SERVICE DES BASSES TEMPERATURES

FIRST / SPIRE

SPIRE SORPTION COOLER DEVELOPMENT PLAN

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Département de Recherche Fondamentale sur la Matière Condensée
Service des Basses Températures

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CONTENTS

1 Introduction

The FIRST/Planck mission of the ESA Horizon 2000 Science Programme accommodates in the carrier option two spacecrafts for a joined launch on an ARIANE 5 launcher into a L2 orbit in 2007.
FIRST, the Far Infrared and Submillimetre Telescope, is a multi-user observatory type mission performing astronomical investigations in the infrared and submillimetre wavelength range. The FIRST payload is consisting of three instruments :

- HIFI
- PACS
- SPIRE

The instruments are mounted in the FIRST payload module. The spacecraft provides the environment for astronomical observations in the infrared wavelength range from about 85 to 600 micron requiring cryogenic temperatures for the cold focal plane units.
The Spectral and Photometric Imaging Receiver (SPIRE) will cover the 200 – 670 µm spectral range using bolometric detectors. The cooling of the detector arrays down to 300 mK will be effected by a ^3He sorption cooler.

1.1 Scope of the document

This document describes the development plan of the FIRST/SPIRE helium sorption coolers. This development plan is based on the applicable document referenced in § 2. This development plan does not include activities related to the drive electronic.
This document is a preliminary version which will be completed later.

2 Documents

2.1 Applicables documents

	Title	Author	Reference	Date
AD1	Instrument Requirements Document	B. Swinyard	SPIRE-RAL-PRJ-000034 Issue 0.20	15 Sept 99
AD2	SPIRE sorption cooler specifications	L. Duband	GS/SBT/SPIRE/2000-01	April 00

2.2 Reference documents

	Title	Author	Reference	Date
RD1	SPIRE A Bolometer Instrument for FIRST – A proposal submitted to ESA	Various	N/A	Feb. 1998
RD2	Cooler redundancy – conclusion on what to do about it	B. Swinyard, L. Duband	SPIRE-RAL-NOT-000341	Feb. 2000

2.3 Glossary

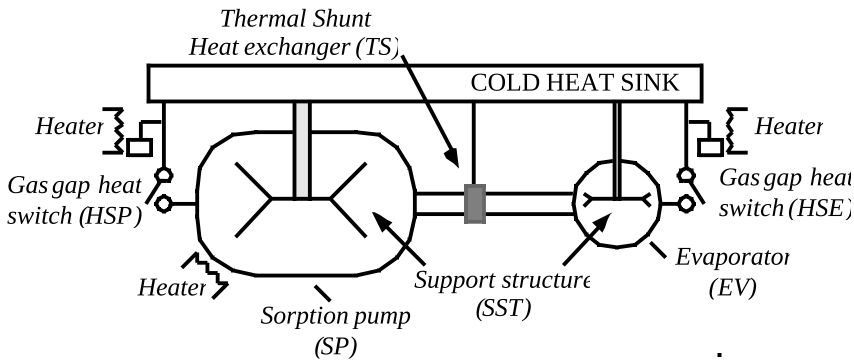
AD	Applicable Document
CEA	Commissariat à l' Energie Atomique
CDR	Critical Design Review
CQM	Cryogenic Qualification Model
CSL	Centre Spatial de Lièges
DDR	Detailed Design Review
EV	Evaporator
FIRST	Far Infrared and SubmillimetreTelescope
FS	Flight spare
HSE	Heat Switch (on evaporator)
HSP	Heat Switch (on sorptrion pump)
HIFI	Heterodyne Instrument for FIrst
MGSE	Mechanical Ground Support Equipment
N/A	Not Applicable
PACS	Photoconductor. Array Camera and Spectrometer
PFM	ProtoFlight Model
RFA	Request For Approval
S/C	SpaceCraft
SAp	Service d'Astrophysique
SBT	Service des Basses Températures
SCO	Sorption Cooler (full unit)
SP	Sorption pump
SPIRE	Spectral and Photometric Imaging Receiver

3 Description of the sorption cooler

The cooling of the SPIRE detectors down to 300 mK will be effected by a helium three sorption cooler. This sub-Kelvin sorption cooler provides a wide range of heat lift capability at temperature below 400 mK. It relies on the capability of porous materials to adsorb or release a gas when cyclically cooled or heated. Using this physical process one can design a compressor/pump which by managing the gas pressure in a closed system, can condense liquid at some appropriate location and then perform an evaporative pumping on the liquid bath to reduce its temperature. Helium sorption refrigerators have no moving parts, are vibrationless and can be designed to be self contained and compact with a high duty cycle efficiency.

As shown on the figure hereafter the cooler is basically made of 6 components designated as a sorption pump SP and an evaporator EV connected via a pumping line to a thermal shunt TS comprising an heat exchanger, two gas gap heat switches HSP and HSE respectively connected to the sorption pump (SP) and evaporator (EV), and finally a support structure SST. SP, EV, TS and the pumping line are assembled to form a unique component which is the actual “heart” of the cooler. This component is held within SST, which provides firm mechanical support (launch environment) while minimising any parasitic conductive load on the cooler (low temperature environment).

Heat switches are then required for operation of the cooler. The two switches are used to control the temperature gradient; during the condensation phase they are set such that the sorption pump can be heated to release the helium gas and such that liquid condensation occurs into the evaporator EV maintained as the coldest point. The liquid is held into EV by capillary attraction inside some porous material : both the surface tension and the vapour pressure provide forces that drive and hold the liquid at the coldest point. Then the switches are set such that the sorption pump is thermally grounded to the heat sink and such that the evaporator is thermally isolated. The sorption pump provides an evaporative pumping on the liquid helium bath which temperature quickly drops to sub-Kelvin temperature.



Cryogenic switches can be based upon different physical mechanisms. Gas gap heat switches have been selected as the preferred design for the present project.

Gas gap heat switch utilises concentric copper cylinders separated by a small gap which is filled with or emptied of He gas to achieve the switching action. The thermal separation between the two ends is achieved by a thin-walled tube which also provides the mechanical support. The presence or absence of gas is controlled by a miniature cryogenic adsorption pump that can be temperature regulated. Thus one of their main feature is the absence of any moving part, and consequently operation of the cooler is almost then fully controled by three heaters.

For operation in a zero-G environment two aspects are addressed: the liquid confinement and the structural strength required for the launch. The confinement within the evaporator is provided by a porous material which hold the liquid by capillary attraction, and a suspension system using Kevlar wires is designed to firmly support the refrigerator during launch while minimising the parasitic heat load on the system.

4 Constraints

4.1 Development constraints

4.1.1 Technical constraints

The main specifications for the SPIRE sorption cooler are reported in the following table and refer to [AD1] and [AD2].

Reference from AD1	Decription
Performance Requirements	
IRD-COOL-R01	The coolers shall be able to cool and maintain at 300 mK the detector assembly
IRD-COOL-R02	It is desirable to be able to vary the detectors temperature up to 320 mK. Electronic control shall be provided to perform this task in the flight electronic
IRD-COOL-R04	The temperature drift of the evaporator cold tip shall be no more than 10 mK/h
IRD-COOL-R05	The temperature fluctuations at the evaporator cold tip shall be no more than 150 $nK.Hz^{0.5}$ in a frequency band from 0.1-100 Hz
IRD-COOL-R06	The system low frequency temperature stability with active temperature control shall be TBD nK at 0.015 Hz at a maximum power dissipation of TBD µW
IRD-COOL-R07	The heat lift at 300 mK shall be 10 µW at a minimum
IRD-COOL-R08	The hold time shall be no less than 46 hours
IRD-COOL-R09	The recycle time shall be no more than 2 hours
System Requirements	
IRD-COOL-R10	The mechanical interface is with the instrument 4 K structure
IRD-COOL-R11	The thermal interfaces are with the 1.8 K pumped helium bath (FIRST cryostat)
IRD-COOL-R12	The thermal load onto the cryostat during cold operation shall be no more than 1 mW. 0.1 mW is allowed for the conduction from 4 K to 2 K through the support structure
IRD-COOL-R13	The time averaged thermal load onto the FIRST cryostat shall be no more than 3 mW over the 48 hours cycle
IRD-COOL-R14	The overal mass of the cooler shall be no more than 0.8 kg (this number will be revisited once the mounting interfaces are clearly defined)
IRD-COOL-R15	The maximum enveloppe for the cooler shall be no more than 200 x 100 x 100 mm
IRD-COOL-R16	The preferred orientation is with the axis pump-evaporator along the S/C Y axis, with the evaporator at the Y end – TBC
IRD-COOL-R17	It is desirable to increase all heaters resistances (currently 402 ohms), so the resistance of the cryoharness can also be increased. The maximum voltage available is 28 volts.

During its lifetime SCO is :

- designed under CEA-SBT responsability
- manufactured and assembled under CEA-SBT responsability, part in the industry, part at CEA-SBT
- qualified and accepted under CEA-SBT responsability, part at CEA-SBT, part at CSL. The test plan includes thermal tests and environmental tests, arranged in such a way the thermal performance are verified at completion of the test plan.

SCO undergoes then a final class 100 cleaning at CSL, is packed at CSL and is then transported to TBD and integrated in the FPU under TBD responsability.

SCO undergoes the project test plan under TBD responsability.

SPIRE is then delivered to ESA under RAL responsability.

SPIRE is integrated in the FIRST satellite under ESA responsability.

SPIRE CQM is to undergo the ESA cryoqualification program under ESA responsability.

SPIRE PFM is to undergo the ESA acceptance program.

On the launch pad, before launching, the SPIRE FPU is cooled down to its operating temperature and launched.

SPIRE FS is prepared in the event of SPIRE PFM failure.

4.1.2 Organisation
CEA-SBT is responsible for the SCO (three models). The PA/QA related activities are subcontracted to CSL; throughout the project duration CSL is responsible for all PA/QA tasks. CEA-SBT designs the SCO and subcontract its manufacturing and part of its assembling to identified subcontractors. CEA-SBT contributes to the definition of the drive electronic. This drive electronic is under SAp's responsability.

4.1.3 Calendar constraints
According to the latest schedule available, the main SPIRE project rendez-vous are :

Rendez vous	Date
PDR	June 2000
DDR	October 2000
SCO CQM delivery to SPIRE	Summer 2002
CDR	
SPIRE CQM delivery to ESA	
SCO PFM delivery to SPIRE	Spring 2004
SPIRE PFM delivery to ESA	
SCO FS delivery to SPIRE	Spring 2005
SPIRE FS delivery to ESA	
FIRST launch	2007

As shown further our proposed calendar is different, but compatible with the above schedule since the three cooler models shall be available before the above dates. However our proposed calendar is based on a start date for the overall design of the CQM cooler as of September 2000. If this start date is changed the calendar will have to be delayed accordingly.

4.2 Risk analysis

The risk analysis hereafter only refer to this development plan not being completed.

Risk	Impact	Preventive action	Note
Major failure during assembling process	Development plan must be updated. Delivery dates are delayed by TBD months	None	This type of failure can only occurs on the sorption pump + evaporator + heat switches. Consequently only part of the cooler would have to be re-manufactured.
Major failure during prequalification tests (proof pressure test, etc..)	Idem as above	Leak before burst and ultimate pressure tests will be performed on samples.	Idem as above
Failure of test cryostat	TBD	Two tests cryostat are supplied	
Unavailabilty of main test team member	None	Other group members are involved in the project.	One person is identifed as responsible for the test plan, but other group members are involved to a level such they can replace the missing person.
Qualification failure	Development plan must be updated. Delivery dates are delayed by TBD months	None	

4.3 Redundancy

The redundancy aspects have specifically covered in RD2. The conclusion of this document indicate that :

- it is not possible to have complete insurance against the random mechanical failure of the cooler pressure vessel or mechanical support – this must be achieved by design and test.
- The wiring and electronics can and will be made fully redundant.
- It is possible to give full insurance against the mechanical failure of any single heat switch but only at the expense of reduced thermal efficiency and/or 300 mK performance.

We conclude that we should have a baseline cooler design that has redundant heat switches on both the pump and the evaporator. If it turns out that the qualification programme for the heat switches demonstrates conclusively that they will not fail mechanically we can always thermally disconnect the redundant switches or remove them all together. In the meanwhile the design will proceed assuming they are present in order that the space envelope; mass; interfaces and wiring are correctly incorporated into the system level design. In the event of single heat switches being implemented we will also implement redundant heaters in the heat switch sorption pumps to ensure full electrical redundancy is maintained.

We note that, with a 4 litre STP cooler and a 2hour/46 Hour duty cycle, there is almost no margin on the cooling power of the cooler. This becomes critical with the addition of the extra redundant heat switches and the consequent extra load at 300 mK. The size of the cooler is driven among other things by the requirement to dissipate less than 3 mW average power on the 2 K plate. If this number can be revised then we can change the design to accommodate, for instance, an 8 litre STP unit (TBD) and/or change the duty cycle efficiency. Our preference would be to have a larger cooler as this will be less restrictive in terms of operations.

The decision to implement full mechanical redundancy in the sorption cooler heat switches and to increase the size of the sorption cooler cannot be for the SPIRE project alone. We require guidance from the FIRST project team as to whether they consider the reduction in risk from adopting these measures outweighs the inevitable loss in mission lifetime.

5 Work description

5.1 Task plan

The general plan is defined through the following table; the tasks are listed chronologically. Parallel tasks are grouped under the same sequence number.

Sequence	Task n°	Task Name	Responsability
All		PA/QA follow up throughout activities	CSL
All		Project management	CEA-SBT
1	1.1	Technical requirements	CEA-SBT
	1.2	Overall design	CEA-SBT
	1.3	Detailed design	CEA-SBT
	1.4	Test plan and test set-up design	CEA-SBT
2	2	DDR – Design approval	
3	3.1	Cooler manufacturing and assembling	TBD
	3.2	Test set up manufacturing	TBD
	3.3	Test predictions	CEA-SBT
	3.4	Manufacturing progress meeting	
4	4	Test readiness review and approval	
5	5	Pre qualification test	CEA-SBT
6	6	Thermal test program – first set	CEA-SBT
7	7	Environmental test program	CSL
8	8	Thermal test program – second set	CEA-SBT
9	9	Delivery preparation	CSL
10	10	Delivery	CEA-SBT/CSL

These tasks will be further detailed in a subsequent version of this document.

The tasks 3 to 10 are repeated for all three models, CQM, PFM and FS.
In between each model an additional task references as “ Correction of design and correction approval if needed” may be performed.

5.2 Development and model philosophy

The model philosophy is compliant with the SPIRE project requirements.

5.2.1 Preliminary design

The overall design of the sorption cooler takes advantage of the know-how of CEA-SBT in sorption cooling technologies. This design benefits the design heritage of the orbital sorption cooler which successfully flew in April 1995 on board the Infrared Telescope in Space.

Moreover as part of the ESA Technology Research Program (TRP) CEA-SBT was awarded a contract which purpose is to bring the existing sorption cooler technology to a level compatible with space missions. This work will be completed in fall 2000. A ^{3}He sorption cooler prototype, which initial specifications are closed to that of the SPIRE cooler, has already been designed, manufactured, assembled and is currently undergoing the test program which shall lead to its qualification.
This prototype design has been substantially improved and features our latest advances. The design of the SPIRE cooler is very similar and will be further refined based on the obtained results.

The thermal performance are evaluated using a software tool developed at CEA-SBT. This software has been already used in the design of various sorption coolers and has proven to be a very usefull tool. It continues to evolve as more experimental data are made available.

The sorption cooler uses a suspension system utilizing Kevlar wires to firmly support the cooler during launch while minimizing the parasitic heat load on the system during cold operation. A mathematical model has been developed to predict the resonant frequencies. In addition a full finite elements modelisation has been done on the present prototype cooler to further confirm the mechanical behaviour.

The thermal performance are verified by test. The on orbit performance (liquid confinement) are validated by operating the cooler in various orientation, in particular upside down, during the low temperatrue phase.

A vibration test is performed to verify the mechanical behaviour; this vibration test includes a low level sine sweep to check the resonant frequencies.

5.2.2 Procurements of long delay cryogenic components

Once the preliminary design has been validated by the PDR, the procurement for long delay cryogenic components is initiated if money is available. These components include mostly space qualified thermometers, heaters and connectors.

5.2.3 Detailed design and CQM manufacture

The detailed design encompasses all the functions. The design is verified by more detailed modelisation where necessary, in particular a numerical modelisation of the mechanical characteristics is performed. This detailed design benefits from the outcome of the ESA TRP contract.

The detailed design is presented at the Detailed Design Review. The DDR must have been held before the CQM manufacture can be initiated.

A test program is produced which contains the tests sequence to be performed on the sorption cooler which contributes, together with analysis and other verification methods, to qualification.
This test program covers the functional performance and environmental tests required to provide confidence in the ability of the cooler to meet the specified requirements. Performance measurements will be made before and after the environmental tests, designed to detect changes in performance parameters which may indicate a potential failure.

The CQM cooler includes all the functions of the flight design and undergoes the full test program. All external components (thermometers, heaters, etc…) are of flight grade.

The CQM cooler shall permit to validate all modifications implemented in the design at the outcome of the TRP contract.

A test cryostat that can be operated in any orientation between –90° and +90° to enable testing of the cooler in a wide range of orientation will be developped. It is indicated that CEA-SBT has already developped such cryostats and possess this know-how.

The environmental tests will be performed at CSL.

A test referenced as the "Health Check" is established. This test allows to verify nominal operation of the cooler from a mechanical, leaktightness and thermal point of view. This health check will be performed whenever necessary to check for the integrity of the cooler.

5.2.4 Flight design modifications and PFM/FS manufacture

Following the CQM qualification program, some modifications may have to be implemented in the design.
If the changes are major and require further thermal experimental validation CEA-SBT will use for this purpose a simple development model prototype developed in the framework of the ESA TRP contract.

Otherwise the changes are implemented in the flight design, and the SCO PFM and SCO FS are manufactured and assembled at the same time.

They both undergo the full test program successively, PFM first.

5.3 Verification plan

The CQM, PFM and FS coolers are designed based on our mechanical and low temperature know how and manufactured and assembled by qualified and skilled subcontractors and CEA-SBT.
All precautions are taken to guarantee successful devices and the coolers are controlled at various step during their fabrication.
The table hereafter is a verification matrix in which for each relevant specification or requirement is indicated whether it is verified by analysis, design, test and/or inspection.

These verifications apply to all three models.

		Verification method			
AD2 §	**Heading**	**Analysis**	**Design**	**Test**	**Inspection**
4.1	***Functional requirements***	X	X	X	
4.2	***Operational requirements***				
4.2.1	Safety	X		X	
4.2.2	Lifetime	X	X		
4.2.3	Operating modes		X	X	
4.2.4	Commands	X		X	
4.2.5	Monitoring	X		X	
4.3	***Environmental requirements***				
4.3.1	Thermal environment		X	X	
4.3.2	***Mechanical environment***				
4.3.2.1	Limit loads and launch levels	X	X	X	X
4.3.2.2	Acoustic noise	N/A	N/A	N/A	N/A
4.3.2.3	Shock handling loads	X	X	X	X
4.3.2.4	Orbit		X	X	
4.3.2.5	Ground		X	X	
4.3.3	***Electrical environment***		X		
4.3.4	***Radiation environment***		X		
4.3.5	***Optical environment***	N/A	N/A	N/A	N/A
4.4	***Design & construction requirements***				
4.4.1	Interchangeability		X		
4.4.2	Control electronics	N/A	N/A	N/A	N/A
4.4.3.1	Maximum operating pressure		X		
4.4.3.2	Proof pressure and Burst pressure	X	X	X	
4.4.4	Mechanical strength requirements	X	X	X	
4.4.5	Fatigue life and fracture control	X		X	
4.4.6	Mechanical stiffness requirement	X	X	X	
4.4.7.1	Design margin – Structural	X	X	X	
4.4.7.2	Design margin – Thermal	X	X	X	
4.4.8	*Parts, Material and processes*	X	X		X
4.4.8.6	Cleanliness			X	
4.5	***Interface requirements***				
4.5.1	Thermal interface to detector		X	X	
4.5.2	Mechanical interface to the heat sink		X		
4.5.3	Thermal interface to the heat sink		X	X	
4.5.4	Electrical interface		X	X	
4.6	Logistic requirements		X		X

5.4 PA/QA

Product and Quality Assurance will cover the overall duration of the project. The main activities are :

- definition of the PA/QA plan
- definition of the cleanliness plan
- configuration control and management of the documentation
- product/quality assurance during the definition phases by document writing, verification and updating (PA/QA plan ; Parts, Material and Processes list ; Critical Items List ; Single Point Failure List, EEE Parts List ; FMEA ;...)
- product/quality assurance during the manufacturing phases by inspections, controls and by document writing, verification and updating (Cleaning procedures ; Processes procedures ; Assembly Procedures ; Inspection and Control reports ;...)

- product/quality assurance during the verifications and tests phases by inspections, controls and by document writing, verification and updating (Test procedures ; Cleanliness Reports ;...)
- Non Conformance system management during all the phases (Non Conformance Reports, Request for Waiver, Request for Approval)
- Management of the coolers data packages

5.5 Ground associated equipment

The main ground equipment to be developped and required for the coolers qualification is a test cryostat.
This test cryostat shall provide temperature down to 1.8 K. Its autonomy at 1.8 K shall be at least 48 hours in normal orientation (see hereafter). One particular feature is the capability of this cryostat to be operated tilted to any angle between –90° and +90°. When tilted the 48 hours requirement does not apply.
This feature allows to mount the coolers such they can be thermally tested during the low temperature phase in almost all orientations, i.e. rightside-up, horizontal and upside down.
CEA-SBT has developed similar cryostat in the past.

6 Development calendar

Item	Action	Date
Detailed design	Production of 3D drawings	Fall 2000
CQM	Manufacture	Winter 2000-2001
CQM	Assembling	Spring 2001
CQM	Qualification (test program)	Summer 2001
CQM	Delivery	Fall 2001
PFM & FS	Manufacture	Winter 2001-2002
PFM & FS	Assembling	Spring 2002
PFM	Qualification (test program)	Summer 2002
PFM	Delivery	Fall 2002
FS	Qualification (test program)	Spring 2003
FS	Delivery	Summer 2003

Note that due to the uncertainties in the current SPIRE project, the start date for the CQM cooler overall design is assumed to be September 2000, and rough periods have been indicated. If this start date is changed the calendar will have to be delayed accordingly.

Note : Potential modifications to be implemented in PFM and FS at completion of the qualification program might require some delay. In this case this calendar will need to be revisited.

The detailed planning for the CQM cooler is given in appendix A (assuming a Sept. 2000 start date for the overall design).

7 Description of deliverables

7.1 Deliverable model

Model	Flight representativity	Difference with flight	Deliverables
CQM	90%	Thermometers and heaters are not of flight grade	1
PFM	100%	None	1
FS	100%	None	1

7.2 associated equipment

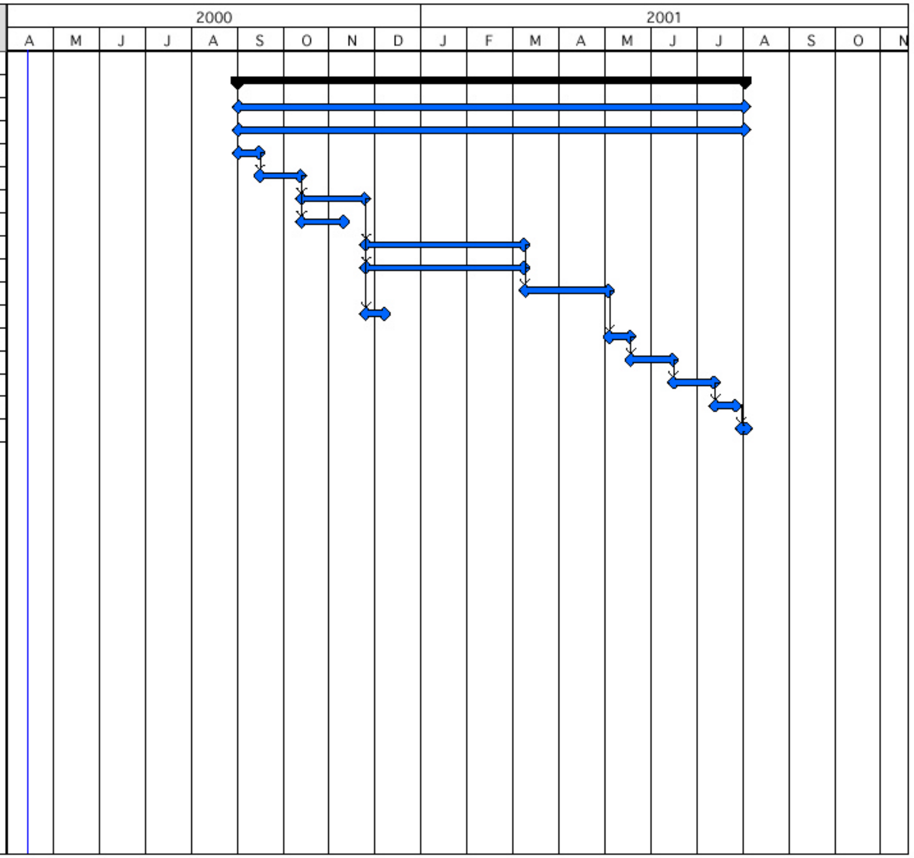
Specific tools are provided with each coolers – these include mounting and tension verification tools.

7.3 Associated documentation

A user manual is provided.

Appendix A

	Activity	Duration	Start Date	Stop Date
0				
1	CQM Cooler			
2	Project management	48w	1/09/00	2/08/01
3	PA/QA activities	48w	1/09/00	2/08/01
4	Technical requirements	2w	1/09/00	14/09/00
5	Overall design	4w	15/09/00	12/10/00
6	Detailed design	6w	13/10/00	23/11/00
7	Test plan/test set-up desi	4w	13/10/00	9/11/00
8	Cooler manufacturing	15w	24/11/00	8/03/01
9	Test set-up manufacturing	15w	24/11/00	8/03/01
10	Cooler assembling	8w	9/03/01	3/05/01
11	Test predictions	2w	24/11/00	7/12/00
12	Prequalification test	2w	4/05/01	17/05/01
13	Thermal test program 1/2	4w	18/05/01	14/06/01
14	Environmental test progra	4w	15/06/01	12/07/01
15	Thermal test program 2/2	2w	13/07/01	26/07/01
16	Cooler delivery	1w	30/07/01	3/08/01



Project: CQM cooler planning

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Draft planning - To to be revisited