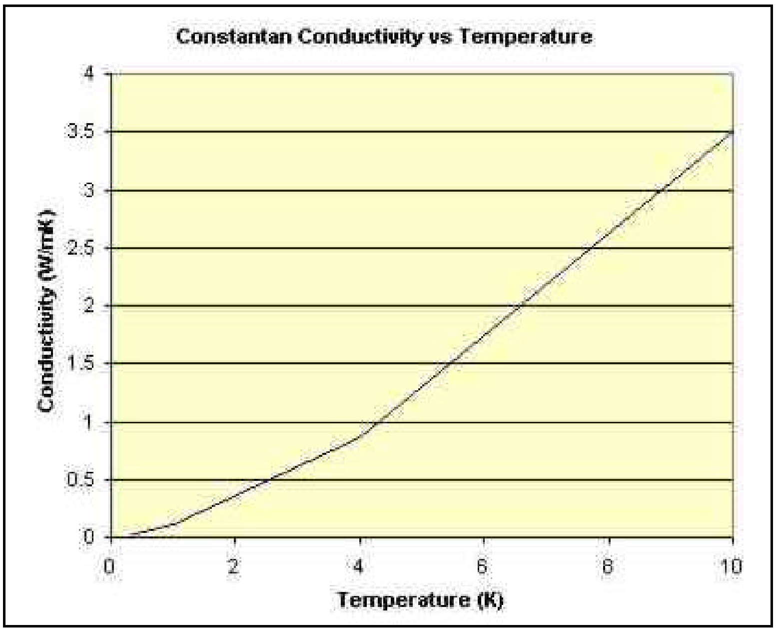
2770	feedhorn1	D	0.3	Copper
2800	photo_detector2_2k	D	2	Aluminium Alloy 6082
2810	photo_detector2_strap	D	0.3	Copper (UHP)
2820	photo_detector2_top_ring	D	0.3	Invar
2830	photo_detector2_spacers	D	0.3	Invar
2840	photo_detector2_bot_ring	D	0.3	Invar
2850	photo_detector2_cover	D	0.3	Invar
2870	photo_feedhorn2	D	0.3	Copper
2900	photo_detector3_2k	D	2	Aluminium Alloy 6082
2910	photo_detector3_strap	D	0.3	Copper (UHP)
2920	photo_detector3_top_ring	D	0.3	Invar
2930	photo_detector3_spacers	D	0.3	Invar
2940	photo_detector3_bot_ring	D	0.3	Invar
2950	photo_detector3_cover	D	0.3	Invar
2970	photo_feedhorn3	D	0.3	Copper
SPECTROMETER 4K STAGE				
3000	spect_input_fold_mirrorA	D	4	Aluminium Alloy 6082
3010	spect_collimatorA	D	4	Aluminium Alloy 6082
3020	spect_collimatorB	D	4	Aluminium Alloy 6082
3030	spect_beam_divider1	D	4	Aluminium Alloy 6082
3040	spect_fold_mirror1A	D	4	Aluminium Alloy 6082
3050	spect_fold_mirror2A	D	4	Aluminium Alloy 6082
3060	spect_fold_mirror1B	D	4	Aluminium Alloy 6082
3070	spect_fold_mirror2B	D	4	Aluminium Alloy 6082
3080	spect_rooftop_mirrorA	D	4	Aluminium Alloy 6082
3090	spect_rooftop_mirrorB	D	4	Aluminium Alloy 6082
3100	spect_beam_divider2	D	4	Aluminium Alloy 6082
3110	spect_camera_mirrorA	D	4	Aluminium Alloy 6082
3120	spect_camera_mirrorB	D	4	Aluminium Alloy 6082
3200	spect_mirror_mechanism	D	4	Aluminium Alloy 6082
3250	spect_calibrator	D	4	Aluminium Alloy 6082
SPECTROMETER 2K STAGE				
3400	spect_2k_box_px	D	2	Aluminium Alloy 6082
3410	spect_2k_box_mx	D	2	Aluminium Alloy 6082
3450	spect_2k_baffle	D	2	Aluminium Alloy 6082
3460	spect_mirror12A	D	2	Aluminium Alloy 6082
3470	spect_mirror12B	D	2	Aluminium Alloy 6082
SPECTROMETER 0.3K COLD LINK				
3650	spect_300mK_busbar_cold	D	0.3	Copper (UHP)
3655	spect_300mK_busbar	D	0.3	Copper (UHP)
3660	spect_300mK_busbar	D	0.3	Copper (UHP)
3665	spect_300mK_busbar_warm	D	0.3	Copper (UHP)

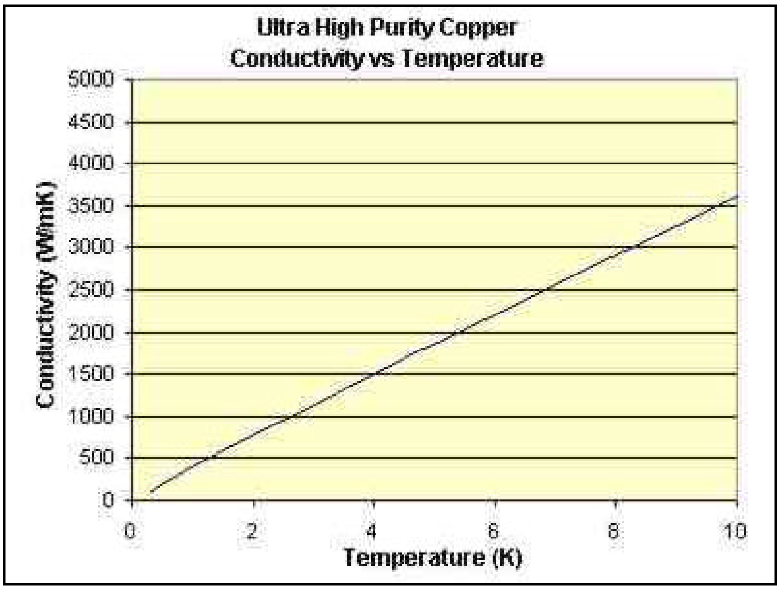
SPECTROMETER DETECTORS				
3700	spect_detector1_2k	D	2	Aluminium Alloy 6082
3710	spect_detector1_strap	D	0.3	Copper (UHP)
3720	spect_detector1_top_ring	D	0.3	Invar
3730	spect_detector1_spacers	D	0.3	Invar
3740	spect_detector1_bot_ring	D	0.3	Invar
3750	spect_detector1_cover	D	0.3	Invar
3770	spect_feedhorn1	D	0.3	Copper
3800	spect_detector2_2k	D	2	Aluminium Alloy 6082
3810	spect_detector2_strap	D	0.3	Copper (UHP)
3820	spect_detector2_top_ring	D	0.3	Invar
3830	spect_detector2_spacers	D	0.3	Invar
3840	spect_detector2_bot_ring	D	0.3	Invar
3850	spect_detector2_cover	D	0.3	Invar
3870	spect_feedhorn1	D	0.3	Copper
COOLER				
4000	cooler_4k_structure	D	4	Aluminium Alloy 6082
4200	cooler_2K_pump	D	4	Ti6Al4V
4250	cooler_shunt	D	2	Ti6Al4V
4300	cooler_300mK_evap	B	0	Ti6Al4V
4400	cooler_pump_HS	D	4	Ti6Al4V
4500	cooler_evap_HS	D	2	Ti6Al4V
JFET BOX				
5000	photometer_JFET_box	D	10	Aluminium Alloy 6082
5500	spectrometer_JFET_box	D	10	Aluminium Alloy 6082
STRAPS TO FIRST CRYOSTAT				
6000	L1_strap_main_structure	D	4	Copper (UHP)
6100	L0_strap_2k_boxes	D	2	Copper (UHP)
6200	L0_strap_cooler_pump	D	2	Copper (UHP)
6300	L0_strap_cooler_evap	D	2	Copper (UHP)
FIRST CRYOSTAT				
10000	first_10k_optical_bench	B	10	-
20000	first_L0_helium_tank	B	1.7	-
21000	first_L1_cooling_pipes	B	4	-
22000	first_instrument_shield	B	10	-
23000	first_shield1	B	34	-

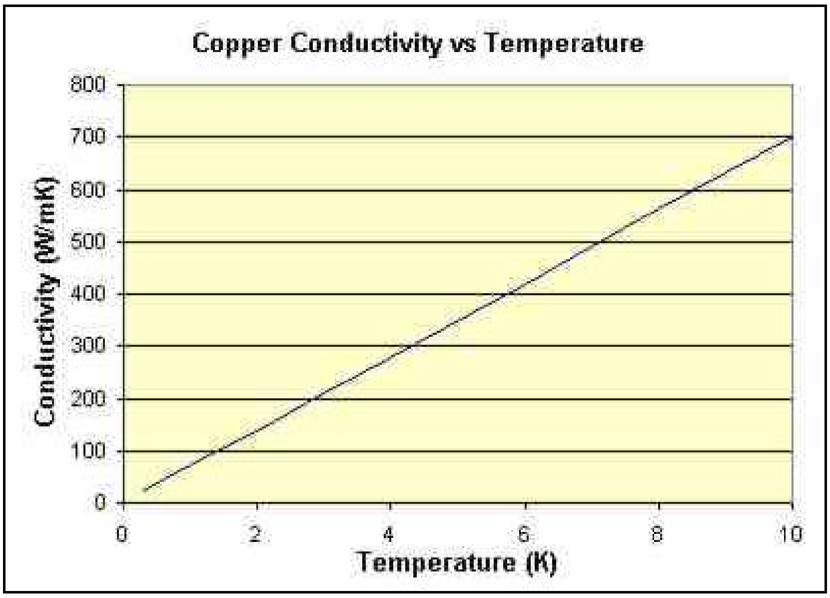
APPENDIX B: THERMAL CONDUCTIVITIES VS TEMPERATURE

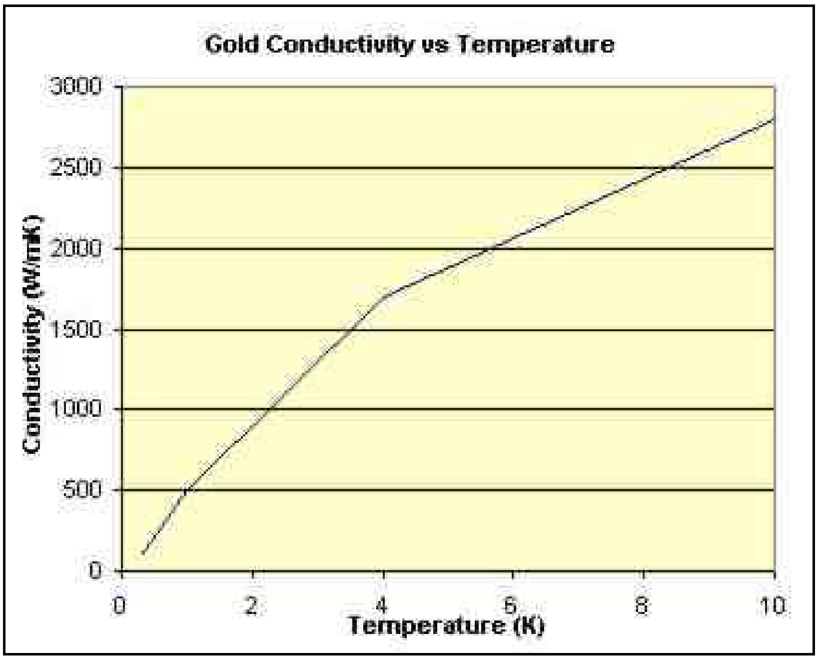


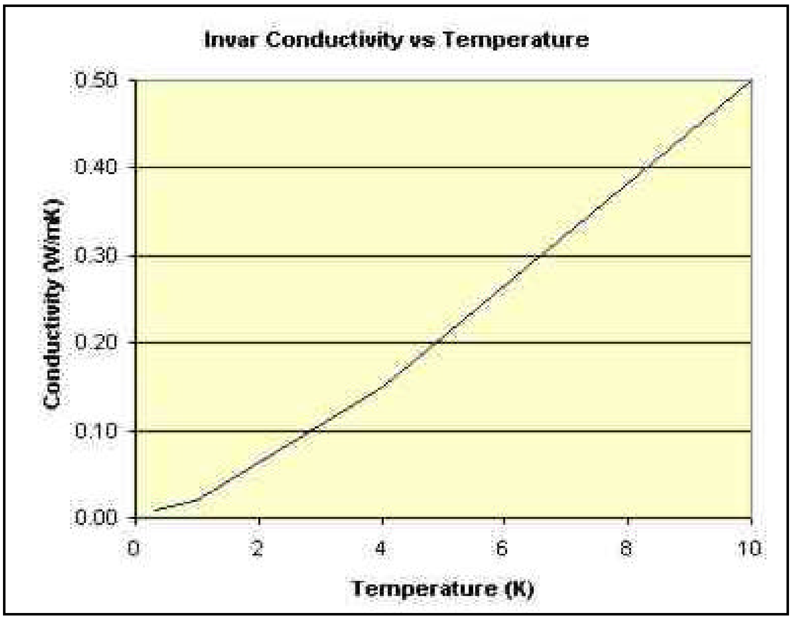


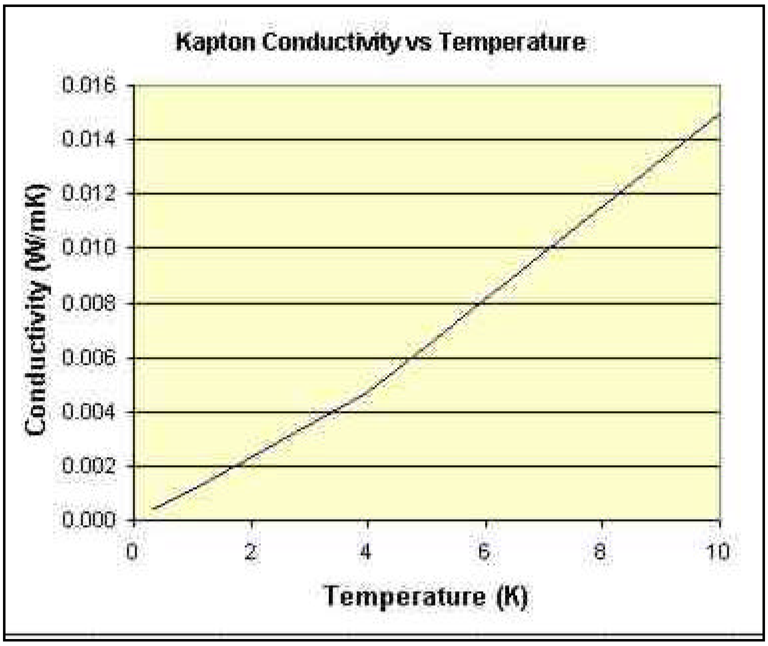

Constantan Conductivity vs Temperature
Conductivity (W/mK)
Temperature (K)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10

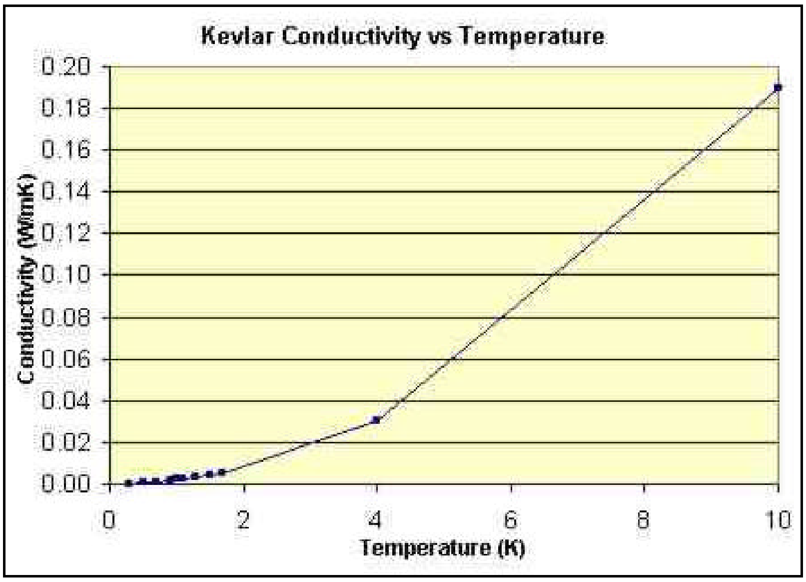

Ultra High Purity Copper
Conductivity vs Temperature
Conductivity (W/mK)
Temperature (K)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
2
4
6
8
10

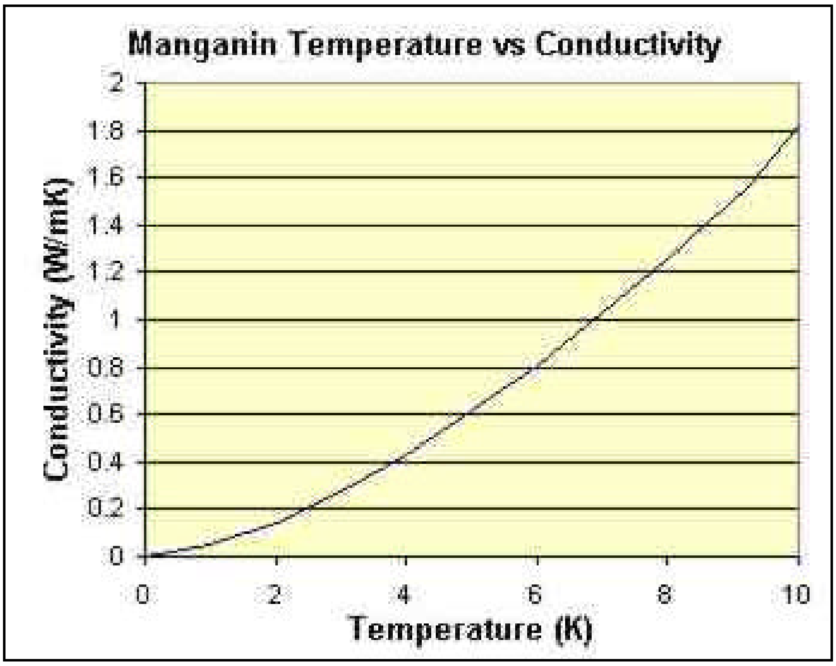

Copper Conductivity vs Temperature
Conductivity (W/mK)
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
Temperature (K)

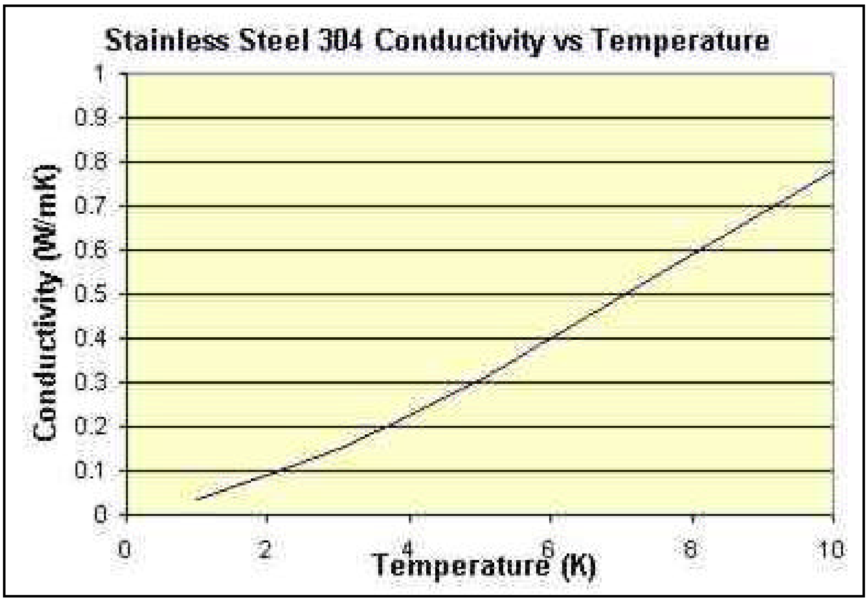

Gold Conductivity vs Temperature
Conductivity (W/mK)
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
Temperature (K)

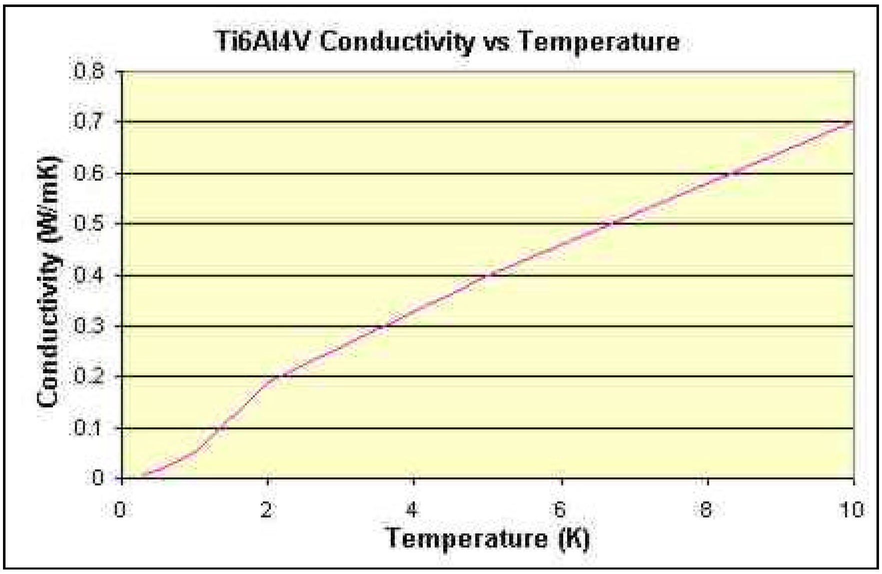

Invar Conductivity vs Temperature
Conductivity (W/mK)
0.50
0.40
0.30
0.20
0.10
0.00
0
2
4
6
8
10
Temperature (K)

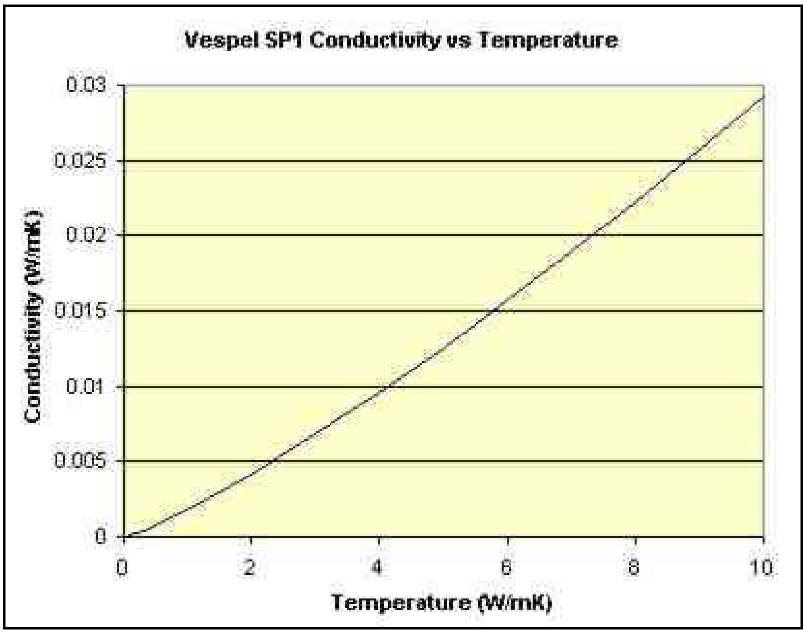

Kapton Conductivity vs Temperature
Conductivity (W/mK)
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
2
4
6
8
10
Temperature (K)


Kevlar Conductivity vs Temperature
Conductivity (W/mK)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
Temperature (K)


Manganin Temperature vs Conductivity
Conductivity (W/mK)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
Temperature (K)


Stainless Steel 304 Conductivity vs Temperature
Conductivity (W/mK)
Temperature (K)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10


Ti6Al4V Conductivity vs Temperature
Conductivity (W/mK)
Temperature (K)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
10

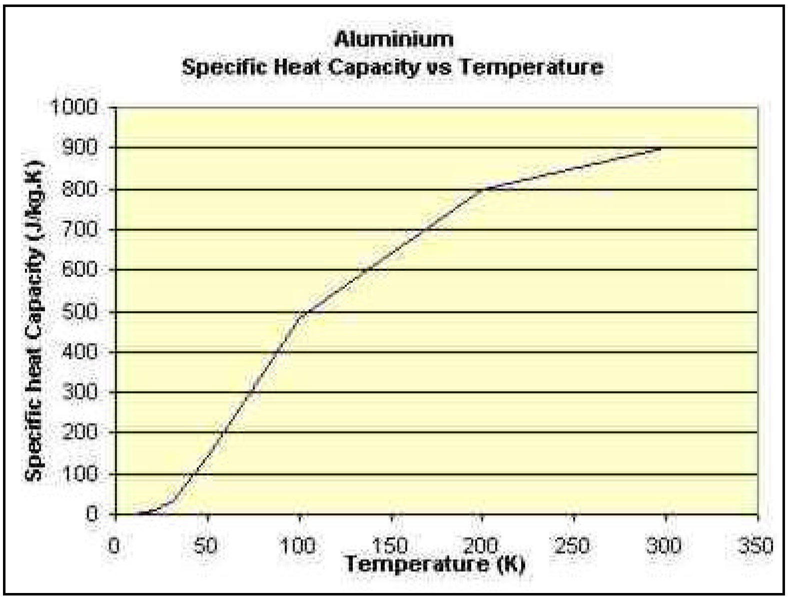


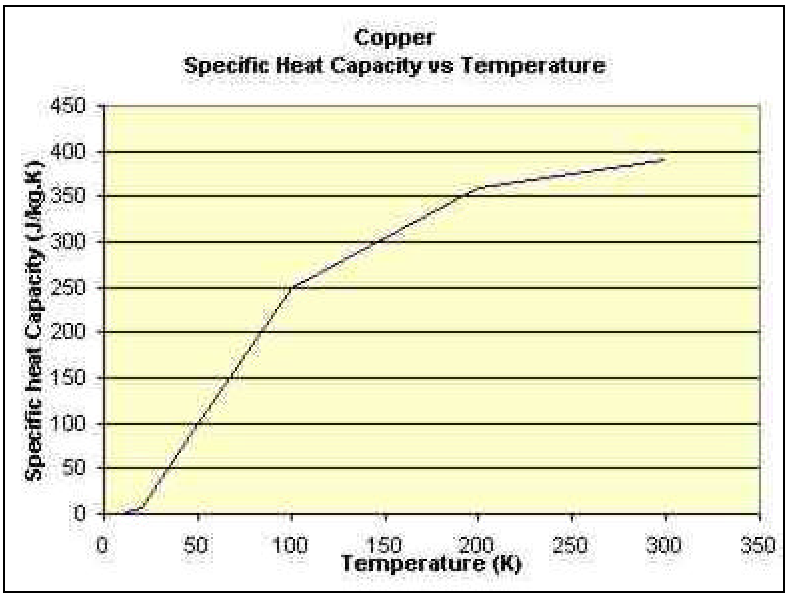
References

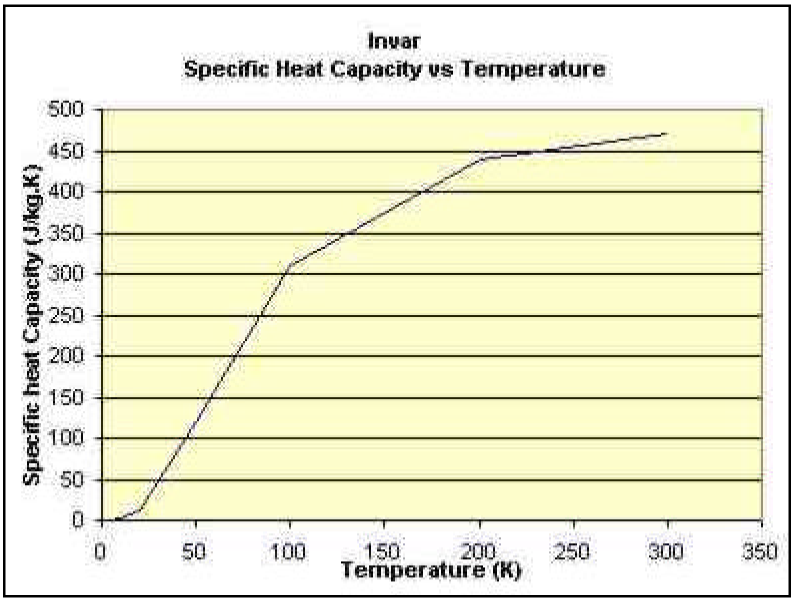
Material Name	Reference
Aluminium Alloy 6082	AD2.4.5
UHP Copper	AD2.7.5
Copper	AD2.8.4
Kevlar 49 Thread	AD2.7.2 / AD2.7.5
Invar	AD2.7.5
Kapton	AD2.7.5
Constantan	AD2.7.5
Manganin	AD2.8.4
Brass	AD2.8.4
Stainless Steel 304	AD2.8.4
Titanium Alloy Ti6Al4V	AD2.8.3
PTFE	AD2.8.4

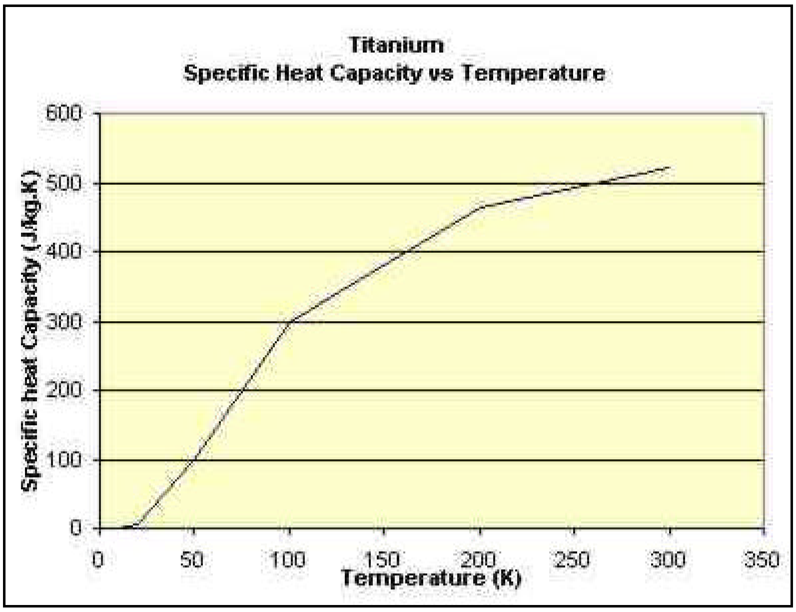
Table B.1: Thermal Conductivity References

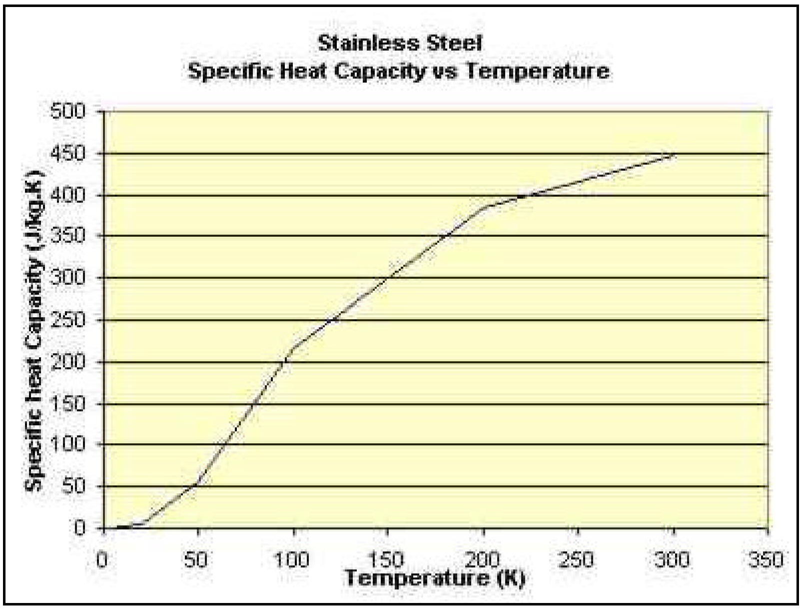
APPENDIX C: SPECIFIC HEAT CAPCITIES VS TEMPERTURE






Invar
Specific Heat Capacity vs Temperature
Specific heat Capacity (J/kg.K)
500
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
Temperature (K)


Titanium
Specific Heat Capacity vs Temperature
Specific heat Capacity (J/kg.K)
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
Temperature (K)



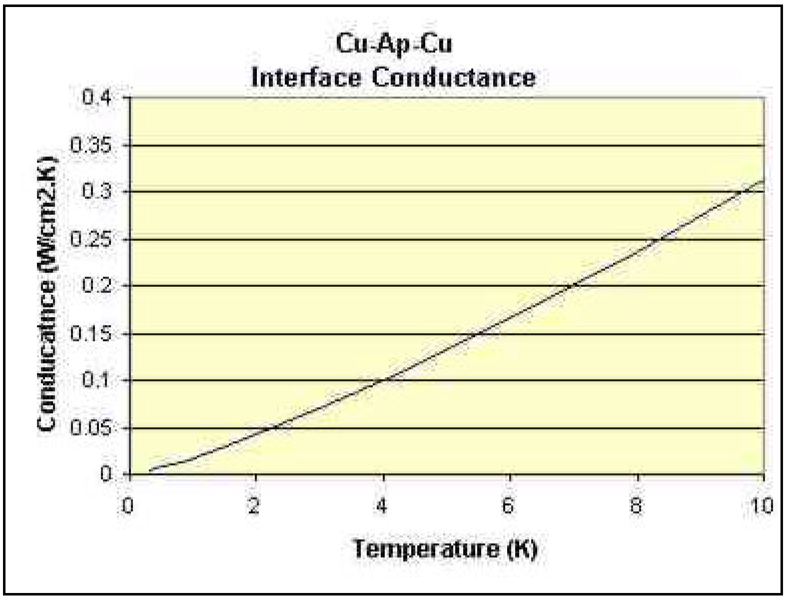
References

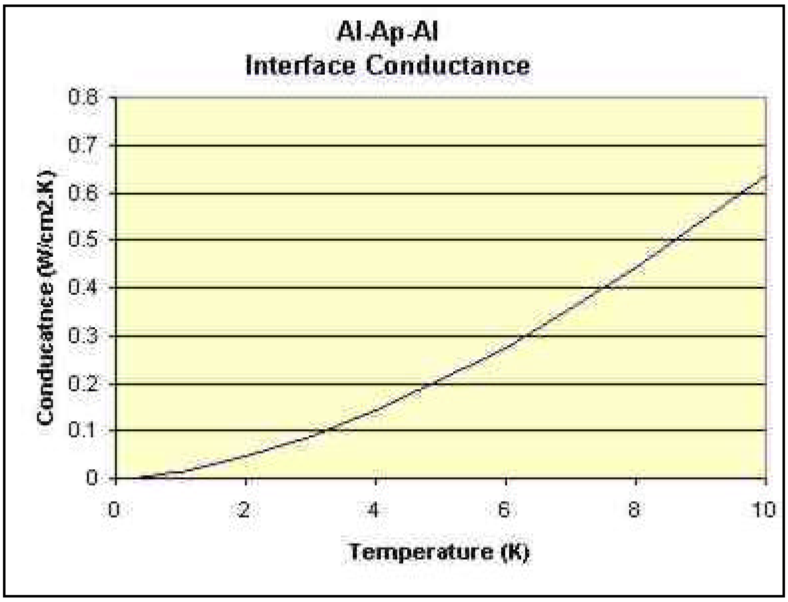
Material Name	Reference
Aluminium	AD2.8.1
Copper	AD2.7.5
Invar	AD2.7.5
Titanium	AD2.8.2
Stainless Steel	AD2.8.2

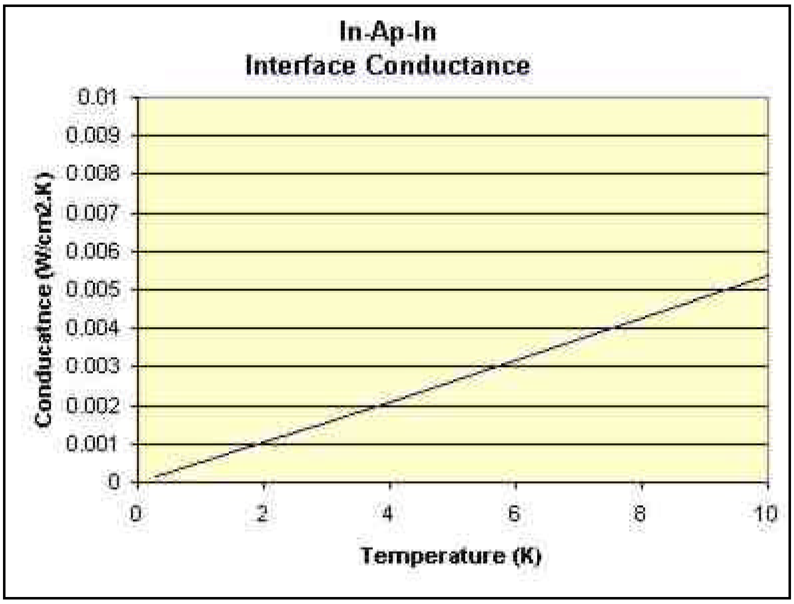
Table C1: Specific Heat Capacity References

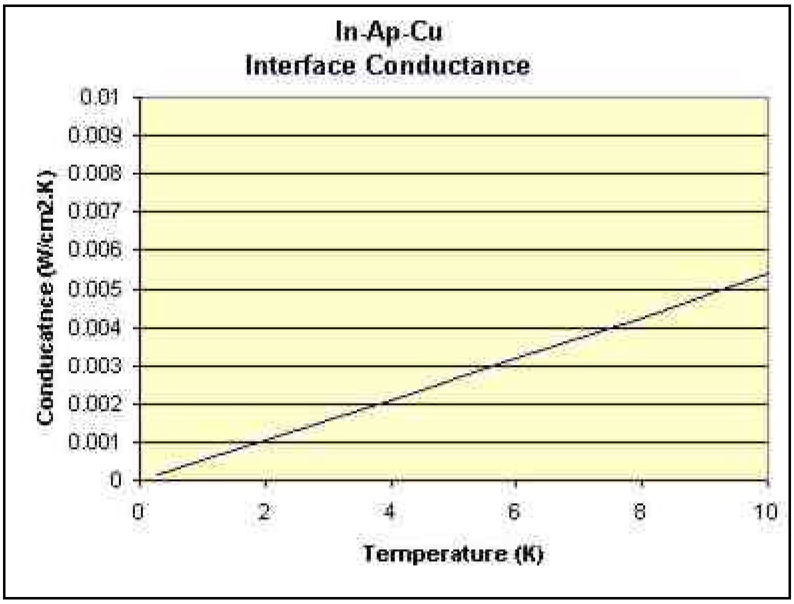
APPENDIX D: JOINT CONTACT CONDUCTANCE

Apeizon Grease Interfaces

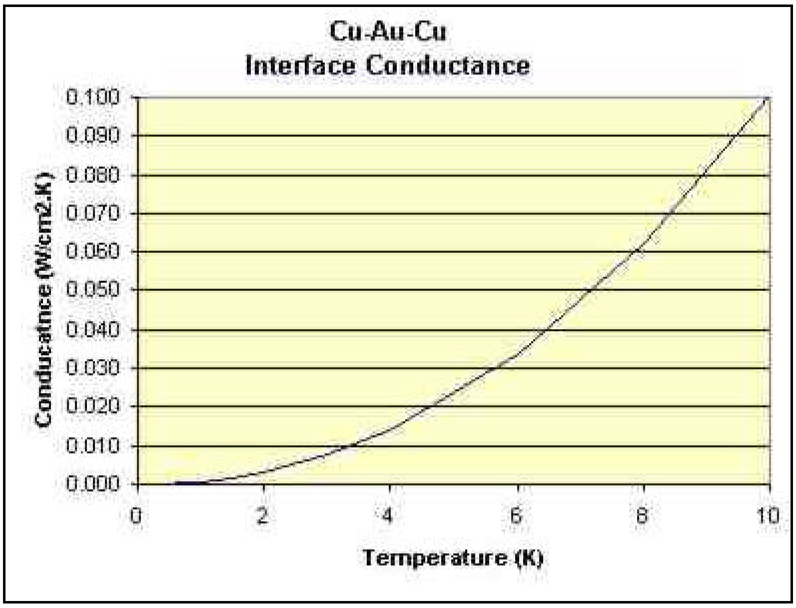


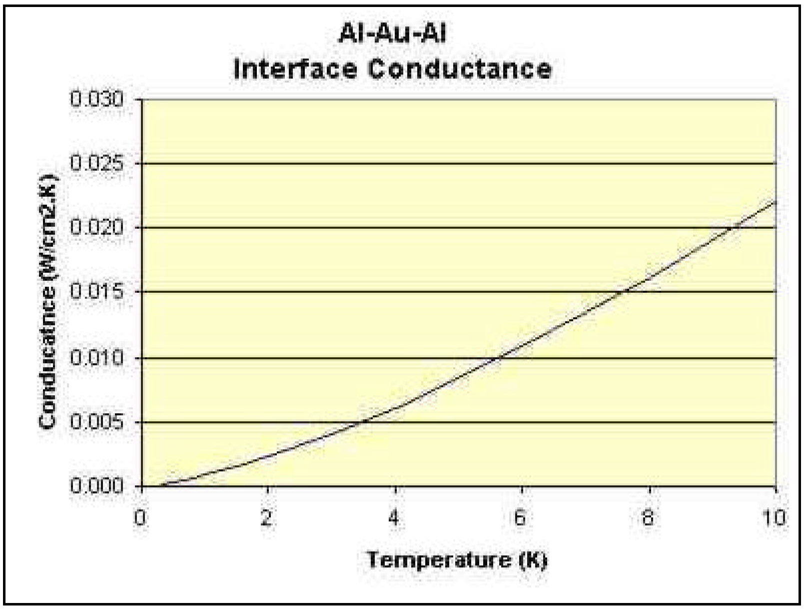


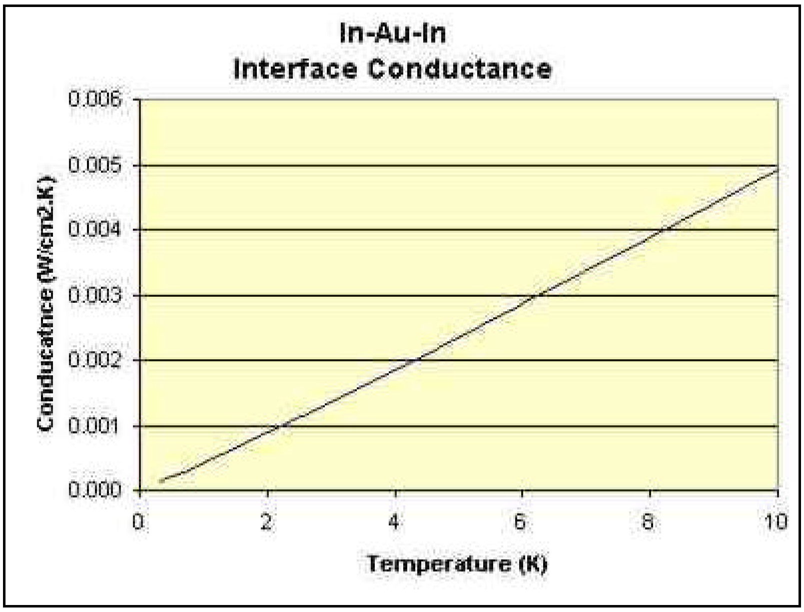

In-Ap-In
Interface Conductance
Conducatnce (W/cm2.K)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
6
8
10
Temperature (K)

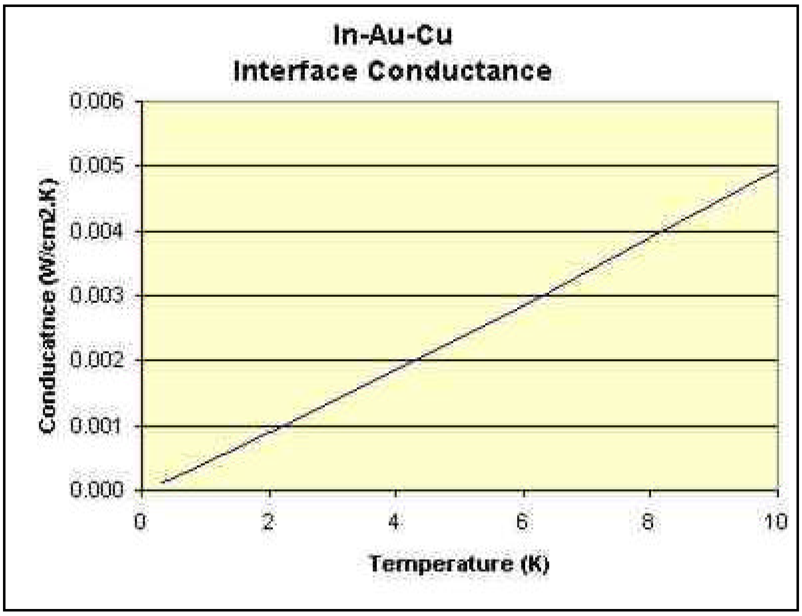

In-Ap-Cu
Interface Conductance
Conducatnce (W/cm2.K)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
6
8
10
Temperature (K)

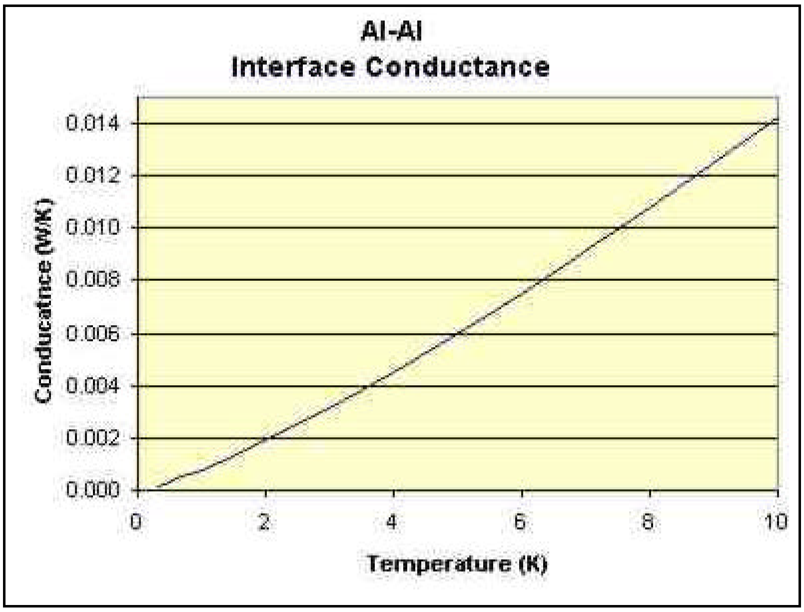
Gold Plated Interfaces






In-Au-In
Interface Conductance
Conducatnce (W/cm2.K)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
2
4
6
8
10
Temperature (K)


In-Au-Cu
Interface Conductance
Conducatnce (W/cm2.K)
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
2
4
6
8
10
Temperature (K)



References

Interface Name	Description	Assumed Contact Force	Reference
Cu-Ap-Cu	Uncoated Copper - Apeizon - Uncoated Copper	670N	AD2.8.6
Cu-Ap-In	Uncoated Copper – Apeizon - Uncoated Invar	670N	*AD2.8.6
In-Ap-In	Uncoated Indium – Apeizon - Uncoated Invar	670N	*AD2.8.6
Al-Ap-Al	Uncoated Aluminium – Apeizon - Uncoated Aluminium	670N	AD2.8.6
Cu-Au-Cu	Gold Plated Copper - Gold Plated Copper	670N	AD2.8.5
Al-Au-Al	Gold Plated Aluminium – Gold Plated Aluminium	670N	AD2.8.5
Al-Al	Aluminium-Aluminium	670N	AD2.8.5

*Assumed that Invar behaves as Stainless Steel.

Table C1: Joint Interface Conductances