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CHANGE RECORD

Issue	Date	Sheet	Description of Change	Release
1.0	Aug 22, 2008	All	Initial Release	===
1.1	Oct 15, 2008	All	2nd revision, Post TV HealthCheck included	

TABLE OF CONTENTS

1. Applicable and Referenced Documents

Number	Title
AD1	Planck FM TV/TB Test Specification, H-P-3-ASP-TS-0893 v. 4.0
AD2	Planck SCS TV/TB Test Procedures PL-LFI-PST-PR-025 v. 2.2
AD3	Planck SVM TBT Thermocouples Location, H-P-TN-AI-0117 v. 3.0
AD4	Planck Sorption Cooler ICD, PL-LFI-PST-ID-002 v. 3.1
AD5	Herschel/Planck IID-A, SCI-PT-IIDA-04624 v. 4.0
RD1	Planck SCS User Manual, PL-LFI-PST-MA-002, v.1.0
RD2	Planck Sorption Cooler Electronics User Manual, PL-MA-CRS-0036 v. 2.0
RD3	Planck SCE TC and TM Structures, TS-PSCBC-100010-LPSC, v. 8.2
RD4	Planck SCE OBSW Problem Report – SPR-PSCBC-600094-LPSC/delete
RD5	Planck SCE S2K 3.1 IEGSE USER GUIDE, UM-PSCZ-600124-LPSC v.1.1
RD6	Planck SCE MIB User Guide UM-PSCZ-600092-LPSC 01_05
RD7	Planck Sorption Cooler Two Phase Flow Summary, JPL D-46303
RD8	Planck Cryo-chain Operations, Planck/PSO/2007-017

2. Executive Summary of PFM2 Sorption Cooler Testing

2.1. Test Summary

The Planck sorption cooler nominal unit was actively tested from 27 June until 7 August 2008. It was tested in two main thermal conditions: beginning-of-life; and end-of-life power conditions. These two cases correspond to input powers of 304 and 470 W, and hot radiator interfaces of 270 and 273 K for the cold and hot cases respectively. For the cold case the last pre-cooling stage (PC3C or V-groove 3 temperature) was 47 K and 48 K for the hot case. Cooler performance is determined by these two interfaces.

For the testing, the sorption cooler met all of its 4 main requirements- cold-end temperature and fluctuations, heat lift or cooling power, input power- except for temperature fluctuations. This non-compliance with requirements was expected, and is due to gravitationally induced two-phase flow irregularities. The temperature fluctuation requirement was also not met in the JPL sub-system testing nor the ESA PFM1 test for the same reason.

Lifetime of the sorption cooler system was more accurately accessed with the results of the current testing. With the determination of the 3rd V-groove temperature and the LFI instrument load, a more refined estimate of the lifetime can be made. With these conditions as baseline, the nominal cooler will be capable of operating for 15.5 months, while the redundant can operate for 13.5 months. Minimum mission requirements of 9.1 months for each unit are easily met.

In addition to complying as expected to the fundamental requirements, additional confidence was gained in cooler operation through the process of periodic look-up-table updates. As expected, this confidence increases by making small and more frequent adjustments.

Finally, the sorption cooler electronics (SCE) performed flawlessly. All modes of the sorption cooler were executed properly. One issue was the inability to synchronize the SCE with the spacecraft computer. This issue has been the object of active testing and investigation, and has been resolved by a software modification.

More detailed discussion of the test results are discussed in Section 5. Sections 6 & 7 discuss the temperature fluctuations and the mission lifetime, respectively.

3. Scope & Introduction

This document reports the results of SCS testing performed during the PFM2 test campaign at the CSL (Centre Spatial de Liège) facilities. Both SCS TMU's were integrated on the S/C but only the unit indicated by SCS-N, officially considered the Nominal one of the two delivered by JPL, was tested. Ground testing of the Redundant unit, FM1, was performed in March 2006.

The test campaign spread over about 2 months, from late June to mid-August 2008. This report covers tests, results and issues related to the SCS only.

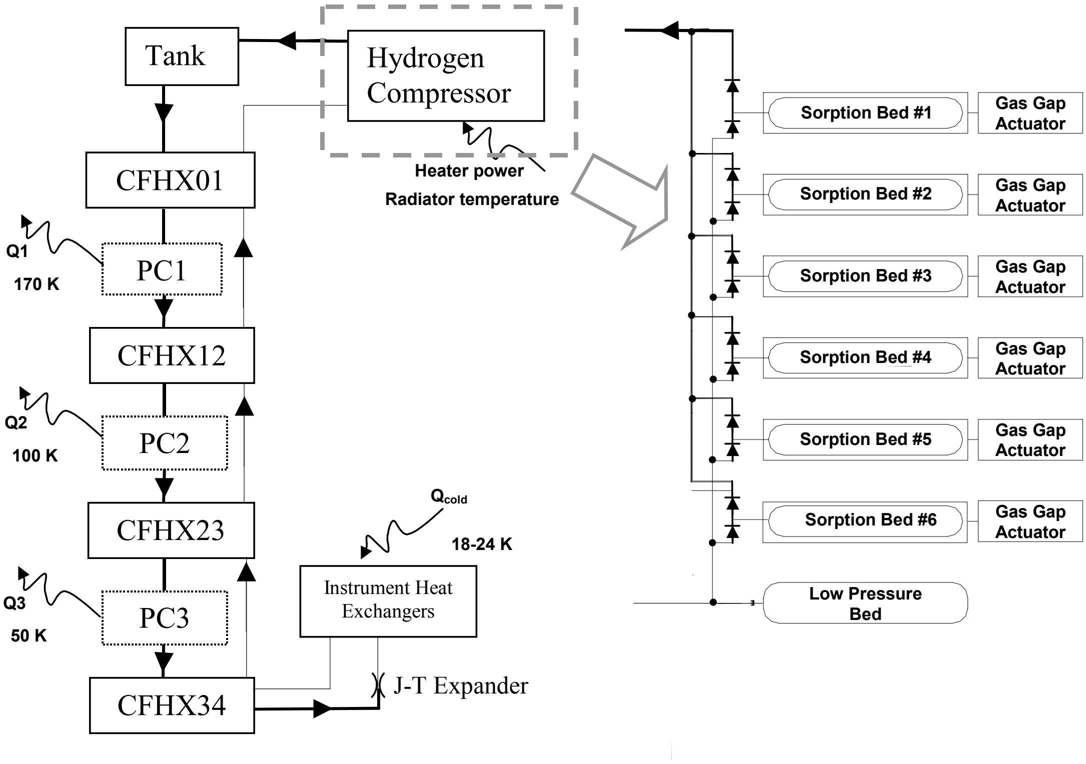


Figure 3-1. Planck Sorption Cooler Schematic

3.1. SCS General Description

The Planck Sorption Cooler uses isenthalpic (Joule-Thomson) expansion of hydrogen gas to produce approximately 1 W of heat lift at ≤19 K. A six-element sorption compressor is used to produce a pressure of 4.8MPa. The Joule-Thomson expander is chosen for a nominal mass flow rate of 6.5 mg/s. To provide the required cooling the high-pressure gas needs to be cooled to below 60 K. This is accomplished with a counter-flow, tube-in-tube heat exchanger and three pre-cooling stages nominally set at 155, 115, and 55K. With the pressure and mass flow, the temperature of the coldest pre-cooler determines the amount of cooling power while the higher temperature pre-coolers reduce the amount of heat released at the last pre-cooler. To provide independent temperatures for the two Planck instruments, two liquid-vapor heat exchangers (LVHX1 and LVHX2) are used to remove heat from the instruments. Temperature stability is obtained by maintaining the vapor pressure constant by compressor element absorption. During absorption, heat is rejected to a radiator whose temperature is crucial for determining the absorption pressure and in turn the temperature and temperature stability of the two instruments. Figure 3-1 is a schematic depiction of the cooler. A detailed description of the Sorption Cooler System can be found in RD1.

3.1.1. Planck Sorption Compressor

The “engine” of the cryocooler is the sorption compressor. It serves two main functions: 1) production of high-pressure hydrogen gas flow at ~4.8 MPa; and 2) to maintain a stable gas recovery rate, which keeps the return pressure, and thus the liquid temperature, constant. This is done by the use of compressor elements (or “beds”) whose principle of operation is based on the properties of a unique sorption material that is able to absorb large amounts of hydrogen isothermally at relatively constant pressure and to desorb high-pressure hydrogen when heated to around 200 C. Heating of the sorbent material is accomplished by electrical resistance heaters while the cooling is achieved by thermally connecting the compressor element to a radiator sized to reject the cooler input power at 270 K ±10 K. Six compressor elements are required for the compressor to operate cyclically. At any moment one bed is releasing gas (desorption) at 5 MPa, three are absorbing gas to maintain the vapour pressure constant, while the other two beds are being heated and cooled in preparation for desorption and absorption respectively. The ability of the compressor to maintain the vapour pressure of the liquid constant is determined by the absorption properties of the sorbent material. As a compressor element fills with hydrogen, the pressure will rise slightly and this is the main source of temperature fluctuations at the LVHX’s. The cycle time of the compressor is 667 seconds and is determined by the cooler requirements and the 60-second spin cycle of the Planck spacecraft.

As each compressor element undergoes the cyclic heating and cooling, a gas-gap heat switch is used to couple or decouple the compressor element to the radiator depending on its state. The heat switches use a sorbent material that when heated releases gas to turn the switch “ON” and when cooled reabsorbs the gas to isolate the element. During the heat-up and desorption cycles the heat switch is “OFF”, while during the cooldown and absorption cycles the heat switches are “ON”.

The compressor also includes four 1-liter tanks on the high-pressure side (HPST). These tanks serve as a gas ballast to smooth mass flow variations due to the desorbing compressor elements. On the low pressure side of the compressor is a low pressure storage bed (LPSB) that stores hydrogen gas when the cryocooler is not operating to keep the system pressure below 1 Bar. Additionally, the LPSB stores gas that is evolved as the cooler ages. Two heaters are mounted to the LPSB. One is used in nominal operation to control the gas concentration in the compressor elements, while the second is used when the cooler is started to move gas from the LPSB to the HPST. Check valves direct flow out of the compressor elements into the HPST and control flow from the low pressure manifold and the LPSB back into the absorbing beds.

3.1.2. Piping Assembly and Cold End (PACE)

The Piping Assembly and Cold End comprise the two main parts of the PACE. The piping assembly consists of a tube-in-tube heat exchanger and three pre-cooler interfaces. This assembly serves to pre-cool the high-pressure gas stream to below 60 K to produce the required cooling power. The three pre-coolers in flight will attach to V-groove radiator panels with nominal temperatures of 155 K (PC1), 110 K (PC2), and 55 K (PC3). For PC3, three stages are implemented to distribute the heat into the radiator panel.

A carbon cold trap is also located on the coldest radiator to remove condensable contaminants from the high pressure gas stream. As shown in Figure 3-2, the Cold End as the second assembly, consists of the Joule-Thomson (JT) expander, two liquid-vapour heat exchangers, and an assembly (formerly known as LR3), to heat balance the Cold End.

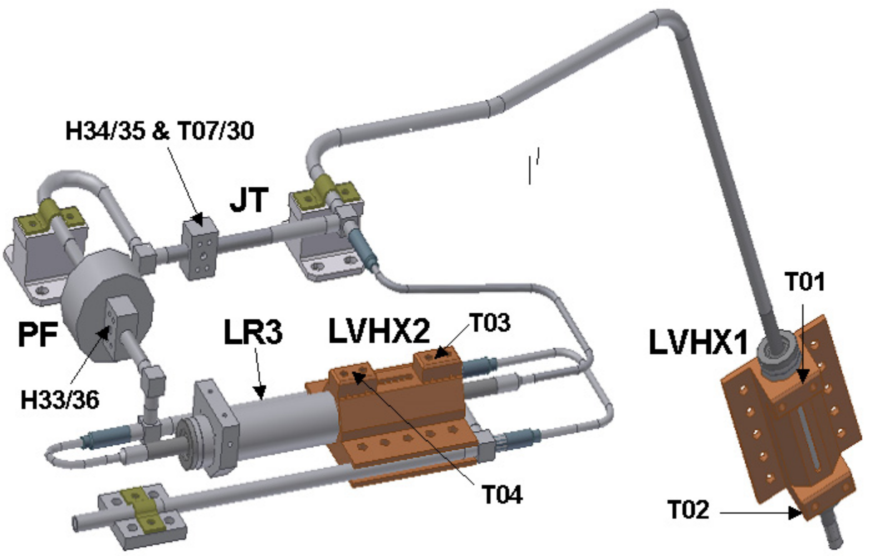


Figure 3-2 Schematic of Cold End.

The JT expander is selected to produce a flow of 6.5 mg/s +/- 5% for an input pressure of 4.8 MPa. The first liquid-vapour heat exchanger, LVHX1, attaches to the HFI instrument. It is designed to provide a temperature lower than 19 K with 190 mW of cooling power. The second LVHX, attaches to the LFI instrument to provide a temperature less than 22.5 K and 646 mW of cooling power. At the interface of LVHX2 and LFI, a copper block is designated as the Temperature Stabilization Assembly (TSA). Two stainless steel strips are sandwiched in between to define the conductance between the TSA and LVHX2. This arrangement allows active temperature control at the interface using a PID algorithm. 150 mW is allocated for the TSA for implementation of this temperature control scheme. In addition, the high-pressure gas stream exchanges heat with LVHX2 to pre-cool the gas and maintain its temperature constant before passing through the JT expander. Other elements of the cold-end include a tube-in-tube heat exchanger that joins the last pre-cooler to the cold-end, and a particle filter that protects the JT expander.

3.1.3. SCS sensors

The TMU include T and P sensors, used to monitor and control the SCS, can be summarized in the following tables.

T sensors

Item	Location	Nominal (K)	Resolution requested for specified Range				Type
			Range I (K)	Resolution I (K)	Range II (K)	Resolution II (K)	
T1	LR1	18	16-25	0.010	20-80	1	CERNOX
T2	LR1	18	16-25	0.010	20-80	1	CERNOX
T3	LR2	20	16-25	0.010	20-80	1	CERNOX
T4	LR2	20	16-25	0.010	20-80	1	CERNOX
T5	LR3	20	16-24	0.004			CERNOX
T6	LR3	20	16-24	0.004			CERNOX
T7	JT	20	16-25	0.010	20-150	1	CERNOX
T8	PC3C	55	40-80	0.1	80-330	2	CERNOX
T9	PC3B	70	40-80	0.1	80-330	2	CERNOX
T10	PC3A	80	40-80	0.1	80-330	2	CERNOX
T11	PC2	100	80-150	0.1	150-330	2	CERNOX
T12	PC1	160	140-190	0.1	190-330	2	CERNOX
T13	HPST1	300	220-320	0.040			PRT
T14	HPST2	300	220-320	0.040			PRT
T15	Shell CE1	270	220-350	0.040			PRT
T16	Shell CE2	270	220-350	0.040			PRT
T17	LPSB	300	220-320	0.040			PRT
T18	LPSB	300	220-320	0.040			PRT
T19							
T20	CE1	40	0 - 275	0.3	275-425	1	KTC
T21	CE2	40	0 - 275	0.3	275-425	1	KTC
T22	CE3	40	0 - 275	0.3	275-425	1	KTC
T23	CE4	40	0 - 275	0.3	275-425	1	KTC
T24	CE5	40	0 - 275	0.3	275-425	1	KTC
T25	CE6	40	0 - 275	0.3	275-425	1	KTC
T26	Shell CE3	270	220-350	0.040			PRT
T27	Shell CE4	270	220-350	0.040			PRT
T28	Shell CE5	270	220-350	0.040			PRT
T29	Shell CE6	270	220-350	0.040			PRT
T30	JT	20	16-25	0.010	20-150	1	CERNOX

P Sensors

Name	Location	Nominal (bar)	Range (bar)	Resolution (bar)	Resolution (mV)	Accuracy (bar)	Input (Vdc)	Return (Vdc)
P1	CE1	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P2	CE2	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P3	CE3	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P4	CE4	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P5	CE5	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P6	CE6	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P7	HPST	50	0 – 67	0.07	5	0.3 FSR	28	0 – 5
P8	LPSB	0.5	0 – 3.4	0.01	14	0.02	28	0 – 5

Another set of important sensing lines is acquired by the electronics in order to monitor power used or dissipated and to check the SCE box operating temperatures. These extra values are:

SCE sensors

Channel	Type	Range
28V	Internal voltage	26 to 29 V
+12V	Internal voltage	11 to 13.1 V
VCC	Internal voltage	5 to 5.2 V
+15V	Internal voltage	14 to 17.3 V
-15V	Internal voltage	-14 to -17.3 V
31V	Internal voltage	29.9 to 35.7 V
SCE_T(1)	Internal T Readout Module	-24 to +85 C
SCE_T(2)	Internal T Power Module	-24 to +85 C
SCE_T(3)	Internal T Digital Module	-24 to +85 C
SENSE_LPSB	Heater Current	0 to 0.96 A
SENSE_LR3N	Heater Current	0 to 0.80 A
SENSE_LR3R	Heater Current	0 to 0.80 A
GG_CE(1)	Heater Current	0 to 1.84 A
GG_CE(2)	Heater Current	0 to 1.84 A
GG_CE(3)	Heater Current	0 to 1.84 A
GG_CE(4)	Heater Current	0 to 1.84 A
GG_CE(5)	Heater Current	0 to 1.84 A
GG_CE(6)	Heater Current	0 to 1.84 A

3.1.4. The Sorption Cooler Electronics (SCE)

The SCE (nominal or redundant) is the electronics unit operating the SCS (nominal or redundant). The purpose of the SCE is to:

- Drive the sorption cooler by
  - switching control for the sorption bed heaters

- switching control to the heat switches
- timing signals for the switching
- controlling of power to the compressor elements in the “desorbing” state
- controlling the T (PID) of the Temperature Stabilization Assembly (TSA) in the SCCE.

- Detect abnormal situations and react if a problem is detected in order to ensure the sorption cooler and its environment health. This is done by reading temperature and pressure sensors values from the sorption cooler.
- Read temperature, voltage and intensity sensors from sorption cooler electronic.
- Receive commands from CDMU sent by users from ground
- Send housekeeping data to CDMU that will be transmitted to ground by telemetry.

Block Diagram of the Sorption Cooler Subsystem (SCS)Figure 3-3 shows the SCE Nominal and Redundant in the S/C environment.

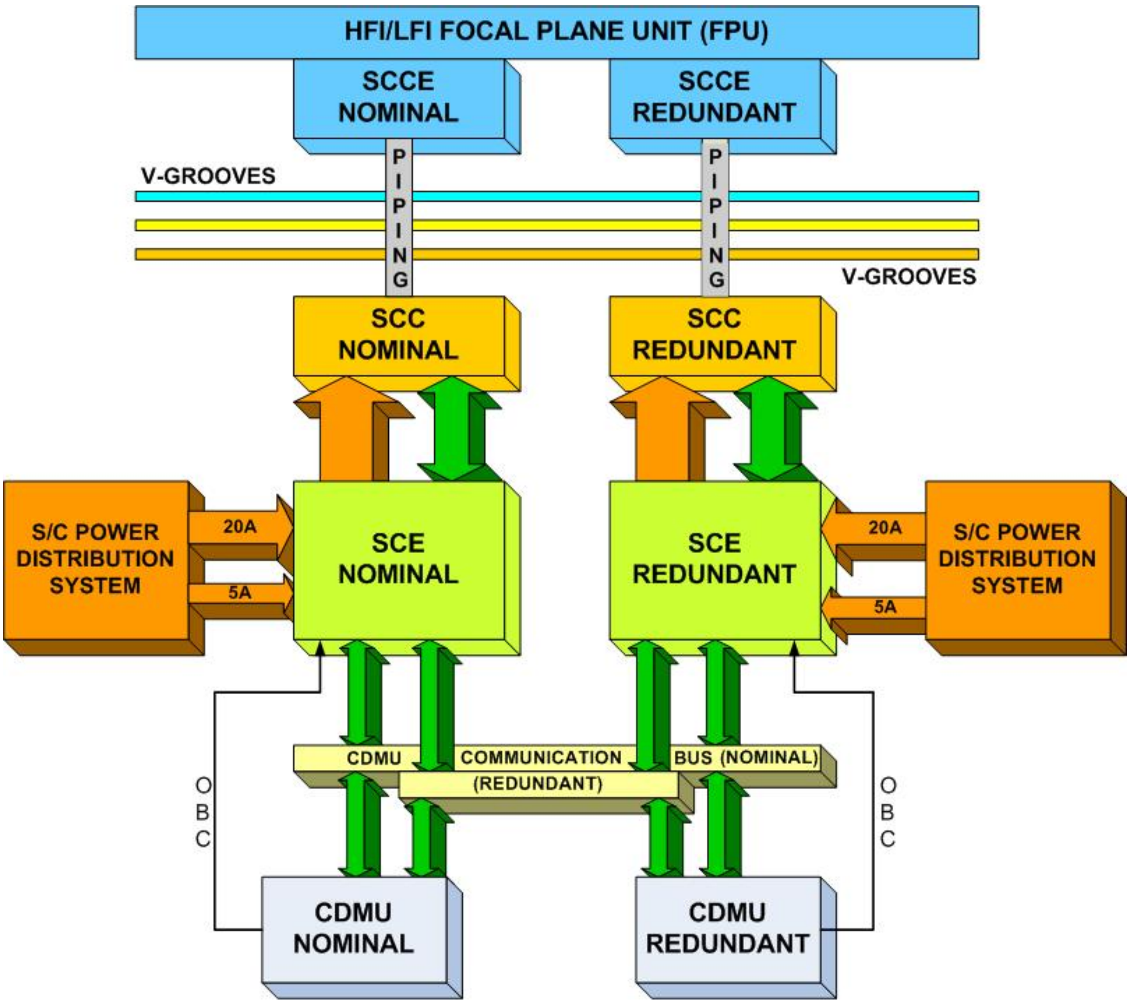


Figure 3-3 Block Diagram of the Sorption Cooler Subsystem (SCS)

The Figure 3-3 shows the interface relationships between the SCE and the other parts of the SCS, together with the top-level redundancy concept of the SCS itself:
The nominal SCE is active while the other one is in “not-operating redundancy state”. The selection of the working SCE is made by the S/C by selecting the appropriate 28 V lines.
The interface with the spacecraft will be able to handle a baseline data rate of 2 kbit/s and will be compliant with the MIL-STD-1553B standard, with the SCE acting as a remote terminal and the CDMS as the bus controller.
The SCE subsystem will include DC/DC converters with a nominal input DC voltage of 28 V and +5V, +15V, –15V and 31V or +12V.
The SCE will also contain ADCs and Multiplexer components allowing the read data from the sensors (voltage, current, temperature and pressure). The interface to the heaters will be realized with DAC’s components and power MOS radiations tolerant transistors.
Data communication interface will be implemented following the MIL-STD 1553B standard, through one nominal and one redundant transformer in the long stub configuration.
The specifications and detailed descriptions of the SCE SW and HW can be found in RD1 and RD2.

3.2. SCS requirements

TMU Spec	Requirement Value
Cold End Temperature	**17.5 K < LVHX1 < 19.02 K** **17.5 K < LVHX2 < 22.50 K**
Cooling Power	**Cooling power @ LVHX1 > 190 mW** **Cooling power @ LVHX2 > 646 mW** **TSA dissipation = 150 mW** **Total Cooling Power > 986 mW**
Input Power	**TMU Input power < 426 W @ BOL**
Cold End Temperature Fluctuations	**ΔT @ LVHX1 < 450 mK** **ΔT @ LVHX2 < 100 mK**

Table 3-1. Primary verification criteria for SCS TMU performance

In Table 3-1 are summarized the SCS requirements: they are the primary reference values to evaluate the cooler performance.

4. Test configuration

The PFM2 test configuration is, as regards SCS functionality and performance is equivalent to the final flight configuration.

For a detailed description of the Test configuration refer to AD1.
For a detailed description of Test Technical Description see AD2.
For a detailed description of SVM Test Thermal Instrumentation see AD3.

Figure 4-1 shows the configuration of EGSE (see RD5) used to operate the spacecraft and for performance testing during the PFM2 test campaign.

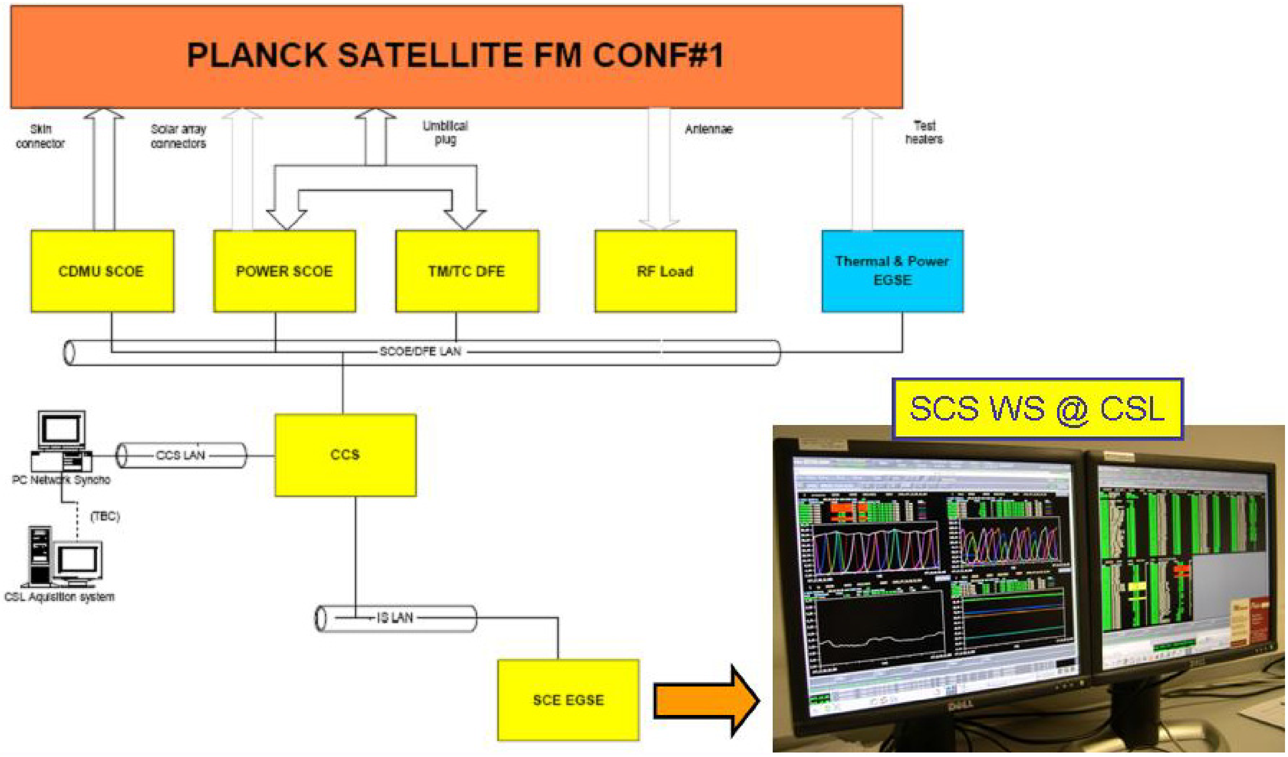


Figure 4-1 ***Configuration of spacecraft EGSE for PFM1***

The CCS is the system controlling the sequencing of the test and required while the experiment (SCE in this case) EGSE in only limited to monitoring the status of the cooler and the procedures of the test.

4.1. Test Objectives

The main goals of the PFM2 test campaign are:

Functional validation of the Sorption Cooler Nominal Unit (SCS-N) on the S/C with FM PLM in full flight representative conditions (Warm Radiator and V-grooves at Flight Nominal Temperature). Two main cases were run: Warm radiator cold; and Warm radiator cold. For the cold case the SCS is tuned to produce the heat lift necessary for the instruments and its operation, subject to the constraint of maximizing SCS lifetime. For the warm case the SCS is tuned to produce its maximum power, 470 W, which will simulate end-of-life conditions. For each case the SCS must meet its requirements, Table 3.2.
In addition, other minor tests will be performed. These are discussed in Section 5, where the verification matrix is presented along with a discussion of results for each test phase.

4.2. Test History

The actual operation of the SCS-N unit started on Friday June 27th 2006 and was completed by Friday August the 7th, for a total of 41 days. Number of cycles for each compressor element was 720.

5. Verification Matrix and Test Results

5.1. PrTV-1-2-d SCS Warm Healthcheck Nominal Unit

Before starting the SCS a Warm Healthcheck process in thermal-vacuum was performed to check that the system was in the nominal status. To ensure that no damage occurred at the SCS during all activities (and in particular transportation to testing site) performed after last HealthCheck (HC). “Warm HC” is a reduced procedure with respect to the “full HC”, due to the fact that cold sensors and heaters cannot be checked in warm conditions for hardware safety reasons. This HC will provide a reference baseline for the functional verifications to be performed at the end of test campaign.

5.1.1. PrTV-1-2-d Verification Matrix

Phase #	PrTV_1_2_d				
Test name:	SCS-N Pre TV HealthCheck				
Test objectives:	To check system health after transportation and integration in cryofacility before starting TVTB				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected events packets	✓		SCS-N Warm HealthCheck has been fully successful	N/A	N/A
Sensors response as expected	✓			N/A	N/A
Power consumpiton as expected	✓			N/A	N/A

5.1.2. PrTV-1-2-d Test Results

The whole process can be shown in Figure 5-1 where the upper section of the graph shows the LPSB temperature behaviour while the lower section illustrates the compressor elements temperature and pressure.

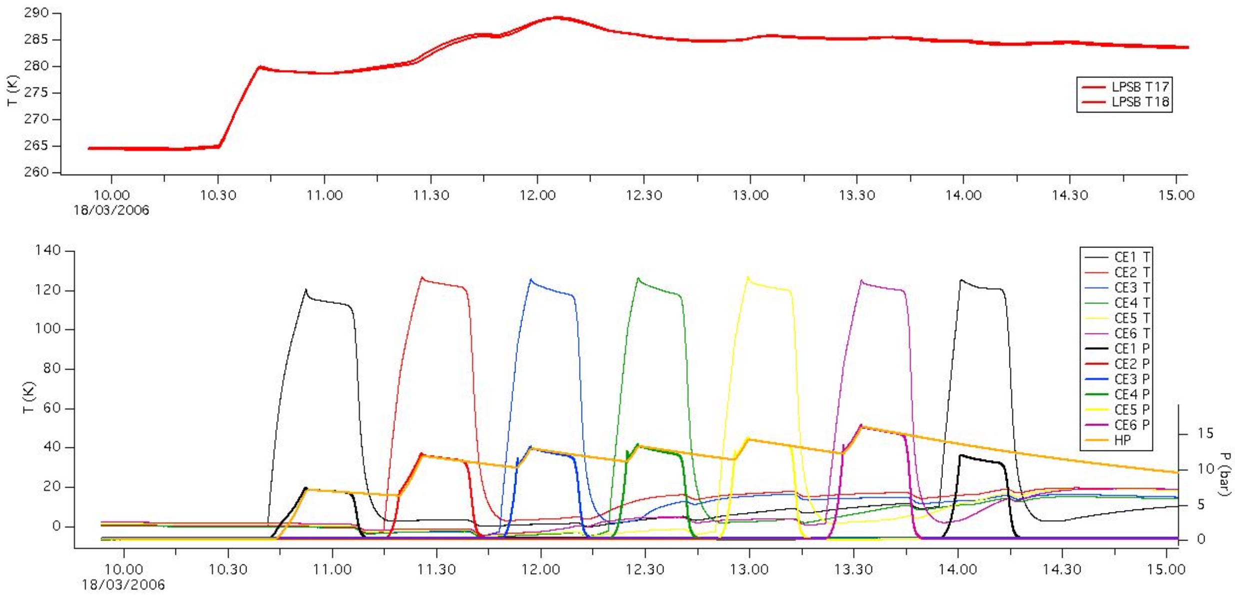


Figure 5-1 Healthcheck procedure: LPSB test (upper), Beds T and P (Lower)

The results of the Healthcheck process were fully compliant to the nominal status required to operate the SCS: For this reason, it was then decided to start the Sorption Cooler.

5.2. Ph-4-05-e SCE Switch On

At the end of Phase 4-05 (Ph-4-05-e), the SCE shall be switched On in READY Health Monitoring, in order to monitor the remaining part of PLM cooldown.
Objective of this test is to start the SCE-N in READY Mode (Health Monitoring) to monitor SCS status during passive cooldown.

5.2.1. Ph-4-05-e Verification Matrix

Phase #	**04_05_e**				
Test name:	SCE Switch-On during cooldown				
Test objectives:	To switch the SCE ON in READY Mode - Health Monitoring to monitor SCS status during passive cooldown				
Verification matrix					
Check	**Passed?**			**Recovered?**	
	Yes	**No**	**Notes**	**Yes**	**No**
No unexpected events packets			SCE Synch process was unsuccessful. It has been possible to synchronize the unit only after multiple tries. Investigation of SCE synch problem are on-going in the framework of an NCR		**NCR Opened**
No unexpected sensor readings	✓		SCE was regularly activated, sensing lines were working as expected	N/A	N/A

5.2.2. Ph-4-05-e Test Results

The synchronization process between the SCE and the spacecraft computer was initially unsuccessful. Synchronization would occur after multiple attempts, but it was neither predictable nor repeatable. This problem is the subject of an ongoing investigation that will include the flight spare and AVM models. A software work-around has been implemented in the flight software version 99 Rev. 7 b4. All other aspects of the switch-on process were successful.

5.3. Ph-5-01 SCS Start-up

The SCS was started at 7:30 on 27 June. Liquid hydrogen was produced 200 hours later and the nominal mode was entered 20 hours after liquid production.
Objective of this test is to start the SCS-N and take it into Run Mode and Nominal Operations.

5.3.1. Ph-5-01 Verification Matrix

Phase #	**05_01**				
Test name:	SCS Start-up				
Test objectives:	To start the SCS-N and take it into Run Mode and Nominal Operations.				
Verification matrix					
Check	**Passed?**			**Recovered?**	
	Yes	**No**	**Notes**	**Yes**	**No**
No unexpected events packets			A wrong value mapped in the EAT of OBCP, made the system trip power OFF as soon as it entered Nominal Mode. Error in an obsolete table in SCS documentation was found. It will be corrected in next SCS UM Issue. Solution adopted was the disabling of OBCP. In the meantime table has been corrected even if it is likely that SCS OBCP will be disabled also in flight ops or at least used in a shorter list of events for safety issues.	✓	
Data saved and stored in the I-EGSE	✓		Problems with SCS EGSE TM data retrieval have been experienced due to the mis-interpretation of date and time at the very beginning of the test. EGSE synch has been corrected by LPSC team and since then all needed TM have been correctly retrieved by SCS operators. Together with this modifications other required improvements such as full database ingestion and TC echo retrieval have been implemented for SCS EGSE full functionality.	N/A	N/A
SCS shall enter RUN Mode	✓		RUN Mode entered as expected	N/A	N/A
SCS shall enter Nominal Operations	✓		Except for the unexpected event reported above, smooth transition into Nominal has been observed	N/A	N/A
SCS shall meet performance requirements	✓		Performance requirements met in Nominal Mode	N/A	N/A

5.3.2. Ph-5-01 Test Results

The startup and cooldown process were performed as expected. Cooldown was within the predictions of the Thales thermal model. Transition to the nominal was prevented due to the spacecraft OBCP software. When the SCE tried to transition to the nominal mode, the OBCP would shut the SCS off. For the test, the OBCP was disabled. Thales will correct the problem with their software.
During the cooldown the SCS performed without any issues. The entire cool down process is shown in Figure 5-3-1.

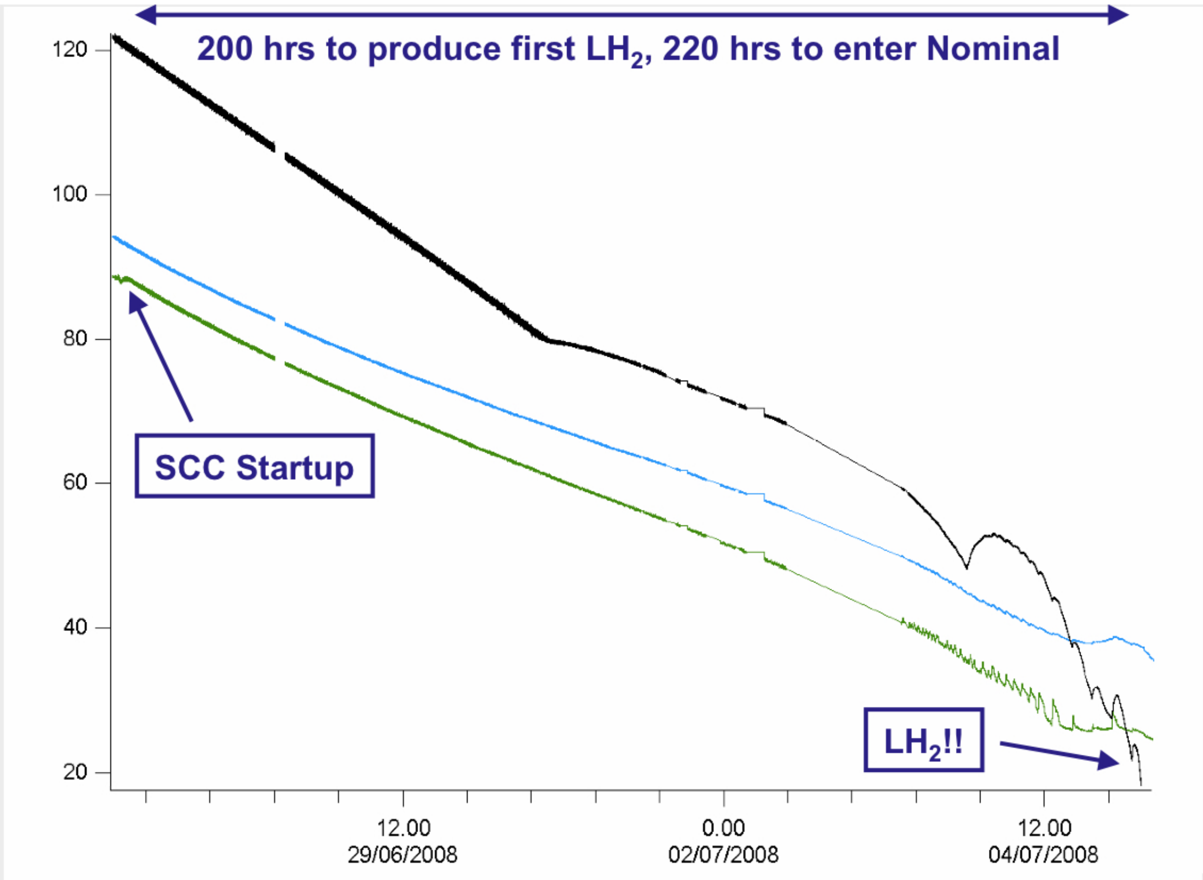


Figure 5-3-1 Cooldown of the SCS cold-end. Total time from SCS start-up to the production of liquid was 200 hours. Temperature traces are: black LVHX1; blue LVHX2; green Joule-Thomson valve (K).

5.4. Ph-5-02-e SCS parameters and TSA tuning

Objective of this test is to adjust the SCS operational parameters for nominal cooler performance in order to ensure optimal conditions for instruments test. In such a way, the cooler will perform in nominal conditions meeting all its requirements. This is a fundamental step for the entire test, an out of balance SCS has a strong impact on the thermal status of other sub-systems and of the test.

5.4.1. Ph-5-02-e Verification Matrix

Phase #	**5_02_e**				
Test name:	SCS parameters and TSA tuning				
Test objectives:	To adjust the SCS operational parameters for nominal cooler performance in order to ensure optimal conditions for instruments test. In such a way the cooler will perform in nominal conditions meeting all requirements. This is a fundamental step for the whole cryo test, an SCS out of balance has an impact on the whole cryo test.				
Verification matrix					
Check	**Passed?**			**Recovered?**	
	Yes	**No**	**Notes**	**Yes**	**No**
No unexpected event Packets			During TSA PID activation a LUT parameter in the PID Section was set too low. This triggered an error that made the ASW declare the TSA heater as BAD even if from the HW point of view the heater was ok. LUT value has been increased and full functionality of PID control heater has been restored. Investigations of why the value set in the LUT (that was selected in the expected range) was too low are on-going. This parameter is used by ASW to check TSA heater health and it does not have any impact on TSA functionality.	✓	
SCS shall remain in Nominal Operations	✓		Once entered in Nominal Model, SCS quickly reached a stable working point and maintained itself in a steady state even in the occurrance of external conditions or load variations. The Cold End shows robustness against external perturbation by automatically adjusting cold end heat balance.	N/A	N/A
SCS shall meet performance requirements	✓		Cold End T's, Input Power, Cooling Power requirements are fully met	N/A	N/A
T fluctuations at TSA below 100 mK			TSA ΔT peak-to-peak have been osberved around 106mK 3σ rs variation are on the order of 60-70mK Higher fluctuations were expected due to gravitationally induced 2-phase flow **Not blocking for LFI test**		**NCR Opened**
LVHX1 DT shall remain below 450 mK			LVHX1 ΔT peak-to-peak have been osberved around 520mK 3σ rms variation are on the order of 270mK Higher fluctuations were expected due to gravitationally induced 2-phase flow **Not blocking for HFI test**		**NCR Opened**
TSA PID control power below 150 mW			Average TSA power is around 190 mW due to the higher two-phase fluctuations and setpoint required for LFI. Higher dissipation was expected and accepted to keep LFI working point constant during tuning tests	✓	

4.4.1 Ph-5-02-e Test Results – Cooler Parameters

The cooler parameters were set for the interface conditions of the cold spacecraft thermal balance at midnight 20 July, 2008. The two primary interfaces, V-groove three and warm radiator temperatures were 47 and 270 K, respectively. Table 5-4-1 summarizes the final cooler parameters for this case. Excessive temperature fluctuations, due to gravitationally induced plug-flow events, resulted in a cycle-time lower than what will be used on flight. In addition, a full cooler cycle- six times the cycle-time- modulation resulted in non-uniform gas-gap delays at the start of the cooldown cycle. The resultant performance will be discussed in Sec. 5.6.

Heatup power (W)	Desorption power (W)	LPSB power (W)	Cycle Time (s)
112	160	1.30	940

	Gas-gap delay (s)
CE1	65
CE2	8
CE3	0
CE4	43
CE5	75
CE6	48

Table 5-4-1. Cold-case SCS Parameters

5.4.2. Ph-5-02-e Test Results – PID Tuning

PID tuning parameters were: 500 for the proportional, 15 for the integral, and 0 for the derivative.

5.5. Ph-6-09 SCS Heat Lift Measurement

The objective of this test is to measure the cooling power produced by the SCS in the Cold TB Case. This is a fundamental verification of cooler functional performance and LFI thermal behaviour: it will allow not only to measure SCS performance in terms of heat lift but also to provide an indirect estimation of the LFI passive dissipation (parasitics).

5.5.1. Ph-6-09 Verification matrix

Phase #	06_09				
Test name:	SCS Heat Lift Measurement				
Test objectives:	To measure the produced cooling power of the SCS in the Cold TB Case. This is a fundamental verification of cooler functional performance and LFI thermal behaviour: it will allow not only to measure SCS performance in terms of heat lift but also to provide an indirect estimation of the LFI passive dissipation (parasitics)				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓			N/A	N/A
SCS cooling power shall be compliant to requirement with a max error of 100mW	✓		SCS heat lift has been measured, with respect to instruments dissipation and parasitics. An excess of 150 mW (+100, -0) over instruments load has been measured.	N/A	N/A

5.5.2. Ph-6-09 Test Results

Heat lift of the sorption cooler was determined of 15 July, 2008. This was done by determining the heat lift excess using the TSA heater, and by estimating the instrument loads. The excess heat lift was measured to be 355 mW, where 200 mW is for the TSA. The LFI load was estimated by use of the temperature difference between the TSA and the LVHX2, and the JPL measured thermal resistance between these two stages. This gave about 670 mW +/- 50 from LFI. HFI was assumed to be 100 mW, with the same uncertainty of +/- 50 mW. Thus the total heat lift was 1125 mW.
Calculating the heat lift from the SCS working pressures and PC3C temperatures gives a value of 1155 mW. This compares well to the measured 1125 mW. Thus, to experimental uncertainties, the SCS is performing nominally.

5.6. Phase 5 - Cold SCC Thermal Balance Performance

The Cold SCC Thermal Balance Test started at about 12 AM on 20 July 2008. As discussed above, the warm radiator temperature was about 270 K for this case and V-groove 3 was 47 K. The SCS ran almost 10 days under these conditions.

5.6.1. Temperature and temperature fluctuations

Temperature data (from top to bottom) for the TSA, LVHX2, and LVHX1 are shown in Figure 5-6-1. The TSA stage is controlled to a set point of 18.7 K, with fluctuations of 120 mK. These fluctuations are greater than the requirement of 100 mK. For LVHX1 the temperature is 17.09 while fluctuations are about 550 mK, again greater than the requirement. In addition, the power to control the TSA is ~200 mW that exceeds the 150 mW requirement.
Each of these requirement excesses are attributable to gravitationally induced plug flow, which were to be expected for the cold-end orientation for this test (the excessive TSA power

is mainly due to the use of a constant set point of 18.7 K, but some of the excess power is due to the plug flow). A more detailed discussion of this issue will made later when a comparison is made between the present cold-case and the hot-case in Sec. 6.
Finally, a cooler cycle modulation is clearly present in the data, i.e. due to differing performances of the individual compressor elements, the temperature of the cold-end varies over 6 bed cycle. Attempts were made to remove this modulation by adjusting the gas-gap timing as was discussed in 5.4.1.

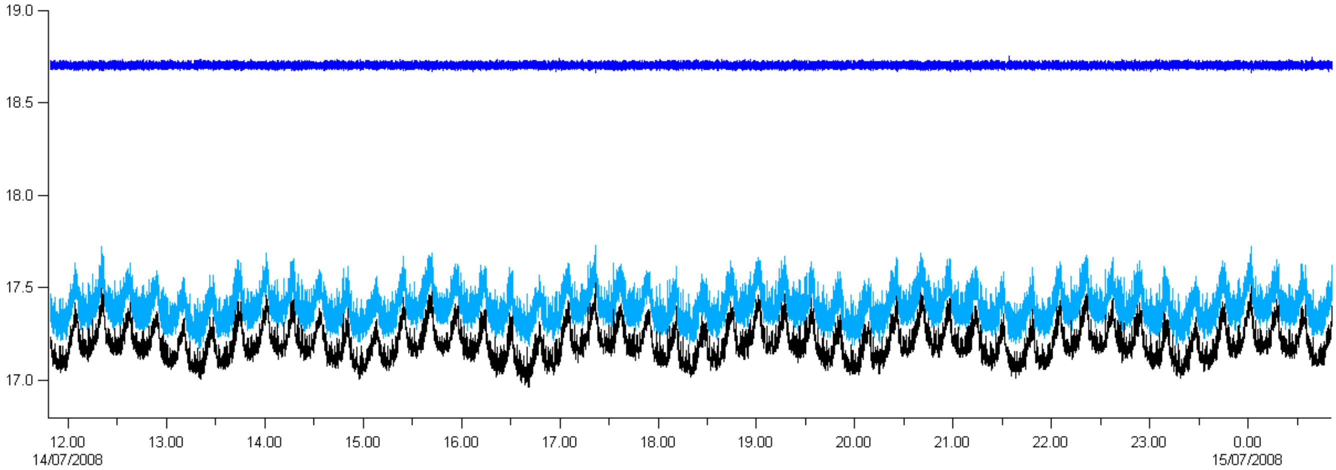


Figure 5-6-1 Cold Case cold-end temperatures. The dark blue trace is the TSA stage, the lighter blue is LVHX2, and the black is LVHX1.

5.6.2. Cold SCC Thermal Balance Test Results Summary

TMU Spec	Cold Case Results	Requirement Value
Cold End Temperature	17.09 K LVHX1 18.7 K TSA	17.5 K < LVHX1 < 19.02 K 17.5 K < LVHX2 < 22.50 K
Cooling Power	1125 ± 75 mW	Cooling power @ LVHX1 > 190 mW Cooling power @ LVHX2 > 646 mW
Input Power	304 W	TMU Input power < 426 W @ BOL
Cold End Temperature Fluctuations	550 mK LVHX1 120 mK TSA	ΔT @ LVHX1 < 450 mK ΔT @ LVHX2 < 100 mK

Table 5-6-1 Cold Case results summary

5.7. Ph-6-08 TSA Failure Test

This test shall verify the Instruments performance/behaviour in case of TSA failure, i.e. the impact on instruments performance of the raw unfiltered T fluctuations directly transmitted to the HFI (cryo-chain and 4K load) and LFI (FPU). The TSA is a critical stage for the SCS performance. For this reason there is 100% redundancy in both SCS FM units. Nevertheless there might be contingency situations requiring cooler operations (for either a limited or extended period of time) without Cold End stabilization as in the case, for example, of a hardware failure. It is crucial to test the impact of a disabled TSA on both instruments and cryo-chain functionality: higher raw, uncontrolled temperature oscillations will be entirely transmitted through the instruments interfaces

5.7.1. Ph 06_08 Verification Matrix

Phase #	06_08				
Test name:	TSA Failure Test				
Test objectives:	This test shall verify the Instruments performance/behaviour in case of TSA failure, i.e. the impact on instruments (and cryochain) performance of the raw unfiltered T fluctuations directly transmitted to the HFI (cryochain and 4K load) and LFI (FPU) since a higher raw, uncontrolled T oscillations will be entirely transmitted trough the instruments interfaces.				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓			N/A	N/A
SCS shall meet all performance requirements except cold end temperature fluctuations	✓		TSA failure was completed successfully. SCS cold end behavior as expected.	N/A	N/A

5.7.2. Ph-6-08 Test Results

Figure 5-7-1 shows the TSA turned off and the resultant fluctuations on the TSA stage. These are about 320 mK, which should be compared to the 550 mK on the LVHX2 stage. See next page.

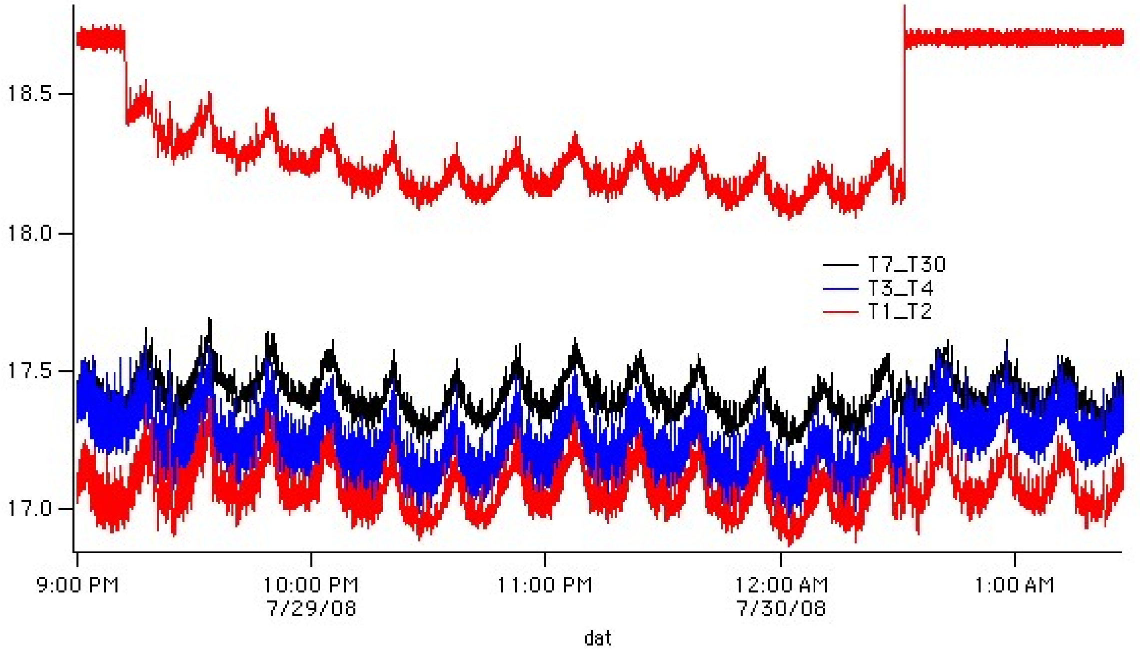


Figure 5-7-1. TSA shutoff.

4.8 Ph-7-01 SCS Cycle Time and Input Power small adjustment

SCS operations will be optimized to maximize cooler lifetime. The baseline operational scenario is requiring frequent (monthly or weekly) small adjustment steps of the cooler parameters. This test is intended to check possible effects on cooler balance and instruments performance of such small tuning iterations.
Objective of this test is to change SCS tuning parameters (usually cycle time and input power) by the typical amount of a weekly tuning step (i.e. by about 10-20 s and few watts) to check cooler response and performance to this variation together with instrumental effects on scientific data. This test will check and, possibly, quantify the effect of small cooler performance variations on instruments scientific output.

5.7.3. Ph-7-01 Verification Matrix

Phase #	07_01				
Test name:	SCS Cycle time and Power small adjustment				
Test objectives:	Objective of this test is to change SCS tuning parameters (usually cycle time and input power) by the typical amount of a weekly tuning step (i.e. by about 10-20 s and few watts) to check cooler response, readjustment and performance to this variation together with instruments effect on scientific data. This test is will allow to verify if such possible effects of small cooler performance variations on instruments scientific output.				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓			N/A	N/A
SCS shall remain in Nominal Operations	✓			N/A	N/A
SCS shall meet performance requirements	✓			N/A	N/A
No evident instability shall be noticed in cold end	✓		No instabilites were observed in the cold end. A small drift in temperature of the LVHXs was expected and measured due to the decrease of LPSB power.	N/A	N/A

5.7.4. Ph-7-01 Test Results

Adjustment values are shown in Table 5-8-1. The two input powers were heatup and desorption powers were increased by 2 W. The cycle-time was decreased by 15 s, from 940 to 925 s. Finally, the LPSB was reduced by 0.1 W.
The result of these changes was an increase of 0.8 Bar for the SCS high pressure, this was mainly due to the increase in the desorption power. The LVHX1 temperature decreased by 30 mK, which was attributable to the LPSB power decrease. This temperature would have continued to decrease as the time-constant of the LPSB is very large.

	Initial	Final
Heatup Power	160	162
Desorption Power	109	111
Cycle-time	940	925
LPSB Power	1.25	1.15

Table 5-8-1 Parameters changed for Ph-7-01.

5.8. Ph-8-01-a SCS Warm Case LUT

Objective of this test is to verify SCS performance in Warm TB and TV conditions and its impact on SVM thermal balance. Major thermal interfaces will be taken up to worst case temperatures in order to check PPLM functionality in these conditions. SCS shall be verified in worst case, end of life, maximum dissipation case: 470 W.

5.8.1. Ph-8-01-a Verification Matrix

Phase #	8_01_a				
Test name:	SCS Warm LUT upload				
Test objectives:	To verify SCS performance in Warm TB and TV conditions. Major thermal interfaces will be taken up to worst case temperatures in order to check PPLM functionality in these conditions. LUT values for the Hot Case depend on the test objective defined by TAS. If objective is to nominally run the SCS in hot (or worst case) boundary conditions then cycle time and input power will be tuned on the basis of these conditions. In this case, required performance shall be achieved and maintained until boundary conditions remain stable. If objective is to verify TB in SCS worst case, end of life, max dissipation then this case will be a repetition of PFM1 hot case and approximately same values (480s, 466W) could be used. In this case, nominal required performance cannot be ensured.				
Verification matrix					
Check	**Passed?**			**Recovered?**	
	Yes	**No**	**Notes**	**Yes**	**No**
No unexpected event Packets	✓			N/A	N/A
SCS shall be in Nominal Operations	✓		SCS went back into Nominal only 30 min after LUT change for Hot TVTB Max Dissipation case	N/A	N/A
SCS shall meet performance requirements	✓		All performance requirements were met	N/A	N/A

5.8.2. SCS settings

The SCS input values are summarized in Table 5-8-1. The total input power was 470 W when the cooler was in normal mode. In order to produce the full end-of-life power, the cycle-time was 525 s. This is nominally twice the cycle-time for beginning of life, so for the 5 days of the test, the cooler lifetime was consumed at twice the rate for nominal operations.
With this input power the warm radiator reached a temperature of ~273 K. This temperature was not stable for the test period. As a consequence the cold-end temperature was observed to drift.
Likewise, the 3rd V-groove drifted from about 46.9 to 47.7 K over the test period. Since the SCS was run with a heat-lift excess of about 0.5 W, performance was not impacted.

5.8.3. Temperature and temperature fluctuations

Fluctuations for the hot-case were ~350 mK peak-to-peak for LVHX1 and 60 mK peak-to-peak for the TSA stage. Here the SCS

Heatup power (W)	Desorption power (W)	LPSB power (W)	Cycle Time (s)
222	216	1.35	525

	Gas-gap delay (s)
CE1	65
CE2	8
CE3	0
CE4	43
CE5	75
CE6	48

Table 5-8-1. Cold-case SCS Parameters

requirements are met. This is in contrast to the cold-case where the requirements were not met for the two instrument interfaces. A discussion of the difference will be made later.

5.8.4. Hot SCC Thermal Balance Test Results Summary

TMU Spec	Cold Case Results	Requirement Value
Cold End Temperature	17.47 K LVHX1 18.7 K TSA	17.5 K < LVHX1 < 19.02 K 17.5 K < LVHX2 < 22.50 K
Cooling Power	Not measured	Cooling power @ LVHX1 > 190 mW Cooling power @ LVHX2 > 646 mW
Input Power	470 W	TMU Input power = 470 W @ EOL
Cold End Temperature Fluctuations	350 mK LVHX1 60 mK TSA	ΔT @ LVHX1 < 450 mK ΔT @ LVHX2 < 100 mK

Table 5-8-2 Hot Case results summary

5.9. Ph-10-05-a SCS Failure Test

This phase shall verify the Instruments response and behaviour in case of SCS failure, i.e. the impact on instruments and cryo-chain FDIR of an unexpected SCS stop.

5.9.1. Ph-10-05-a Verification Matrix

Phase #	10_05_a				
Test name:	SCS failure Test				
Test objectives:	This test shall verify the Instruments response and behaviour in case of SCS failure, i.e. the impact on instruments and cryo-chain FDIR of an unexpected SCS stop				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓		Cold End Warm-up has been monitored	N/A	N/A

5.9.2. Ph-10-05-a Test Results

The SCS was turned off at about 14:15 PM on 5 August. Figure 5-9-1 shows the behavior of the SCS high pressure manifold and the two instrument temperature interfaces. Liquid was lost from the cold-end after ~2.25 hours. Both instruments were on and dissipating nominal instrument powers during the entire test period. The HFI interface reached 24.3 K after about 4 hours, while the LFI interface reached 27.3 over the same period.

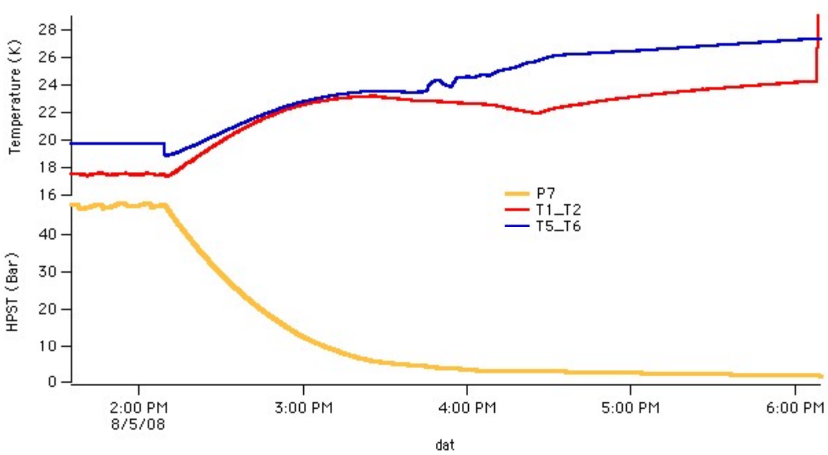


Figure 5-9-1 SCS failure test. Plot shows decay of high pressure (P7) and the increase of LVHX1 (T1_T2) and the TSA stage (T5_T6).

5.10. Ph-10-05-b SCS Switchover Test

In order to complete SCE FM Redundant qualification on board the Planck S/C, a switchover from the Nominal Unit to the Redundant is performed ***during*** the execution of SCS N Failure Test.

This SCE FM-R qualification is based on a simple switchover procedure to activate the SCE R and perform a short Healthcheck:

- Shutdown SCS Nominal
- Initialise SCS Redundant
- GOTO READY MODE, enter Health Monitoring
- SCS R Healthcheck (TBC)
- Shutdown SCS Redundant
- Initialise SCS Nominal
- GOTO READY MODE
- GOTO RUN Mode SCS N

On ground, the orientation of the second (redundant) cooler fixed by the test setup prevents the redundant cooler compressor elements (CE) from being activated. For this reason only a short Healthcheck procedure (no actual gas desorption) will be executed, including the check of cold end sensors and heaters .

5.10.1. Ph-10-05-b Verification Matrix

Phase #	**10_05_b**				
Test name:	**SCS Switchover to Redundant Unit**				
Test objectives:	In order to complete SCE FM Redundant qualification on board the Planck S/C, a switchover from the Nominal Unit to the redundant is planned during the SCS N failure Test (previous Chapter 14.1). This qualification is based on a simple switchover procedure down to the activation of SCE R and a short Healthcheck				
Verification matrix					
Check	**Passed?**			**Recovered?**	
	Yes	**No**	**Notes**	**Yes**	**No**
No unexpected event Packets in both SCS FM units	✓				
Switchover procedure correctly executed	✓		Switchover was executed with no problems		
No errors/failure detected in SCS R	✓		SCS-R Healthcheck confirmed good health of all components and subsystems		

5.10.2. Ph-10-05-b Test Results

Switchover to the redundant SCS unit occurred at about 18:00 on 5 August. The sequence to monitoring mode was done, and then a modified health-check procedure was run. Figure 5-10-1 shows results for the temperatures of each compressor element, which shows the proper response for all elements. The functionality of the redundant cooler was verified with this test.

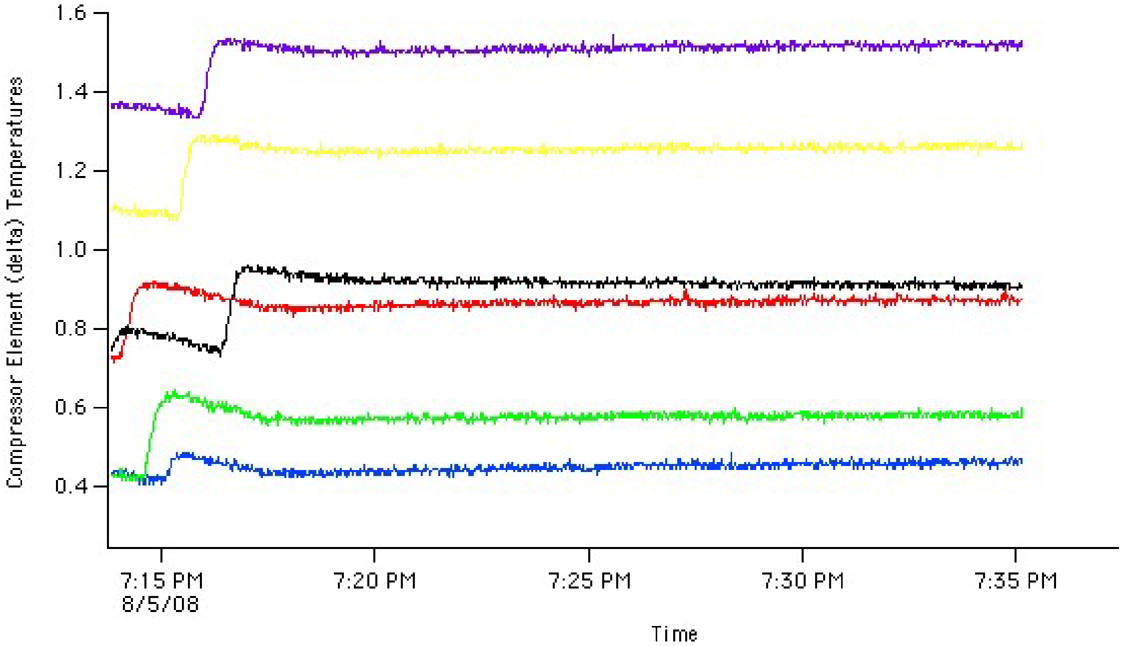


Figure 5.10.1 Plot of compressor element temperatures, verifying the functionality of the compressor element heaters.

5.11. Ph-11 Transition to SAFE Mode

In Phase 11, before transition to Safe Mode, SCS should be operated in RUN (Conditioning) for the shortest possible time in order to minimize impact on system warmup. Nominal stable conditions shall not be required to proceed with this Phase.

5.11.1. Ph-11 Verification Matrix

Phase #	11				
Test name:	SVM Transition to SAFE Mode				
Test objectives:	This is a test of S/C Safe Mode Transition. Power lines to payload will be disabled. SCS is abruptly switched-off.				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓		Cooler was in good health after Safe Mode transition and was re-started correctly		

5.11.2. Ph-11 Test Results

Transition to the spacecraft safe-mode occurred the morning of 7 August. After the return of spacecraft power the health of the SCS was verified.

5.12. Ph-12 SCS Shutdown and Warm-up

In this Phase the SCS will be shut-down to start the PPLM warm-up. This test was not complete at the time of this report, although it was shown that the system was in Health monitoring mode.

5.12.1. Ph-12 Verification Matrix

Phase #	12_01_a				
Test name:	SCS Shutdown (monitor of Warm-up)				
Test objectives:	Shut-down the SCS to start the PPLM warm-up. This test shall verify the cooler behaviour during warm-up. This test will provide fundamental data for correlation of transient SCS TMM.				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected event Packets	✓				
SCS stable in Health Monitoring operations	✓		30 min after "post-Safe Mode" restart, SCS was taken into READY Mode (Health Monitor) correctly		

5.12.2. Ph-12 Test Results

SCS was placed into monitoring mode for the warm-up on 8 August 2008.

5.13. PsTV-01-3 SCS Warm Healthcheck Nominal Unit

At the end of the TV/TB test campaign, a Warm Healthcheck process in thermal-vacuum was performed to ensure that the system was in nominal health after all cryo test and return to ambient conditions. As for PrTV-1-2-d, “Warm HC” is a reduced procedure with respect to the “full HC”, due to the fact that cold sensors and heaters cannot be checked in warm conditions for hardware safety reasons. This HC results shall be compared to the result of PrTV-1-2-d and will provide a reference baseline for the functional verifications to be performed in the next ground testing activities.

5.13.1. PsTV-01-3 Verification Matrix

Phase #	PsTV_1_3				
Test name:	SCS-N Post TV HealthCheck				
Test objectives:	To check system health after TVTB test campaign				
Verification matrix					
Check	Passed?			Recovered?	
	Yes	No	Notes	Yes	No
No unexpected events packets	✓		Post TV Warm HC process fully successful	N/A	N/A
Sensors response as expected	✓			N/A	N/A
Power consumpiton as expected	✓			N/A	N/A

5.13.2. PsTV-01-3 Test Results

The results of the Healthcheck process, executed on August 20th 2008, were fully compliant to the nominal status required and to the results of PrTV-1-2-d, pre-TV test Warm Healthcheck. For this reason, it was then decided to declare successfully concluded the Sorption Cooler TV/TB test campaign.

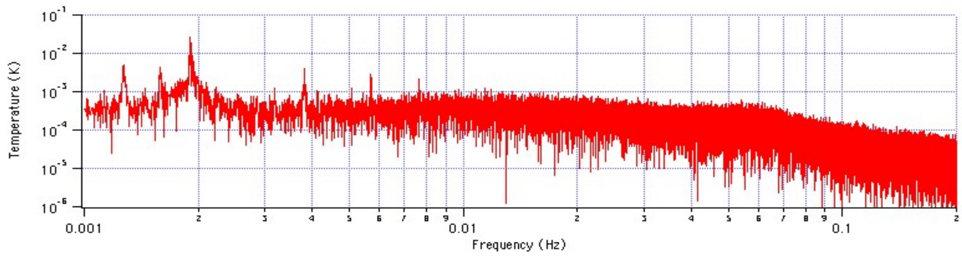
5.14. Sorption Cooler Electronics Performance

The Sorption cooler electronics behaviour was conforming to the specification and requirements, the measurement ranges and resolution were as expected. All functional modes performed without issue.
An investigation into the synchronization problem has provided a software solution that will allow a reliable synchronization of the SCE.

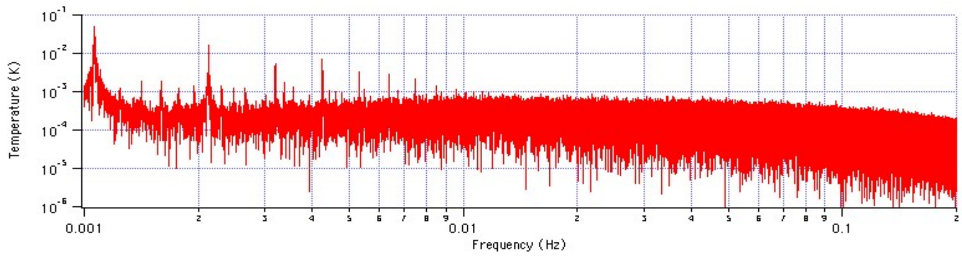
6. Temperature Fluctuations

6.1. Comparison between Cold and Hot Cases

As discussed in the relevant sections summarizing the cold and hot cases, temperature fluctuation requirements were not met in the former case while for the latter case the requirements were met. The behavior of these fluctuations is attributable to gravitationally induced plug flow events that have been recently summarized in JPL Document D-46302 (RD7). Evidence for this is can be seen in Figure 6-1. The figure shows the temperature fluctuations for LVHX1 in the frequency domain. As can be clearly seen, for the hot case the contribution from 10 Hz to about 20 Hz is much smaller when compared to the cold-case.
The 10-15 Hz contribution is indicative of the two-phase plug events, and they are clearly suppressed in the hot-case. Another difference between these two cases is the amount of heat-lift excess. For the hot-case the excess is about 500 mW, while for the cold-case the excess is about 150 mW. Differing levels of excess mean liquid is in different locations in the counter-flow heat exchanger.
What is most likely happening here is that the periodic filling of a pooling region and the subsequent sweeping away of the liquid is occurring at a different frequency because the pooling regions are different. It would have been possible to bring the fluctuations for the cold-case to those of the hot-case by increasing heat lift excess. The LFI and HFI instrument teams did not deem this necessary as the two-phase fluctuations at 10-20 Hz are suppressed passively by the instruments thermal mass, and their performances were not impacted, so it was not done. Finally, as is stated in D-46302, it is expected by JPL that these effects due to gravitational pooling will be absent in the micro-gravity environment, so the requirement is expected to be met in flight.



Hot case



Cold case

Figure 6-1. Fourier transforms of the LVHX1 temperature fluctuations for the hot and cold thermal test cases.

7. Lifetime

7.1. Lifetime estimates with PFM2 interfaces and heat load values

With the PFM2 testing several of the parameters that impact the SCS lifetime were determined; namely: V-groove three temperature; and the LFI instrument load to the sorption cooler. The V-groove three temperature for the cold and hot cases were 47 and 48 K, respectively. In addition, actual estimates of the LFI heat load were made to +/- 50 mW, as explained in Section 5.5.2. TSA load was directly measured during the testing. HFI heat load could not be measured, but was estimated from the heat lift measurement to be 100 mW +50 /-25 mW. These loads are summarized in Table 7-1-1.

LFI	670 mW
HFI	100 mW
TSA	205 mW

Figure 7-1-1. Cold-end heat loads

The TSA load of 205 mW exceeds the allocation of 150 mW because LFI required operation at the same set point temperature throughout the testing. If only the allocated 150 mW is used, a small amount of life, on the order of two weeks, can be obtained.
Based on these loads and interface temperatures, the lifetime of the two sorption coolers are estimated to be 15.5 months for the nominal unit (FM2) and 13.5 months for the redundant (FM1). The uncertainty in these numbers is +/- 0.5 months. These lifetime values are for the remaining life on the two coolers; all previous testing is not included. FM1 has 1700 cycles and FM2 has 720 cycles. These lifetime estimates exceed the minimum mission lifetime of 9.1 months for each cooler. Lifetime estimates at other pre-cooler temperatures are presented in the ESA document, Planck Cryo-chain Operations, Planck/PSO/2007-017 (RD8).
The regeneration process can increase the lifetime, but further testing is needed to understand the efficiency of this process when applied to highly degraded compressor elements. This testing should be performed at the end of the JPL life cycle tests in February 2008.