SPIRE Instrument
Thermal Mathematical Model

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RAL

TMM Requirements

TMM created 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).

TMM - Overview

Detailed TMM of SPIRE created in ESATAN v8.4.2.

TMM incorporates:

- 138 diffuse nodes (structure, mirrors, detectors, cooler, straps, etc.)
- 5 boundary nodes (Cryostat L0, L1, Optical Bench, Shield 1, SPIRE cooler evaporator)
- Temperature dependant thermal conductivities, interface conductances and heat capacities.
- Integrated conductivities for all couplings between different temperature stages.
- Detector reduced node model, based on that supplied by T.Cafferty.
- Cooler nodal breakdown, as supplied by L.Duband.
- FIRST Cryostat reduced node model as supplied by ESA (suitable for use in steady-state analysis only).

TMM - Current Status

Steady State Model

- Steady-State model completed, with the exception of He Cooler performance details.
- Steady-State temperatures and heat flows under nominal operating conditions obtained.

Transient Model

- Transient model completed with exception of accurate detector feedhorn masses and transient version of FIRST Cryostat model. Therefore transient results to date do not account for the effect of changes in FIRST Cryostat - SPIRE interface temperatures due to changes in SPIRE loads.
- Transient responses during Operating Mode Change and Cooler Recycling obtained.
- Transient analysis of initial cooldown awaiting information from Spacecraft on actual FIRST cooling curve before predicted response of SPIRE can be obtained.

TMM Description - Nodal Breakdown

Structure

- Structure discretised in order to show temperature gradients through FPU. A total of 10 nodes are used to represent the walls of the Spectrometer and Photometer and 16 nodes for the Optical Bench.

Mechanisms and Calibration Sources

- The mechanisms and calibration sources are each represented by single node. The components are assumed to be hard mounted to the structure with a bare aluminium to aluminium interface. The conductance across this interface is varied according to temperature.

Mirrors

- Each mirror is modelled as a single node. The mirrors are hard mounted to the structure with a bare aluminium to aluminium interface. The conductance across this interface is varied according to temperature.

2K Boxes

- The Photometer and Spectrometer 2K Box structures are discretised into 3 nodes and 2 nodes respectively. Baffles and mirrors within the boxes are modelled as separate nodes, as are the detectors.

TMM Description - Nodal Breakdown

Detectors

- The detector part of the TMM is a simplified version of the reduced node detector model provided by JPL (AD2.1.9). Each detector is discretised into 7 nodes as follows: 2K stage, Top Plate, Spacer, Bottom Plate, Cover, Feedhorn and Strap (to Busbar).

Straps

- Each of the L1 and L0 interface straps are modelled as an individual node, in order that their thermal mass is accounted for in transient analysis cases.

Busbars

- The Photometer and Spectrometer bus bars are discretised along their lengths into five and four nodes respectively (due to their different lengths and number of supports).

Cooler

- The cooler part of the model is based on the nodal breakdown provided by L.Duband (AD2.1.13). A total of 6 nodes are used to represent the cooler, as follows: 4K stage, Pump, Shunt, Evaporator, Pump Heat Switch, Evaporator Heat Switch.

JFET Box

- The JFET box is represented by a single diffuse node, hard mounted to the FIRST Optical Bench. The harnesses between the JFET and the Spacecraft are assumed to be sunk to the FIRST Shield 1 temperature.

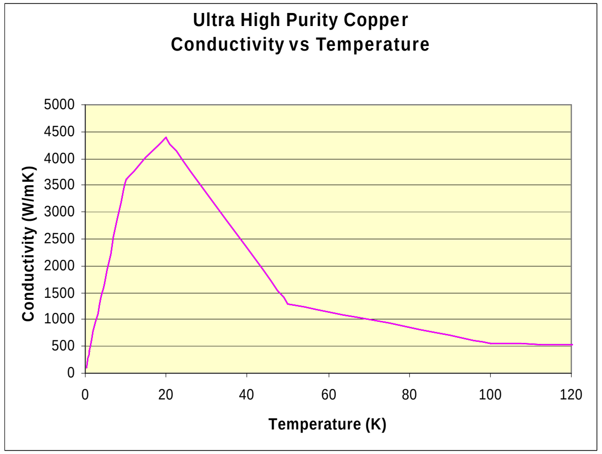
TMM Description - Conductive Couplings

Conductance Across Joints

- L1 strap joints assumed to be Cu-Au-Cu.
- L0 Box Strap joints assumed to be Cu-Apeizon-Cu.
- L0 Cooler Strap Joint assumed to be Cu-Au-Cu.
- 300mK joints assumed to be Cu-Apeizon-Cu.
- Mechanisms, calibration sources and mirrors assumed bolted to Structure with bare Al-Al interfaces.

Copper Strap Conductivity

- L1 Straps assumed to be ISO Copper.
- L0 straps and 300mK links assumed to be OFHC, ultra high purity Copper. k (W/cmK) ≈ 4T.



TMM Description

Radiative Couplings

- External walls of FPU coupled to FIRST Shield 1 (~34K) assuming emissivities of 0.1 and 0.05 respectively.
- Internal radiative loads shown to be insignificant due to low temperatures.

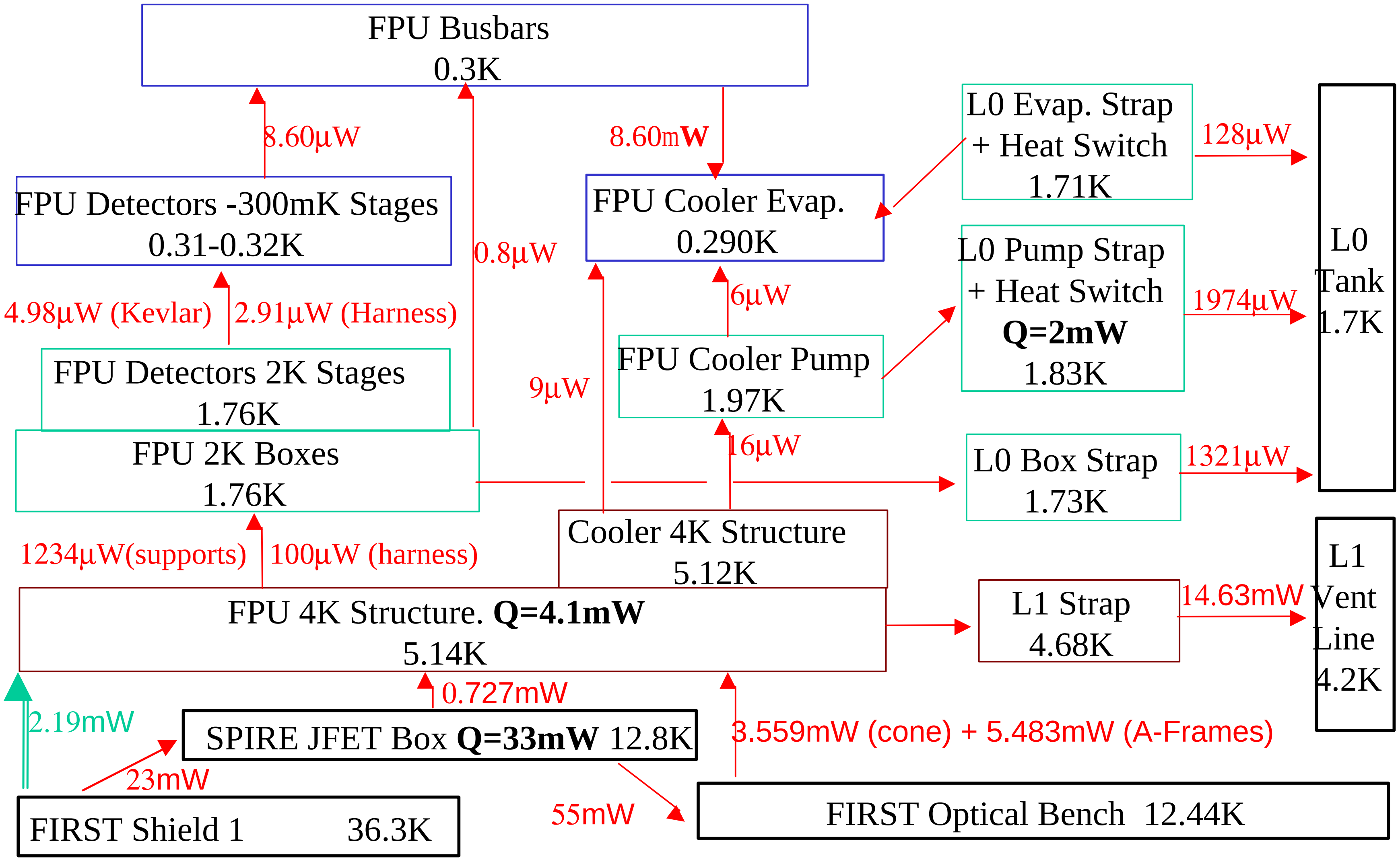
Component Powers (ref: 'SPIRE Thermal Transient Cases For Cryostat Study', BS, 14-12-00)

- Cold Read-Out Electronics = 9.4mW (spectrometer) / 33.0mW (photometer)
- Cooler Heat Switch = 2mW
- Cooler Heater = 90mW (during cooler recycling only)
- Photometer Calibrator = 2mW
- Spectrometer Calibrator = 5mW
- Beam Steering Mechanism = 4mW
- Spectrometer Mirror Drive = 2.4mW (average over scan)

Cooler Representation

- Evaporator modelled as boundary node held at 290mK during steady-state cases.
- Evaporator modelled as diffuse node when Cooler is OFF during transient cases. As cooler switches ON Evaporator becomes boundary node with temperature reduced gradually to 290mK (assumed cooling rate).

TMM Results - Steady State Photometer Mode



TMM - FUTURE WORK

- Add cooler performance characteristics to TMM.
- Include accurate detector feedhorn masses.
- Run cooldown case with FIRST cooling curve.
- Update conductances of FPU supports and cooler-detector cold link as test results become available.
- Update model as design progresses.
- Modelling of Test Cryostat and analysis of test set-up.

INSTRUMENT REQUIREMENTS

Parameter	Specification
Heat leak to FPU from FIRST Optical Bench	6mW for delta T = 11-4.2 = 6.8K
Conductive heat leaks down 2K box support	1mW for delta T = 4.2 - 1.7 = 2.5K
Detector temperature	T <310mK
Detector array stability	150nK/√Hz between 0.03 and 25Hz.
Parasitic heat leak on 300mK detector stage	<1.6µW per array <8µW total
Temperature difference between cooler cold tip and detector arrays	< 20mK
Temperature gradient along compliant links from bus bars to Cooler or detectors	2mK/link
Total heat leak down the Photometer 300mK strap supports	0.6µW
Total heat leak down the Spectrometer 300mK strap supports	0.4µW
Cooler maximum heat load	> 10µW at 290mK evaporator temperature

FIRST CRYOSTAT - SPIRE INTERFACE COUPLINGS

From	To	Description	XSection	Length	Material	Interface Type	Contact Area
FIRST Optical Bench	FPU 4K Stage	Cone Foot	Non-Uniform. Diameter = 35 to 70mm	35mm	Stainless Steel	-	-
FIRST Optical Bench	FPU 4K Stage	2 A-Frame Feet	2 x 22.5mm2 = 45mm2	35mm	Stainless Steel	-	-
FIRST Optical Bench	JFET Box	Bolted	-	-	-	Al-Al	8 bolts
FIRST L1 Vent Pipes (AD2.2.1 / AD2.3.2)	FPU Wall	Strap	20mm x 1mm = 20mm2	300mm	ISO Copper	Cu-Au-Cu	6.58cm2
FIRST L0 (AD2.2.1)	FPU 2K Boxes	Strap	20mm x 1mm = 20mm2	500mm	UHP Copper	Cu-Ap-Cu	6.58cm2
FIRST L0 (AD2.2.1)	FPU Cooler Pump HS	Strap	20mm x 1mm = 20mm2	500mm	UHP Copper	Cu-Au-Cu	6.58cm2
FIRST L0 (AD2.2.1)	FPU Cooler Evap.HS	Strap	20mm x 1mm = 20mm2	500mm	UHP Copper	Cu-Au-Cu	6.58cm2
FIRST Shield 1	JFET Box	Harness	8.78E-6mm2 18.5E-6mm2 222E-6mm2	300mm	Brass Stainless PTFE	-	-

SPIRE INTERNAL COUPLINGS

From	To	Description	XSection	Length	Material	Interface Type	Contact Area
JFET Box (AD2.1.6)	FPU 4K Stage	Harness	12mm2 6.72mm2 94mm2	150mm	Kapton Stainless Vespel	-	-
4K structure	Phot. 2K Box	3 Blade Supports	3 x 10mm2 = 30mm2	30mm	Stainless Steel	-	-
4K structure	Spec. 2K Box	3 Blade Supports	3 x 10mm2 = 30mm2	30mm	Stainless Steel	-	-
4K Structure (AD2.1.10)	2K Detectors	Detector Harness	5mm2 21mm2 50mm2	80mm	Manganin Kapton Vespel	-	-
2K Box (AD2.1.11)	300mK Phot. Busbar	3 Busbar Supports	3 x 2.2mm2 = 6.6mm2	40mm	Vespel SP1	-	-
2K Box	300mK Spec. Busbar	2 Busbar Supports	2 x 2.2mm2 = 4.4mm2	40mm	Vespel SP1	-	-
2K Detector (AD2.1.9)	300mK Detector	5 Detector Supports	5 x 16 threads x 0.3mm2 = 24mm2	25mm	Kevlar 49 Thread	-	-
2K Detectors (AD2.1.10)	300mK Detectors	Harness	14mm2 0.275mm2	30mm	Kapton Constantan	-	-
0.3K Detector (AD2.1.2)	Busbar	Strap	Diameter 1mm = 0.78mm2	20mm	UHP Copper	Cu-Ap-Cu	1cm2
Phot. Busbar (AD2.1.2)	Phot. Busbar	Busbar	Diameter 4mm = 12.57mm2	400mm	UHP Copper	-	-

From	To	Description	XSection	Length	Material	Interface Type	Contact Area
Spec.Busbar (AD2.1.2)	Spec. Busbar	Busbar	Diameter 3mm = 7.07mm2	250mm	UHP Copper	-	-
Phot. Busbar (AD2.1.2)	Spec. Busbar	Strap	Diameter 1mm = 0.78mm2	20mm	UHP Copper	Cu-Ap-Cu	1cm2
Phot. Busbar (AD2.1.2)	Cooler Evaporator	Strap	Diameter 1mm = 0.78mm2	20mm	UHP Copper	Cu-Ap-Cu	1cm2

ASSUMED SURFACE EMISSIVITIES

Surface	**Emissivity**
FIRST Shield 1	0.05
FPU external walls	0.l*
JFET Box	0.2

STEADY-STATE CASE DEFINITION

Component	**Node No.**	**POWER (mW)**	
		Photometer Operation	**Spectrometer Operation**
Cold Read-Out Electronics	**5000**	**33.0**	**9.4**
Cooler Pump Heat Switch (mean)	4400	2.0	2.0
Cooler Heater	4200	0.0	0.0
Photometer Calibrator	2090	1.5	0.0
Spectrometer Calibrator	3250	0.0	5.0
Beam Steering Mechanism	2100	2.6	0.0
Spectrometer Mirror Drive	3200	0.0	2.4
TOTAL FPU Dissipation		**6.1**	**9.4**

OPERATIONAL MODE CHANGE CASE DEFINITION

Time (mm:ss)	Sub-System	Node No.	Status	Power Dissipation (mW)
00:00	Cold Read-Out Electronics	5000	ON (Phot.)	33.0
00:01	Photometer Calibrator	2090	ON	2.0
10:00	Photometer Calibrator	2090	OFF	0.0
10:01	Cold Read Out Electronics	5000	ON (Spec.)	9.4
10:02	Spectrometer Calibrator	3250	ON (stabilising)	5.0
10:32	Spectrometer Calibrator	3250	OFF	5.0
10:32	Mirror Drive	3200	ON(stabilising)	2.4
14:32	Mirror Drive	3200	ON (Scanning)	2.4
14:32	Calibration Source	3250	OFF	0.0

COOLER RECYCLING CASE DEFINITION

Time (h:mm:ss)	Sub-System	Node No.	Status	Power Dissipation (mW)
0:00:00	Cold Read-Out Electronics	5000	OFF	0
0:00:00	Mechanisms / Calibrators	-	OFF	0
0:00:00	Cooler	4300	OFF	0
0:00:01	Cooler Evap HS Cooler Pump HS	4500 4400	ON OFF	2 0
0:00:02	Cooler Heater	4200	ON	90
0:30:00	Cooler Heater	4200	OFF	0
0:30:01	Cooler Evap HS Cooler Pump HS	4500 4200	OF ON	0 2
0:30:00 to 2:00:00	Cooler / Detectors	4300	Cryopumping to 290mK	0
2:00:00	Cold Read Out Electronics	5000	ON	33
2:10:00	Photometer Calibrator	2090	ON	2
2:12:00	Photometer Calibrator	2090	OFF	0
2:12:01	Beam Steering Mechanism	2100	ON	4
2:42:00	Beam Steering Mechanism	2100	OFF	0

STEADY-STATE TEMPERATURE RESULTS - PHOTOMETER OPERATION

Node No.	Node Name	T (K)
1000	spire_4k_optical_bench	5.14
2090	photo_calibrator	5.33
2100	photo_beam_steering_mechanism	5.28
2410	photo_2k_box_mid	1.76
2600	cooler_photo_strap	0.2947
2620	photo_spect_strap	0.3008
2660	photo_300mK_busbar	0.2999
2700	photo_detector1_2k	1.76
2710	photo_detector1_strap	0.3012
2720	photo_detector1_top_ring	0.3082
2730	photo_detector1_spacers	0.3137
2740	photo_detector1_bot_ring	0.3189
2750	photo_detector1_cover	0.3190
2770	feedhorn1	0.3021
3200	spect_mirror_mechanism	5.14
3250	spect_calibrator	5.14
3410	spect_2k_box_mx	1.76
3660	spect_300mK_busbar	0.3032
4000	cooler_4k_structure	5.12
4200	cooler_2K_pump	1.97
4250	cooler_shunt	1.71
4300	cooler_300mK_evap	0.29
4400	cooler_pump_HS	1.97
4500	cooler_evap_HS	1.71
5000	spire_10k_JFET_box	12.80
6000	L1_strap_main_structure	4.68
6100	L0_strap_2k_boxes	1.73
6200	L0_strap_cooler_pump	1.83
6300	L0_strap_cooler_evap	1.71
10000	first_10k_optical_bench	12.44
20000	first_L0_helium_tank	1.7
21000	first_L1_cooling_pipes	4.19
23000	first_shield	36.28

STEADY-STATE HEATS LEAKS FOR PHOTOMETER OPERATION

	No. Off	Heat Leak (mW)	Total Heat Leak (mW)
Detector Kevlar Supports	5	1.00	4.98
Detector Harness	5	-	2.81
Busbar Vespel Supports	5	0.16	0.80
TOTAL			8.60

Breakdown of Heat Leaks to 300mK Stage – Photometer Operation

	No. Off	Heat Leak (mW)	Heat Leak (mW)
2K Box Supports	6	0.241	1.234
Detector Harness	5	-	0.100
Cooler Heat Switch Dissipation	1	-	2.000
Cooler Heat Leaks	-	-	0.109
Cooler Absorbed Loads	-	-	-0.024
TOTAL			3.423

Breakdown of Heat Leaks to L0 (2K) Stage – Photometer Operation

	No. Off	Heat Leak (mW)	Total Heat Leak (mW)
FPU Cone Support	1	3.558	3.559
FPU A-Frame Supports	2	2.719	5.438
Harness to JFET	1	0.727	0.727
Radiative Loads		-	2.231
Power Dissipation		-	4.100
Losses to 2K Stage			-1.443
TOTAL			14.625

Breakdown of Heat Leaks to L1 (4K) Stage – Photometer Operation

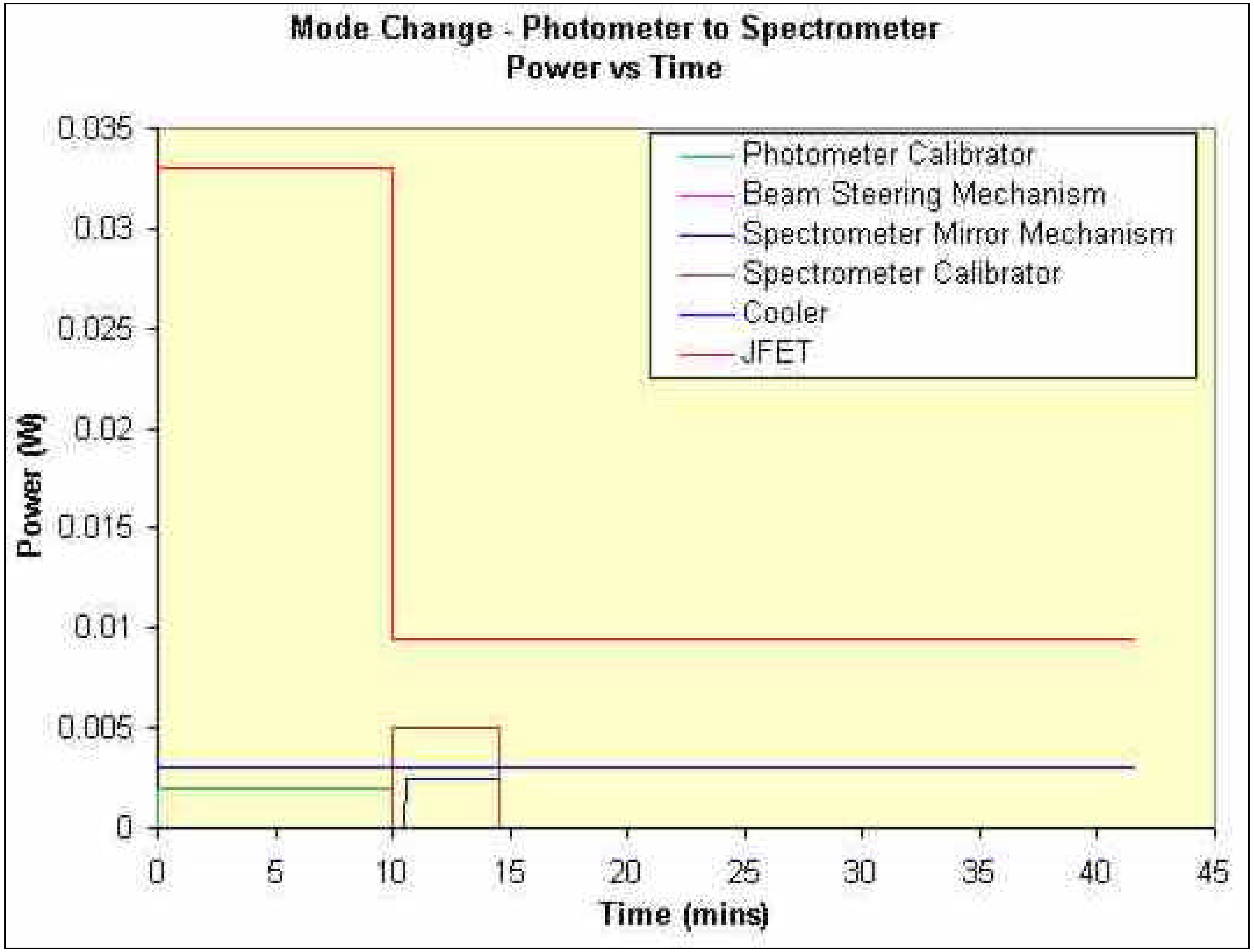
	No. Off	Heat Leak (mW)	Total Heat Leak (mW)
JFET Dissipation	-	-	33.000
JFET – Shield 1 Harness	-	-	23.000
JFET – FPU Harness	-	-	-0.727
FIRST Optical Bench to FPU	-	-	-8.997
TOTAL			46.276

Breakdown of Heat Leaks to L2 (10K) Stage – Photometer Operation

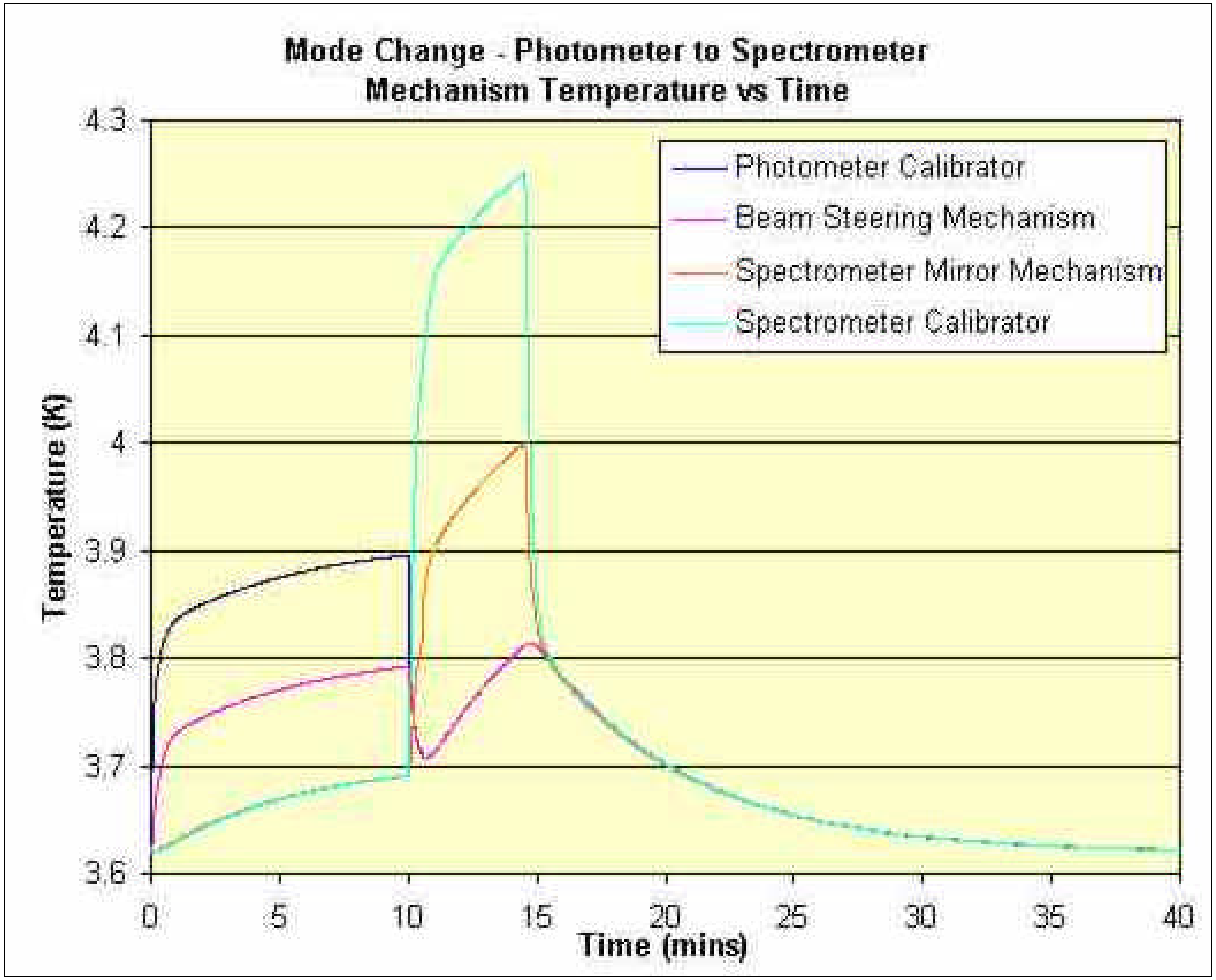
Strap	**Heat Load (mW)**
L0 – 2K BOX STRAP	*1.321*
L0 – EVAP STRAP	*0.128*
L0 - PUMP STRAP	*1.974*
L0 - TOTAL	3.423
L1 STRAP	14.625

Summary of FIRST Cryostat Strap Heat Loads – Photometer Operation

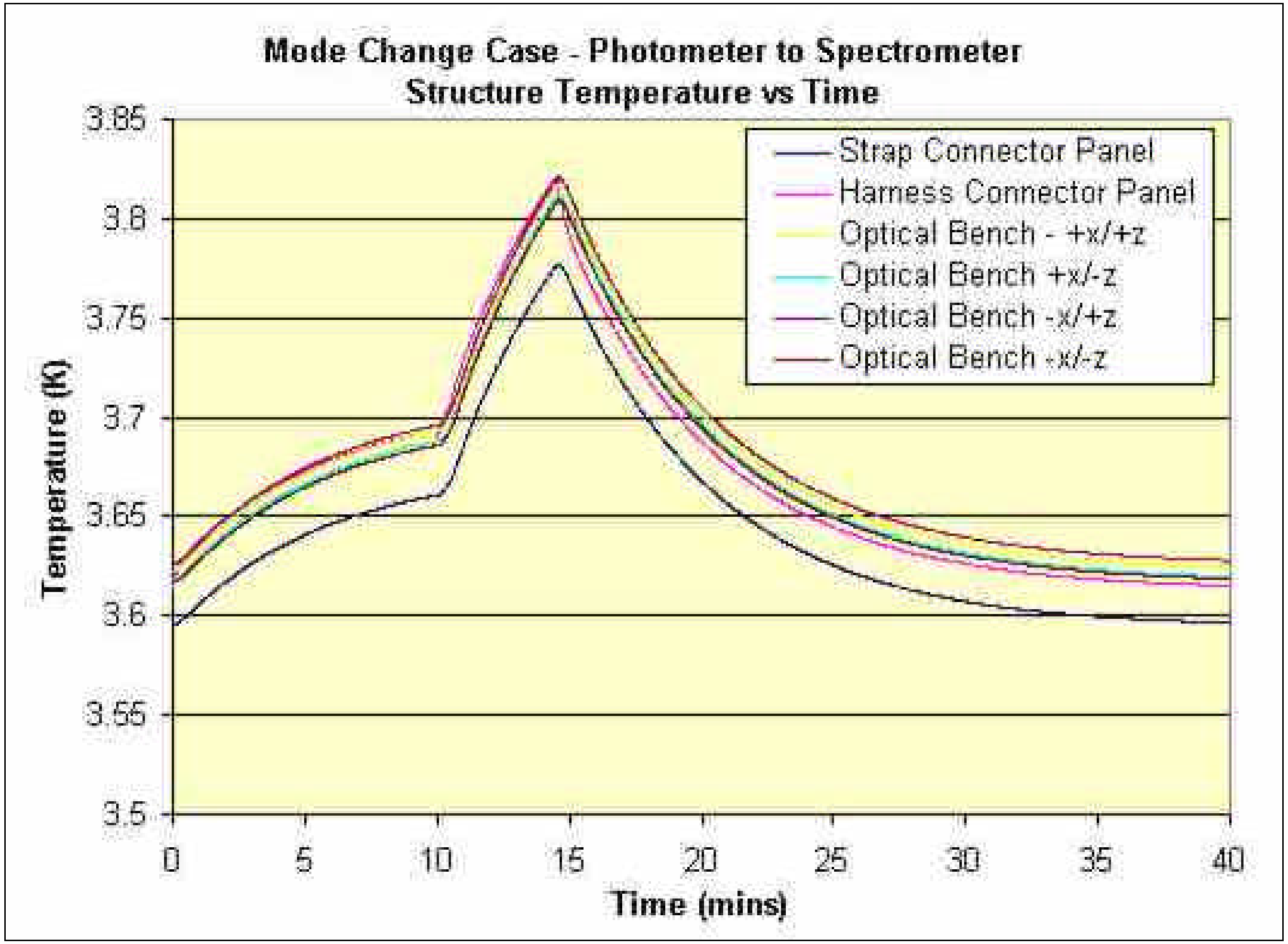
MODE CHANGE CASE RESULTS



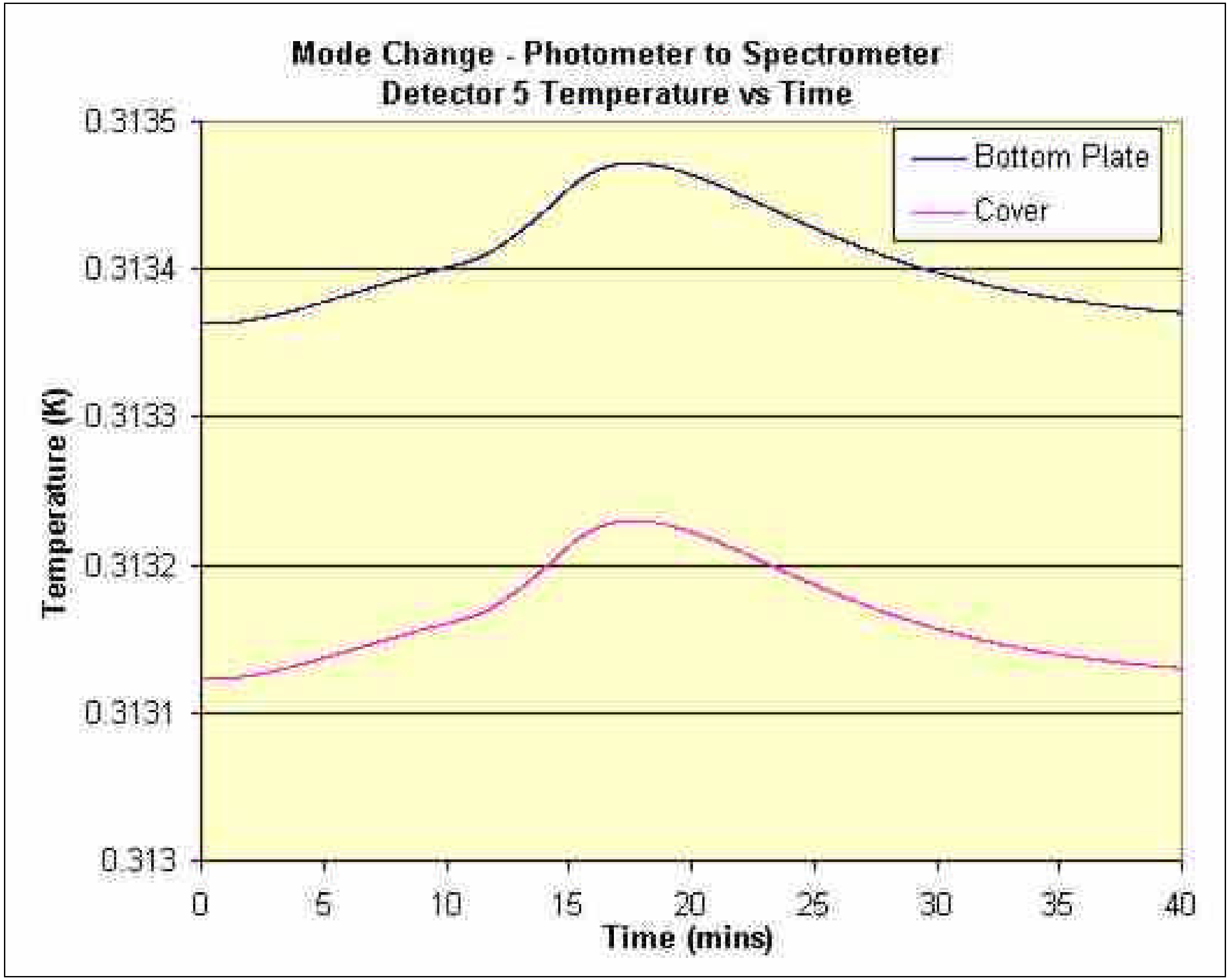
Mode Change Case - Powers



Mode Change Case –Mechanism Temperatures

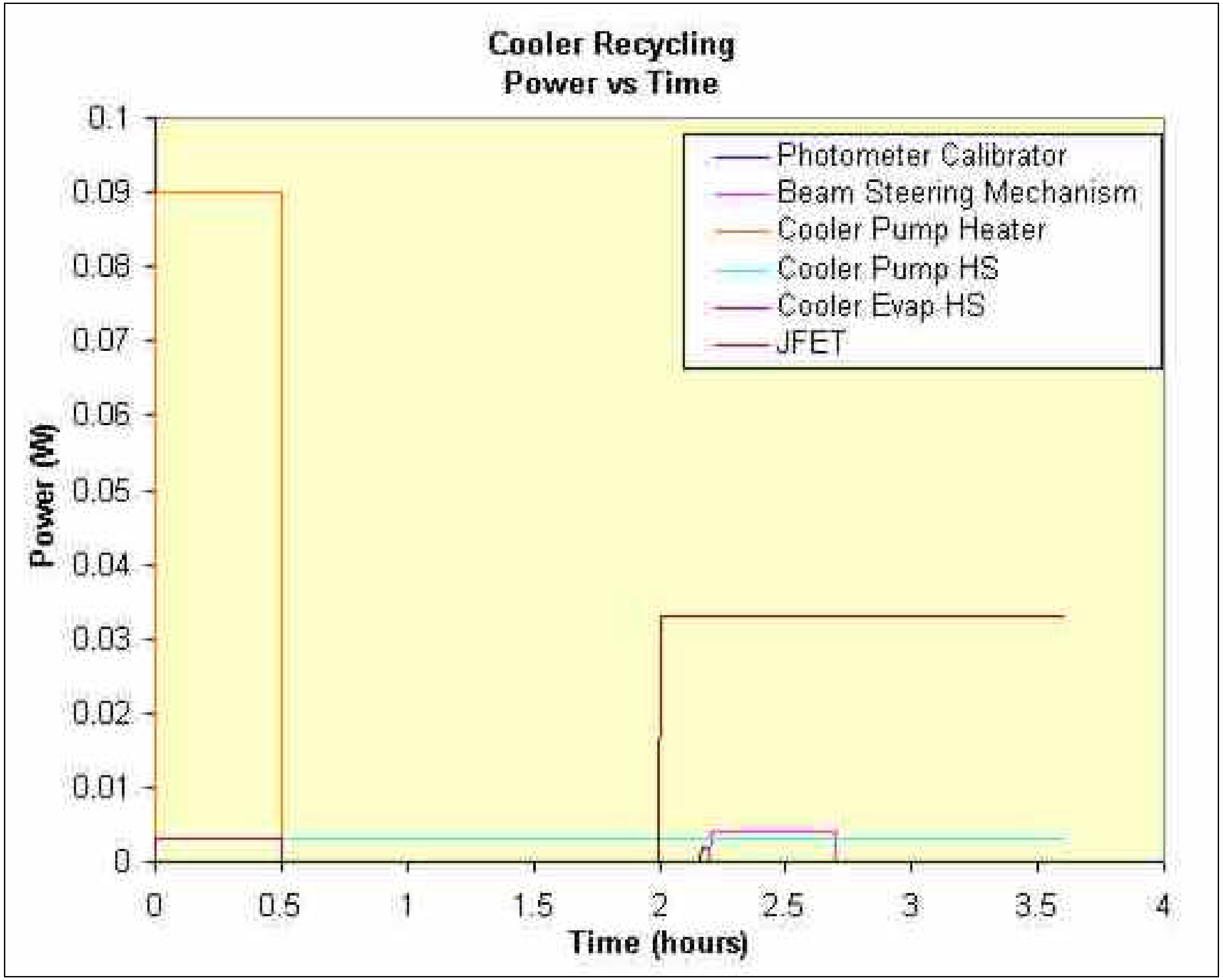


Mode Change Case – Optical Bench Temperature

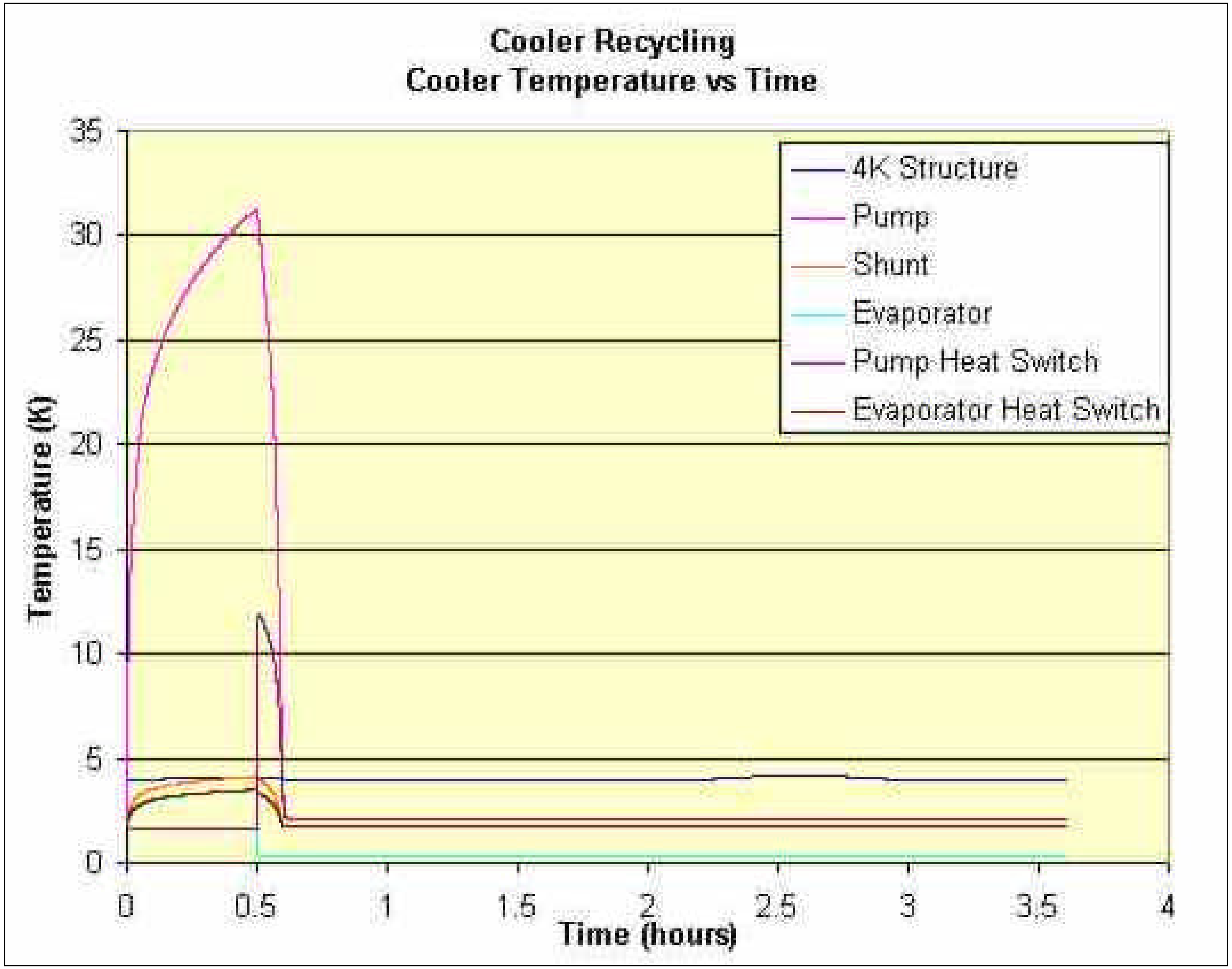


Mode Change Case – Detector Temperature

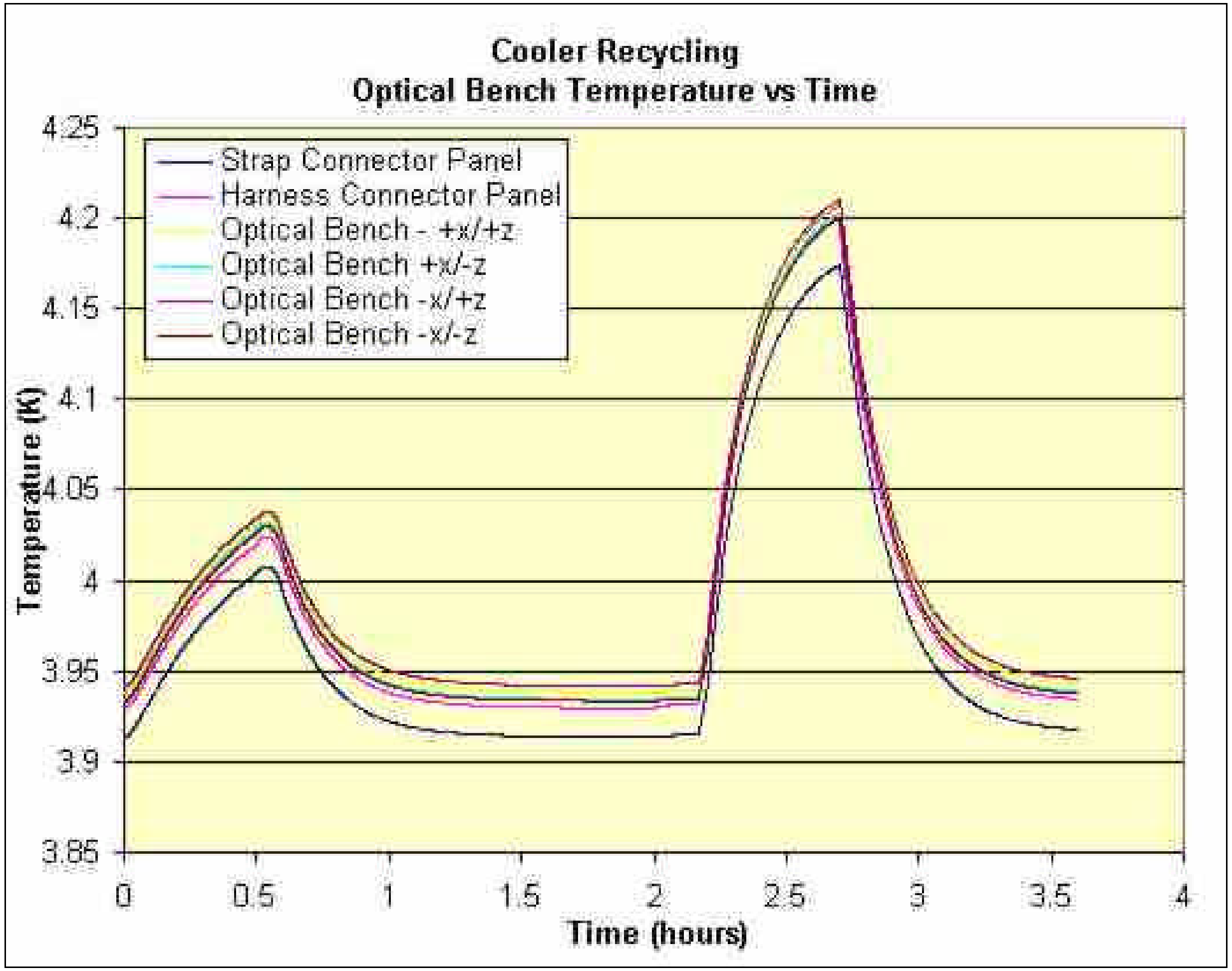
COOLER RECYCLING CASE RESULTS



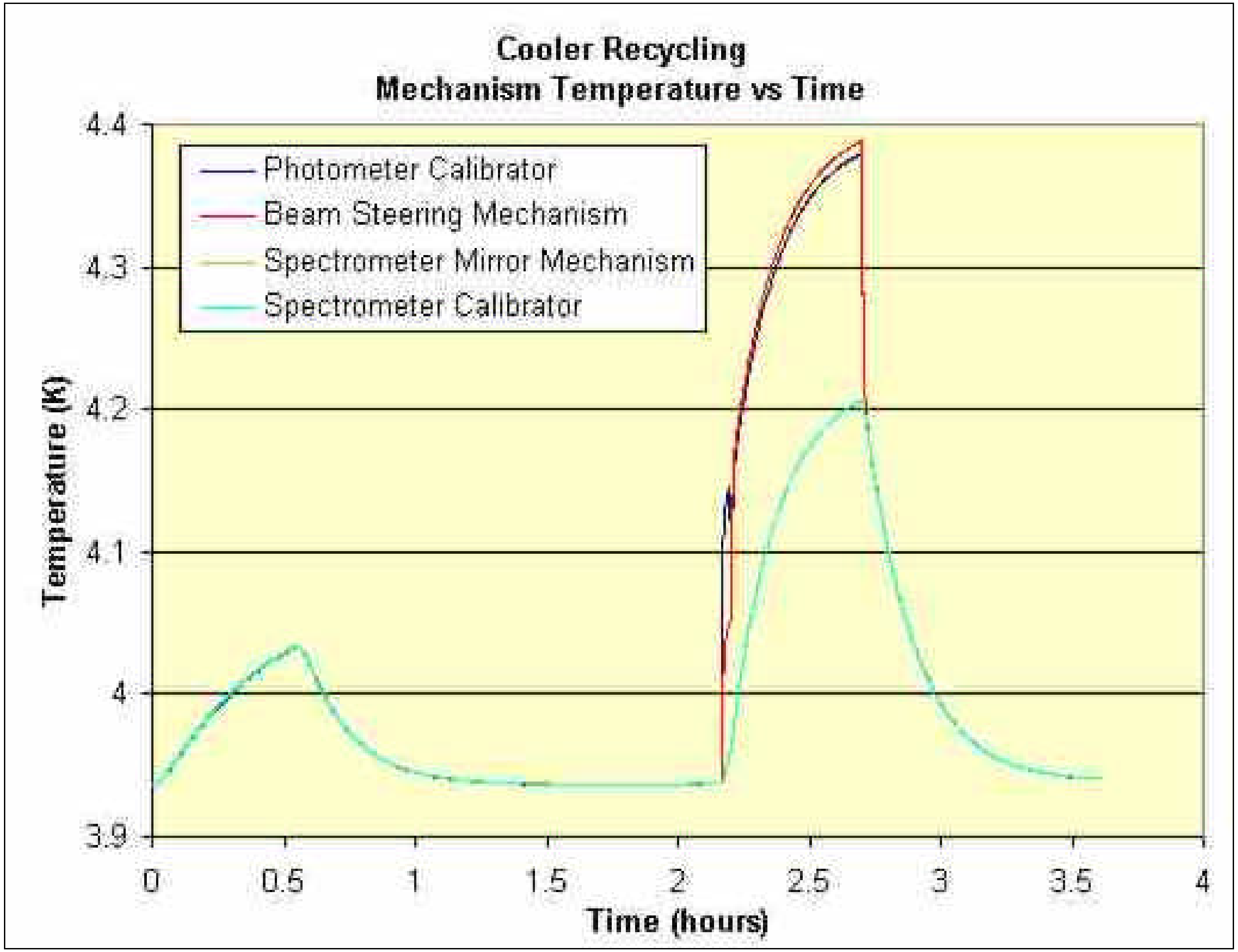
Cooler Recycle Case – Powers



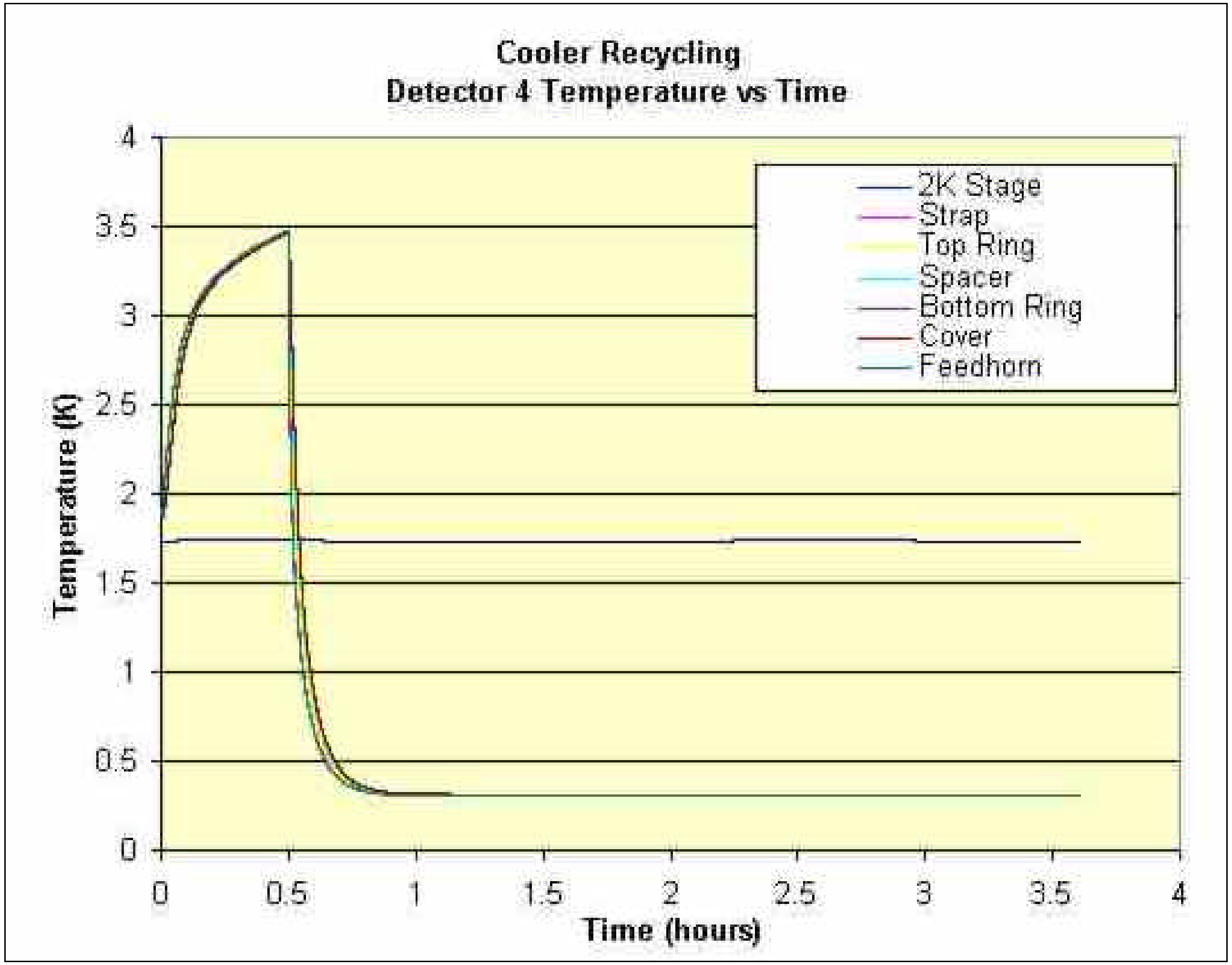
Cooler Recycle Case – Cooler Temperature



Cooler Recycle Case – Optical Bench Temperatures



Cooler Recycle Case – Mechanism Temperatures



Cooler Recycle Case – Detector Temperatures

ANALYSIS RESULTS VS INSTRUMENT REQUIREMENTS

Parameter	**Specification**	**Analysis Results**	**Specification Achieved?**
Heat leak to FPU from FIRST Optical Bench	6mW for delta T = 11-4.2 = 6.8K	9.04mW for delta T = 12.44-5.14 = 7.3K	No
Conductive heat leaks down 2K box support	1mW for delta T = 4.2 - 1.7 = 2.5K	1.234mW for delta T = 5.14 – 1.76 = 3.38K	?
Detector temperature	T <310mK	311mK to 318mK	No
Detector array stability	150nK/√Hz between 0.03 and 25Hz.	TBD	-
Parasitic heat leak on 300mK detector stage	<1.6μW per array <8μW total	1.37 to 2.05μW per array 7.81μW total	No Yes
Temperature difference between cooler cold tip and detector arrays	< 20mK	21 to 28mK	No
Temperature gradient along compliant links from bus bars to Cooler or detectors	2mK/link	~6mK/link	No
Total heat leak down the Photometer 300mK strap supports	0.6μW	0.48μW	Yes
Total heat leak down the Spectrometer 300mK strap supports	0.4μW	0.32μW	Yes
Cooler maximum heat load	> 10μW at 290mK evaporator temperature	8.60μW	Yes