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prepared by Cryo-Ops Working Group

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APPROVAL

Title	Planck Cryo-chain Operations	issue 3	revision 0

Authors	Cryo-Ops Working Group [COWG]: C. Lawrence J. Tauber J-L. Puget F. Piacentini G.L. Morgante D. Pearson J-J. Fourmond C. Leroy M. Piat W. Holmes L. Terenzi D. Taylor With inputs and support from: E. Gavila (Thales Alenia Space) C. Damasio (ESA H-P Project Team)	date 05-May-2009

Approved by	J. Tauber (ESA Project Scientist)	date

CHANGE LOG

reason for change	Issue	revision	Date
- First version.	0	1	01 June 2007
- Comments from D. Texier.	0	2	06 June 2007
- Section on SCS from D. Pearson and G. Morgante. - Model from J-J Fourmond (Planck Operations scenario).	0	3	18 July 2007
- Updated cool-down model prediction (Emmanuel Gavila timeline). - Updated with System Optimisation section.	0	4	24 September 2007
- Updated Tuning in CPV section, after meeting in Bologna.	0	5	13 November 2007
- Inserted Routine phase operations and monitoring section.	0	6	17 December 2007
- 4K cooler routine phase configuration section added; - General revision by F. Piacentini.	0	7	23 January 2008
- Inserted J. Tauber comments. - New format for cool-down operations. - Included details of SCS switchover (from G. Morgante). - Included details of SCS heat-lift measurements (from G. Morgante). - Revised cool-down timeline and added cool-down plot from Emmanuel Gavial model run.	0	8	03 March 2008

reason for change	Issue	revision	Date
- 4K cooler routine phase ops revised. - More homogeneous tables format. - Reference to FOPs added in tables (to be populated). - Coolers routine phase strategy moved before tuning operations.	0	9	04 March 2008
- Inserted comments from D. Pearson and G. Morgante about SCS operations. - Table with operational parameters and nominal values inserted. - Inserted J-L Puget answers to F. Piacentini. - Inserted placeholders and introductions for *Expected Anomalies* and *Failure cases* sections. - Reference to FOP procedures removed. - Included first list of SCS anomalies and failures after discussion from G. Morgante. - Hold-Points revised after discussion at ICWG #19. - Inserted a section describing the sequence of operations to cool-down from passive cooling condition. - Strategy for 4K cooler setting and HFI PIDs tuning revised, with input from the HFI calibration document.	0	10	14 April 2008
- Included G. Morgante and D. Pearson inputs.	0	11	16 May 2008
- Clean-up for First Formal Issue.	1	0	26 May 2008
Formal Issue: - Included J-L Puget comments. - Included D. Texier comments. - Included C. Leroy comments. - Included Annex 1: SCS activation strategy.	1	1	7 July 2008
- Improved performance section.	2	0	03 August 2008
- Inserted JLP comments after CSL TB/TV Tests (July 08).	2	1	12 August 2008

reason for change	Issue	revision	Date
- Update for submission to IFAR.	2	2	20 August 2008
- Update after CSL Tests (J-L Puget & D. Pearson).	2	3	22 October 2008
Improved after 30 Oct 08 meeting (contingencies) - Changes and additions by J. Tauber. - Changes and additions by J-L Puget. - Changes and additions by D. Pearson. - Changes and additions by F. Piacentini. - Consolidated by D. Taylor.	2	4 up to 7	20 November 2008
- Major update after Project Review.	2	8	03 February 2009
Second update after further Project comments: - Deletion of SCS switch-over after initial cooling. - Introduction of LFI staged tuning during HFI activities. - Population of Annex 1 (cross references to User Manual Procedures). - Cosmetic changes for clarity throughout the document.	2	9	16 March 2009
Update for launch version: - Revision of Initial Cool-down Sequence to provide 4K cooler plateau temperatures for LFI tuning activities. - Update of Annex 1 with cross references to User Manual Procedures.	3	0	05-May-2009

CHANGE RECORD

Issue: 2 Revision: 0

reason for change	page(s)	paragraph(s)
Introduced a new Chapter 2 with configuration and performance data.		Chapter 2
Inserted an operation for the setting of the WR temperature in CPV phase.		3.2.1

Issue: 2 Revision: 1

reason for change	page(s)	paragraph(s)
Included List of Tables and List of Figures.	9	
Inserted J-L Puget comments after CSL TB/TV Tests.		3.1

Issue: 2 Revision: 2

reason for change	page(s)	paragraph(s)
Cosmetic Changes (formatting etc).	Whole Document	
Table with coolers parameters setting moved at the beginning of the document.		Table 1
Included BOL and EOL in the table with nominal parameters settings.		Table 5
Section with expected updates inserted.		1.4
Revision by C. Lawrence.	Until page 33	
Moved discussion about SCS activation from 3.1.7 to 3.1, added lifetime estimation at 47 K.		3.1

Issue: 2 Revision: 3

reason for change	page(s)	paragraph(s)
Update with CSL results: coolers performances and cool-down timeline	Chapter 2 and 3	
New cool-down figures taken from CSL cool-down	Chapter 3	
Completely revised Anomalies and Contingencies section	Chapter 4	
Table with recovery times included	Chapter 4	
Table with summary of reaction to contingencies	Chapter 4	

Issue: 2 Revision: 2.4 -> 2.7

reason for change	page(s)	paragraph(s)
Complete update and clean-up of document as discrete versions, in particular to improve the figures from CSL Tests to complete the Anomalies and Contingencies section, and to include results from an updated HFI Thermal Model for some contingency cases.	All	

Issue: 2 Revision: 8

reason for change	context of change	paragraph(s)
Project Review CRYO-01	Reference numbers of ADs and RDs provided where possible	§1.2
Project Review CRYO-02	Clarification of mission lifetime and correlation with cooler lifetimes.	§2.4.1, §2.6.2
Project Review CRYO-04	New Figure 2 inserted to show lifetime of both Sorption Coolers as a function of V-groove 3 temperature.	§2.4.1
Project Review CRYO-17	Clarification of WR settings -corrected 3.2.1 to be in agreement with §2.2 and introduced new section §3.1.8.	§3.2.1
Project Review CRYO-18	Reference is now made to Sorption Cooler Lifetime & Operations Document which describe Cycle Time and Power Settings.	§3.2.2, §3.2.3
Project Review CRYO-19	4K cooler frequency cooling – section updated to clarify this is a contingency in case microphonic lines are observed.	§3.2.5
Project Review CRYO-21	Section updated to reflect the role of monitoring and fine adjustments during routine operations, and the treatment of anomalies.	§3.3
Project Review CRYO-22	Monitoring of LVHX-1 temperature - reference is now made to Sorption Cooler Lifetime & Operations Document.	§3.3.1
Project Review CRYO-23	Reference is now made to Sorption Cooler Lifetime & Operations Document.	§3.3.5
Project Review CRYO-24	Reference is now made to Sorption Cooler Lifetime & Operations Document.	§3.3.6
Project Review CRYO-25	Reference made to Sorption Cooler Lifetime & Operations Document. Evaluation of lifetime will be done by monitoring the rate at which the cycle-time is changing and comparing this rate to that found at JPL for a single-element lifetime test.	§3.3.8

reason for change	context of change	paragraph(s)
Project Review CRYO-26	Dilution Cooler residual lifetime - pressures and flows are measured. An algorithm given by CRTBT lab and Air Liquide to evaluate the residual lifetime is implemented in the Weekly Health Report (WHR) software.	§3.3.9
Project Review CRYO-27	The goal is to detect clogging or other abnormal behaviour of the 4K cooler. The pressure should be stable within 20% for a given set of parameters. Clogging gives a very obvious signal, and reference is made to §4.4.8 - 4K Cooler JT Plug).	§3.3.10
Project Review CRYO-29	VCS error signals - the error signals are the force transducer between the two compressors. For all harmonics it is checked that the force transducer signal does not exceed the noise. If this happens a VCS parameter adjustment must be planned during an upcoming DTCP.	§3.3.14
Project Review CRYO-30	Modified table and reference made to §4.4.8 (4K Cooler JT Plug Contingency).	§3.3.20
Project Review CRYO-33	Atomic procedure references at a level below system level will now be provided under Annex 2.	§1.1
Project Review CRYO-34	Reference numbers of ADs and RDs provided where possible (see CRYO-01).	§1.2
Project Review CRYO-37	Cooler lifetimes (see CRYO-02 and CRYO-04).	§2.4.1
Project Review CRYO-38	Reference to §3.1.7 deleted. Strategy is fully described under Annex 1.	§2.4.2
Project Review CRYO-40	Reference is now made to the CPV Detailed Timeline.	§3.1.7
Project Review CRYO-43	Reference to procedures - title of this section changed to 4K VCS Adjustment and reference made to HFI User Manual.	§3.1.22
Project Review CRYO-45	Reference made to SCS UserManual. Liquid removal in the off-state cooler will be assessed by the perfomance of the on-state cooler, specifically the heat lift, but the presence of liquid in the off-state cooler will not affect the cooldown time of the on-state cooler.	§3.1.27

reason for change	context of change	paragraph(s)
Project Review CRYO-47	Reference is now made to Sorption Cooler Lifetime & Operations Document (see CRYO-24 and CRYO-23).	§3.2.2
Project Review CRYO-48	Reference is now made to Sorption Cooler Lifetime & Operations Document.	§3.2.3
Project Review CRYO-49	This section revised to further expand on the objectives and to clarify this is an optional activity to be done only if microphonics lines are seen after SRT/VCS adjustment has been performed.	§3.2.5
Project Review CRYO-50	This section revised. The logic is to implement the stroke amplitude determined at CSL. If the heat lift is not large enough to allow the PID to work properly (it needs 2 mW of margin) without exceeding the required cold tip temperature (less than 4.7 K), the stroke amplitude will be increased by a value determined from the dependencies reported in 2.5.3 (Static Performance of the 4K Flight Configuration).	§3.2.7
Project Review CRYO-51	Procedure reference has been provided.	§3.3.4
Project Review CRYO-52	§3.3.16 and §3.3.17 are related but not identical. 3.3.16 describes weekly monitoring of the 4 K heat lift margin, which will change slowly as the SCS is readjusted and the pre cooling temperature rises (it is predicted that the effect is about 0.5 mW thus within the initial margin, thus no adjustment should be needed during a SCS lifetime). 3.17 describes what to do if the margin gets too small. Duplicate language in 3.3.17 has been removed.	§3.3.16, §3.3.17
Project Review CRYO-53	This section updated. Exact criteria have been written in the Contingency §4.4.8.	§3.3.20
Project Review CRYO-54	Reference made to §4.4.2 (SCS JT Plug Contingency).	§3.3.21
Project Review CRYO-61	Atomic procedure references at a level below system level will now be provided under Annex 2 (see CRYO-33).	§Generic
Project Review CRYO-62	Section updated.	§2.5.1

reason for change	context of change	paragraph(s)
Project Review CRYO-63	Reference provided for SCS operations.	§2.4.2
Project Review CRYO-65	There are no other criteria other than the temperature. The TBC has been removed from the Table.	§3.1
Project Review CRYO-66	The User Manual is the reference. The document has been corrected.	§3.1.2, §3.1.3
Project Review CRYO-71	TBC has been removed. The 4K and dilution coolers can stay on. The amount of liquid Helium at the 1.6K stage can last several hours. The switch-over if done within one hour should not affect the 100mK stage.	§3.1.26
Project Review CRYO-73	Reference is now made to Sorption Cooler Lifetime & Operations Document.	§3.2.2
Project Review CRYO-74	Modelling activity is not relevant for the TSA tuning and has been removed.	§3.2.3
Project Review CRYO-76	The operations described in this section are monitoring activities and little impact is expected on the rest of the system. However, the impact has been described where this is applicable. (the label "impact on system" should be understood as "impact on the rest of the system". Where none is listed, there is NO impact).	§3.3
Project Review CRYO-77	The note under Table 9 was left in erroneously from earlier versions and has been replaced with a more explanatory note.	§4.2
Project Review CRYO-79	An automatic procedure cannot be run because of a software error that prevents entering the proper value for the energy deposited into the beds. If there is a plug, the procedure will have to be run by command. The risk is low, therefore correcting the software is not justified. A note has been added in the document.	§4.4.2
Project Review CRYO-81	Reference to the Science Team has been removed.	§4.4.5
Project Review CRYO-83	Typo has been corrected.	§2.4.1
Project Review CRYO-84	The TBC has been removed and replaced with the correct numbers.	§3.1.7

reason for change	context of change	paragraph(s)
Project Review CRYO-85	The tables from the HFI Calibration and Performance document have been put in §2.6.2.	§3.1.17
Project Review CRYO-86	See CRYO-71.	§3.1.26
Project Review CRYO-87	Document corrected as stated in CRYO-17.	§3.2.1
Project Review CRYO-88	The table `has been updated.	§4.4.3
Project Review CRYO-91	A new figure and caption have been inserted in the document.	§2.4.1
Project Review CRYO-92	See CRYO-91.	§2.4.1
Project Review CRYO-93	New phrasing has been inserted.	§2.4.2
Project Review CRYO-94	For practical purposes the Commissioning and CPV documents are the same. CPOP added as a reference.	§3.1
Project Review CRYO-95	An explanatory sentence has been inserted.	§3.1
Project Review CRYO-98	LFI FPU should be at 40K and Table 4 has been changed to 40 K.	§3.1.9
Project Review CRYO-99	There is no LFI or LFI FEM switch-off for planned SCS switch-over at the end of initial cool-down or in-flight at end-of-SCS life (see CRYO-45).	§3.1.27
Project Review CRYO-101	When temperatures rise significantly above the set temperature, all PIDs go to zero power by design. Text has been modified to clarify this.	§4.1
Project Review CRYO-103	Reference has been provided for SCS User Manual.	§4.3

Issue: 2 Revision: 9

reason for change	context of change	paragraph(s)
Deletion of SCS switch-over after initial cooling	No SCS switch-over from FM1 to FM2 after initial cooling. FM2 (nominal unit) is used for initial cool-down and subsequent survey operations until end-of-life.	§2.4.2 §3.1 Annex 1
Introduction of LFI staged tuning during HFI activities	Parallel operations during initial cool-down to provide "plateau" temperatures on 4K Cooler for stable LFI tuning activities.	§3.1
Population of Annex 1 (cross references to User Manual Procedures) Project Review CRYO-26 Project Review CRYO-33 Project Review CRYO-87 Project Review CRYO-89 Project Review CRYO-103	Provision of cross references to detailed procedures in User Manuals.	Annex 1 (was Annex 2)
Cosmetic changes for clarity throughout the document	General clean-up and homogeneity of tables for: - Initial Cool-down - Initial Tuning - Routine Operations - Anomalies - Contingencies	 §3.1 §3.2 §3.3 §4.3 §4.4

Issue: 3 Revision: 0

reason for change	context of change	paragraph(s)
Addition of Figure 5 to show modelling of Initial Cool-down.	Figure included after latest model runs by HFI to show 4K cooler plateau temperatures of 22K, 18K and 15K for LFI tuning activities.	§3.1
Modification of Table 6 and sub-sections for change in Initial Cool-down.	Reflects updated modelling results from HFI.	§3.1 §3.1.20 §3.1.22a §3.1.23
Update of User Manual References.	New User Manuals released, and check by HFI, LFI, SCS experts on original entries made in Issue 2.9.	Annex 1

Important Note:

The section and subsection heading numbers that follow for Chapters 3 & 4 are cross-referenced in the CPV Detailed Timeline (RD-10) and therefore should not be changed. Deleted sub-sections should be kept as placeholders and additional sub-sections given a suffix number.

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1 INTRODUCTION

1.1 *Scope and Objectives*

The Planck cryo-system comprises the following main elements:

- The warm radiator of the Payload Module, maintained in the 260-280 K range
- The radiating surfaces on the Payload Module (PPLM), which passively cool the payload below ~50 K on the 3rd V-groove, and ~40 K on the reflectors
- The 20 K Sorption Cooler, which is pre-cooled by the passive radiators to 60 K and cools the LFI focal plane and the HFI interface to ~18 K
- The 4 K cooler, which is pre-cooled by the passive radiators and the 20 K cooler and cools the outer parts of the HFI-FPU and the LFI reference loads to ~4 K
- the 0.1 K dilution cooler, which is pre-cooled by the passive radiators, the 20 K cooler, and the 4 K cooler, and cools the inner HFI-FPU box to ~1.6K and the HFI detector plane to ~0.1 K.

These elements have been developed by JPL and Industry within the two instruments consortia and under the overall management of the Herschel-Planck Project Team. The Sorption Cooler is common to both instruments but managed by the LFI Project Manager. The two other coolers were developed by the HFI team.

The main objective of this document is to define the optimum operation of this complex cryo system during:

- cool-down of the system after launch, and in the early stage of the mission;
- tuning of the system;
- routine operations;
- special operations such as the switchover between the two Sorption Coolers, and their regeneration;
- anomalies and contingencies.

The document also contains information about the expected lifetime of the elements.

The underlying goal of this document is to set an operational scenario that maximises the scientific return of the mission by optimizing cooler performance and minimizing risk.

To achieve its objective, this document describes the operations and performance of the full cryogenic system of Planck, including an initial specification of the expected operating parameters and how they will be chosen. This document addresses the operations of the cryo-cooler chain as a system, including timelines. It is not the objective of this document to report in detail the operations and procedures required to run each cooler. This information is reported in the User Manuals in references [AD-01 to AD04].

This document is intended to be a reference for the development of system-level operational procedures related to the cryo-chain. Although it is a living document which will be updated as understanding of the cooling chain and its best operating point evolves, it is NOT intended to be a repository of critical operational information such as the specific values of cooler parameters. The latter must always be validated by the corresponding authority.

This document is produced by and represents the views and recommendations of the Cryogenic Operations Working Group (COWG), a group of cooler experts which was created to develop strategies for operating the cryo system that maximise performance and lifetime and minimise risk, including defining the best operating point of the whole system, the initial cool-down sequence, and the routine operations. The COWG has been supported by inputs from industry (Thales Alenia Space) and the H-P Project Team

1.2 References

1.2.1 APPLICABLE DOCUMENTS

[AD-01] Planck LFI User Manual
PL-LFI-PST-MA-001, Issue 4, Rev. 0, 22nd March 2009

[AD-02] Sorption Cooler System User Manual
PL-LFI-PST-MA-002, Issue 3, Rev. 0, 20th March 2009

[AD-03] HFI User Manual
UM-PH921-300334-IAS, Issue 2, Rev. 2, 17th March 2009

[AD-04] Hershel/Planck Satellite User Manual
H-P-1-ASP-MA-0693, Issue 3, Rev.1, June 2008

[AD-05] Science Ground Segment Management Plan
Planck/PSO/2008-012, Issue 1, July 2008

1.2.2 REFERENCE DOCUMENTS

[RD-1a] HFI PFM Calibration and Performances Document
CA-PH412-600824-IAS

[RD-1b] Planck Sorption Cooler Lifetime and Operations Document
JPL Document, D-46301

[RD-02] CReMA: Hershel/Planck Consolidated Report on Mission Analysis
PT-MA-RP-00100-OPS-GMA

[RD-03] Planck Operations Scenario, Planck
PSO/2001-001

[RD-04] LFI Operations Plan
PL-LFI-PST-PL-011

[RD-05] LFI-IOCTA-DD
LFI Testing Plan during the Planck Commissioning and CPV phase
PL-LFI-PST-PL-013

[RD-06] LFI-IOCTA
There is no formal reference for this document (Excel Spreadsheet)

[RD-07] HFI Operations Plan
PL-HFI-IAP-PL-101

[RD-08] HFI-IOCTA-DD
PL-HFI-IAS-PL-CPV

[RD-09] HFI-IOCTA
PL-HFI-IAS-PL-IOCTA (Excel Spreadsheet)

[RD-10] Planck CPV Detailed Timeline
PSO-2007-18

[RD-11] Commissioning Phase Operations Plan (P-CPOP) & Associated Timeline (PCOP)
SRE/PT-49187

[RD-12] Simulation Results by Thales/Emmanuel (COWG Thermal Analysis Support
H-P-3-ASP-AN-1432

[RD-13] Deleted

[RD-14] HFI Commissioning Plan
Reference to be allocated (Excel Spreadsheet)

[RD-15] Test Plan of the LFI Instrument during the Commissioning and CPV Phase
PL-LFI-PST-PL-013

[RD-16] HFI CQM CSL Cryogenic Chain Test Report
TR-PH600734-IAS

[RD-17] Herschel/Planck Mission Analysis: Launch Window for Fast Transfer of Planck
PT-PMOC-MGT-TN-1804-OPS-GFA

[RD-18] Planck PLM Flight Prediction update after CQM Test Correlation
H-P-3-ASP-AN-1173

[RD-19] Planck SGS CPV Operations Plan
PSO/2002-012

[RD-20] Planck SGS Routine Phase Operations Plan
PSO/2004-013

[RD-21] Cryogenic Tests Report
TR-PHED-500745-AIRL, J. Delmas, P.Camus, October 2005

[RD-22] Dilution Cooler Performances
TN-PH750-701023-IAS, G. Guyot, 2008

[RD-23] Overview of the CQM Calibration & CSL Cryogenic Chain Test
VG-PH260-500564-IAS, G. Guyot, January 2005

[RD-24] Scientific Report on the TB-TV Tests for the Planck Cryogenic Chain
TR-PH215-701005-IAS, J-L. Puget, C. Leroy et alia., October 2008

[RD-25] Filtering and Unclogging Test Report
TR-PHEC-500676-AIRL, J..Butterworth, April 2005

[RD-26] HFI FM CSL: Instrument Functional Test Report
TR-PH430-701002-IAS 1/2, T. Maciaszek, November 2008

1.3 Structure of Document

Important Note:

The section and subsection heading numbers that follow for Chapters 3 & 4 are cross-referenced in the CPV Detailed Timeline (RD-10) and therefore should not be changed. Deleted sub-sections should be kept as placeholders and additional sub-sections given a suffix number.

Chapter 1 this Chapter provides an introduction, purpose and scope of the document.

Chapter 2 describes the performance and baseline configuration for the main elements of the cryogenic system at individual level and as a system. Section 2.8 describes the main dependencies between the various elements and the proposed setting of cooling chain parameters.

Chapter 3 describes cool-down operations (Section 3.1), initial tuning (Section 3.2), and routine operations (Section 3.3).

Chapter 4 describes anomalies and contingency situations. Expected anomalies such as JT plugs (for which a failure analysis is not needed and a reaction and recovery plan can be made in advance) are described in Section 4.3, whilst failure cases (with contingency recovery) are described in Section 4.4.

Chapter 5 defines the management structure of the cooling chain operations in the different phases of the mission (CPV, survey).

1.4 Updates of Document

This version of the document (February 2009) has been prepared for submission to the Flight Qualification and Acceptance Review (FQAR). It takes into account the results of the TB-TV CSL Tests of June-July-August 2008 and a Project Review of this document held during a November 2008 to January 2009 timeframe.

1.5 List of Acronyms

ARB	Anomaly Review Board
BOL	Beginning Of Life
CQM	Cryogenic Qualification Model
CSL	Centre Spatiale de Liege
COWG	Cryogenic Operations Working Group
CPV	Commissioning and Performance Verification
CReMA	Consolidated Report on Mission Analysis
DCCU	Dilution Cooler Control Unit
DQR	Daily Quality Report
DTCP	Data Tele-Commanding Period
EOL	End Of Life
FEM	Front End Module
FM1	Flight Model 1
FM2	Flight Model 2
FPU	Focal Plane Unit
HFI	High Frequency Instrument
ICWG	Instrument Coordination Working Group
JT	Joule-Thomson
LEOP	Launch and Early Orbit Phase
LFI	Low Frequency Instrument
LGA	Low Gain Antenna
LPSB	Low Pressure Stabilisation/Storage Bed
LVHX1	Liquid Vapour Heat eXchanger 1 (liquid reservoir, SCS to HFI interface)
LVHX2	Liquid Vapour Heat eXchanger 2 (liquid reservoir, SCS to LFI interface)
MGA	Medium Gain Antenna
MOC	Mission Operations Centre
MRB	Materials Review Board
OD	Operational Day
PID	Proportional-Integral-Derivative (controller)
PPLM	Planck PayLoad Module
SCC	Sorption Cooler Compressor
SCS	Sorption Cooler System
SCS-FM1	Sorption Cooler System Flight Model 1 Unit
SCS-FM2	Sorption Cooler System Flight Model 2 Unit
SVM	Service Module
TBC	To Be Confirmed
TBD	To Be Defined
TBP	To be Provided
TB-TV	Thermal Balance/Thermal Vacuum
TBW	To Be Written
TSA	Temperature Stabilisation Assembly
TPF	Task Parameter File
VCS	Vibration Control System
WHR	Weekly Health Report
WR	Warm Radiator

2 COOLING CHAIN PERFORMANCE AND BASELINE CONFIGURATION

2.1 *Overview*

Figure 1 gives a schematic view of the Planck cryogenic system, with a view of the thermal path through cryogenic stages. Table 1 lists the essential dependencies in the cryo system.

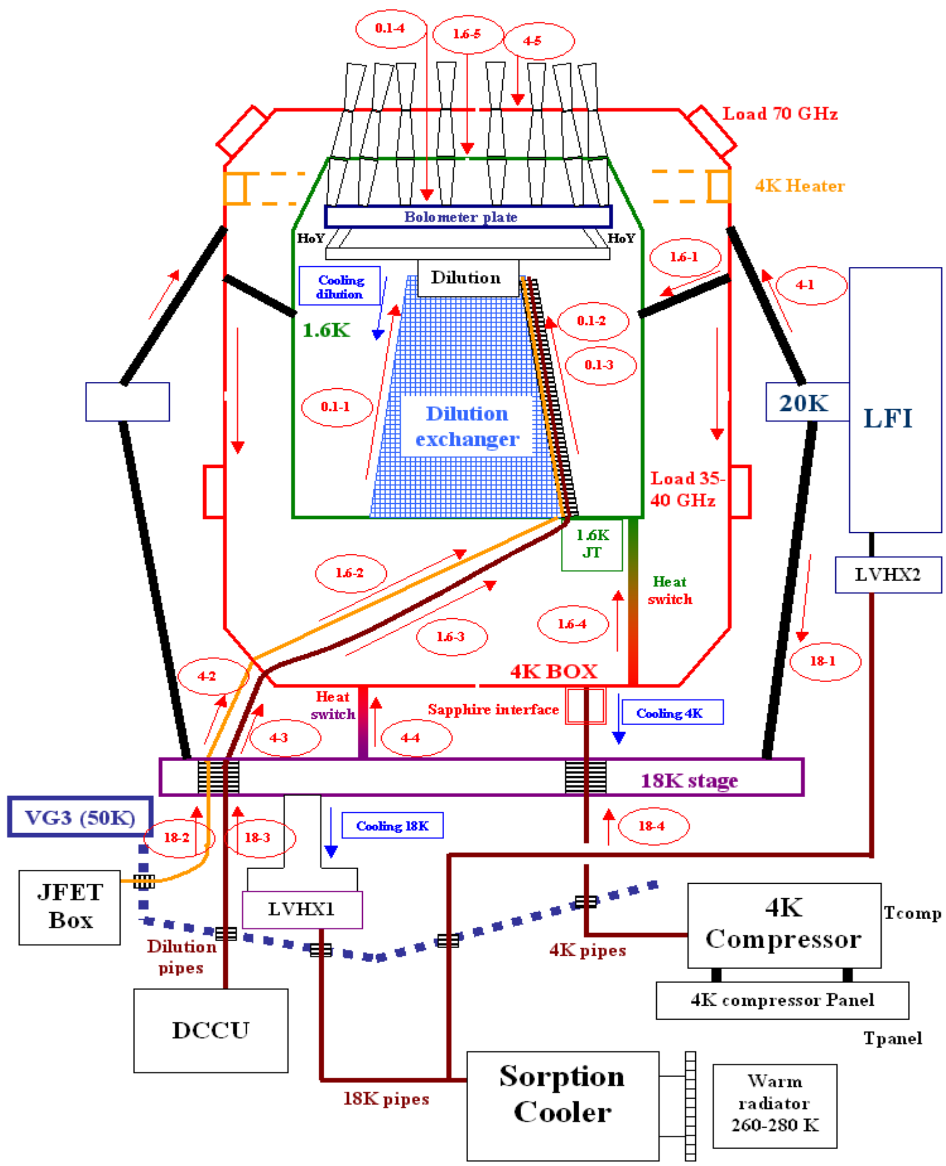

Figure 1: Summary of Thermal Path through the Cryogenic Stages

ITEM	Affected by	Main effects into	Trade-off
VG-3 temperature	SC mass flow	Efficiency of the SCS -> -> SCS required mass flow -> -> SCS power & cycle time	
WR temperature	SCS power	T(LVXH1 & 2)	
	WR heater power	4K cooler efficiency	
		4K cooler heat load	
WR stability	WR heater control	T(LVXH1 & 2) stability	
SCS Power Cycle Time TSA power LPSB	VG3 temperature	SCS heat lift	
	WR temperature	SCS temperature-> 4K efficiency -> 1.6K efficiency	
	WR stability	SCS stability	
		SCS lifetime	
		T stability of 4K box	
		T stability of 4K loads	
		Temperature and stability of LFI detectors	
4K cooler	LFI temperature; T(LVXH1); T(VG3)		Temperature and heat-lift
Fill pressure		4K cooler efficiency and temperature	
Stroke frequency		Could affect microphonics if VCS off Small effect on cooling power	
Stroke amplitude		Affect gas flow	Heat-lift and lifetime
PID power		Temperature and T stability; Margin on heat-lift (found to be large in TB-TVtests)	Temperature and T stability
VCS		Dilution (via micro-vibrations if VCS off)	
Dilution cooler Flow rate 1.6K PID power Dilu-plate PID Bolo-plate PID	4K and 1.6K precooling T; Micro-vibrations	Instability of 1.6 and 4K if 1.6K too cold (unstable evaporation)	Heat lift, temperature, lifetime
	SVM temperature	Changes the isotopes flow for a given choice of restrictions	T, T stability vs. margin (long timescale)
			T, T stability vs. margin (short timescale)

Table 1: Critical Interface Items and Related Dependencies in the Planck Cryogenic System

2.2 Mission Lifetime

The lifetime of the Planck mission is one of the main drivers for the cryo-chain operations, the goal being to guarantee that none of the coolers curtails the nominal or extended mission. The scientific operations of Planck are divided into Survey Units, each one of which corresponds to an independent observation of the full sky. The official definitions of these units are described in the Planck SGS Routine Operations Plan [RD-20].

For the purposes of this document, the mission lifetime to be supported is defined as:

- Commissioning and CPV phase (from start of cool-down to end of CPV phase): 9 weeks or 2.25 months (note that from launch 3 weeks are spent on activities not requiring coolers, so that the total Commissioning+CPV phase duration is 3 months).
- First survey: 7.5 months
- Second survey: 6.5 months
- Extended mission: 12 months (allowing two more surveys).

The nominal mission lifetime to be supported by coolers is therefore 16.25 months, and 28.25 including the extended mission.

It is considered scientifically important that each survey be conducted continuously and with a stable thermal environment, which implies that the cryo-chain configuration should not be changed within each survey, rather any configuration changes should be implemented between surveys.

The different length of time assigned to each survey is related to the fact that 7.5 months are required to fully cover the sky with all detectors, but when more than one continuous year of observations is available, it is possible to select full-sky coverages from the complete observed period with more freedom. The first survey is also the one which is most important to be fully completed in view of the cryogenic nature of the mission. The actual durations for completion of each survey depends on the exact scanning strategy and will be determined in flight based on actual payload operation. The above pre-selection of survey start/end times is intended to provide milestones useful to plan changes of cooler configuration which may introduce survey gaps or thermal discontinuities, e.g. Sorption Cooler switchover.

2.3 Passive Elements

The temperature of the passively cooled elements plays a major role in the determination of the performance and temperatures of the active elements.
The passive elements to be considered are:

- The Warm Radiator (WM)
- The three V-grooves (VG-1,2,3)
- The Reflectors.

Values for the expected temperature in flight according to a static thermal model are reported in [RD-18], in particular in Table 4.3-1 of that document. The Warm Radiator of the Sorption Cooler is expected to require extra heat initially in order to stay above the minimum temperature of 262 K set by the qualification levels of some equipment. As the hydride in the Sorption Cooler degrades with time, the Sorption Cooler power will have to be increased. This will increase the load on the Warm Radiator and its temperature will start rising after a period of stability.

During the thermal vacuum test of the FM1 system at CSL (CSL-FM1 test) the Warm Radiator had to be heated to stay above its minimal temperature. The temperature of the WR was chosen to be around 270K, assumed to be the end of life of the Sorption Cooler. This temperature is not optimal from several points of view (higher LVHX1 temperature and thus decreased margin on the 4K cooler). The degradation of the Sorption Cooler was not accurately measured during the TB-TV test; if a slower degradation than previously assumed should be confirmed by the aging test ongoing at JPL it would lead to less heating of the warm radiator during the mission life.

During the CSL-FM1 test, the temperature drifts on the 4K compressor SVM panel was 0.3 K/day. It was 0.6 K/day on the PAU SVM panel. These drifts are likely to be upper limits as predicted by the THALES thermal model.

For setting the WR temperature during the mission, there are two strategies.

1) The first is to start as low as possible and let the warm radiator temperature rise as the SC is readjusted.
2) The alternative is to start high enough to have a constant temperature over one year (from beginning to end of life of one cooler).

The COWG supports the first strategy in view of the gain in margin on the cooling chain, and of the current knowledge of the Sorption Cooler lifetime, degradation and adjustment operations during flight.

2.4 Sorption Cooler Configuration for Routine Operations

2.4.1 DEPENDENCIES AND SETTINGS

The Sorption Cooler performance and lifetime depends primarily on the temperatures of two interfaces and the heat load from the two instruments. The two interfaces are the warm radiator (WR) and the final pre-cooling stage on V-groove 3. Since the lifetime of the two Sorption Coolers is critical, it is run in such a way to maximise lifetime. Below, the results of the spacecraft level thermal vacuum and balance tests are discussed to provide the most likely settings for the mission.

The Sorption Cooler:

- cools the LFI through the LVHX2/TSA interface, thereby determining the temperature at the end of the struts that support the HFI.
- cools the HFI 18K stage on which the Helium of the 4K cooler is pre-cooled (LVHX1)

The temperature of LVHX1 (T_{LVHX1}) is critical for the whole HFI cryogenic chain. The FM2 CSL test gives this temperature as a function of the warm radiator temperature and the temperature of the VG3:

$$T_{LVHX1} = 16.5\ K + 0.05\ (T_{WR} - 262) + 0.01\ (T_{VG3} - 45)$$

The Sorption Cooler lifetime is increased when the compressor element cycle time is a maximum and when the temperature of the compressor elements is minimised. The main influence on setting the cycle time and the amount of input power is the temperature of the 3rd V-groove (see Figure 2 and Figure 3). A lower V-groove 3 temperature provides more heat lift capability. At 60 K the heat lift is ~1 W, while at 45 K it is ~2W for a 50 Bar inlet pressure. Increased available heat lift allows a lower pressure to be used, as the typical required heat lift from the instruments is 1 W. A lower pressure allows a longer cycle-time because less energy is needed to reach the working pressure. In addition, a lower pressure results in a lower compressor element temperature, which increases lifetime.

Figure 2 below shows a typical beginning of life dependance of input power and pressure to maintain the heat lift constant for FM1 (for the FM2 the input power will be 27 W higher).

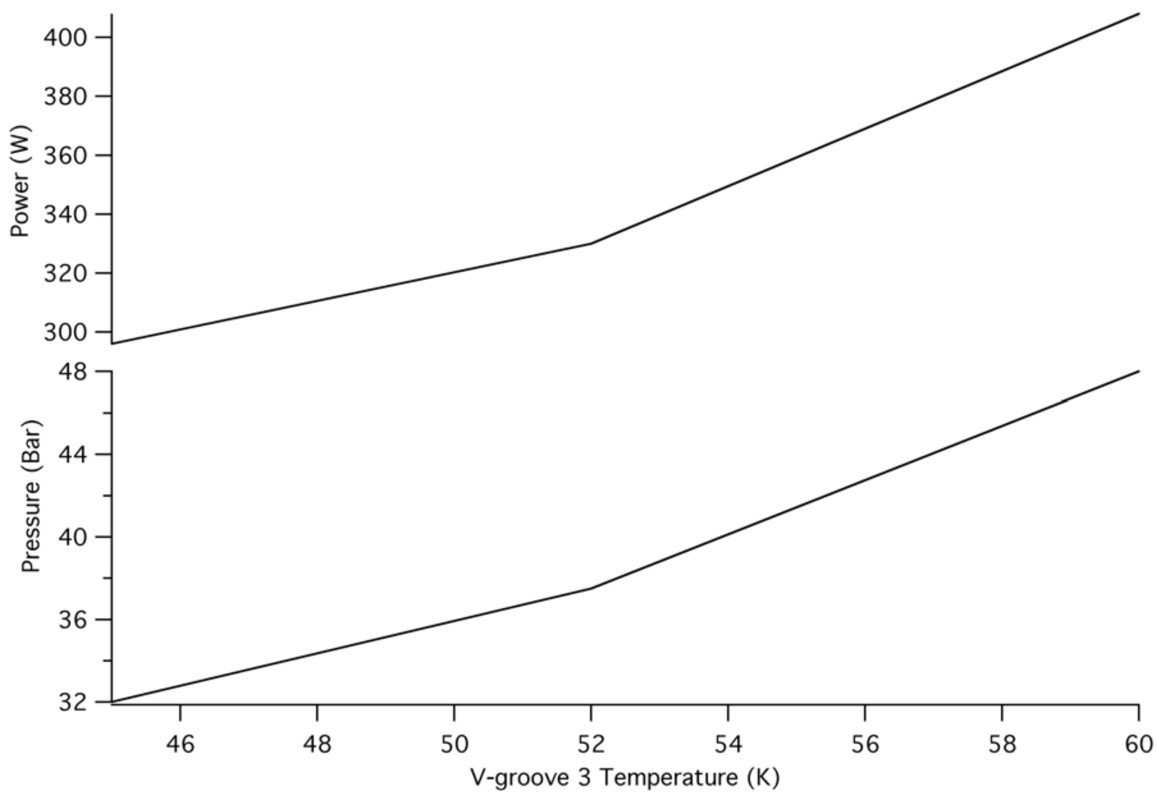

Figure 2 SCS Input Power and Pressure vs V-groove 3 Temp to Maintain a Heat Lift of 1060 mW

Note:

Data is based on JPL testing at 45K, 52K and 60K V-groove 3 temperatures.

A precise prediction of the SCS operating parameters is difficult due to the non-linear behavior of the system. Specifically, the cooler performance can only be predicted with a full thermal model of it and the two spacecraft interfaces. Further, SCS operating points depend on three variables -

temperature, pressure, and concentration – for the compressor elements and the LPSB. Also, the required mass flow will in turn impact these same variables.
The basic approach to establishing the parameters of the cooler is to use pre-existing data that is close to the two interface conditions and the applied heat load. A linear scaling is used, but the further from any tested case, the less accurate will be the predictions, and this will result in the need for more iterations to the cooler settings. For more details see "Planck Sorption Cooler Lifetime and Operations".

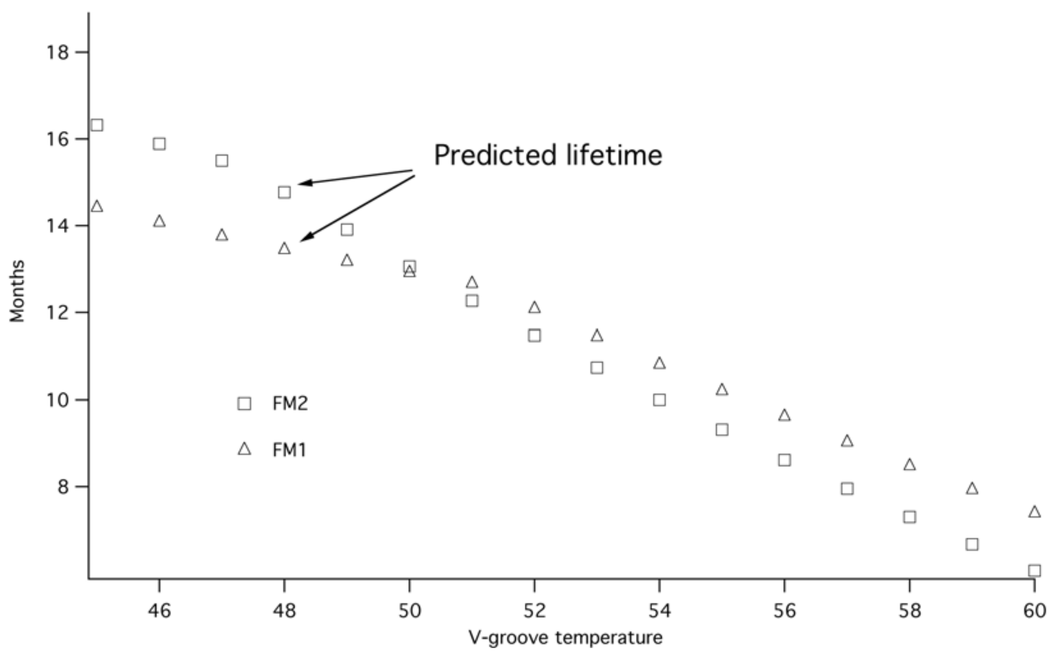

Figure 3 SCS Lifetime as a Function of V-groove 3 Temp for FM1 & FM2 Units

Notes:

Lifetime in months for the two Sorption Coolers is given as a function of third V-groove temperature for a heat load of 1060 mW. Prediction values of 13.5 and 15.5 months for FM1 and FM2 respectively are for a V-groove 3 at 47K. This temperature and the 1060 mW heat load are based on results from TB-TV tests in the summer of2008 at CSL.

During the CSL flight testing (FM2 testing), which provided a thermal environment very similar to flight conditions, the V-groove temperature was 47 K. The cycle-time used in for this testing was 940 s. This cycle-time was limited due to temperature fluctuations in the cold-end exceeding the requirements. The observed fluctuations were 550 mK while the requirement is 450mK. These excessive fluctuations were identified as being due to two-phase plug flow events at a frequency of about 20 s. It is expected that these will be absent in flight, in which case the cycle-time can be increased. Early instrument reports indicated that the measured high fluctuation levels would not impact instrument performance due to the high frequency of the two-phase flow events. However, a system level analysis of the impact of temperature fluctuations on the two instruments is important in maximising Sorption Cooler lifetime.

Instrument heat loads were estimated to be 670 mW from LFI, with a less than 30 mW contribution from HFI. The TSA power consumed was 200 mW, which exceeded the requirement of 150 mW. An additional 90 mW was allocated for parasitics and operations margin. There is a relatively large uncertainty in the estimated instrument loads, but the total number is consistent with the cooling power measurement performed during the PFM2 testing to a level of +/- 50 mW.
For the testing the warm radiator was 270 K resulting in a LVHX1 temperature of 17.1. The LFI interface temperature was 18.7 K. This temperature was the reason that the TSA power was 200 mW, 50 mW above the requirement. During the test campaign LFI requested that a constant temperature be used for all the testing. The higher set-point was established for non-equilibrium conditions and was maintained throughout the testing. Again a systems view is needed to see if additional lifetime of the Sorption Coolers can be obtained by lowering the set-point.

Finally, the input power used for the testing was 305 W. This is well below the requirement, and lifetime predictions show that input power will not be the limiting factor for a 47K V-groove temperature. What will limit the lifetime is the total number of cycles, and lifetime can only be influenced by an increase in the cycle-time or a decrease in the heat lift need by the instruments and the TSA. This results in a tradeoff between the level of temperature fluctuations at the cold end and lifetime.

The estimated lifetime of the two flight models is 15.5 months for FM2 and 13.5 for FM1 based on the PFM2 testing conditions (i.e. V-groove 3 temperature = 47 K, and total nominal heat load of 1060 mW) and assuming that the cycle-time can be increased due to the absence in flight of the two-phase flow events. These estimates have an uncertainty of order 0.5 month. The end of life temperature of the cooler cold end is expected to be higher by at most 0.5 K.

These estimates indicate that:

- FM2 or FM1 alone are not able to support the full nominal mission of 16.25 months.
- FM2 would be able to support the nominal mission (not including Commissioning but including CPV) with a 1.5 month margin.
- FM1 has a negative margin of 0.5 months to support the nominal mission not including Comm+CPV
- The total mission lifetime provided by both coolers is 29 months which allows to support the full nominal+extended missions with <1 month positive margin.

The process of regeneration may be implemented near end of life to increase the mission life, but further testing is needed to understand the regeneration of a highly degraded compressor element. Other mission scenarios for other v-groove 3 conditions have been considered. At 45 K FM2 is marginally able to support the nominal mission of 16.25 months. Above a 57 K pre-cooler the nominal mission cannot be supported even with 2 coolers.

2.4.2 PERFORMANCE & OPERATIONAL SCENARIOS

The Sorption Cooler System consists of two units, SCS-FM1 and SCS-FM2 The operational baseline is to use the ***Nominal Unit (FM2)*** for initial cooldown and continue operations with this until end-of-life.

SCS-FM1 Unit was used in CQM TB-TV test at CSL in 2006. SCS-FM2 Unit was used in PFM TB-TV test at CSL in 2008. The approach is to operate the Sorption Cooler such that science performance is maximised while meeting the lifetime requirements of the two coolers.

In orbit both units are required to match the lifetime of the dilution cooler (see 2.4.1). In addition, the goal is to switch from one cooler to the other only in between surveys. FM2 (the longest lived of the two coolers), is not able to support the sum of Comm+CPV and first two surveys, but it could however support the first two surveys alone. Finally, if one of the units was performing in flight less than expected, a little flexibility in stretching lifetime can be achieved by trading it off against temperature fluctuation level.
When the HFI reaches its lowest temperature of 100 mK, a detailed set of operational parameters for the two coolers will be chosen depending on their performance.
The main parameters to tune the Sorption Coolers are:

1) **Cycle Time**
2) **Input Power**

These are set initially at the end of Cool- down, as described later (in section 3.2) and in the SCS User Manual [AD-02]. As the hydride of the Sorption Cooler ages, it will be necessary to decrease the Cycle-Time and increase the Input Power to keep the cooler operating within temperature fluctuation and heat lift requirements. The input power adjustment consists of changing the heatup power, the desorption power, and less frequently, the LPSB power (the heatup power will typically be changed with the cycle-time to maintain the temperature fluctuation level, the desorption power will be changed to keep the cooling power constant, and the LPSB power will be used to keep the cold-end temperature constant.

These adjustments simply require an update of the Cycle Time and Input Power Parameters based on the monitoring of:

1) **LVHX1 & LVHX2 Temperature**
2) **LVHX1 & LVHX2 Temperature Fluctuations**
3) **High Pressure of the Cooler (heat lift)**

Specific update values will be hard to predict, so the current plan is to update these parameters weekly. Sorption cooler performance is highly non-linear, so if small changes are made, these changes are not expected to induce large effects on the LVHX1 & 2 temperature. Small and frequent temperature changes will not impact the science measurements greatly and eliminate the need for corrective actions . For details on the SCS operations, see Planck Sorption Cooler Lifetime and Operations [RD-1b].

The effect of these steps on the science is currently being analyzed by the DPCs, and will be used to assess the best Cycle Time update strategy. During the CPV phase a test will be performed to see the effect of cycle change on the science data in order to confirm this strategy. Since aging of the coolers will result in temperature changes with time in the absence of adjustments, the beneficial impact on Sorption Cooler lifetime from frequent Cycle Time adjustments is likely to be the decisive factor in the choice.

Further details on these adjustments can be found in the JPL document, "Planck Sorption Cooler Lifetime and Operations" [RD-1b].

2.5 4K Cooler Configuration for Routine Operations

A detailed description of setting parameters for the HFI coolers is given in the HFI Calibration Report [RD-1a]. The major elements are sketched below.

The 4 K cooler gas is pre-cooled at the LVHX1 heat exchanger with the Sorption Cooler. The LVHX1 temperature is thus one of the critical interfaces of the 4K cooler; it affects strongly the cooler performance and the heat load on the 4K box of the HFI FPU (the 4K cooler heat lift decreases with increasing LVHX1 temperature when the heat load on the 4K box increases).

The CSL FM1 tests have shown that the warm radiator of the Sorption Cooler had to be heated to stay above its minimum temperature of 262K.
The aging of the hydride performance of the Sorption Cooler implies that its power input has to be slowly increased (together with a decrease of the cycling period see section 2.2). The LVHX1 temperature is directly related to the low pressure, which itself is directly linked to the warm radiator temperature. Altogether the CSL FM1 test has shown that the temperature should increase by about 0.5K between beginning of life and end of life of the cooler. The temperature will always be below about 18 K. It should be remembered that the pre-cooling temperature is 0.35K above the temperature of LVHX1.
This gives the likely pre-cooling temperature range of 16.85 K to 17.5 K, with a worst case of 18.5 K.
The temperature of VG3 (provided by the payload passive cooling) strongly affects the Sorption Cooler performance, but has only a small effect on the 4K box heat load.

The 4K cold head pre-cools the 3He and 4He gas of the dilution cooler. The intermediate 1.6 K stage is cooled by a JT expansion of these outgoing gases and the dilution of the two isotopes provides cooling at 100mK after being precooled at the 1.6K stage..
The 1.6 K JT has gas flow impedance lower than optimal; however, it was decided not to change the JT after it was shown in calibration that the required performance was obtained even at the maximum pre-cooling temperature of 5K. Nevertheless, at a 5K precooling temperature the 1.6 K JT becomes marginal, requiring a higher 3He/4He flow rate than required by the dilution part. Thus the preferred 4K pre-cooling temperature is below 4.7K. This brings the 1.6-100 mK dilution cooler into the normal range, where the dilution sets the isotope flow requirement.

Finally, considering the problems encountered with the lead-in wires, an operating point using a reduced stroke for the compressors (7mm) is preferred to the maximum one (8.8mm).

2.5.1 ADJUSTABLE AND ENVIRONMENT PARAMETERS

The 4K cooler has 3 adjustable parameters:

- **Stroke Amplitude (Sa) of the Compressors** : a single command for both high pressure and low pressure compressors.
- **Compressor Frequency** : this can be chosen between 35 and 45 Hz in a list of frequencies depending on two parameters adjustable by telecommand NS (3 values) and fdiv. This fixes simultaneously the compressor frequency and the data sampling frequency as one of 3 harmonics of the 4K cooler frequency (4, 9/2, 5 for the three values of Ns) to allow efficient removal of any EMC effect on the data.
- **Filling Pressure** : this parameter is adjustable before flight. The filling pressure has been chosen to be 4.5 bars (see next section for the rationale for this choice)

There are 2 environmental parameters which affect the 4K cooler:

- **He Pre-cooling Temperature** provided by the Sorption Cooler. This temperature is at most 0.35 K higher than the LVHX1 cold head temperature, thus 16.85 (rounded conservatively to 17K in the discussions later) for a 16.5 K cold head possible at the beginning of life.
- **Base Plate Temperature** on which the compressors are mounted.

Finally the electrical power available is limited by the **Charge Regulator** which limits current peaks from the spacecraft power supply to the 4K CDE:

- "CCR in" parameter < 130 Watts.

2.5.2 STATIC PERFORMANCE REQUIREMENTS

The 4K cooler cools the HFI-FPU 4K box. The temperature of this box, and thus of the HFI feed horns, affects the thermal emission from the feed horns. The exact value of the temperature is not critical, as the HFI bolometer noise is dominated by the cosmological background photon noise and by the detector chain noise. The heat lift must be large enough to handle the heat load on the 4K box as predicted by the thermal model and tested on the CQM during the CSL-CQM test (depending mostly on the 18 K pre-cooling), with a 20% margin over the worst case. The FM 4K box was shown to have a heat load ~1.5 mW higher than the CQM measurements; This has been checked during the CSL FM2 tests.

2.5.3 STATIC PERFORMANCE OF THE FLIGHT CONFIGURATION

The cooler performance were found very close to the predictions based on the RAL and CSL-CQM tests (the present 4K cooler configuration is using the spare (CQM) compressors and the FM JT and cold pipes) as a function of relevant parameters given in the document "4K cooler performances evaluation following exchange of models.doc" prepared for the IFAR. The heat lift performance has been measured during the thermal balance test and has shown a 4.5 mW heat lift margin for 3.5 mm stroke amplitude. The heat lift is somewhat better than the predicted values.

The performances of the 4K FM cooler as measured in the TB-TV test at CSL are:

Heat lift = 18.3 mW+ 3.4 (Sa - 7.5mm) -1.1 (Tpc-17K) +0.6 (Filling pr - 4.5bars)
Heat load = 10.6 mW +0.5 (Tpc -17K) +0.065 (Tvg3 -45K) + Heaters
T = 4.47 K -0.12 (Sa -7.5mm) + 0.007 (Tpc -17K) -0.032 (Heat lift-Heat load)

2.5.4 SENSITIVITY TO EXTERNAL PARAMETERS

The sensitivity of the 4K cooler to heat loads measured on the FPU is 32 mK/mW.
The sensitivity of the cold tip temperature to the pre-cooling temperature (predicted by RAL to be 7mK/K) was measured at CSL to be 7+-1 mK/K.
The sensitivity of the 4K cooler to the compressor temperature is 5mK/K.

2.5.5 PROPOSED NOMINAL CONFIGURATION AND MARGINS

The 4K nominal configuration in flight is planned to be as follows:

- **Frequency : 40.08 Hz**
- **Stroke Amplitude : 7 mm**

With a pre-cooling temperature of 17.2 K and a heat lift of 16.4 mW, the resulting heat lift margin is 6 mW.

2.6 Dilution Cooler Configuration for Routine Operations

Ref : Cryogenic Tests Report, Jean Delmas, Philippe Camus, 21 October 2005 [RD-21]
Ref : Dilution Cooler Performances, Guy Guyot 2008 [RD-22]

2.6.1 1.6K JT PERFORMANCE AND STABILITY

With a high dilution isotopes mass flow, the 1.6K JT is performing very well (it can give a temperature as low as 1.25 K). As seen during the CSL test, the excess liquid helium generated when operating at high helium isotopes flow and low power on the 1.6K PID leads to liquid accumulation under gravity on the low part of the pipe between 1.6 and 4K. This results in unstable evaporation or two-phase flow/bubbling leading to out-of-specifications temperature fluctuations. Raising the temperature with the PID to at least 1.4 K(isotope flow Fmin) or 1.35 K (isotope flow Fmin2) led to the removal of this effect and to in-spec temperature fluctuations.

2.6.2 PERFORMANCE OF THE FLIGHT CONFIGURATION

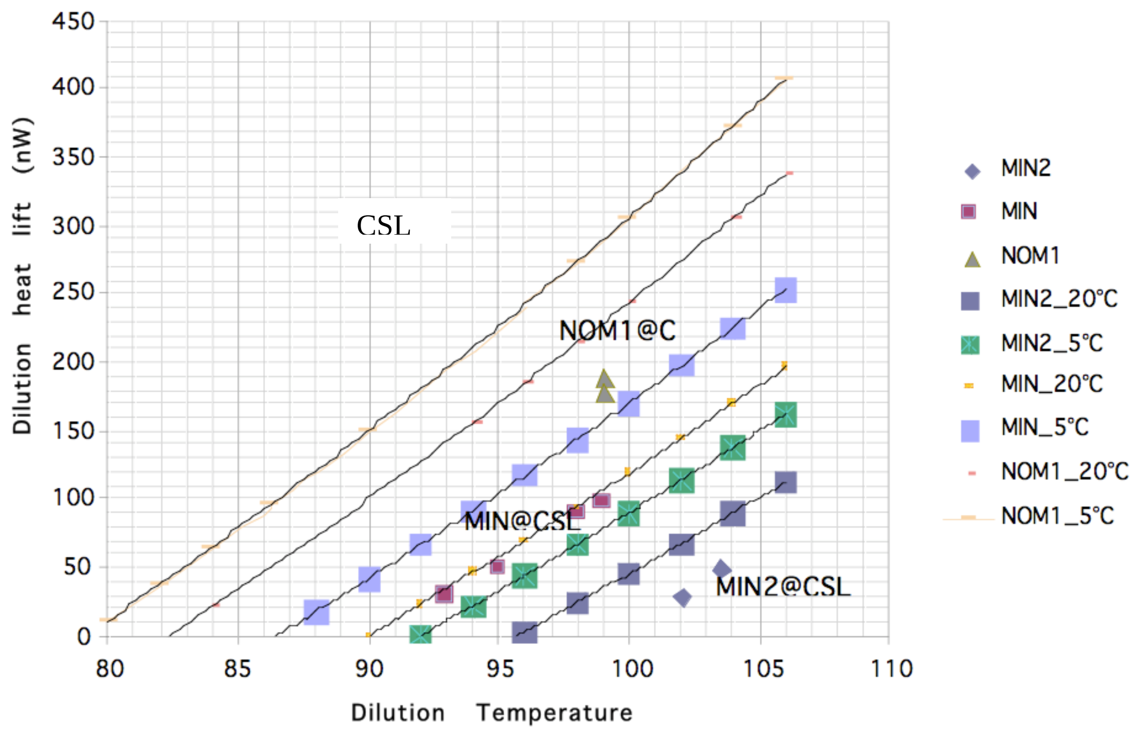

Figure 4: Plots of Available Cooling Power as a Function of Dilution Cold Head Temperature

Notes:

Given for increasing isotopes flow (and thus cooler power) order: Fmin2, Fmin, Fnom1), established following the TB-TV test, see RD-24.

Isotope flows with the Mu-Space pressure regulators are given in the following table.

Flows	flow 4He	Ftot (DN3+DN4)	flow 3He
	µmol/s	µmol/s	µmol/s
FMIN2	14,5	19,8	5,4
FMIN	16,6	22,9	6,3
FNOM1	20,3	27,8	7,5
FNOM2	22,6	30,8	8,2

Table 2 Isotope Flows with the Mu-Space Pressure Regulators

The parameters expected for the two lowest flows for temperatures and lifetime are given below. It shows that the nominal configuration is the Fmin2 if the cryo system behaves as expected.

Tprecool	4.6 K	4.6 K
He flow	Fmin2	Fmin
T dilu (PID1 80 nW, PID2 out)	98 mK	85 mK
Tdilu (PID1 80nW, PID2 on with ~40nW)	100 mK	87 mK
Life time (with full 3He tank)	32 months	28.5 months
Survey duration	30 months	26.5 months
Margin with respect to nominal	16 months	12.5 months

Table 3 Expected Parameters for Nominal Temperature and Lifetime

During the TB-TV test, the heat input on the bolometer plate from micro-vibration is about 3 times higher (36 nW instead of 10 nW) the heat input seen during the FM test in Saturne. The in flight one should be <1nW.

The results in Figure 4 can be fitted with linear dependencies to predict the performances in flight for the heat lift available for temperature regulation with respect to:

- the He isotopes flow restriction configuration for 273 K temperature of the DCCU,
- the temperature of the DCCU in flight
- the heat load from the bolometer plate (measured by the temperature difference between bolometer plate and dilution plate)

Heat Lift Margin (nW) =

$$3.2\ 10^{-3}\ \mathrm{HeFlow}(\mu\mathrm{moles/sec}) * T_{dil}^{2} * ((T_{DCCU}-273)/273)^{1.5}$$

-250 ($T_{JT1.6K}$ -1.28)	(heat load from 1.6K stage)
-20 (Tbolo-Tdilu)	(heat load from bolometer plate)
-487 nW	(parasitic heat load)

Taking the lowest flow restriction configuration: Fmin2 (18.8 µmole/sec at 273 K) and a DCCU temperature of 8°C (min is 5°C, in flight it is expected to be close to the min) gives 100mK with 30nW of heat lift and 34 months of operations

The stability provided by the PID1 (dilution) provides temperature fluctuations well within the requirement. The PID2 (bolometer plate) will not be used except as a back up of the dilution PID.

2.7 HFI FPU Overall Thermal Balance

Ref: HFI CQM CSL Cryotest Report February 20th 2006, Guyot et al [RD-23]

The overall thermal balance of the FPU was tested in the CSL CQM tests. A schematic of all the interfaces is shown in Figure 1.
Heat loads and sensitivity to environment from the different interfaces of the FPU are as follows:

- from HFI-LFI interface flange at 21.5 K: 6.5 mW
- from "18K" HFI plate at 18 K: 3.1 mW (pipes and He dilution, heat switch and harness)
- changes of heat load due to changes in the LFI temperature: 0.45 mW/K
- sensitivity of heat input to changes in the Sorption Cooler cold tips LVHX1 and LVHX2 temperatures: 0.6 mW/K
- total heat input on CQM FPU 4K box is given in Section 2.5.3
- gradient between feed horns and back of FPU 0.25 +-0.05 K
- dT between cold tip and back of the FPU 40 mK (conduction through sapphire interface 300 mW/K)

Time constants of the FPU:

- conduction PID to feed horns about 100 sec
- conduction feed horns to Cernox at back of the FPU 370 sec
- conduction feed horns to cold tip of 4K cooler 600 sec
- heating of FPU 2800 sec

Table 4 shows the heat load budgets on the Planck coolers.

SCS:	**Power:**
H Lift:	1100 mW
LVHX1 max H Load	30 mW
4K Cooler:	
H Lift (depending on settings)	16-18 mW
H Load Total	12-14 mW
H Load Radiative (50K + 18K)	1.5 mW
H Load 4-1	6.24 mW
H Load 18-1	0.5 mW
H Load 4-2+4-3+4-4	3.1 mW
H Load PID	1.8 mW
1.6K Stage:	
H Lift (depending on settings of the flow rate and 4K temperature)	200-300 μW
H Load 4K	
Dilution Cooler:	
Heat Lift (depending on settings of the flow rate and 0.1K temperature)	Typically 50 nW
Heat Load parasitic	487 nW
PIDs	
PID 4 K (Max heating power)	1.84 mW, ΔT=60mK
PID 1.6 K (Max heating power)	0.45 mW
PID1 (Max heating power)	11 μW

Table 4 Heat Load Budget between Planck Cryogenic Stages and Coolers

2.8 Summary of Cooler Parameters and Baseline Configuration

2.8.1 CRITICAL COOLING CHAIN INTERFACE PARAMETERS

The most critical parameters, as interfaces in the cryogenic chain are:

- T(VG3)
- T(WR)
- T(LVHX1)
- T(4K)

2.8.2 CRITICAL PARAMETERS FOR SCIENTIFIC PERFORMANCE

The parameters critical for the scientific performances are:

- Stability T(LVHX1)
- Stability T(4K)
- Stability T(100mk) – HFI bolometers plate

2.8.3 LIST OF COOLER PARAMETERS AND NOMINAL VALUES

The list of all the cooler adjustable parameters and their nominal values is reported in Table 5.

Cooler	**Parameter**	**Operating range**	**Nominal value**	
			BOL	**EOL**
Passive cooled	Warm radiator temperature T(WR)	260-280K	260K	
Sorption Cooler	Active Unit	FM2/FM1	FM2	
	Cycle Time	480-1200 s	~1000 s	
	Input Power	280-470W	300W	
	TSA power	<150mW	~200mW	
	TSA Set point	17-21.5K	18.7 K	
	LPSB (Low Pressure Storage Bed)	0-5W	~1W	
4K Cooler	Fill pressure		4.5bars	
	Compressor frequency	34-45Hz	40.08Hz	
	Compressor Stroke amplitude	0-8.8mm	7 mm	
	Charge Regulator Power		130W	
	VCS status	ON/OFF	ON	
	4K PID status	ON/OFF	ON	
	4K PID power	0-1.8 mW	1.0 mW	0.5 mW
Dilution Cooler	He-4 flow		17umole/s	
	He-3 flow		5.5umole/s	
	1.6K PID status	ON/OFF	ON	
	1.6K PID power		as needed to get 1.36K	
	Dilution plate PID status	ON/OFF	ON	
	Dilution Plate PID power		30 nW	

Cooler	**Parameter**	**Operating range**	**Nominal value**	
			BOL	**EOL**
	Bolometers plate PID status	ON/OFF	OFF	
	Bolometers plate PID power			

Table 5: List of Adjustable Cooler Parameters and Nominal Values

2.8.4 DEPENDENCIES BETWEEN COOLER PARAMETERS

Table 1 at the beginning of Chapter 2 summarises the dependencies between cooler parameters.

3 CRYOGENIC SYSTEM OPERATIONS

The document describes the timelines of the Cryogenic System operations performed in flight.
The phases of Planck operations in flight are described in the Planck Operations Scenario document [RD-3] and are: LEOP; Commissioning Phase (CP); Calibration and Performance Verification Phase (CPV); 1st survey; 2nd survey; and subsequent surveys. Cryogenic operations are in parallel with all the phases of the mission and determine the performance of the instruments and the lifetime of the mission.

- Section 3.1 describes the cool-down operations
- Section 3.2 describes the operations performed during the initial tuning phase
- Section 3.3 describes the operations and monitoring activities in routine phase.

Each phase of the Cryogenic Operations (cool-down, initial tuning, and routine maintenance) is described with a summary table (Table 6, Table 7 and Table 8) and the details of the operations are described in the subsections following each table.

3.1 First Cool-down

The Planck spacecraft will operate near the L2 point of the Sun-Earth system. Cruise and injection into this orbit are described in the CReMA [RD-2].

A new cruise strategy proposed in spring 2007 allows Planck to reach the L2 orbit in about 50 days, with full data rate available after day 25. The details of the trajectory and manoeuvre timing are strongly dependant on the launch date and exact time. Details are in [RD-17].

The high level description of the cool-down sequence is given in Table 6 and more detail is provided in the following subsections.

Notes:

This sequence is indicative only, and is meant to provide an overview of the planned cool-down sequence. The details are provided in the Commissioning Phase Operations Plan [RD-11] and associated Commissioning and CPV Timelines [RD-11, RD-10].

The sequence is keyed to providing intermediate stable 4K temperatures for LFI tuning steps during the initial cool-down (i.e. at 22K, 18K, 15K). A plot of this cool-down sequence is provided in Figure 5, which is taken from the HFI Thermal Model.

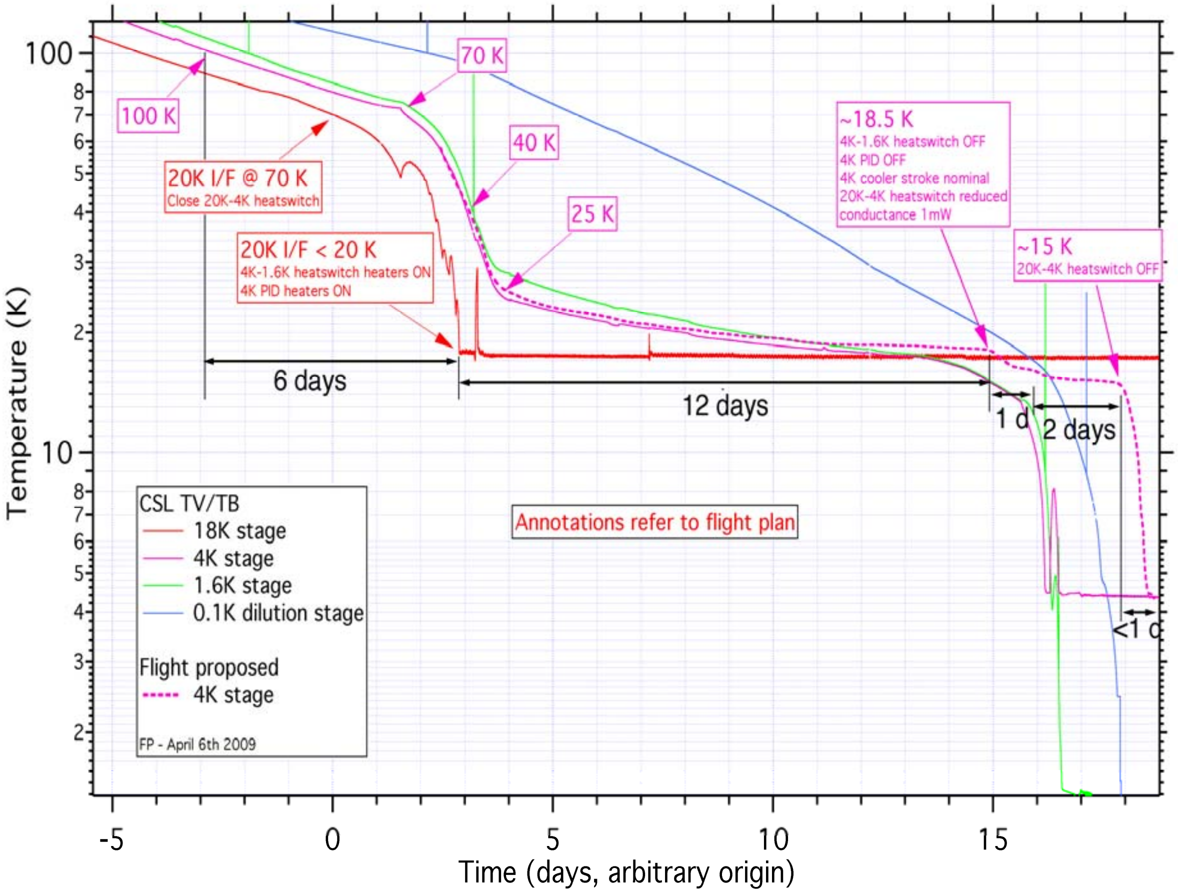

Figure 5 Cool-down Profile from HFI Thermal Model

HOLD POINTS

The cool-down happens in parallel with critical CPV tests, and with the transfer to L2, characterized by important orbit manoeuvres. To be able to perform sequences of CPV activities without interference by commissioning activities or orbit manoeuvres, a number of **hold points** have been defined.

The hold points are moments in which the cool-down can be interrupted before a critical part of the timeline is executed. For this reason, the ICWG has defined regions with sequences of CPV tests that can't be interrupted by orbit manoeuvres [RD-10], and hold points in the cool-down timeline have been set consequently.

Note:

Hold points require two decisions to be made: a decision to stop the normal sequence; and a decision to continue the normal sequence after a stop. The mechanism to make decisions is part of the Commissioning Phase Operations Plan and Planck SGS CPV Science Operation Plan [RD-11, RD-19].

ID	OD	Operation/Status	Condition
1.	1	Launch operations	
2.	1	Set Dilution cooler to a minimum flow-rate.	Within L+10 hours
3.	1	Set 4K cooler to 2mm amplitude	Within first day
4.	1-14	Telescope and FPU decontamination	Start within first day
5.	15-19	Passive cooling	Heaters OFF
6.	20+	HOLD POINT 1	Before turning ON SCS
7.	20	Turn ON SCS FM2 unit	Temp. FPU < 100K
8.	20	Set the WR temperature	SCS FM2 unit active
9.	26	Turn ON Heat Switch (18K-4K)	Temp. 4K stage = 70K
10.	26	Turn ON LFI FEM	Temp. 20K stage = 40K
11.	28	SCS cool-down completed (20K)	SCS in nominal operations
12.	28-30	SCS TSA tuning	SCS in nominal operations
13.	30	Turn ON Heat Switch (4K-1.6K) Nominal & Redundant Heaters, max power This operation has a negative impact on the cool-down when the 4K JT is above 10K, slows down the cooling rate and helps to stabilise the 4K cooler temperature **for the 1st and 2nd stages of LFI Matrix Tuning.**	Temp. 4K stage ~ 25K
14.	30	Turn on 4K PID Nominal and Redundant Heaters, max power This adds ~ 8 mW of power on the 4K stage and further delays the cooling rate of the 4K stage	4K-1.6K heat switch ON
15.	31-32	LFI Matrix Pre-tuning	Temp. 4K stage < 25K and slowly decreasing
16.	33-42	LFI Matrix Tuning Steps 1 & 2 at “plateau temperatures” of 22K and 18K	Temp. 4K stage ~ 22K and slowly decreasing
17.	42	Turn OFF Heat Switch (4K-1.6K) Nominal & Redundant Heaters	Temp. 4K stage = 20K, and LFI tuning at 22K and 18K completed
18.	42	Turn OFF 4K PID heaters	
19.	42	Set Heat Switch (18K-4K) with low power on charcoal pump for reduced conductance	
20.	42+	Step deleted (HOLD POINT 2 now after Step 21)	Before set-up for LFI Matrix Tuning Step 3.
21.	42	Set 4K cooler stroke amplitude to 90% (nominal stroke)	

ID	OD	Operation/Status	Condition
22a		HOLD POINT 2	
22.	42	Set Dilution cooler flowrates to slow cool-down values (FNOM1)	Temp. 1.6K < 20K Temp. 4K stage slowly decreasing
23.	43	Step deleted [Turn ON Heat Switch (18K-4K) with low power on charcoal pump for reduced conductance - this is now Step 19 since 18K-4K Heat Switch is left ON]	
24.	43-45	LFI Matrix Tuning Step 3 at “plateau temperature” of 15-16K	Temp. 4K stage ~ 15K
25.	45	Turn OFF Heat Switch (18K-4K)	
26.	46	4K Vibration Control System Setting	
27.	47	4K stage at temperature, first setting of 4K PID	Temp .4K stage < 4.7K
28.	48	1.6K stage at temperature, first setting of 1.6K PID	1.6K stage cold
29.	48	Set dilution cooler flows to fast cool-down values (FNOM2)	4K stage cold
30.	48-50	LFI Matrix Tuning Step 4	4K stage cold
31.	50	Dilution cooler cold end at 100mK	Temperature at 100mK
32.	50	Set dilution cooler flows to nominal values (Fmin2), first setting of dilution cooler PID	Tdilu < 100mK
33.	50+	SCS cooling power measurement (heat lift)	Can be done any time after cryo-chain is stable

Table 6: First Cool-down Sequence

The operational day at which each operation is estimated by a thermal model of the payload [RD-12]. In practice the operations will be executed by manual commands whenever the applicable conditions are reached. This timing has been confirmed in the TBTV test at CSL in Summer 2008, in which the pre-cooling loop had a very limited effect. The present HFI thermal model confirms this cool down sequence duration although the estimate is conservative at several points: turning the 4-1.6K switch only for one or two DTCPs for LFI calibration will shorten the cool down by at least one day. The 1.6K reaches its nominal temperature 6hours after the 4K reaches its own nominal temperature (one day assumed).

Figure 6, Figure 7 and Figure 8 show a typical cool-down profile, as measured during TB-TV test in CSL in Summer 2008.

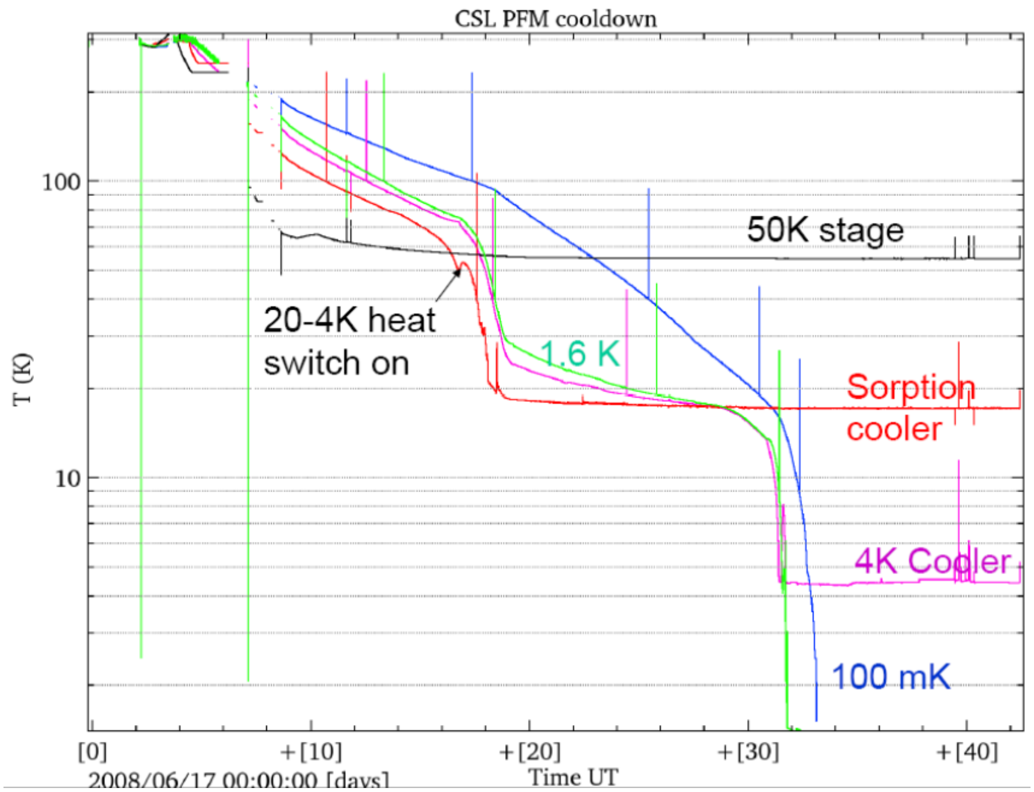

Figure 6: Cool-down Profile from TB-TV Tests at CSL in Summer 2008 (300K to 1.4K)

The cool-down profile does not take into account the 14 days of decontamination at 250K.

The cool-down profile does not take into account the 3 days in which LFI requires to have the reference loads at 22K for pre-tuning; nor the stable points for LFI tuning at 22K, 18K and 15K.

The cool down from 1.4K to 100 mK (see Figure 5) will be very similar to the one observed in the TB-TV tests when it lasted 2.5 days . It should also be noted that during all the operations the warm radiator will be kept in the required range of temperatures by means of heaters.

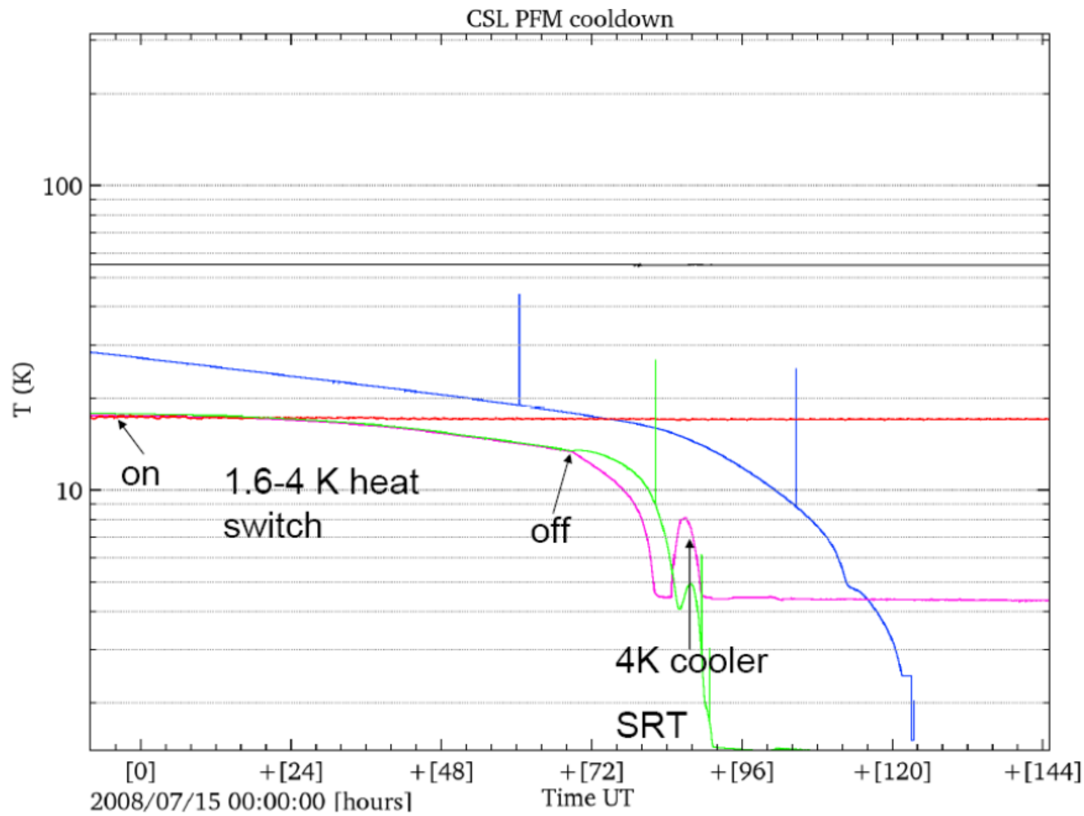

Figure 7: Cool-down Profile from TB-TV Tests at CSL in Summer 2008 (20K to 1.4K)

Notes:

Data extracted from RD-24.

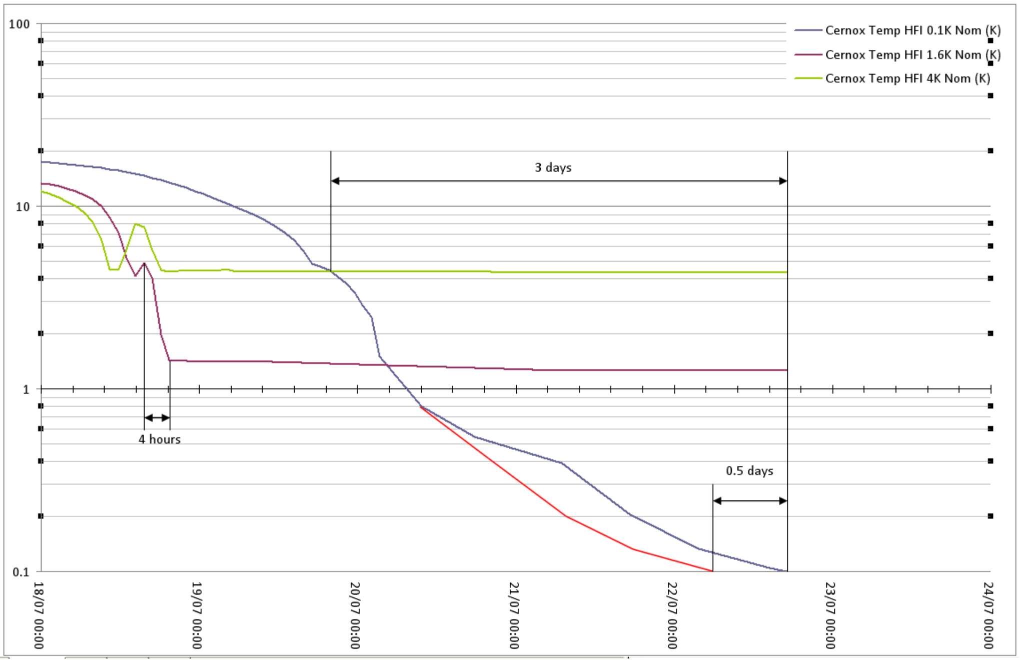

Figure 8: Cool-down Profile from TB-TV Tests at CSL in Summer 2008 (1.4K to 0.1K)

The operations are described in the following subsections referenced to the ID column in Table 6 and using tables with the following format:

Conditions to start	
Foreseen OD	
Duration	
Objectives	
Details	
Impact on system	
Extended DTCP	Required, Favourable, Not needed
Reference Docs	

3.1.1 LAUNCH OPERATIONS

Conditions to start	Countdown
Foreseen OD	1
Duration	
Objectives	Safety of the cryogenic system during launch and soon after
Details	Before launch, the 4K cooler unit is switched on, and remains powered in order to electromagnetically lock moving parts in the compressor [AD-03]. 4K cooler in Launch mode: 4K drive bus ON, 4K ELECTRONIC OFF. The dilution cooler cold end is mechanically connected to the 4K cooler stage by means of clamps that get passively disconnected by differential thermal contraction when they reach the temperature of 220K. During launch the dilution cooler flow-rate is zero (valves closed).
Impact on system	None
Extended DTCP	N/A
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.2 SET DILUTION COOLER TO MINIMUM FLOW RATE

Conditions to start	Within 2 hours after launch
Foreseen OD	1
Duration	
Objectives	Open Dilution Cooler input and exhaust valves.
Details	HFI must be turned ON for a short time during which the Dilution Cooler mixture and HP valves must be opened by ground command: - OPEN MIXTURE NOMINAL VALVE FV301 (venting) - OPEN MIXTURE REDUNDANT VALVE FV351 (venting) - OPEN 4He NOMINAL HP VALVE HPLV101 (input) - OPEN 3He NOMINAL HP VALVE HPLV201 (input) In this stage, with the JT system at high temperature, the Helium isotopes flow-rate is limited by the viscosity of the gas to a very low value, less than about 1.5μmole/s. The gas is going through flow restrictors FR101 and FR202.
Impact on system	The Helium isotopes flow starts here
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.3 SET 4K COOLER TO 2MM AMPLITUDE

Conditions to start	Within 2 hours after launch
Foreseen OD	1
Duration	
Objectives	This is to clean up the gas in the pipe system of the 4K cooler
Details	Within 2 hours after launch, the 4K cooler must be set to 2mm stroke amplitude with the getter on, as described in the HFI User Manual.
Impact on system	None
Extended DTCP	Not needed
Reference Docs	HFI User Manual HFI Commissioning Plan [RD-14]

3.1.4 TELESCOPE AND FPU DECONTAMINATION

Conditions to start	During LEOP
Foreseen OD	1-14
Duration	14 days
Objectives	To prevent pollution of the reflectors and the FPU during the initial out-gassing phase of the SVM
Details	Heaters are placed in the primary reflector, in the secondary reflector, in the HFI-FPU and in the LFI-FPU. These heaters are activated for 14 days after launch, and keep the units at a temperature above 250K.
Impact on system	Active cool-down is inhibited until the end of this decontamination process.
Extended DTCP	Not needed
Reference Docs	H/P Satellite Users Manual Ch. 5 [AD-4].

3.1.5 PASSIVE COOLING

Conditions to start	End of decontamination, heaters OFF
Foreseen OD	15-19
Duration	The full passive cooling is a long process that takes several days to complete. It is expected from modelling that the fraction of passive cooling that is needed before the activation of the Sorption Cooler takes 5 days
Objectives	Passively cool-down the reflectors, the FPUs
Details	
Impact on system	The SCS can't be activated before the LFI FPU has reached 100K
Extended DTCP	Not needed
Reference Docs	Thales Thermal Model Simulations [RD-12] CSL TB/TV Test Results [RD-24]

3.1.6 HOLD POINT 1

Conditions to start	Before activation of the Sorption Cooler System
Foreseen OD	20
Duration	Unknown
Objectives	This hold point can be used to ensure that the operational conditions are satisfactory for the continuation of the cool-down and CPV phase activities to be performed during the cool-down between 100K and 20K.
Details	• This hold point can be released as soon as the S/C condition is such that the correct data-rate is available for the cool-down upcoming CPV activities • the correct solar aspect angle for is achieved for instruments cool-down • commissioning phase activities pre-cool-down have been completed
Impact on system	The active cool-down is on hold. Passive cool-down progresses independently
Extended DTCP	Not needed
Reference Docs	Commissioning Phase Operations Plan & Timeline [RD-11]

3.1.7 TURN ON SCS FM2 UNIT

Conditions to start	Temperature of LFI FPU less than 100K
Foreseen OD	20
Duration	2 hrs
Objectives	• Start the Active cool-down • Commission SCS FM2 Unit • Provide a measurements of the SCS-FM2 performance • FM2 will be used for the entire CPV phase.
Details	FM2 is started and ran until both instruments are ready for observations.
Impact on system	Start of the cool-down.
Extended DTCP	Not needed
Reference Docs	SCS User Manual [AD-02]

3.1.8 SET THE WR TEMPERATURE

Conditions to start	SCS-FM2 Unit active.
Foreseen OD	20
Duration	TBC
Objectives	Set the temperature of the Warm Radiator to lowest possible temperature compatible with requirements and passive cooling conditions.as written in Section 2.3.
Details	See S/C User Manual.
Impact on system	This has an impact into the Temperature of LVXH1 & 2; the 4K cooler efficiency; 4K cooler heat load
Extended DTCP	Not needed
Reference Docs	Herschel/Planck Satellite User Manual [AD-04]

3.1.9 TURN ON HEAT SWITCH (18K-4K)

Conditions to start	Temperature of 4K cold end reaches 70K
Foreseen OD	26
Duration	From PFM-2 test the duration was 8.3 days.
Objectives	Accelerate 4K stage cool-down.
Details	The Heat Switch (20K-4K) connects the 20K stage to the 4K stage. It works in a passive way when the temperature of the 4K stage is above 70K, but must be actively powered below this limit and switched OFF at 20K.
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.10 TURN ON LFI FEM

Conditions to start	LFI FPU at 40K
Foreseen OD	26
Duration	3 x DTCP (all activities in visibility)
Objectives	To activate the 11 LFI Front End Modules
Details	When the temperature of the SCS cold end reaches 40K, the 11 LFI Front End Modules are turned ON in sequence. This is reported here since the FEMs are the major source of heat load on the SCS, and this operation can affect the cool-down timing.
Impact on system	This increases the heat load on the SCS
Extended DTCP	Not needed
Reference Docs	LFI User Manual [AD-1] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

3.1.11 SCS COOL-DOWN COMPLETE

Conditions to start	SCS operating in the nominal operational temperature.
Foreseen OD	28
Duration	About 8 days after SCS-FM2 start-up
Objectives	Achieve SCS nominal operation
Details	This is achieved when the SCS enters nominal operations mode: Nominal temperatures for the two LVHXs are from 16.7 to 19.0 K. Pressures 48 to 30 Bar. As soon as the cooler is in nominal ops the cold end temperature reaches the value set by the boundary conditions. At this stage the SCS parameters (Input Power, Cycle Time) will be set according to ground based tests, 1) Calculate input power levels and cycle-time based on V-groove 3

	and warm radiator temperatures along with the heat lift measurements performed during thermal vacuum testing. 2) Input these values into cooler look-up table (LUT). 3) Start the cooler into nominal operations and verify that the input power is correct After TSA tuning and Heat Lift measurements these parameters will be updated.
Impact on system	LFI can start major CPV activities once the SCS reaches nominal operating temperature.
Extended DTCP	Not needed
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations Document [RD-1b]

3.1.12 SCS TSA TUNING

Conditions to start	SCS operating in the nominal operational temperature.
Foreseen OD	28-30
Duration	29 hours (one 5 hours DTCP, plus 19 hours outside DTCP, plus a second 5 hours DTCP, plus 1 hour in the next DTCP).
Objectives	Thermally stabilise the SCS interface to the LFI FPU, in order to allow LFI CPV tuning activities. The tuning is a trade-off between thermal stability and extra heat load on the cooler. The LFI requirement is a stability with peak-to-peak fluctuation of less that 100mK.
Details	The final TSA tuning will be executed when the full Cryogenic System enters in nominal operations, with nominal load from the instruments and stable boundary conditions. A preliminary TSA tuning is performed at this stage, to stabilize the SCS and operate it in a configuration similar to the nominal one. Note that, according to the model, at OD 28 the 4K cooler JT will not be at 20K yet. Its temperature will be drifting. Preliminary tuning can be done at this stage, such as setting the gains, but the final set-point can only be found after the HFI heat load onto the LVHX1 is within 25 mW of the steady state.
Impact on system	This will thermally stabilize the LFI FPU, allowing for continuation of LFI CPV activities. This will increase the heat load on the SCS.
Extended DTCP	Not needed
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations Document [RD-1b]

3.1.13 TURN ON HEAT SWITCH HEATERS (4K-1.6K) - MAX POWER

Conditions to start	Temperature of the 4K stage ~ 25K
Foreseen OD	30
Duration	
Objectives	Delay the 4K cooling rate to allow LFI Pre-tuning and LFI Tuning Stage 1 & Stage 2 at 22K & 18K
Details	The Heat Switch (4K-1.6K) connects the 4K stage to the 1.6K stage. It works in a passive way when the temperature of the 4K stage is above 20K, but must be actively powered below this limit and switched OFF at 5.2K. The activation of this heat switch (nominal and redundant heaters at maximum power) increases the power load into the 4K cooler and has a negative impact on the cooling power.
Impact on system	Slows down the 4K cool down when operated above 10K.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.14 TURN ON 4K PID HEATERS - MAX POWER

Conditions to start	Temperature of the 4K stage ~ 25K 4K-1.6K Heat Switch ON
Foreseen OD	30
Duration	
Objectives	Delay the 4K cooling rate to allow LFI Pre-tuning and LFI Tuning Stage 1 & Stage 2 at 22K & 18K
Details	The activation of the 4K PID at this point (nominal and redundant heaters at maximum power) further delays the 4K cool-down profile by injecting ~ 8mW on the 4K stage
Impact on system	Slows down the 4K cool down
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.15 LFI MATRIX PRE-TUNING

Conditions to start	Temperature of the 4K stage ~ 25K and slowly decreasing 4K-1.6K Heat Switch and 4K PID ON at maximum power
Foreseen OD	31-32
Duration	2 days max
Objectives	Perform LFI Matrix Pre-tuning ready for LFI Tuning Steps 1 & 2 at ~22K & 18K

Details	
Impact on system	
Extended DTCP	Favourable if needed
Reference Docs	LFI User Manual [AD-01] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

3.1.16 LFI MATRIX TUNING STEPS 1 & 2

Conditions to start	Temperature of the 4K stage ~ 22K and stable LFI Pre-tuning completed
Foreseen OD	33-42
Duration	10 days max
Objectives	Perform LFI Matrix Tuning Steps 1 & 2 at ~22K & 18K
Details	
Impact on system	
Extended DTCP	Favourable if needed
Reference Docs	LFI User Manual [AD-01] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

3.1.17 TURN OFF HEAT SWITCH HEATERS (4K-1.6K)

Conditions to start	Temperature of 4K stage ~ 20K LFI Tuning Steps 1 & 2 completed
Foreseen OD	42
Duration	
Objectives	Readiness for 4K cool-down to 15K for LFI Tuning Step 3
Details	
Impact on system	Allows 4K cool-down
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.18 TURN OFF 4K PID HEATERS

Conditions to start	Temperature of 4K stage ~ 20K LFI Tuning Steps 1 & 2 completed
Foreseen OD	42
Duration	
Objectives	Readiness for 4K cool-down to 15K for LFI Tuning Step 3
Details	
Impact on system	Allows 4K cool-down

Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.19 SET HEAT SWITCH (18K-4K) - LOW POWER

Conditions to start	Temperature of the 4K stage ~ 20K
Foreseen OD	42
Duration	
Objectives	Allow 4K cooler cooling below ~20K
Details	When the 4K stage reaches a temperature of ~ 20K, the 18K-4K heat switch is set with low power on the charcoal pump to reduce conductance of the heat switch gas gap. This slows down the 4K stage cooling which stabilises after ~3 days to allow LFI Tuning Step 3 at 15K
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.20 STEP DELETED (WAS HOLD POINT 2)

Conditions to start	LFI Tuning Steps 1 & 2 completed. Hold before the activation of the final 4K cool-down, obtained by setting the 4K cooler stroke amplitude at 90%.
Foreseen OD	42
Duration	This hold point can be released as soon as LFI tuning objectives are met
Objectives	
Details	Before starting further cool-down of the 4K stage, a hold point is needed to ensure that LFI have completed Tuning Steps 1 & 2
Impact on system	
Extended DTCP	Not needed
Reference Docs	Commissioning Phase Operations Plan & Timeline [RD-11]

3.1.21 SET 4K COOLER TO NOMINAL AMPLITUDE

Conditions to start	From the cooler point of view this operation can be performed as soon as the SCS cold end goes below the temperature of 30K. In practice, due to the LFI Tuning activities, this operation is delayed until Hold-Point 2 is released.
Foreseen OD	42
Duration	
Objectives	To continue cool-down of the 4K cooler below ~ 18K
Details	When SCS cold end temperature is less than 30K, the amplitude of the 4K

	Cooler compressor can be increased to 3.5mm. Since LFI has two tuning steps at 22K & 18K, it is required to wait until the completion of these activities.
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.21a HOLD POINT 2

Conditions to start	LFI Tuning Steps 1 & 2 completed. Hold before the activation of the final 4K cool-down, obtained by setting the 4K cooler stroke amplitude at 90%.
Foreseen OD	42
Duration	This hold point can be released as soon as LFI tuning objectives are met
Objectives	
Details	Before starting further cool-down of the 4K stage, a hold point is needed to ensure that LFI have completed Tuning Steps 1 & 2
Impact on system	
Extended DTCP	Not needed
Reference Docs	Commissioning Phase Operations Plan & Timeline [RD-11]

3.1.22 SET DILUTION COOLER FLOW RATES TO SLOW COOL-DOWN VALUES

Conditions to start	Temperature of the 1.6K stage below 20K Temperature of the 4K stage slowly decreasing
Foreseen OD	42
Duration	
Objectives	To run the dilution cooler with the correct flow-rate
Details	When the temperature of the 1.6K stage goes below 20K, the flow-rates of the isotopes in the dilution cooler are driven by the values set by the DCCU. The current plan is to set the flow control valves to the FNOM1 setting at this point to slow down the 4K cool-down and allow LFI Tuning Step 3
Impact on system	Slows the 0.1K cool down
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.23 STEP DELETED

3.1.24 LFI MATRIX TUNING STEP 3

Conditions to start	Temperature of the 4K stage ~ 15K and stable LFI Tuning Steps 1 & 2 completed
Foreseen OD	43-45
Duration	2 days max
Objectives	Perform LFI Matrix Tuning Step 3 at ~16K
Details	
Impact on system	
Extended DTCP	Favourable if needed
Reference Docs	LFI User Manual [AD-01] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

3.1.25 TURN OFF HEAT SWITCH (18K-4K)

Conditions to start	Temperature of 4K stage ~ 15K and slowly decreasing LFI Tuning Step 3 completed
Foreseen OD	45
Duration	
Objectives	Allow 4K cooler cooling below ~15K
Details	4K stage cold in ~ 1 day
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.26 4K STAGE AT NOMINAL TEMPERATURE

Conditions to start	This is a status. The condition is to have the 4K JT cold. The optimal performance requires a temperature below 4.7K
Foreseen OD	46
Duration	
Objectives	It is a status
Details	At this stage a first tuning of the 4K PID is performed, in order to provide to LFI a stable cold load reference [RD-06]
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.27 4K VCS ADJUSTMENT

Conditions to start	4K stage at temperature, first setting of 4K PID completed
Foreseen OD	47
Duration	
Objectives	Vibration Control System Setting. This implies an SRT (injection of a perturbation on one harmonics of the compressor profile) and the calculation of the new profile to reduce the vibrations, then iterate until level of vibration is in the noise.
Details	Details are given in the HFI user manual. This activity is here only for reference
Impact on system	If not properly optimised, microphonics lines might appear in the data. If this happens the parameters will be reoptimised.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.28 1.6K STAGE AT NOMINAL TEMPERATURE

Conditions to start	This is a status. The condition is to have the 1.6 JT cold, with a temperature below 1.6K.
Foreseen OD	48
Duration	
Objectives	It is a status
Details	The lowest temperature is not necessarily the best one. The instable liquid Helium evaporation observed in TB-TV test showed that the temperature needs to be above 1.35K for Fmin2 dilution flow. If the unstable evaporation appears in flight (zero G might avoid it) the 1.6K pid shoud be used to bring this temperature high enough to suppress it. This is not the 1.6 PID tuning
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.29 SET DILUTION COOLER FLOW RATES TO FAST COOL-DOWN VALUES

Conditions to start	4K stage cold
Foreseen OD	48
Duration	
Objectives	To run the dilution cooler with high flow-rate to speed up final cool-down
Details	When the temperature of the 1.6K stage goes below 20K, the flow-rates of the isotopes in the Dilution Cooler are driven by the values set by the

	DCCU. The current plan is to set the flow control valves to the FNOM2 setting to speed-up the cool-down.
Impact on system	Accelerate the 0.1K cool down
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.30 LFI MATRIX TUNING STEP 4

Conditions to start	Temperature of the 4K stage cold LFI Tuning Step 3 completed
Foreseen OD	48-50
Duration	2 days max
Objectives	Perform LFI Matrix Tuning Step 4 at 4K
Details	
Impact on system	
Extended DTCP	Favourable if needed
Reference Docs	LFI User Manual [AD-01] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

3.1.31 DILUTION COOLER COLD END AT 100 MK

Conditions to start	This is a status. The condition is to have the dilution plate below 100mK
Foreseen OD	50 (it is expected to be 2-3 days after 1.6K at temperature [RD-16]
Duration	
Objectives	It is a status. After this is measured, the dilution flows can be set to the nominal predicted in-flight values
Details	
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI CQM CSL Cryotest Report [RD-16] HFI Commissioning Plan [RD-14]

3.1.32 SET DILUTION COOLER FLOWS TO NOMINAL VALUES

Conditions to start	Dilution and bolometer plate 100mK
Foreseen OD	50
Duration	
Objectives	To set the flow-rates to nominal values. Fmin2
Details	During the cool-down from 1.6K stage cold, the dilution flows were set to FNOM2 values to speed up final cool-down. When the dilution and the bolometer plate reach 100mK the flows can be set to their nominal values:

	Fmin2: 14.5µmoles/s of He-4 and 5.4µmoles/s of He-3
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.1.33 SCS COOLING POWER MEASUREMENT

Conditions to start	4K cooler at temperature Instruments running nominally (full Sorption Cooler loads) Sorption cooler is tuned to 100 mW greater than balance with the TSA controlling temperature
Foreseen OD	50
Duration	6 hours
Objectives	To measure the cooling power of the SCS
Details	Test: 1. Switch off TSA to measure LFI load on LVHX2 (TBC) 2. Switch TSA on again and change TSA set-point, TTSA, to increase the heat load to the Sorption Cooler. Approximately 200 mK is 100 mW. 3. Use the measurement of the TSA heater circuit current, ITSA, and the TSA heater resistance, ~480 ohm, to check the transfer function between TTSA and the heat load applied to the Sorption Cooler. 4. If dry-out of LVHX2 is observed before LVHX2 T stabilises (usually takes about 30 min), then cooling power produced is confirmed. End of test. 5. If no dry-out is noticed then increase TSA set-point by 100mK (that is about 50mW) and wait for the liquid to evaporate. 6. Follow this procedure until LVHX2 dry-out is observed (few steps are needed). End of test.
Impact on system	Measurement will change temperature changes at the instrument interfaces that will be unstable for the duration of the test.
Extended DTCP	Yes (6 hours requested)
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations Document [RD-1b]

3.2 Initial Tuning of the Cryogenic System

Optimal tuning of the Planck Cryogenic System is a complex process in which several elements need to be taken into consideration. The performance of the instruments is linked to the temperature values, temperature stability, and lifetime of the system. Not only the lifetime per se, but also the ability to complete a number of surveys without gaps induced by cryogenic operations is a crucial element in optimizing the mission return. The best tuning will be a trade-off of those elements, with the goal of maximizing mission performance, by means of:

- Maximising lifetime;
- Minimising thermal fluctuations;
- Maintaining long-term stability;
- Completing surveys.

During the cool-down the system will be set as soon as each of the coolers reaches its working condition as defined in the commissioning activities plan [RD-11]. But only at the end of the cool-down, and when also the instruments are turned on and working in a stable configuration, it will be possible to tune the full cryogenic system in a rather final configuration.
This tuning will progress in parallel with the Calibration and Performance Verification phase, and in fact will be part of it. The sequence of tuning operation is described in Table 7 and in the following subsections, and is reported in the CPV Detailed Timeline [RD-10].
The initial tuning is extremely critical, because in the few days in which it is performed it must be up the knowledge of the cryogenic system in-flight conditions, such to tune it in a way that remains valid for the longer possible period, possibly one full survey or more. Any change during a survey may result in a degradation of the scientific return, due to a discontinuity in the operational condition of the instruments. For this reason, new setting and tuning (apart from the foreseen routine cooler operations) in routine phase must be motivated by a significant improvement in overall performance, to be trade-off with the thermal discontinuity given by the change itself. The only degradation of the cryogenic chain with life time known today is the aging of the hydride of the Sorption Cooler. It will lead to a 0.5 K increase in the pre-cooling temperature of the 4K cooler leading in turn to a 0.75 mW loss in heat lift. We thus must start with a 4K PID power of 1.4 mW leading to 0.65 mW at the end of life of the Sorption Cooler.

ID	Operation	Condition
1.	WR Temperature Adjustment	After Cool-down completed, SCS-FM2 Unit active
2.	SCS Cycle Time and Input Power setting	After Cool-down completed, SCS-FM2 Unit active; WR temperature set.
3.	TSA Tuning after Initial Cool-down	After setting of SCS cycle time and input power. It takes 29 hours
4.	SCS-FM2 Heat-Lift Measurement	After TSA tuned

ID	Operation	Condition
5.	4K Frequency Tuning (**Optional**) To be done only if microphonics lines are seen after SRT/VCS is done, which appears unlikely, given that nothing was seen in TB-TV test	After SCS tuning with bolometers at 100 mK: goal is to minimise noise features in the noise spectra. Takes 2 days and 5 hours.
6.	4K PID Set-up	After 4K frequency set up
7.	4K Stroke Setting (**Optional**). The nominal value obtained in TB-TV tests will be put on and the margin expected (not large) will be tested with the PID	After FPU thermal balance, goal is to get >2mW margin at b.o.l of Sorption Cooler
8.	4K PID Fine Tuning (**Optional**)	4K stroke set; goal is to have PID power ~1.4 mW
9.	1.6K PID Set-up	After dilution flow set-up during commissioning
10.	Dilution Cooler Flow Optimisation (**Optional**) The lowest value Fmin2 will be set and the performances will be compared with the TB-TV ones, if acceptable it will be kept	After 4K stable. Goal minimum flow compatible with Tbolo<105 mK
11.	Dilution Cooler Plate PID setup	After dilution tuning
12.	Bolometer Plate PID Set-up	After dilution plate tuning. Goal is check the parameters. Then baseline is to put this PID OFF
13.	1.6K PID Set-up (**Optional**)	Dilution nominal flows being set
14.	100mK Dilution PIDs Adjustment (**Optional**) It is unlikely that the 1.6K PID will influence the dilution PID set up.	1.6K PID set. The PID is set to a minimum with enough margin so the power stays in the range 30-50 nW
15.	Iteration of Cryogenic System Settings (if needed)	After the system is set
16.	Change of SCS Cycle Time At pre-determined times: one month after previous setting and after 1 month + 1 week.	One month after previous setting

Table 7: Tuning and Optimisation in CPV Phase

3.2.1 WARM RADIATOR TEMPERATURE ADJUSTMENT

Conditions to start	After cool-down completed; SCS-FM2 Unit active.
Duration	TBC
Objectives	The goal is to operate the cryo chain with the minimum temperature compatible with requirements, passive cooling conditions and cryo chain operations. If the initial set up satisty this condition no action is needed. If it is not a reduction of the WR heaters power will be required.
Details	Procedure in the S/C user manual.
Impact on system	This has an impact into the Temperature of LVXH1 & 2; the 4K cooler efficiency; 4K cooler heat load
Extended DTCP	[TBC]
Reference Docs	Herschel/Planck Satellite User Manual [AD-04]

3.2.2 SCS CYCLE TIME AND INPUT POWER SETTING

Conditions to start	After cool-down completed; SCS-FM2 Unit active; WR temperature set.
Duration	This is a setting operation, done in real time, during DTCP
Objectives	Set the SCS to minimise the intrinsic fluctuation level in LVHX2. Define the best SCS operation strategy to put the system in the condition to complete two surveys with the FM2 Unit, before switch over.
Details	The tuning of the SCS Cycle Time and Input Power is a periodical operation. In particular the Cycle Time update has a crucial impact on the lifetime of the mission. A frequent update of the Cycle Time results in a longer lifetime. As a drawback, the changes generate temperature steps in the Sorption Cooler Cold end. The impact on science data of these changes must be evaluated during CPV phase to confirm or update the baseline assumption of a weekly update. For this reason, it is planned to set the SCS Cycle Time at the end of the cool-down, and to keep it fixed for about one month, until the First Light CPV test, which consists of two weeks of nominal survey. We will then update the Cycle Time in the middle of the First Light Test, and before the end of it. It is important to note that the Input Power parameter will be set weekly in any case. The housekeeping information needed to set these parameters is: - the temperature data of the HFI and LFI side of interfaces; - Warm radiator and V-groove3 temperatures; - Measured heat lift As discussed in the cool-down section, the initial values of Input Power and

	Cycle Time will be derived from on ground measurements V-groove 3 temperature, warm radiator temperature and heat lift measurements. At this stage the values can be updated using in-flight measurements. The evolution of these parameters is then derived from housekeeping trend. It is envisaged that some historical data is needed before the correct trend is identified. Before the construction of this historical data, ground based measurements and models will be used to predict the evolution.
Impact on system	Cooler tuning establishes the best SCS parameters for performance and lifetime optimisation. No impact on instrument activities.
Extended DTCP	Not needed
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations Document [RD-1b]

3.2.3 TSA TUNING AFTER INITIAL COOL-DOWN

Conditions to start	After SCS cycle time and input power set
Duration	This operation takes two consecutive DTCP, and the time in between. Total time is 29 hours. So 5 hours DTCP, 19 hours no DTCP, 5 hours DTCP.
Objectives	Minimise thermal fluctuations for LFI Focal Plane to below 100mK p-p. Constraints: LVHX2 temperature, power needed by TSA, …
Details	At the end of the cool-down, after activation of the SCS-FM2 Unit and setting of the Cycle Time and Input Power parameters, a second instance of TSA tuning is needed, in order to adjust the system after it reaches stability. In this operation, we will start from CSL parameters. CSL parameters can be overestimated for flight condition. The set point can be better optimised. We want to keep the same setting for the survey.
Impact on system	The TSA applies a power that can be up to 150mW at the LFI interface. The real value is expected to be much smaller than that and to impact only LFI; It is more important to keep the fluctuations in the requirements than minimise absolute temperature; The 4K PID system is effective in damping the fluctuations of the 4K reference loads of the 70 GHz LFI channels
Extended DTCP	Not needed
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.2.4 SCS-FM2 HEAT-LIFT MEASUREMENT

Conditions to start	TSA tuned SCS-FM2 Unit Active
Duration	6 hours
Objectives	To measure the cooling power of the SCS in nominal configuration
Details	Test: 1. Switch off TSA to measure LFI load on LVHX2 (TBC) 2. Switch TSA on again and change TSA set-point, TTSA, to increase the heat load to the Sorption Cooler. Approximately 200 mK is 100 mW. 3. Use the measurement of the TSA heater circuit current, ITSA, and the TSA heater resistance, ~480 ohm, to check the transfer function between TTSA and the heat load applied to the Sorption Cooler. 4. If dry-out of LVHX2 (dryout will be observed by the rise of LVHX2 relative to LVHX1) is observed before LVHX2 T stabilizes (usually takes about 30 min), then cooling power produced is confirmed. End of test. 5. If no dry-out is noticed then increase TSA set-point by 100mK (that is about 50mW) and wait for the liquid to evaporate. 6. Follow this procedure until LVHX2 dry-out is observed (few steps are needed). End of test.
Impact on system	None, except thermal fluctuations during the test
Extended DTCP	Yes (6 hrs requested)
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.2.5 4K FREQUENCY TUNING (OPTIONAL)

Conditions to start	SCS and TSA must be set
Duration	The required test takes 3 consecutive DTCP and no antenna coverage is required for the intermediate times
Objectives	The frequency has very little impact on the heat lift or the temperature. The only reason to go to frequency different from the nominal 40.08Hz frequency is to minimise an unexpected excitation of mechanical resonances in the spacecraft or the instrument which would generate microphonics lines in the detector spectrum after VCS activation.
Details	The frequency of work of the 4K cooler is directly related to the HFI modulation frequency (Fmod). No microphonics effect has been seen during TB-TV tests, thus this not likely to lead to the need to explore beyond the nominal frequency (40.08 Hz). Induced EMI-EMC effects have been shown to be removed very efficiently when the 4K and sampling frequencies are locked. A small range of frequencies around the nominal 40.08 Hz one (maximum

	efficiency of the cooler) is enough to minimise noise lines. F cooler = 40.08 Hz, ns = 40 is the nominal configuration set up during cool down. If microphonic lines in the data remains after VCS activation an exploration of 2 frequencies (one higher one lower than the nominal one) will be explored: F cooler = 38.85 Hz, ns = 40 F cooler = 41.06 Hz, ns = 40 The sampling frequency of the data should be larger than 90 Hz. The VCS adjustment procedure should be redone after each frequency change. It is very likely that one of the two will take the 4K cooler away from the excited resonance and thus solve the problem. If the problem remains a frequency futher away from the nominal one should be tested in the direction which shows improvement.
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.6 4K PID SETUP

Conditions to start	4K frequency set
Duration	It is a setting operation done in real time during DTCP
Objectives	Minimise the fluctuation spectrum on the HFI horns, and of the 70 GHz LFI loads. Set the PID with enough extra power to be able to cope with the foreseen degradation of Sorption Cooler performance. In this case, the foreseen evolution is a rise in temperature of the LVHX1 of about 0.5 K. The power provided by the PID should be 1.4mW at the beginning of a survey going down to 0.65 mW at the end of life of the Sorption cooler.
Details	After setting of the 4K cooler frequency, the PID on the 4K stage must be set. The optimal parameters of the PID found during the TB-TV tests will be implemented. Then a small number of parameters in the vicinity of these will explored (initiated during DTCP and then done out out of DTCP). If a better configuration is found after analysis of the temperature fluctuation levels this configuration will be uploaded.
Impact on system	It should be noted that any significant change on the SCS setup, and in particular the switchover, will require a new setting of the 4K PID if the temperature changes by more than 0.5K.
Extended DTCP	The first tuning should be done using the parameters established after CSL TB-TV. The final tuning should be done by planning a set of PID parameters changes around the nominal values (outside of the DTCP) and the optimisation done by analysis afterwards.
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.7 4K STROKE CHECKING SETTING (OPTIONAL)

Conditions to start	4K PID set
Duration	
Objectives	Check if the nominal amplitude provides a heat lift margin of 2 mW for a temperature lower than 4.6 K. This provides an FPU thermal balance which can be carried out with the PID. This is done by increasing the heat input at the nominal configuration..If this is verified (it is likely to be the case) no other action is needed. If the heat lift is too low the stroke amplitude is then adjusted to get the 2 mW margin using the measured dependence of heat lift with parameters obtained in ground testing and reported in section 2.5. The final step is to check this optimisation using the PID. The temperature of the cold head should stay below 4.7K. If this condition is not fulfilled it takes priority on the minimisation of the stroke amplitude.
Details	
Impact on system	This will set the final value of the 4K cooler cold end, and LFI 4K reference loads.
Extended DTCP	This must be done during DTCP and can make use of an extended DTCP.
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.8 4K PID FINE TUNING (OPTIONAL)

Conditions to start	4K stroke set
Duration	It is a setting operation done in real time during DTCP
Objectives	To fine tune the 4K PID if needed
Details	After setting of the 4K cooler frequency and amplitude, the PID on the 4K may need a fine tuning. It **is *unlikely*** this operation will be needed. The final tuning if needed should be done by planning a set of PID parameters changes around the nominal values during outside of the DTCP and the optimisation done by analysis afterwards.
Impact on system	Minimal
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.9 1.6K PID FINE TUNING

Conditions to start	Dilution flows set
Duration	

Objectives	To minimise the fluctuations of the 1.6K HFI filters.
Details	Starts from the values obtained during ground testing. Similarly to the 4K PID tuning systematic changes around the nominal values will be planned outside of DTCP and analysis will be done off line to see if a fine tuning is needed. See RD-1a.
Impact on system	
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14] HFI PFM Calibration and Performances Document [RD-1a]

3.2.10 DILUTION COOLER FLOW OPTIMISATION (OPTIONAL)

Conditions to start	The first setting is done during commissioning phase. The dilution is not sensitive to the 4K temperature. The 1.6K JT is sensitive to the 4K temperature if it is above 4.7K. Below that value the dilution does not depend of the 4K parameters. The margins on the cryo chain observed in the TB-TV tests makes the 3 coolers fine tuning essentially independent of each other. There should not be a need to adjust the dilution flow if the 4K cold head is well below 4.7 K.
Duration	
Objectives	Optimise trade-off between lifetime and sensitivity (temperature).
Details	The only parameter to be tuned for the dilution cooler is the mass flow of the isotopes. The current estimation gives as best value the Fmin2 configuration. This must be confirmed and set. If the temperature goes above 105mK in this configuration, the Fmin configuration should be used. See RD-1a.
Impact on system	No impact on the rest of the system.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14] HFI PFM Calibration and Performances Document [RD-1a]

3.2.11 DILUTION COOLER PLATE PID SETUP

Conditions to start	Dilution flow rate set.
Duration	After setting, the temperature fluctuations must be monitored for several hours.
Objectives	The temperature fluctuations of the dilution plate at high frequency (>10mHz) is provided by the passive damping of the Homium-Ytrium. The PID is only used to damp long period fluctuations and drifts. This setting is essentially independent of the rest of the cooling chain (negligible fluctuations transferred from the other coolers down to the 100 mK stage.

Details	The dilution plate PID parameters have been optimised during the TB-TV test. This configuration will be implemented. If the fluctuations are not exceeding significantly those observed in the TB-TV tests no tuning is needed. See RD-1a.
Impact on system	No impact on the rest of the system.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14] HFI PFM Calibration and Performances Document [RD-1a]

3.2.12 BOLOMETER PLATE PID SETUP

Conditions to start	After dilution plate PID setting (PID2), if needed
Duration	After setting, the temperature fluctuations of the dilution plate will be below the requirements. The PID of the bolometer plate will be set up with the parameters found in TB-TV tests. The behaviour will be monitored for one day to check that the temperature stability is not better than the one observed with the Bolometer plate PID OFF. Following the analysis a decision will be taken about the opportunity to keep the PID2 ON. (Nominal option is OFF). This depends on the perturbations of the heat load on the bolometer plate in flight. It is expected to be dominated by the modulation of the galactic cosmic rays by the solar wind fluctuations on period of hours to days, and to be significantly smaller than the one seen in ground testing dominated by vibration dissipation in the bolometer plate.
Objectives	If needed, to minimise the fluctuation spectrum of the focal plane
Details	See [RD-1a]
Impact on system	When the PID will be switched off (nominal case) it takes 10 hours for the bolometer plate to fully stabilise. This does not prevent other activities but except bolometers adjustment.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14] HFI PFM Calibration and Performances Document [RD-1a]

3.2.13 1.6K PID SET-UP READJUSTMENT (OPTIONAL)

Conditions to start	Dilution flows set
Duration	
Objectives	To minimise the fluctuations of the 1.6K HFI filters. If the dilution flow has been changed, an adjustment could be needed. The 1.6K stability obtained in the ground testing has always been very much better than the requirement. It is very unlikely than this adjustment will be needed.
Details	The stability of the 1.6K stage will be measured. If satisfactory no

	adjustment needs to be done.
Impact on system	No impact on the rest of the system.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.14 100MK DILUTION PIDS ADJUSTMENT (OPTIONAL)

Conditions to start	1.6K PID set, and readjustment of the 100mK PIDs configuration needed
Duration	
Objectives	This is a placeholder for an operation that may be needed to improve the bolometer plate thermal stability after the 1.6K PID has been set. Very unlikely to be needed.
Details	See [RD-1a]
Impact on system	No impact on the rest of the system.
Extended DTCP	Not needed
Reference Docs	HFI User Manual [AD-03] HFI Commissioning Plan [RD-14] HFI PFM Calibration and Performances Document [RD-1a]

3.2.15 ITERATION OF CRYOGENIC SYSTEM SETTINGS

Conditions to start	After the full system is set, a number of set up parameters are already conditional, and should be iterated only if the tuning done in the TB-TV tests at CSL is found not to fulfil the requirements in flight. ***This final iteration of set-up parameters is very unlikely.***
Duration	Check of the system; it will be a passive operation: analysis during the mini-survey test. Iteration is a quite severe operation in terms of time and should be undertaken only if a significant gain is expected. The various parts of the cryo chain are quite independent of each other. The critical interface parameters makes a very small and well understood list.
Objectives	Improve system performance parameters, such as lifetime, sensitivity, and operational profile.
Details	At this stage the system has been tuned. It is important to verify that the global tuning is appropriate for the mission. For operational profile we intend the logic of the operations including the timing of critical operations, i.e. Sorption Cooler switch, with respect to the surveys completion.
Impact on system	No impact on the rest of the system.
Extended DTCP	Not needed
Reference Docs	LFI User Manual [AD-01] Test Plan of LFI during Commissioning and CPV Phase [RD-15]

	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b] HFI User Manual [AD-03] HFI Commissioning Plan [RD-14]

3.2.16 CHANGE SCS CYCLE TIME

Conditions to start	One month after first setting
Duration	It is a setting operation. Instrument must be in nominal configuration, to be able to detect thermal impact on the data
Objectives	Verify the assumptions made on the hydride degradation; Assess the effect of the SCS evolution on the data, like changes during constant cycle time and after cycle time changes; Confirm the cycle time updating strategy; Determine the initial Cycle Time and Input Power parameters for Routine phase
Details	This is based on the assumption that we have already a baseline strategy for SCS parameters update. The predetermined times can be the middle of the First Light CPV test that happens about one month after the previous setting, and before the end of the First Light CPV test, that is one week after previous setting. These operations only address the first 2 changes of the SCS parameters during CPV phase. And will be used to assess the validity of the assumptions made about hydride degradation and hence to determine the values of the parameters for initial part of the routine phase.
Impact on system	No impact on instruments.
Extended DTCP	Not needed.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3 Routine Phase Operations and Monitoring

In the routine phase it will be necessary to perform the following operations and monitoring activities

This section lists the monitoring activities and operations to be executed in routine phase.
Some monitoring is aimed at the early detection of anomalies (e.g. for unclogging of coolers), in which case the recovery actions are described in Section 4 of this document.

The other monitoring is checking performances and expected aging of some subsystems. The hydride of the active SCS will slowly degrade and regular (baseline is weekly) adjustments of power and period will be done. The LVHX1 and 2 temperature will slowly rise (typically 0.5K over the lifetime of one SCS cooler). Small adjustments might be needed to the 4K cooler (PID temperature set up and compressor stroke amplitude). These are part of normal operations and not part of contingencies.

Sorption Cooler Switch-over

The Sorption Cooler Switchover operation will be carried out at a pre-planned time during the routine phase and is described in Section 4. The need for an extended DTCP for this operation is still TBC, since the operation itself is relatively fast, but monitoring to confirm full recovery may be circa 4 hours.

ID	Freq	Activity	Responsible
1.	Daily	Monitor LVHX1 & 2 Temperature	LFI-SCS/HFI, into DQR/WHR
2.	Daily	Monitor LVHX1 & 2 Fluctuations	LFI-SCS/HFI, into DQR/WHR
3.	Daily	Monitor SCS High Pressure	LFI-SCS, into DQR
4.	Daily	Monitor SCS Cooling Power	LFI-SCS, into DQR
5.	Weekly	Set SCS Input Power	LFI-SCS, into WHR
6.	Weekly	Set SCS Cycle Time	LFI-SCS, into WHR
7.	Rare	LPSB power Adjustment	LFI-SCS, into WHR
8.	Weekly	Predict SCS Residual Lifetime	LFI-SCS, into WHR
9.	Weekly	Monitor Dilution Cooler Residual Lifetime	HFI, into WHR
10.	Weekly	Monitor 4K Cooler High and Low Pressures and Flow	HFI, into WHR
11.	Daily	Monitor HFI Temperatures and Fluctuations (4K, 1.6K, 100mK)	HFI, into DQR/WHR
12.	Rare	Readjust PID Parameters (if temperature fluctuations increase)	HFI in connection with LFI

13.	Daily	Monitor LFI Temperatures and Fluctuations	LFI, into DQR/WHR
14.	Weekly	Monitor 4K VCS Error Signals	HFI, into WHR
15.	Rare	Re-tune the VCS (SRT then VCS parameters)	HFI, into WHR
16.	Weekly	Monitor 4K Cooler Margins Measures margin of the 4K cooling power and drifts of heat lift or heat load on the 4K cooler))	HFI, into WHR
17.	Rare	Readjust 4K Stroke Amplitude	
18.	Weekly	Monitor the 1.6 and 0.1 PIDs (measures any drift in the heat lift or heat load of these coolers)	HFI, into WHR
19.	Weekly	Monitor the Setting of the 4K PID	HFI, into WHR
20.	Daily	Detect JT plugs HFI	HFI
21.	Daily	Detect JT plugs LFI	LFI-SCS
22.	End of Cooler Lifetime	Regeneration of Sorption Cooler	LFI-SCS

Table 8: Operations and Monitoring Activities during Routine Phase

3.3.1 MONITOR LVHX1 & 2 TEMPERATURE

Responsible	SCS for both LVHX1 and LVXH2. LFI and HFI will be required to check temperatures on their side of the interface.
Reported in	DQRs
Frequency	Daily
Duration	Values will be averaged over one OD
Objectives	To monitor that the temperatures are within system requirements
Details	Monitor the temperatures of the system is a daily activity. This specific case, of monitoring the LVHX1 (HFI) & LVHX2 (LFI) temperatures is particularly important because it is needed for the frequent update of the SCS Input Power and Cycle Time.
Impact on system	SCS cold end temperature has an impact on 4K cooler performance and on LFI radiometers noise properties.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b] HFI User Manual [AD-03]

3.3.2 MONITOR LVHX1 & 2 FLUCTUATIONS

Responsible	LFI-SCS for LVXH2 HFI for LVHX1
Reported in	DQRs
Frequency	Daily
Duration	Values will be averaged over one OD
Objectives	To monitor that the temperature fluctuations are within requirements
Details	This specific case, of monitoring the LVHX1 (HFI) & 2 (LFI) temperature fluctuations is particularly important because it is needed for the frequent update of the SCS Input Power and Cycle Time.
Impact on system	The monitoring itself has no impact. SCS cold end temperature has an impact on 4K cooler performance and on LFI radiometers noise properties.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b] HFI User Manual [AD-03]

3.3.3 MONITOR SCS HIGH PRESSURE

Responsible	LFI-SCS
Reported in	DQRs
Frequency	Daily
Duration	Values will be averaged over one OD
Objectives	Monitor that HP level keeps constant within required limits
Details	HP is an indicator of heat lift produced. High Pressure rise can indicate the formation of a plug in the SCS JT valve.
Impact on system	Loss of cooling power can lead to SCS cold end warm-up and consequently it will impact both instruments.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.4 MONITOR SCS COOLING POWER

Responsible	LFI-SCS
Reported in	DQR
Frequency	Daily
Duration	Values will be averaged over one OD
Objectives	Monitor SCS heat lift produced

Details	Cooling power is calculated from HP. LFI load to SCS can be estimated from Delta T across the TSA. Accurate heat lift measurement requires LFI and HFI updates on parameters affecting load on SCS.
Impact on system	Loss of cooling power can lead to SCS cold end warm-up and consequently it will impact both instruments.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.5 SET SCS INPUT POWER

Responsible	LFI-SCS
Reported in	WHR
Frequency	Weekly
Duration	Value will be averaged over one OW
Objectives	To maintain the system in an optimal configuration. To maximise lifetime
Details	This is one of the most important routine phase activities, needed to keep the cooler within requirements. Both heat-up and desorption power will be changed. Cold end T fluctuations will provide the main indicator for adjusting heat-up power. Nominally heat-up power will be changed with cycle time. High Pressure is the main indicator for changing the desorption power.
Impact on system	If the input power is not changed the SCS will no longer meet its requirements.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.6 SET SCS CYCLE TIME

Responsible	LFI-SCS
Reported in	WHR
Frequency	Weekly
Duration	The value will be reported for last OW
Objectives	To maintain the system in an optimal configuration. To maximise lifetime
Details	This is the second fundamental activity to maintain the system. As described in in 3.3.5, cycle time will be changed together with heat-up power. Cold end temperature fluctuations will be the main indicator for cycle time (and heatup power) adjustments
Impact on system	Cycle time changes increase T fluctuations and SCS lifetime. They modify the spectral content of thermal fluctuations signature on scientific data. It is important to ensure that cycle time used is not a multiple of S/C spin period (60 sec)

Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.7 LPSB POWER ADJUSTMENT

Responsible	LFI-SCS
Reported in	WHR
Frequency	Reported weekly, but actual adjustments will be performed less frequently
Duration	Reported weekly
Objectives	To maintain the system in an optimal configuration. To maximise lifetime
Details	LPSB power changes are used to adjust hydrides concentration. SCS degradation leads to a decrease of H2 gas stored and desorbed by the compressor beds. Reduction of LPSB power will allow to store this excess gas.
Impact on system	If the LPSB power is not adjusted, the LVHX1&2 interface temperatures will drift
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.8 PREDICT SCS UNITS RESIDUAL LIFETIME

Responsible	LFI-SCS
Reported in	WHR
Frequency	Weekly
Duration	Passive analysis
Objectives	To determine the residual lifetime of both SCS Units
Details	Evaluation of lifetime will be done by monitoring the rate at which the cycle-time is changing and comparing this rate to that found at JPL for a single-element lifetime test.
Impact on system	
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

3.3.9 MONITOR DILUTION COOLER RESIDUAL LIFETIME

Responsible	HFI
Reported in	WHR
Frequency	Weekly
Duration	To determine the residual lifetime of the dilution cooler

Objectives	To determine the residual lifetime of the Dilution Cooler
Details	This monitoring is critical for correct planning of the continuation of the mission. This value is estimated by HFI IOT, and is part of the Weekly Health Report (WHR). Residual lifetime is estimated from current isotopes levels (from P and T) and flow rates through an algorithm to be run by the HFI IOT.
Impact on system	
Reference Docs	HFI User Manual [AD-03]

3.3.10 MONITOR 4K COOLER HIGH AND LOW PRESSURES AND FLOW

Responsible	HFI
Reported in	TBC
Frequency	Weekly
Duration	
Objectives	Monitor the status of the 4K cooler which is also the way to identify plug formation.
Details	*Clogging is dealt with in the contingencies section.*
Impact on system	
Reference Docs	HFI User Manual [AD-03]

3.3.11 MONITOR HFI TEMPERATURES AND FLUCTUATIONS

Responsible	HFI
Reported in	DQR, WHR
Frequency	Daily
Duration	
Objectives	To verify that temperatures are within requirements and monitor long term drifts and plan changes of cooler and/or PID parameters if the margin with respect to the maximum temperature are becoming too small, i.e. 4K <4.7 1.6 <1.6K Dilution Cooler temperature <105mK Monitor fluctuations (power spectrum on all thermometers) and for any drift identified analyse the cause(s). This requires the input of the temperature behaviour of the PLM and of HFI.
Details	
Impact on system	
Reference Docs	HFI User Manual [AD-03]

3.3.12 READJUST HFI PID PARAMETERS

Responsible	HFI, in connection with LFI
Reported in	
Frequency	Rare
Duration	
Objectives	To keep the cryogenic system in the optimal setting for best scientific return
Details	
Impact on system	The temperature stability requirements might not be fulfilled during the adjustment.
Reference Docs	HFI User Manual [AD-03]

3.3.13 MONITOR LFI TEMPERATURES AND FLUCTUATIONS

Responsible	LFI-SCS, HFI
Reported in	DQR, WHR
Frequency	Daily
Duration	
Objectives	To verify that temperatures and fluctuations are within requirements. TSA temperature below 21.5K. The HFI will monitor the LVHX1 temperature and fluctuations.
Details	
Impact on system	High level of temperature fluctuations may impact science data.
Reference Docs	LFI User Manual [AD-01] Planck Sorption Cooler Lifetime and Operations [RD-1b] HFI User Manual [AD-03]

3.3.14 MONITOR 4K VCS ERROR SIGNAL

Responsible	HFI
Reported in	WHR
Frequency	Weekly
Duration	
Objectives	To maintain the VCS performances so there are no microphonics lines significantly affecting the data.
Details	For all harmonics check that the force transducer signal is not exceeding the noise. If this happens a VCS parameter adjustment must be planned during an upcoming DTCP.
Impact on system	No impact on the rest of the system.
Reference Docs	HFI User Manual [AD-03]

3.3.15 RE-TUNE VCS

Responsible	HFI
Reported in	WHR
Frequency	Rare
Duration	
Objectives	To maintain the VCS operational
Details	This must be planned during a DTCP. An SRT must be performed, then readjust VCS parameters
Impact on system	This implies that the data will not be usable during the adjustment period. The survey must be interrupted during this operation.
Reference Docs	HFI User Manual [AD-03]

3.3.16 MONITOR 4K COOLER MARGINS

Responsible	HFI
Reported in	WHR
Frequency	Weekly
Duration	
Objectives	To verify that the 4K cooler is not running close to the limit of Heat Lift
Details	This is performed by monitoring the 4K PID power level, which must not be too low (the fluctuations of the PID power should never reach zero. When the PID power becomes too low HFI will proceed to a raise of the nominal temperature (after coordination with LFI) as long as the temperature stays below 4.7K. If it is not possible to maintain the maximum temperature requirement, HFI will proceed to an increase of the cooler stroke amplitude which will be followed by an SRT and VCS adjustment and possibly a PID adjustment. It is particularly important to verify the presence of margin before the occurrence of critical observations, like planets crossing
Impact on system	No impact on the rest of the system.
Reference Docs	HFI User Manual [AD-03]

3.3.17 READJUST THE 4K STROKE AMPLITUDE

Responsible	HFI
Reported in	WHR
Frequency	Rare
Duration	
Objectives	To maintain the 4K cooler far from critical condition

Details	In case the monitor of margin in the 4K cooler indicates that the cooler is running in a critical condition (see 2.4.12) An update of the cooler stroke amplitude will be necessary in order to increase the cooling power when the PID set up temperature reaches 4.7 K. When this happens, HFI will proceed to an increase of the cooler stroke amplitude as described in §3.3.16. See RD-1a.
Impact on system	As the VCS is interupted during this operation the survey must be interrupted during it.
Reference Docs	HFI User Manual [AD-03] HFI PFM Calibration and Performances Document [RD-1a]

3.3.18 MONITOR SETTING OF THE 4K PID

Responsible	HFI
Reported in	WHR
Frequency	Weekly
Duration	
Objectives	To maintain the correct functionality of the 4K PID
Details	The setting of the 4K PID may be affected by SCS degradation or increase of the heat load or loss of heat lift. It is needed to monitor the setting of the 4K PID and update the parameters in order to cope with the changing boundary conditions (see 3.3.16 and 3.3.17).
Impact on system	No impact on the rest of the system.
Reference Docs	HFI User Manual [AD-03]

3.3.19 MONITOR SETTING OF THE 1.6K AND 0.1K PIDS

Responsible	HFI
Reported in	WHR
Frequency	Weekly
Duration	
Objectives	To maintain the correct functionality of the dilution PIDs
Details	It is important to monitor the temperature fluctuations of the 1.6K and 0.1K stages. When a change is seen an analysis of the cause will be carried out (there are many possible sources, degradation of the PID setting or increase in the intrinsic fluctuations of the Sorption Cooler or 4K or of the 1.6 KJT or of the dilution. After full analysis, actions will be proposed and implemented after coordination with LFI if the Sorption Cooler or 4K cooler is concerned.
Impact on system	No impact on the rest of the system.
Reference Docs	HFI User Manual [AD-03]

3.3.20 DETECT JT PLUG ON HFI

Responsible	HFI
Reported in	
Frequency	Daily
Duration	
Objectives	To detect possible JT plugs in the system and activate recovery in case of detection
Details	JT plugs detection is a daily activity that can trigger specific contingency procedures. Possible HFI locations of JT plugs are - 4K JT orifice and pipes - Dilution and 1.6 K JT orifice and pipes at the different precooling points Monitoring of the Housekeeping data can be used to check for events precursor of JT plugs. See description in Section 4.4.8 for detection in pressure measurements and declogging procedures.
Impact on system	If a plug formation is detected the declogging procedures should be started as soon as possible.
Reference Docs	HFI User Manual [AD-03]

3.3.21 DETECT JT PLUG ON LFI

Responsible	LFI-SCS
Reported in	
Frequency	Daily
Duration	
Objectives	To detect possible JT plugs in the system and activate recovery in case of detection
Details	JT plugs detection is a daily activity that can trigger specific contingency procedures. Possible LFI location of JT plugs is: - 2 SCS JT orifices Monitoring of the Housekeeping data can be used to check for events precursor of JT plugs. In particular the rise in High Pressure is an indicator of the formation of a Plug. See Section 4.4.2 of this document.
Impact on system	
Reference Docs	SCS User Manual [AD-02]

3.3.22 REGENERATION OF SCS

Responsible	LFI-SCS
Reported in	WHR
Frequency	Once, at end of cooler lifetime
Duration	4 days
Objectives	To allow the Sorption Cooler to recover heat lift capability
Details	Regeneration is not the baseline. It is a planned operation that will be scheduled and prepared in detail.
Impact on system	Cold-end will warm to V-groove 3 temperature. No science data possible during this procedure.
Reference Docs	SCS User Manual [AD-02] Planck Sorption Cooler Lifetime and Operations [RD-1b]

4 ANOMALIES AND CONTINGENCIES

In this chapter we report operations in case of non-nominal events (anomalies) and contingencies (unexpected failures).

Generally, "anomalies" are off-nominal behaviors of the cryo-chain which develop slowly over time (allowing time for planning) and require some operational action. "Contingencies" are instead conditions which lead quickly to a non-nominal situation or failure and require a faster response; although for the cryogenic system this response would not be in the same DTCP as the anomaly/contingency situation was detected.

- **Section 4.1** presents general considerations, including the data and modelling used for the thermal impact analysis. Typical warm-up and cool-down profiles are provided, together with estimated recovery times after various periods of downtime.
- **Section 4.2** describes the timeline of the recovery from a passive cooling condition that will be the outcome of some contingency cases. Various reactivation scenarios based on the HFI thermal model are addressed with different Heat Switching logic.
- **Section 4.3** describes the anomaly cases.
- **Section 4.4** describes the contingency cases.
- **Section 4.5** summarises the operational reaction to contingency cases.

For each anomaly or contingency a table is provided as follows:

Possible causes	Possible causes of the fault
Fault Detection	Means of detection of the fault
Fault Isolation	Response (if any, e.g. by MOC), and strategy for other coolers to minimise the effect of the anomaly
Thermal response	Based on CSL data and thermal model
Impact on system	Impact on other elements of the system
ARB (Anomaly Review Board)	Need, participants
Fault Recovery	Recovery steps and timescale
Reference Docs	Pointer to User Manuals (see Annex1 for details)

4.1 General Considerations

This section is based on the modelling of the thermal impact of potential contingencies and failures, using as input the cryogenic chain thermal models (Payload Passive Cooling, Sorption Cooler , 4K Cooler, Dilution Cooler). The models were updated to reproduce the test data gathered during the CSL TV-TB test (cool down and warm up phases as well as failure cases).

- During the test several failure cases were tested, and in addition several (intended and unintended) warm-up events took place during the test. Because the test environment is very close to the flight case, this data is the most reliable guide to the thermal response of the system.

- Thermo-mechanical models which have been correlated with the CSL data are used to simulate cases which are not exactly reproduced during the CSl test. Three are two models used:
    a. One of the satellite and Sorption Cooler, i.e. down to 20 K, developed by Thales Alenia Space.
    b. One of the low-temperature behaviour, i.e. below 20 K, using specific parametric models of the 4K and dilution coolers, which has been developed by JJ Fourmond at IAS. This model has been shown to reproduce with good accuracy the results of the CSL test for all stages down to 1.6 K. Below 1.6 K some convergence problems persist in the model. It should normally be used with as forced input the temperature of the 20 K stage (from e.g. model or measurement). The HFI thermal model has been updated following the CSL TB-TV tests of the Planck FM. A number of failure and recovery cases have been modelled which are considered to cover well the cases which are expected to be encountered in flight:
        - Dilution/1.6K failure
            - Recovery after 12 hours
        - 4K cooler failure (inducing dilution failure after 6 hours)
            - Recovery after 24 hours
            - Recovery after 48 hours
        - Sorption cooler failure (whole cooling chain failure after 6 hours)
            - Recovery after 24 hours
            - Recovery after 48 hours
        - Recovery from 55K

Any unforeseen contingency in the cryo-chain system has to be treated with urgency because the recovery time is potentially very long. The following figure shows a typical (modelled) warm up of the system when cooler hardware or drive electronics either fails or detects a parameter off limits and turns a cooler off, or when when the satellite goes into Survival Mode when the cryo-chain and instruments are automatically turned off by the on-board FDIR.

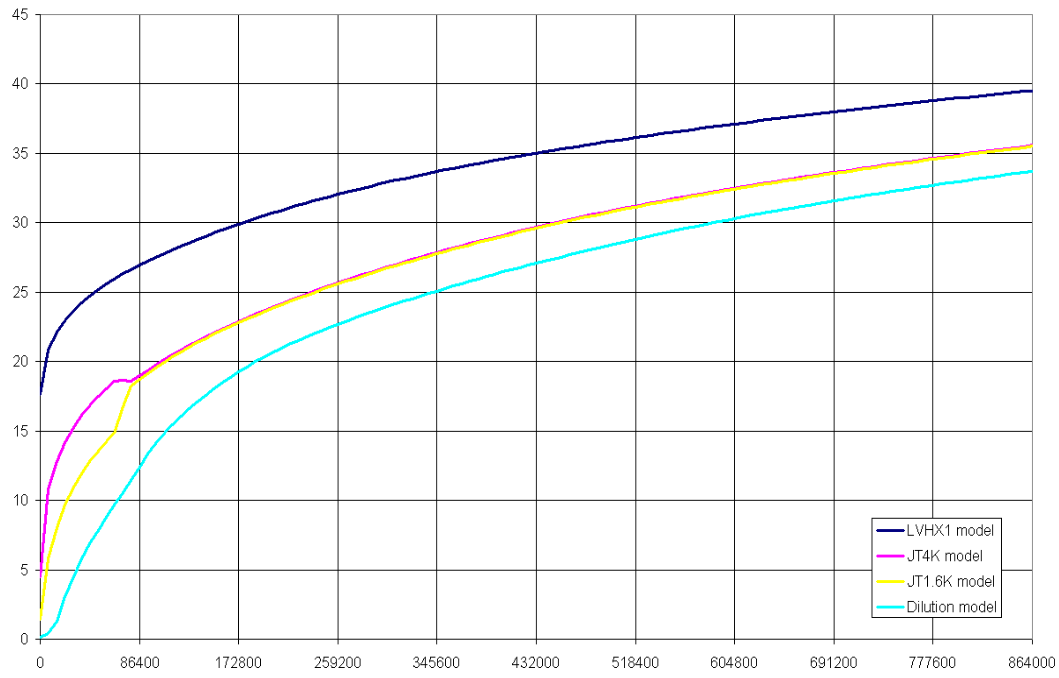

Figure 9: Modelled Warm-up of Low Temperature Stages after Cryo-chain Power-off

Note:

These results are taken from the HFI Thermal Model.

The figure shows that the thermal response is quite rapid, especially in the low-temperature stages. The (autonomous, short daily contact period) nature of the mission is such that a contingency must normally be expected to be detected relatively late, i.e. up to 21 hrs after the event has occurred. When including the need to identify the cause of a contingency before starting any recovery action, the delay between occurrence of the event and start of a recovery can be expected to be one DTCP for the best cases and of order days. For this reason, the first reaction after detection of a contingency must be the stabilisation of the thermal system to stop further warm-up and give time for analysis and decision on recovery. This first reaction could include actions such as:

- Removal of heat loads, e.g. turn off LFI front-ends. (TSA and HFI PIDs go by design to zero power when the temperature of the reference thermometer go above their set point)
- Switch to a redundant SCS unit if the active SCS has failed and the reason is not demonstrated in a very short time.

The cryo-chain does have a certain level of inertia, namely:

- If the SCS (20 K) stage starts to warm up, the 4K cooler is able to hold its temperature for ~2 hrs before reacting. It will them warm up to ~15 K in ~10 hrs and close to 20 K in 24 hrs.
- If the 4K stage starts to warm up, the 1.6 K stage is able to hold its temperature for 5 to 6 hrs, giving potentially time to reactivate the 4K. After these 5 to 6 hrs, the temperature of the 1.6K stage after which it will rise very sharply. It will reach the 4K stage temperature within 24 hrs.

- The 0.1 K stage temperature will follow the rise of the 1.6 K stage very closely. In 24 hrs it will have reached about 12 K.

Once these short hold times are past, the temperatures of all stages will rise steadily and eventually thermalise at the passive temperature of 47K (see Figure 9).

The time needed to return to normal operating temperatures is not the same as the initial cool down time as the inner stages start from a lower temperature than the failing one (contrary to the initial cool down). It will depend critically on the time at which the coolers may be turned back on. As an example, Figure 10 shows the cool-down after a downtime of 24 hrs. More examples are given in the description of specific failure modes under Section 4.4.

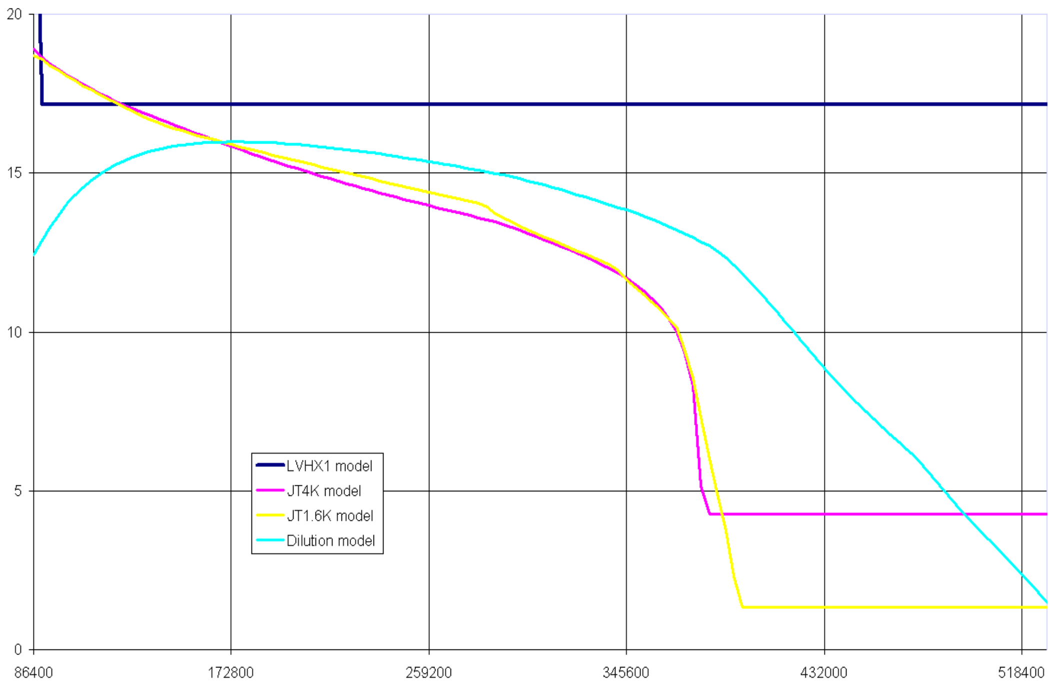

Figure 10: Modelled Restart of Cooling Chain after 24 hours Downtime

Notes:

LFI remains turned off in this model. The 20 K cooler temperature (input to the model) has been artificially set to 20 K; in fact it requires 24 hrs to cool down, so at least the same amount has to be added to all cool-down times.

A summary of the recovery time in various situations is provided in the Table below.

Cooler Failure	Failure Duration (days)	Heat Switches Status on Restart	Time to Recover 100mK (days)	Total Duration HFI non-operative
Dilution	1	OFF	2.5 to 3	3.5 to 4
4K inducing Dilution	1	OFF	5.4	6.4
4K inducing Dilution	2	OFF	7.6	8.6
SC inducing 4K & Dilution	1	OFF	7.5	8.5
SC inducing 4K & Dilution	2	Optimal	10	12
SC inducing 4K & Dilution	2	OFF	11.2	13.2
All from 45K	>10 days	Optimal conf	14	>24 days

Table 9: Recovery Times for Cooler Failure Events

The table indicates that in the most serious failure cases (e.g. safe mode, SCS failure):

- The minimum recovery time is of order 3 to 5 days (for dilution or 4K failure respectively), i.e. if the cooler can be restarted within a few hours of failure detection
- If analysis is required to diagnose the fault (most probable case), implying waiting to the next DTCP for any action, the recovery time will grow immediately to one week.
- f the time from failure to turn on of the coolers is longer than 48 hrs, the recovery time will remain at roughly 2 weeks.

Therefore the critical time period for reaction is clearly within 24 hrs of detection of the failure, and the cost for waiting is of order one extra week of recovery time.

4.2 Cryo-chain Activation from a Passive Cooling Condition

In many failure occurrences, anomalies and failures will eventually bring the system to the status of purely passive cooling condition, i.e. all stages close to the passive temperature of the V-groove 3 (~47K - but note that the models below assume more pessimistic s/c passive temperature of 55 K - the time has been scaled for 45K in Table 9). The recovery time depends (very slightly) on the details of the HFI heat switch operations, as illustrated below.

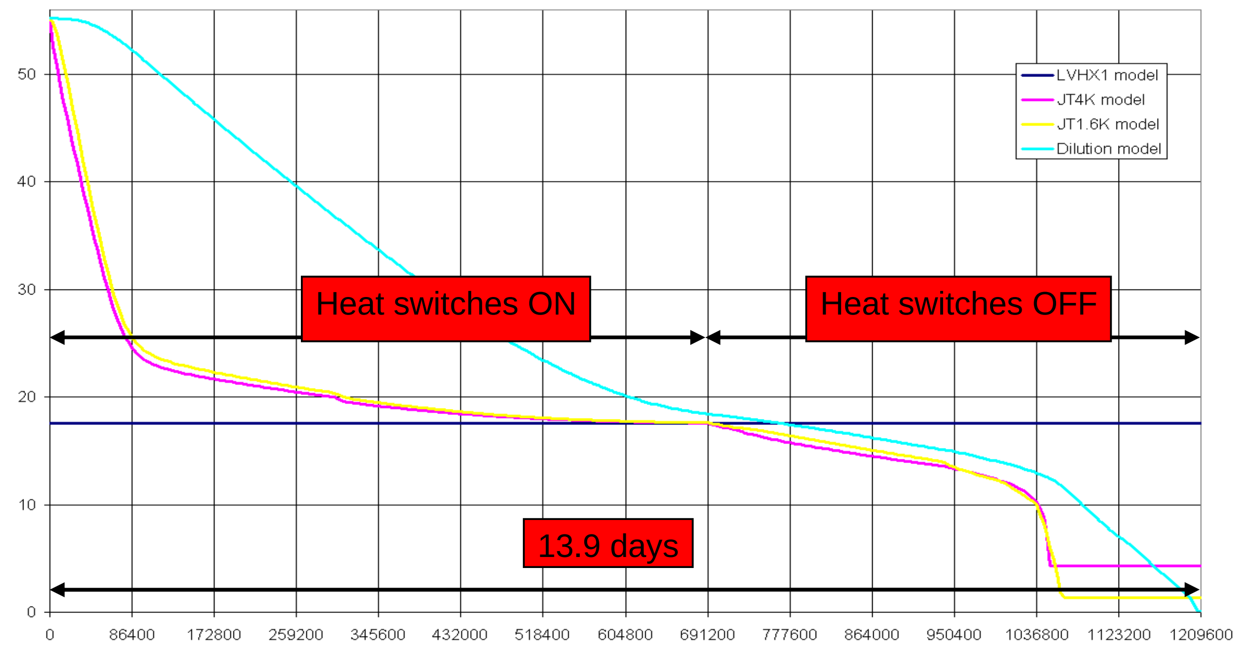

Figure 11: Cryo-chain Activation from a Passive Cooling Condition - 1

Notes:

These results are taken from the HFI Thermal Model, and illustrate cool-down from 55 K stable passive conditions. The SCS cool down is assumed instantaneous. Both heat switches are activated until the 4K stage is warmer than the 18 K stage (first 8 days), and deactivated afterwards. About 13.9 days are required to reach 1.4 K on the 100 mK stage, then 2.5 days are needed to achieve 100 mK. The total time needed is therefore 16.4 days (plus the time needed to cool to 20 K, <48 hrs).

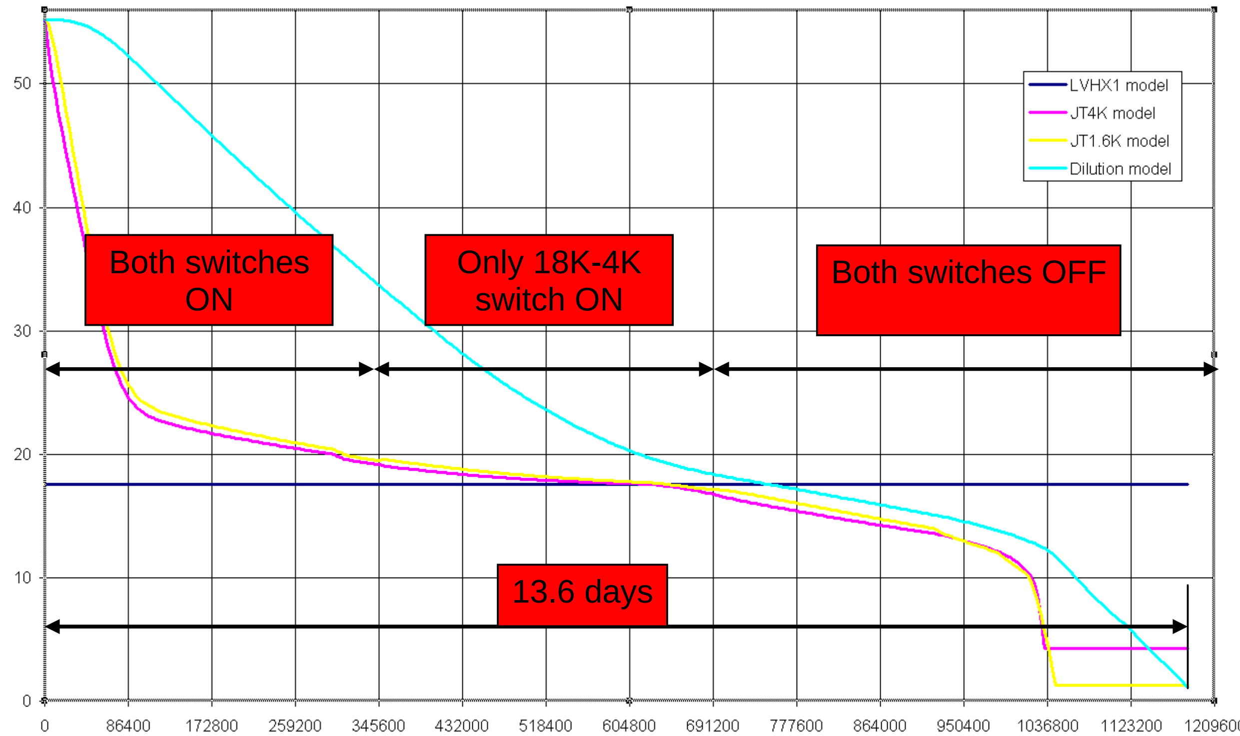

Figure 12: Cryo-chain Activation from a Passive Cooling Condition - 2

Notes:

These results are taken from the HFI Thermal Model, and illustrate cool-down from 55 K stable passive conditions. The SCS cool down is assumed instantaneous. Both heat switches are activated until the 4K stage is warmer than the 20 K stage (first 4 days); the 4K-1.6K heat switch is deactivated after the 4th day, and the 18K-4K switch is deactivated after 8 days (4K stage close to 18 K). About 13.6 days are required to reach 1.4 K on the 100 mK stage, then 2.5 days are needed to achieve 100 mK. The total time needed is therefore 16.1 days (plus the time needed to cool to 20 K, <48 hrs).

The slightly more complex sequence of operations shown in Figure 12 to restart the coolers chain from the stable passive condition is described in Table 10 below.

ID	OD	Operation/Status	Condition
1.	1	Turn ON SCS unit	Problem solved
2.	1	Activate 4K cooler, with nominal frequency and nominal stroke (values prior to failure)	Problem solved
3.	1	Set the dilution flows for cool-down (TBC if Fnom or same as before failure)	
4.	1	Turn ON Heat Switches (20K-4K)	Problem solved Temp. 4K stage < 70K
5.	1	Turn ON LFI FEM	Temp. 20K stage = 30K
6.	3	SCS cool-down completed	SCS in nominal operations

7.	8	Turn OFF heat Switch (20K-4K)	Temp 4K stage ~18 K
8.		4K stage at temperature	Temp < 4.7K
9.		1.6K stage at temperature	Temperature < 1.6K
10.		Dilution cooler cold end at 100milliKelvin	Temperature at 100mK
11.		Set dilution cooler flows to nominal values (as before failure)	Tdilu < 100mK

Table 10: Sequence of Operations to Reactivate the System after a Long Interruption

Note:

In case of an interruption, there will be an ARB/MRB which will decide about the restarting sequence. If there is a requirement to run a specific model this will be performed. The restart sequence will be built from existing sequences of the initial cool- down, modified as needed and considering the results of the problem investigation.

4.3 Expected Cooler Anomalies

This section describes the operations in case of expected anomalies. Expected anomalies are defined as those anomalies that develop slowly over time and can be detected by means of the daily trend analysis of housekeeping data. Generally they do not require a failure analysis, since these events can be expected, even though they are "off-nominal".

4.3.1 SCS UNIT SWITCH-OVER

At some stage the SCS will have to be switched in-flight due to degradation of the nominal unit. An overview of the switch-over sequence is shown in Table 11 below. Further details on this procedure are given in the SCS User Manual (see Annex 1 for procedure cross reference).

The general sequence can be summarised in the following steps:

- Shutdown FM2
- New LUT upload and dump before starting the FM1 Unit
- Initialise FM1
- GOTO READY MODE, enter Health Monitoring
- GOTO RUN MODE
- Wait for FM1 to enter Nominal Operations
- Perform cooler tuning

The whole procedure can take up to 4 hrs, if only one tuning step is required to achieve quasi-steady state. Each extra tuning step can take about 30 min (up to two or three tuning step might be expected) The interactive time needed is given by the different TCs sent, so from Step 1 to 6 in Table 11 this is about half an hour. Time from cooler OFF to cooler ON is about half an hour, BUT before the activated SCS starts producing enough cooling power, it can take 1 - 2 hrs.

It is important to emphasise that the 4K and dilution cooler are able to maintain nominal operations for the whole duration of the switch-over process. The 4K cooler will see increased T fluctuations and some minor drift but it should maintain basic functionality. After SCS switchover the 4K PID will probably need to be readjusted.

Step #	Description	Duration	Comments
	Monitor SCS for TBD seconds	TBD	TBD can be zero
1	Execute SCS FM2 shutdown procedure	~60 s	4K cooler and dilution cooler can stay ON
	Including CDMS request for 5A line OFF		Now SCE FM2 is OFF
	Wait for Event Report from S/C		Practically instantaneous
	Execute LUT update for FM1		
2	Execute SCS FM1 BOOT procedure	~60s	CDMS request for 5A line ON
	Transfer ASW if not automatically executed		
	Wait for Event Report from S/C		Practically instantaneous

Step #	Description	Duration	Comments
3	Execute SCS FM1 INIT procedure	~30 s	
	Wait for Event Report from S/C		Practically instantaneous
4	Execute LUT update, if needed	20 min	
5	Execute SCS FM1 READY procedure	~60 s	To Enter READY
	Wait for Event Report from S/C		Practically instantaneous
	Wait in READY Monitoring for TBD seconds	TBD	TBD can be zero
6	Execute SCS FM1 RUN procedure	approx 2 hrs	To Enter Nominal
	Wait for Event Report from S/C		Practically instantaneous
7	Execute LUT update, if needed	20 min	Cooler Tuning (1 or more steps could be needed)

Table 11: Sequence of Operations for SCS Switch-over in Flight

4.3.2 SOLAR FLARES

Solar flares lead to a rise of the bolometer plate temperature (by up to a few 100 mK depending on the flare intensity and duration which is from hours to days).

Once the extra heat input from the flare has stopped, the bolometer plate recovers its normal temperature in 5 to 12 hours depending on the intensity of the flare (a 5 hours minimum is associated with the Holmium-Ytrium time constant).

This anomaly does not affect the rest of the cooling chain. It creates a small to large gap in the HFI data depending on the duration of the flare (few hours to one week).

Possible causes	Astronomical
Fault Detection	Temperature of the dilution plate rising up to hundreds of mK; high rate in SREM data; Monitoring the difference between bolometer plate and dilution plate temperature
Fault Isolation	No action needed
Thermal response	Temperature rise of the dilution plate up to hundreds of mK
Impact on system	No impact other than on the dilution cooler
ARB	Not needed
Fault Recovery	No steps required. Time scale of recovery 5-12 hours
Reference Docs	No procedures needed

4.3.3 MOON ECLIPSES

No effect predicted on the cooling chain. No action needed

4.3.4 SCS REGENERATION

The regeneration procedure can be used to recover Sorption Cooler lifetime after it has been degraded. Recovery depends upon the degree of degradation that in turn is dependant on the total number of cycles. It is expected that implementation of the regeneration procedure might be performed on the Sorption Coolers at their end of life.

The procedure heats each compressor element to 675 K for a time that depends on the amount of degradation. For an end-of-life cooler, this time is 5 hours. Prior to heating the element, the gas pressure in the element must be reduced to below 1 bar. This typically takes about 9 hours. In addition, about 2 hours is needed for each compressor element to lowers its internal temperature from 675 to 470 K, before turning on the gas-gap heat switch. Finally, the regeneration process leads to a distribution of the gas inventory that does not allow immediate startup.

Based on all of these steps, it is estimated to take approximately 100 hours before a regenerated cooler can be switched on. Details of the regeneration process are given in the SCS UM, specifically, sections 8.5.2 and 9.2.2.2.

4.4 Cooler Contingencies

This section lists possible failure cases, and defines operations needed at the level of the Cryogenic System in order to react to the failure and reactivate the coolers. One of the main assumptions in the reaction to failures it is that the experts must understand and fix the problem before any reactivation attempt is made. In the case of a complex cryogenic system as the one of Planck, this approach can means losing at least several days and possibly weeks of survey coverage, so a good discussion of possible cases can be crucial to improve the mission performance.

For most of the cases an Anomaly Review Board (ARB) will be necessary to define the course of actions needed. But a number of actions can be taken immediately after the contingency is identified, to stabilise the thermal situation and contain its deterioration as much as possible.

The failure can be caused by a problem in the Cryogenic System itself or by some Spacecraft problem triggering a safe mode. In the latter case, we can define possible operations for cooler safety and recovery. It should be noted that in some cases the failure will cause an interruption of the chain long enough to bring the system to the status of passive cooling. From such condition, which also corresponds to the case of late activation, the recovery can be well defined in advance, as described in Table 10.

4.4.1 CRYO-CHAIN POWER-OFF CONDITION

This failure would be triggered by the spacecraft going into its strictest level of Safe Mode (SM) when the whole payload is powered off. The warm-up rate can be seen in Figure 13.

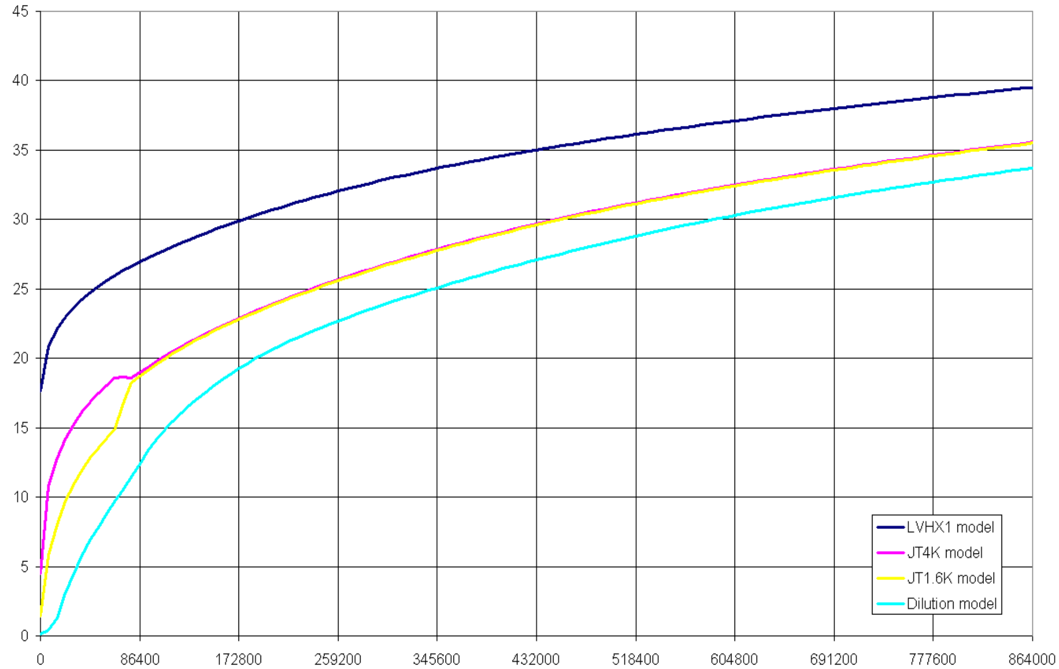

Figure 13: Warm-up Profiles for Cryo-chain Power-off Condition

Note: *These results are taken from the HFI Thermal Model*

The temperatures reached as a function of failure duration are summarised in the table below.

Failure duration (days)	**18K stage (K)**	**4K & 1.6K stages (K)**	**100mK stage (K)**
1	26.9	18.9	12.4
2	29.9	22.8	19.3
3	32.0	25.6	22.7
4	33.7	27.8	25.1
5	35.0	29.6	27.1
6	36.1	31.1	28.8
7	37.1	32.4	30.3
10	39.5	35.5	33.7

Table 12 Temperature of Cooling Stages after Power-off

The recovery time will depend on the failure duration, and the operation of the HFI heat switches during the cool-down. Several situations are illustrated by the model run results in the figures below.

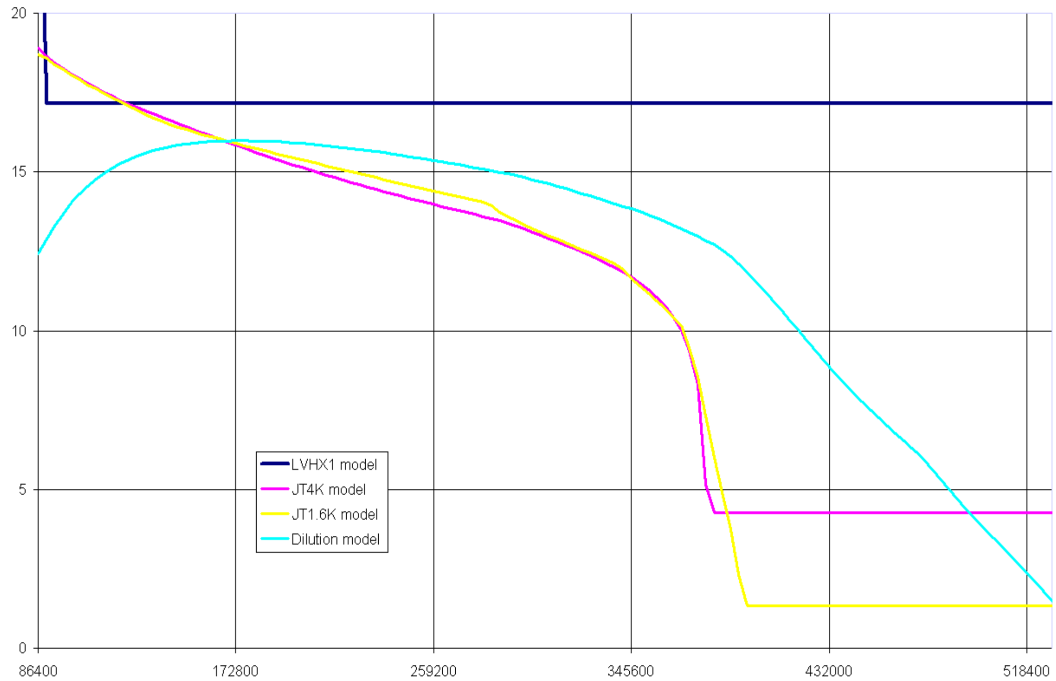

Figure 14: Restart of Cryo-chain after 24 hours Downtime

Notes:

None of the heat switches have been reactivated. The 4K cooler is activated at 20 K (same stroke amplitude as at CSL). In around 5 days the 100 mK stage is back at 1.4 K. Then 2.5 days are needed to go to 100 mK. The total recovery time in this case is therefore 7.5 days (plus one day for 20 K cooling since this model assumes that 20 K is achieved instantaneously TBC).

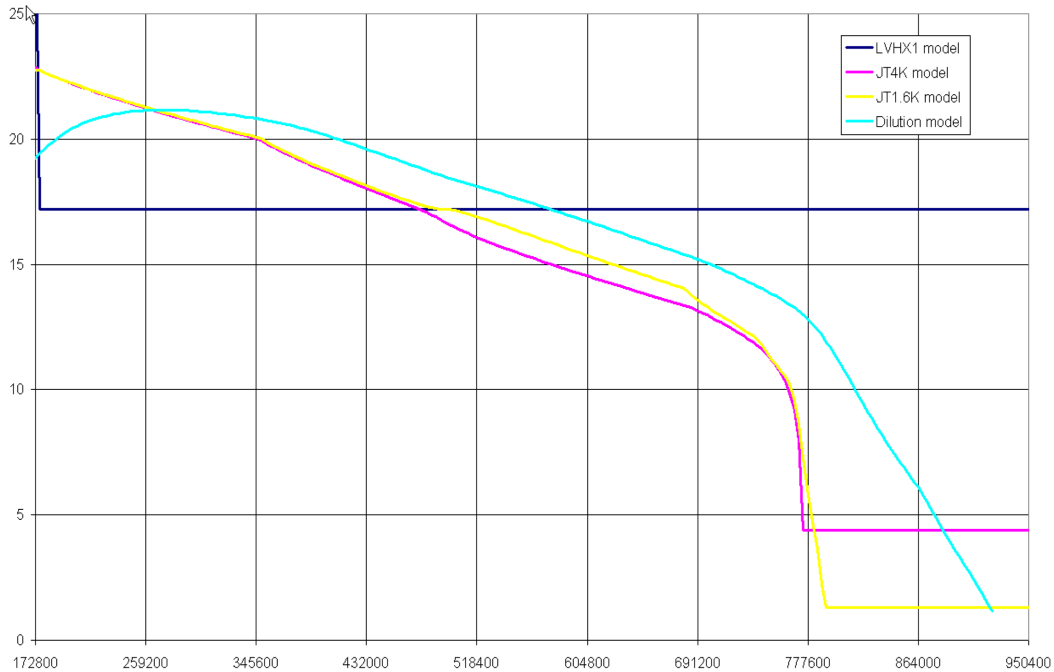

Figure 15: Restart of Cryo-chain after 48 hours Downtime - 1

Notes:

None of the heat switches have been reactivated. The 4K cooler is activated at 20 K (same stroke amplitude as at CSL). In around 8.7 days the 100 mK stage is back at 1.4 K. Then 2.5 days are needed to go to 100 mK. The total recovery time in this case is therefore 11.2 days (plus one day for 20 K cooling since this model assumes that 20 K is achieved instantaneously TBC).

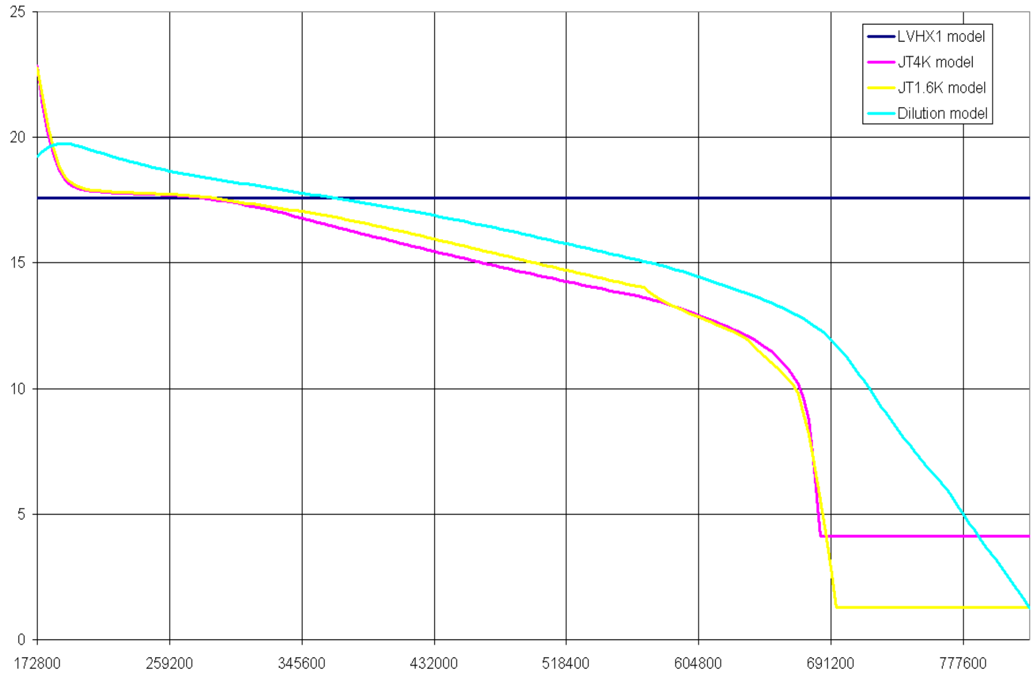

Figure 16: Restart of Cryo-chain after 48 hour Downtime - 2

Notes:

In this case the heat switches have been reactivated during the first 24 hours. The 4K cooler is activated at 20 K (same stroke amplitude as at CSL). In around 7.5 days the 100 mK stage is back at 1.4 K. Then 2.5 days are needed to go to 100 mK. The total recovery time in this case is therefore 10 days (plus one day for 20 K cooling since this model assumes that 20 K is achieved instantaneously TBC). In total the activation of switches saves about 1 day for the cool-down, as compared to the case where the switches are not activated.

This contingency is of course likely to be a very serious one, and therefore will require several days of analysis before any recovery can be attempted. The most likely recovery scenario therefore is that of restarting from stable passive conditions (Section 4.2).

4.4.2 SCS JT PLUG, NEEDING MANUAL INTERVENTION

Automatic detection will not be enabled in flight, and therefore only the JT Plug with manual intervention is considered. The automatic detection cannot be used to a problem with the flight software. Impact is minimal due to the unlikely occurance of a SCS JT plug event. This type of contingency has never been seen in the flight models, but the failure scenario should still be considered.

Two failure cases can be identified, one with a slow onset and the second with a fast onset. The slow kind is really an anomaly case rather than a contingency case, but is addressed here for convenience.

1) Long term Pressure Rise

Possible causes	Contaminants
Fault Detection	No event packet associated Observed by SCS team in House-keeping data, by a trend in the inlet (TBC) pressure
Fault Isolation	No immediate reaction needed
Thermal response	Minimal
Impact on system	Minimal
ARB	Not needed, the CRAT can be used to plan the recovery
Fault Recovery	The SCS defrost recovery procedure can be planned in advance, after clear identification of the issue. The recovery procedure adds 2W over about 15 minutes to the SCS cold end and will have a thermal impact on the rest of the cryo-chain. *Defrost impact on cryo-chain needs more description.* After the defrost has been executed, the cooler will return to normal operation. The pressure needs to be monitored to verify that the plug has been cleared.
Reference Docs	SCS User Manual [AD-02]

2) Quick On-set

This is the more severe case, in which the temperature is rising and fast reaction is required.

Possible causes	Contaminants
Fault Detection	Sorption Cooler System has transitioned into and found in **conditioning mode**; This is reported in an event packet, which is however not specific about the cause (plug)
Fault Isolation	Switch Over to other SCS Unit (if available) TBC
Thermal response	The event causes the SCS to stop cooling and the 20 K temperature to rise. See section TBC. The rest of the cryo-chain will follow after 5-6 hrs. -
Impact on system	Can be minimised by means of: • Turn off LFI front-ends • a switch-over to the second SCS unit. The overall impact depends on severity: - Typical timing can be 10 hrs for the full recovery (15 mins of heaters ON, and then the temperature drops) - Worst case could push the recovery time to 48 hrs
ARB	Needed prior to recovery on affected unit

Fault Recovery	Steps: - In the DTCP the issue is detected - Turn off LFI front-end units - Switch Over to other SCS Unit (if available) - The SCS defrost recovery procedure should be executed within DTCP, after clear identification of the issue. The recovery procedure adds 2W over about 15 minutes to the SCS cold end and will have a thermal impact on the rest of the cryo-chain. The defrost heaters must be stopped before the end of DTCP (even if the plug is not solved). Defrost impact on cryo-chain needs more description. During the recovery procedure: - The 4K cooler can stay ON - LFI is switched OFF (TBC) After the defrost has been executed, the cooler will return to normal operation. The pressure needs to be monitored for 8 hours to verify that the plug has been cleared.
Reference Docs	SCS User Manual [AD-02]

4.4.3 SCS IN READY MODE

Possible causes	TBW
Fault Detection	SCS found in **READY mode**. An event packet is associated with these cases. - Reason for stop will be sent in telemetry by electronics (for most cases) - Most likely will occur due to a electrical or software issue - Many reasons o Covered in UM FMECA
Fault Isolation	SCS switch over during next DTCP, if other unit is available
Thermal response	The SCS stops cooling and the 20 K stage temperature rises rapidly. Thermal impact will be longer than 48 hours.
Impact on system	Same as a SCS failure
ARB	Needed.
Fault Recovery	Immediate reaction should be the same as SCS JT plug, i.e. • Turn off LFI front-ends • Switch over to other SCS unit. The recovery of the affected unit is defined in the ARB.
Reference Docs	Switch-Over and activation procedures are in SCS UM.

4.4.4 SCS COMMUNICATIONS FAILURE

This failure is treated in the same way as 4.4.3 (SCS in READY or SHUTDOWNShut-down Mode)

4.4.5 SCS BED FAILURE

From a functional point of view, there are three cases to consider, depending on how many Beds have been lost.

1) System Working with 5 Beds

Possible causes	TBW
Fault Detection	The bad-bed procedure detects and automatically removes the failed bed from the cycle - On heatup and cool-down 390 K and 100 PSI - Will remove beds if heaters are turned on or are not turned on An event packet will be produced indicating 1 bed failed
Fault Isolation	No immediate reaction needed
Thermal response	The SCS meets requirements (temperature fluctuation levels increase but TSA should be able to absorb it). A small rise in temperature is expected due to increased TSA power.
Impact on system	All the other systems can stay ON. May impact on instruments performance. If the failed bed is not recovered, this has an impact on overall SCS lifetime, to be assessed
ARB	Needed
Fault Recovery	No immediate reaction needed
Reference Docs	Present in UM

2) System Working with 4 Beds

Possible causes	TBW
Fault Detection	The bad-bed procedure detects and automatically removes the failed bed from the cycle - On heatup and cool-down 390 K and 100 PSI - Will remove beds if heaters are turned on or are not turned on An event packet will be produced indicating 2 beds failed. Note: the 1 bed failure event must also have been previously produced. If the system was nominal and is found to be working with 4 beds at start of DTCP, it indicates failure of 2 beds which is symptom of a serious problem.
Fault Isolation	No immediate reaction needed
Thermal	The SCS does not meet requirements, but can stay ON; i.e. the SCS can

response	maintain 20 K temperature (a small rise is expected due to increased TSA power), however the level of fluctuations is likely too large to be absorbed by the TSA.
Impact on system	All the other systems can stay ON. Serious impact on instruments performance. If the failed beds are not recovered, this has a major impact on SCS lifetime, to be assessed
ARB	Needed. Management and Science Team must be involved
Fault Recovery	No immediate reaction needed
Reference Docs	Present in UM

3) System Working with < 4 Beds

Possible causes	TBW
Fault Detection	If more than 2 beds have failed, the SCS Unit is switched OFF. SCS goes into SHUT DOWN mode. An event packet will be produced indicating 3 beds failed.
Fault Isolation	SCS Units switch-over, executed by MOC (TBC), if other Unit available
Thermal response	SCS stops cooling and 20 K temperature rises. Rest of cryo-chain follows after 5-6 hrs.
Impact on system	The whole cryo-chain will fail to keep the system cold after 5-6 hrs. All the other systems can stay ON.
ARB	Needed.
Fault Recovery	As for other SCS major failures: • turn off LFI front-ends • Switch Over to other SCS Unit (if available)
Reference Docs	Present in UM

4.4.6 TSA HEATER FAILURE

The cooler on-board software continuously checks the actual applied current (measured current), and the commanded current. If these differ by 0.1 amp , the heater is declared “bad” and the SCS transitions to READY mode. The thermal impact is then identical to a failed Sorption Cooler, and a telemetry Event Packet is sent for this failure.

If this check fails, the worse case is 2 W being applied to the cold-end. If this occurs, the cold-end will warm to the V-groove temperature in about 12 hours.

Possible causes	TBW
Fault Detection	Temperature fluctuation above above requirements. All the TSA heaters are checked every second
Fault Isolation	TBC

Thermal response	Increased thermal fluctuations
Impact on system	No severe functional impact on other coolers
ARB	Needed
Fault Recovery	TBC
Reference Docs	TBC

4.4.7 4K COOLER FAILURES

The 4K cooler could be stopped by an electronic problem or by the VCS becoming less effective (as seen by a rapid increase of the force transducers signal above the set limits of 2N or 5N). If the cause is well identified the cooler can be restarted during the same DTCP (including SRT and VCS optimisation) thus within 24 hours of the failure. In that case the cooling chain can be back to nominal in 2.5 days. It should also be noted that the 2 days interruption brings the recovery to close to a week.

The failure of the 4K cooler quickly (after 5-6 hrs) triggers the failure of the dilution cooler as well. The warm-up curves shown in the figure below are modelled from a simultaneous failure of 4K and dilution coolers, which is essentially equivalent.

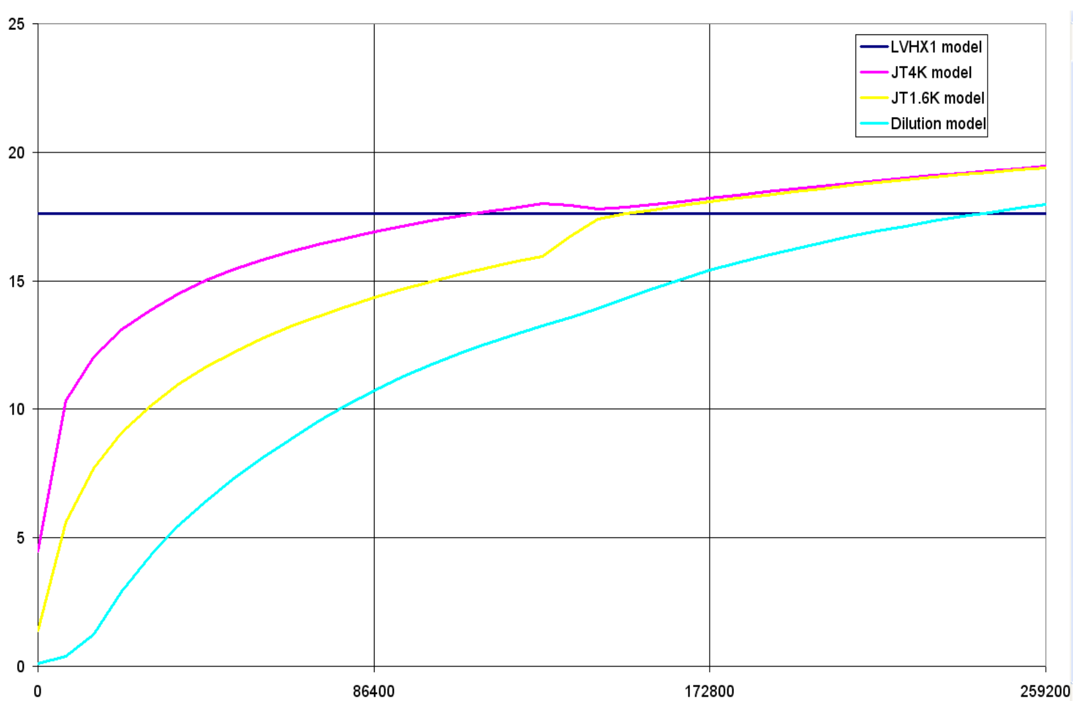

Figure 17: Modelled Warm-up after 4K and Dilution Cooler Failures

Notes:

This assumes the LFI front-ends and all the HFI PIDs are switched off. The temperatures of HFI rise above that of the SCS/LVHX1, mainly because of radiation from the spacecraft (assumed at 55K).

The warm-up temperatures as a function of time are summarised in the table below.

Failure duration (days)	18K stage (K)	4K stage (K)	1.6K stage (K)	100mK stage (K)
1	17.6	16.9	14.3	10.7
2	17.6	18.2	18.1	15.4
3	17.6	19.4	19.4	18.0

Table 13 Warm-up Temperatures of Cooling Stages after 4K Failure

The recovery is simulated (figures below) after 24 and 48 hrs failure duration.

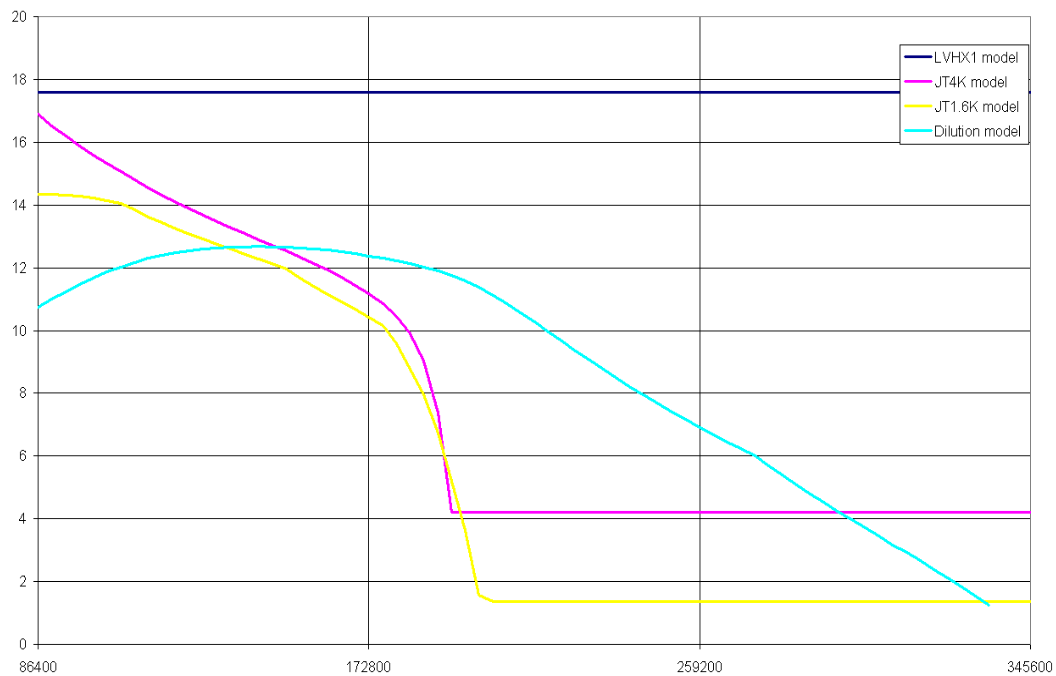

Figure 18: Modelled Recovery - Restart of 4K and Dilution Coolers after 24 hrs Downtime

Notes:

None of the heat switches have been reactivated.

The 1.4 K stage has recovered after 2.9 days, and a further 2.5 days are required to achieve 100 mK. The total recovery time is therefore 5.4 days.

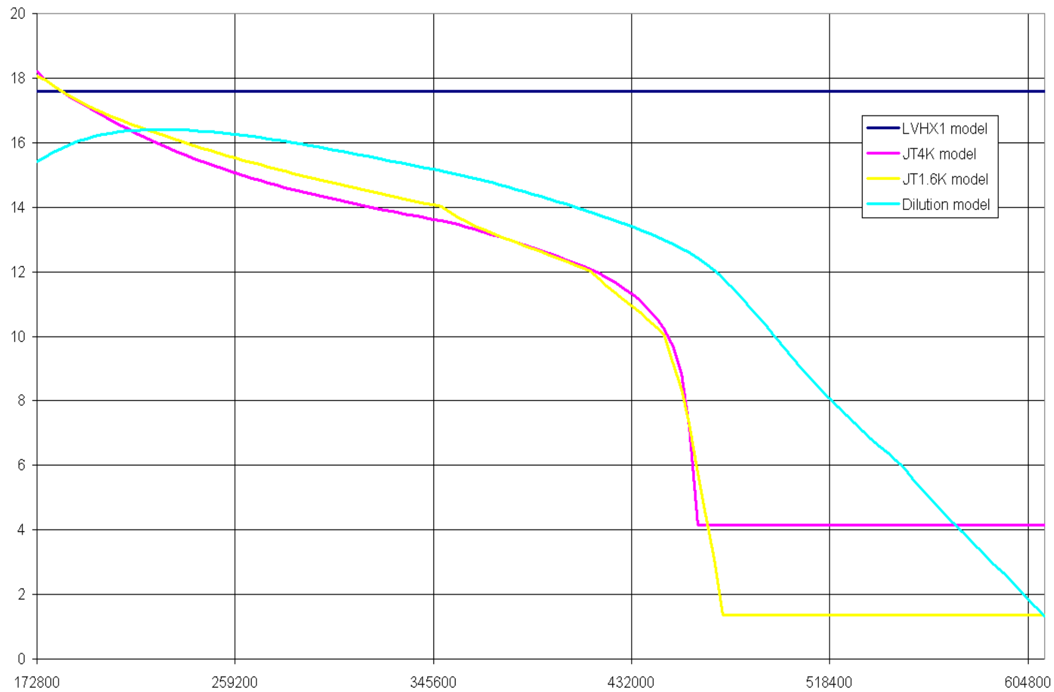

Figure 19: Modelled Recovery -Restart of 4K and Dilution Coolers after 48 hrs Downtime

Notes:

None of the heat switches have been reactivated. The 1.4 K stage has recovered after 5.1 days, and a further 2.5 days are required to achieve 100 mK. The total recovery time is therefore 7.6 days.

Possible causes	If the force levels go above the 2N limit for more than 10 min, the VCS goes OFF (TBC); If the force levels go above 5N, the cooler is switched OFF Anomaly in the electronics
Fault Detection	4K cooler system has restarted 4K cooler system is in STOP
Fault Isolation	No action from MOC

<table>
<tr><td>Thermal response</td><td>- In case of SCS failure
Following a Sorption Cooler failure, the 4K cooler temperature starts to rise after half an hour and rises more slowly to 8K in 2 hours and 15K in 12 hours. The 1.6 K cooler takes around 5 hours to evaporate the liquid helium before the temperature starts to rise reaching 11K after 12 hours (when the 4K is around 14K). After one day the heat switch is active and has brought the 1.6 and 4K to a temperature close to 18K. After 3 days it reaches ~20 K.

- 4K cooler alone
If a failure of the 4K cooler occurs with the Sorption Cooler still working, the rise in temperature is similar for the first day and then is reaches asymptotically the Sorption Cooler temperature.

Recovery timing (TBC)
Recovery from an interruption due to:
- 4 K cooler failure: after 1 day (both 1.6 and 4K close to the Sorption Cooler temperature) full recovery takes 4.5 days: down to 4K and 1.6K takes less than 2 days. The 100 mK stage stays below the 1.6K stage. It takes 2.5 days then to reach 100mK from 1.6K.

- 18K cooler failure: after a day interruption the recovery of the Sorption Cooler is very fast (a few hours) we are close to the previous case . After 5 days we start from 45K it takes about 2 days to recover down to 17K. We are then back to the previous case thus 6.5 days for a full recovery.

A short interruption (~1 day) leads to about one week total gap.
A 5 days interruption leads to a 12 days gap.
This shows that in most cases, cooler failures do not generate small recoverable gaps in the survey.</td></tr>
<tr><td>Impact on system</td><td>No actions needed by other elements</td></tr>
<tr><td>ARB</td><td>Needed</td></tr>
<tr><td>Fault Recovery</td><td>In case of VCS stop, the system reactivates by itself (TBC)
In case of electronics, the system reactivates by itself</td></tr>
<tr><td>Reference Docs</td><td>Existing procedures in the User Manuals</td></tr>
</table>

4.4.8 4K COOLER JT PLUG

This is a major contingency. The compressor cannot be operated warm with nominal stroke. It shuts down to avoid heating of the seals. With a reduced stroke, the Getter can stay on all the time. This will avoid the risk of plugs.

Possible causes	Contaminant in pipes
Fault Detection	Low pressure in the 4K cooler goes down; High pressure increases; The temperature of the 4K stage starts rising after a few hours.

Fault Isolation	MOC doesn't operate autonomously, it rises a flag in case of Out Of Limit. If the system goes off due to vibrations above 5N, it tries to reactivate autonomously Defrost procedure has to be activated by command with power (~200mW max) and time as parameters. - This is done in DTCP, for real time monitoring - The criteria to verify that the plug has been removed are not well defined, because the viscosity reduce the flow at high temperature. The flow as a function of temperature will be used. - The power has an impact into the SCS, that can go OFF due Out-Of-Limit. - The goal is to bring the JT above the 18K stage (20K) which takes of order 1 hour and then to leave it for 6 hours (to remove a Hydrogen Plug). SCS TSA can be turned off (200mW) to cope with the extra power from the heater
Thermal response	The temperature of the 4K stage starts rising after a few hours. 1.6K and 0.1K will follow with a delay of a 6-8 hours - In this condition, a fast reaction can avoid a gap in the science data The defrost mechanism has been tested during TB-TV. It take 4 hours (2 hours heating, 2 hours recovery. If applied when the 1.6K cooler is still working nominally the 1.6K and dilution are basically unaffected. (5 to 6 hours to evaporate the liquid helium). In the case of extra delay, - In 1 days 1.6K and 4K reach 18K - In 2 days, also the dilution is at 18K - From the asymptotic case, it takes 6.5 days to recover. It may be needed to switch OFF the SCS to allow the JT valve to warm enough.
Impact on system	No action needed on other coolers It may be needed to switch OFF the SCS to allow the JT valve to warm enough
ARB	Needed
Fault Recovery	The 4K must be restored to the nominal setting (prior to event) with VCS off. During the recovery time, verify that the plug is gone. Turn VCS on.
Reference Docs	HFI User Manual [AD-03]

4.4.9 DILUTION COOLER FAILURE

Note that there is no 1.6K JT plugging that is NOT included in the dilution failure case described in this section (the 1.6K JT is part of the dilution cooler pipes).

When the Sorption and 4K coolers operate nominally, the dilution (and 1.6K JT cooler) can only fail by clogging at any of the three precooling stages: 45K, 18K 4.5K. Purifiers are implemented in the DCCU making clogging very unlikely (not seen in any of the tests.). Charcoal traps are set up at these three stages and heaters are put just before each of these.

The Air Liquide report [RD-25] shows the results of clogging and unclogging tests.

Any increase of pressure associated in the dilution pipes with decreasing heat lift will be an indication of clogging. The heaters can be put on from 10minutes to hours starting with the lower temperature checking for return to normal and turning off the next heaters if the pipes are stilled clooged.

If the dilution cooler fails, the 1.6 K and 100 mK stages will reach 4 K in less than 24 hours. The recovery time from 4K to 100 mK is 2.5-3 days (including cool-down to 1.6 K in less than 4 hours), which can be deduced from the results of the CSL test (see Figure 20 below).

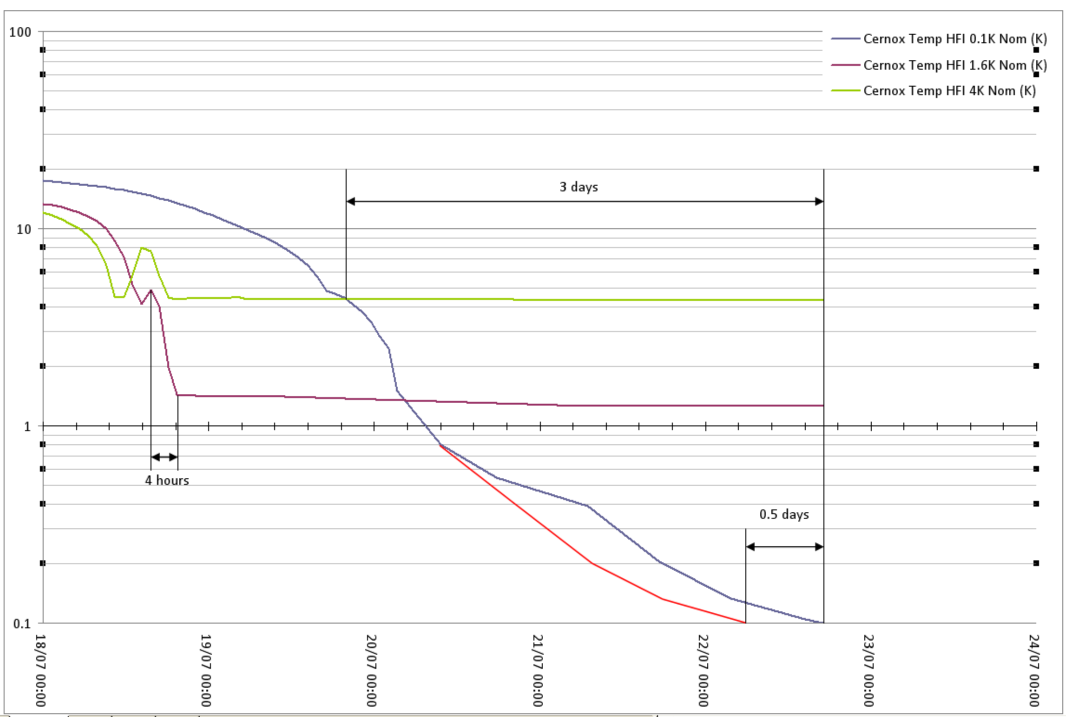

Figure 20: Recovery after Dilution Cooler Failure

Notes:

Recorded Cooldown during the TB/TV test at CSL in Summer 2008. This is used as reference for an estimation of the recovery time in the case of a failure in the dilution cooler system. The Blue curve *reports the data. The changes in slope around 0.8 and 0.5 K are due to problems of cleanliness in the pre-cooling circuit. The red curve reports an estimation of the real cooldown profile, without those problems.*

Possible causes	Clogging Flow valves closed / open due to electronics failure
Fault Detection	Temperature rise PID power increase due to electronic failure Inlet pressure changed
Fault Isolation	No action required from MOC
Thermal response	Impact only at 100mK stage
Impact on system	No action needed on other coolers. Impact depends on understanding of the problem
ARB	Needed
Fault Recovery	Analyse data of the last 12 hr Monitor changes of temperature at 50K or 18K Monitor changes of temperatures in the satellite
Reference Docs	TBW

Dilution Cooler Defrost Contingency Operations

Ref: Filtering and Unclogging Test Report. J. Butterworth, Air Liquide, April 2005 [RD-25]

Tests were done injecting pullutant gases (CH4 and N2) in a dilution test system. This has shown that the clogging is observed as a rise in the pressure as t^2 at the beginning then linearly, over typically two days. It recovers partially and increase again later (pollutant migration). The whole cycle last several days indicating that clogging can be identified and declogging be planned before blocking is complete.

Power available for the 3 defrost heaters at the three pre cooling stages on both Hé3 and He4 lines:

- Wmax 50K= 2W
- Wmax 18K = 150 mW
- Wmax 4K= 25 mW

The defrost on the to lines can be activated simultaneously, making the available power twice these numbers. The defrost strategy is to work from the highest temperatures down. Then the goal is to bring each stage at a temperature significantly higher than the previous stage. In each case the fraction of the maximum power can be chosen between a set of discete values : 3, 10, 30 and 100% of the maximum value. The temperature to be reached is set up by telecommand.

CSL TB-TV tests have shown that:

- 50 K stage, heating up to 80K: with maximum power 80K is reached in less than 5 minutes
- 20K stage is heated to 50K in one hour at maximum power
- 4K stage is heated to 20K in half an hour at maximum power.

4.5 *Summary of Recovery Actions from Anomalies and Contingencies*

This section summarises ***the expected operational reactions by the MOC*** for the anomaly and contingency cases described in the preceding sections.

It is important to note that MOC will not take any immediate recovery action on anomalies and contingencies detected on the cryogenic chain. An ARB will be needed to decide on acourse of action during the next DTCP. This obviously affects the recovery times from a failure (e.g. failure of the nominal Sorption Cooler).

Cooler	Event	Detection	Immediate Reaction
Dilution	Solar Flare	Housekeeping TM	Not needed
SCS	Slow JT Plug	Housekeeping TM	Not needed
SCS	Quick JT Plug	In CONDITIONING Mode	Not needed
SCS	In READY Mode	In READY Mode	Not needed
SCS	In SHUT DOWN Mode	In SHUTDOWN Mode	Not needed
SCS	1-2 Beds Failure	Event Packet	Not needed
SCS	3 Beds Failure	Event Packet	Not needed
4K	Failure	Restarted / STOP	Not needed
4K	JT Plug	Housekeeping TM	Not need
Dilution	Plug (18K, 4K, 1.6K)	Housekeeping TM	Not needed

Table 14: Summary of Reaction to Anomalies and Contingencies

5 MANAGEMENT

The Cryo Operation Working Group (COWG) is currently composed of:

C. Lawrence:	LFI Survey Scientist, Coordinator of the COWG (JPL)
J. Tauber:	ESA, Planck Project Scientist
J-L. Puget:	HFI, Principal Investigator
F. Piacentini:	HFI, Core Team
W. Holmes:	HFI, Cryo-chain Specialist
J-J. Fourmond:	HFI, Thermal Engineer
M. Piat:	HFI, Cooling ChainSpecialist
G.L. Morgante:	LFI, SCS Specialist (JPL)
D. Pearson:	LFI, SCS Specialist (JPL)
L. Wade:	LFI, SCS Specialist (JPL)
L. Terenzi:	LFI, Cooling Chain Specialist
D. Taylor:	ESA, PSO SGS System Engineer (custodian of this document)
C. Damasio:	ESA, Herschel/Planck Project Team
E. Gavila:	THALES, Cryo-chain Specialist (until end of commissioning)

5.1 Management Concept

5.1.1 COMMISSIONING PHASE

The management of the cooling chain during Commissioning rests with the Project Manager. The COWG will provide ad-hoc technical support to the Commissioning Team in daily meetings and ARBs in case of contingencies.

At least one senior member of the COWG will be on-site at ESOC in the PISA Room, and will provide "in-situ" technical advice.

5.1.2 CPV PHASE

The management of the cooling chain during the CPV Phase (i.e. after hand-over of the spacecraft from the Commissioning Team) rests with the Mission Manager, and is described in the following documents:

- Science Ground Segment Management Plan [AD-05]
- SGS CPV Phase Operations Plan [RD-19]

It is expected that most flight operations related to the Cryo-Chain can be carried out according to pre-planned procedures, mainly at individual cooler level. These procedures (nominal and contingency) must be accepted by MOC and be part of the Flight Operations Plan (FOP).

Members of the COWG will be on-site at ESOC in the PISA Room, and will provide “in-situ” technical advice.

5.1.3 ROUTINE OPERATIONS PHASE

The management of the cooling chain during Routine Operations rests with the Mission Manager, and is described in the following documents:

- Science Ground Segment Management Plan [AD-05]
- SGS Routine Phase Operations Plan [RD-20]

It is expected that most flight operations related to the Cryo-Chain can be carried out according to pre-planned procedures, mainly at individual cooler level. These procedures (nominal and contingency) must be accepted by MOC and be part of the Flight Operations Plan (FOP).

The COWG will remain in place throughout the mission, and will be consulted by the managers (using the CRAT mechanism) whenever technical debate over different options arises. The managers (Mission Manager, MOC-SOM, HFI and LFI Operations Managers, PSO Operations Manager) will call on the COWG for expert advice.

ANNEX 1 – USER MANUAL PROCEDURE CROSS REFERENCE LIST

Key:

LFI	=	LFI User Manual	[AD-01]	Issue 4, Rev.0, 22nd March 2009
SCS	=	SCS User Manual	[AD-02]	Issue 3, Rev.0, 20th March 2009
HFI	=	HFI User Manual	[AD-03]	Issue 2, Rev.2, 17th March 2009
S/C	=	Satellite User Manual	[AD-04]	Issue 3, Rev.1, June 2008

SCSL = SCS Lifetime and Operations Document [RD-1b]

Table 15 User Manual Procedure Reference – Initial Cool-down

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
Initial Cool-down	1	Launch Operations	3.1.1	HFI: § 11.13
	1	Dilution Cooler Minimum Flow-rate Setting	3.1.2	HFI: § 11.12.5 HFI: § 11.14
	1	4K Cooler Amplitude Setting (2mm)	3.1.3	HFI: § 11.12.4 HFI: § 11.14
	1-14	Telescope and FPU Decontamination	3.1.4	S/C: § 5.8
	15-19	Passive Cooling	3.1.5	S/C: § 5.8
	20+	HOLD POINT 1	3.1.6	

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
	20	SCS FM2 Unit Switch ON	3.1.7	SCS: § 9.2.1.4
	20	Warm Radiator Temperature Setting	3.1.8	SCS: § 5.8
	26	Heat Switch (18K-4K) ON	3.1.9	HFI: § 11.12.5 HFI: § 11.14
	26	LFI FEM Switch ON	3.1.10	LFI: § 13.1.2.2
	28	SCS Initial Parameter Setup	3.1.11	SCS: § 9.1.3/4 SCSL: § 4
	28-30	SCS Initial TSA Tuning	3.1.12	SCS: § 5 SCSL: § 4
	30	Heat Switch Heaters (4K-1.6K) ON - Max Power	3.1.13	HFI: § 11.12.5 HFI: § 11.14
	30	4K PID Heaters ON - Max Power	3.1.14	HFI: § 11.12.3 HFI: § 11.14
	31-32	LFI Matrix Pre-tuning	3.1.15	LFI: § 13.1.2.7
	33-42	LFI Matrix Tuning Steps 1 & 2 at 22K & 18K	3.1.16	LFI: § 13.1.2.7
	42	Heat Switch (4K-1.6K) OFF	3.1.17	HFI: § 11.12.5 HFI: § 11.14
	42	4K PID Heaters OFF	3.1.18	HFI: § 11.12.3 HFI: § 11.14
	42	Heat Switch (18K-4K) - Low Power	3.1.19	HFI: § 11.12.5 HFI: § 11.14

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
	42+	Step deleted (was HOLD POINT 2)	3.1.20	
	42	4K Cooler Stroke Amplitude to 90%	3.1.21	HFI: § 11.12.4 HFI: § 11.14
	42+	HOLD POINT 2	3.1.21a	
	42	Dilution Cooler Flowrates for Slow Cool-down (FNOM1)	3.1.22	HFI: § 11.12.5 HFI: § 11.14
	43	Step deleted (was Heat Switch (18K-4K) On - Low Power)	3.1.23	HFI: § 11.12.5 HFI: § 11.14
	43-45	LFI Matrix Tuning Step 3	3.1.24	LFI: § 13.1.2.7
	45	Heat Switch (18K-4K) OFF	3.1.25	HFI: § 11.12.5 HFI: § 11.14
	46	4K VCS Adjustment	3.1.26	HFI: § 11.12.4 HFI: § 11.14
	47	First Setting of 4K PID (4K Stage Cold)	3.1.27	HFI: § 11.12.3 HFI: § 11.14
	48	First Setting of 1.6K PID (1.6K Stage Cold)	3.1.28	HFI: § 11.12.3 HFI: § 11.14
	48	Dilution Cooler Flowrate for Fast Cool-down (FNOM2)	3.1.29	HFI: § 11.12.5 HFI: § 11.14
	48-50	LFI Matrix Tuning Step 4	3.1.30	LFI: § 13.1.2.7
	50	Monitor Dilution Cooler Cold-end at 100 mK	3.1.31	HFI: § 11.12.3 HFI: § 11.14

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
	50	Dilution Cooler Flowrate for Nominal Operations (Fmin2)	3.1.32	HFI: § 11.12.5 HFI: § 11.15
	50+	SCS Power Measurement	3.1.33	SCS: § 5.8 SCS: § 9.1.3/4 SCSL: § 4

Table 16 User Manual Procedure Reference – Initial Tuning

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
Initial Tuning	50+	Warm Radiator Temperature Adjustment	3.2.1	SCS: § 5.8 SCS: § 9.1.3/4
	50+	SCS Cycle Time and Input Power Setting	3.2.2	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4
	50+	TSA Tuning after Initial Cool-down	3.2.3	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4
	50+	SCS-FM2 Heat-Lift Measurement	3.2.4	SCS: § 5.8 SCS: § 9.1.3/4 SCSL: § 4
	50+	4K Cooler Frequency Tuning	3.2.5	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	4K PID Setup	3.2.6	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	4K Cooler Stroke Setting	3.2.7	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	4K Cooler PID Fine Tuning	3.2.8	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15

Phase	OD	Operation	Cryo-ops Document Reference	User Manual Reference
	50+	1.6K PID Fine Tuning	3.2.9	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	Dilution Cooler Flow Optimisation	3.2.10	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	Dilution Cooler Plate PID Setup	3.2.11	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	Bolometer Plate PID setup	3.2.12	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	1.6K PID setup	3.2.13	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	100mK Dilution Cooler Plate PID Adjustment	3.2.14	HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	Iteration of Cryogenic System Settings	3.2.15	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4 HFI: § 11.12 HFI: § 11.14 HFI: § 11.15
	50+	Change of SCS Cycle Time	3.2.16	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4

Table 17 User Manual Procedure Reference – Routine Phase Operations

Phase	Frequency	Operation	Cryo-ops Document Reference	User Manual Reference
Routine Phase Operations	Daily	Monitor LVHX1 & 2 Temperature	3.3.1	SCS: § 5.1 SCS: § A.3.5.5 SCSL: § 4 HFI: § TBP
	Daily	Monitor LVHX1 & 2 Fluctuations	3.3.2	SCS: § 5.2 SCS: § A.3.5.5 SCSL: § 4 HFI: § TBP
	Daily	Monitor SCS High Pressure	3.3.3	SCS: § 6.1 SCS: § A.3.5.5 SCSL: § 4
	Daily	Monitor SCS Cooling Power	3.3.4	SCS: § 5.3 SCSL: § 4
	Weekly	Set SCS Input Power	3.3.5	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4
	Weekly	Set SCS Cycle Time	3.3.6	SCS: § 5 SCS: § 9.1.3/4 SCSL: § 4
	Rare	LPSB Power Adjustment	3.3.7	SCS: § 9.1.3/4 SCSL: § 4

Phase	Frequency	Operation	Cryo-ops Document Reference	User Manual Reference
	Weekly	Predict SCS Units Residual Lifetime	3.3.8	SCS: § 5.5 SCSL: § 4
	Weekly	Monitor Dilution Cooler Residual Lifetime	3.3.9	HFI: § TBP
	Weekly	Monitor 4K Cooler High and Low Pressure and Flow	3.3.10	HFI: § 11.12.4
	Daily	Monitor HFI Temperatures and Fluctuations	3.3.11	HFI: § TBP
	Rare	Readjust HFI PID Parameters	3.3.12	HFI: § 11.12.3
	Daily	Monitor LFI Temperatures and Fluctuations	3.3.13	SCS: § 5.1 SCS: § A.3.5.5 SCSL: § 4 HFI: § TBP
	Weekly	Monitor 4K VCS Error Signal	3.3.14	HFI: § 11.12.4
	Rare	Re-tune VCS	3.3.15	HFI: § 11.12.4
	Weekly	Monitor 4K Cooler Margins	3.3.16	HFI: § 11.12.4
	Rare	Readjust the 4K Stroke Amplitude	3.3.17	HFI: § 11.12.4
	Weekly	Monitor Setting of the 4K PID	3.3.18	HFI: § 11.12.3
	Weekly	Monitor Setting of the 1.6K and 0.1K PIDs	3.3.19	HFI: § 11.12.3

Phase	Frequency	Operation	Cryo-ops Document Reference	User Manual Reference
	Daily	Detect JT Plug on HFI	3.3.20	HFI: § 11.12 HFI: § 11.17
	Daily	Detect JT Plug on LFI	3.3.21	SCS: § 6.1.1 SCS: § 6.1.2.1.7 SCS: § 9.2.2.1
	End of Cooler Lifetime	Regeneration of SCS	3.3.22	SCS: § 5.6 SCS: § 8.5.2 SCS: § 9.2.2.2 SCSL: § 4

Table 18 User Manual Procedure Reference – Expected Anomalies

Phase	Operation	Cryo-ops Document Reference	User Manual Reference
Anomalies	SCS Switch-over	4.3.1	SCS: § 9.2.2.3
	Solar Flares	4.3.2	No procedure required
	Moon Eclipses	4.3.3	No procedure required
	SCS Regeneration	4.3.4	SCS: § 5.6 SCS: § 8.5.2 SCS: § 9.2.2.2 SCSL: § 4

Table 19: User Manual Procedure Reference - Contingencies

Phase	Operation	Cryo-ops Document Reference	User Manual Reference
Contingencies	Cryo-Chain Power-off Condition	4.4.1	LFI: § 13.1.2.13 LFI: § 13.3 HFI: § TBP
	SCS JT plug, needing Manual Intervention	4.4.2	SCS: § 6.1.1 SCS: § 6.1.2.1.7 SCS: § 9.2.2.1
	SCS in Ready Mode	4.4.3	SCS: 9.1.5 SCS: § 7
	SCS Communications Failure	4.4.4	SCS: § 7
	SCS Bed Failure	4.4.5	SCS: § 7 SCS: 9.2.2.4
	TSA Heater Failure	4.4.6	SCS: § 7 SCS: § 9.2.2.5
	4K Cooler Failures	4.4.7	HFI: § 11.17
	4K Cooler JT Plug	4.4.8	HFI: § 11.17
	Dilution Cooler Failure	4.4.9	HFI: § 11.17