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Sorption coolers using a continuous cycle to produce 20 K for the Planck flight mission

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Abstract

Two sorption coolers using hydrogen as the working fluid are currently being fabricated and assembled for flight delivery by the Jet Propulsion Laboratory (JPL). Being vibration free, scalable and with the capability for the cold end to be remotely located from the warm spacecraft are the major advantages of this class of cryo-coolers. These systems have been designed to provide a total cooling capacity (per cooler) of 1 W at a cold end temperature less than 19 K. They will be used for the Planck Surveyor mission (2007 launch). In this paper we present the level of maturity of the hydrogen sorption cooler technology at JPL by describing the design and how it has been validated at the subsystem and system levels.

Keywords: Sorption cooler; Cryo-cooler; Joule–Thomson

1. Introduction

Planck [1] is a European Space Agency (ESA) mission, whose main objective is to image the temperature anisotropy of the cosmic microwave background (CMB) at high angular resolution (Fig. 1). Planck will carry two instruments: the high frequency instrument (HFI) and the low frequency instrument (LFI) to enable it to perform these maps. Both the LFI and the HFI instrument sensors need to be cooled to cryogenic temperatures to optimize their signal to noise ratio. The detector cooling system has also to minimize the mechanical vibration to reduce the spurious signal generation on the ultra-sensitive detectors.

The LFI radiometers need a temperature of 20 K reached through a combination of passive cooling to about 60 K and active cooling using a hydrogen sorption cooler to reach lower temperatures. The HFI uses bolometers cooled to 100 mK through a combination of passive cooling (radiator at 60 K), the 20 K sorption cooler, a 4.5 K mechanical Joule–Thomson cooler and a Benoit style open cycle helium dilution cooler. The description of the whole cooling chain has been provided earlier [2,3].

2. Key requirements

The key requirements of the Planck sorption cooler (Fig. 2) are summarized below:

- Provide 0.986 W total heat lift at instrument interfaces using a ⩽60 K pre-cooling temperature at the coldest V-groove radiator on the Planck spacecraft. There are three V-groove radiators on the spacecraft that serve the dual purpose of shielding the cold zones of the telescope/instruments from the warm spacecraft as well as pre-cooling the working fluid, H_2.
- Maintain the following instrument interfaces temperatures:
  - LFI @ ⩽22.5 K [80% of total heat lift].
  - HFI @ ⩽19.02 K [20% of total heat lift].
- Temperature stability (over TMU operating period, ~4000 s):
  - ⩽450 mK, max. to min. at HFI interface.
  - ⩽100 mK, max. to min. at LFI Interface.
- Input power consumption ⩽470 W (end of life; excluding electronics).
- Operational lifetime: ⩾2 years (incl. testing).
- Storage life: ⩾6 years.

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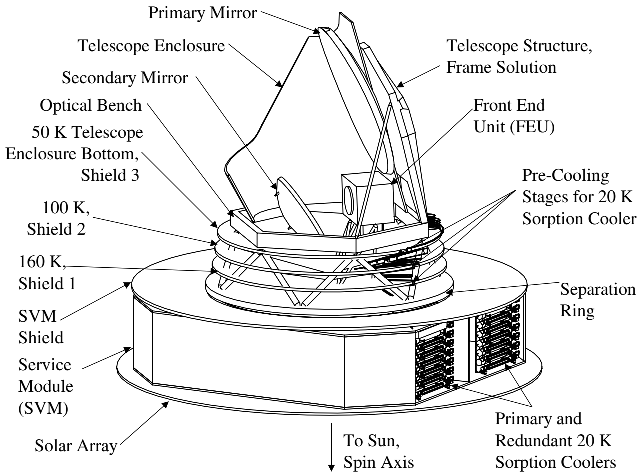

Fig. 1. Sorption coolers mounted on Planck spacecraft.

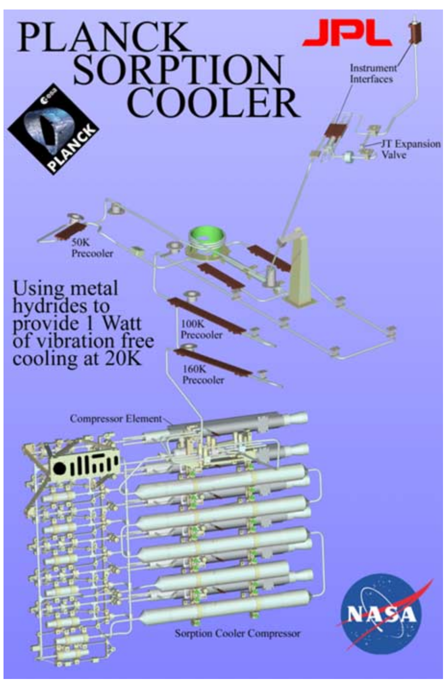

Fig. 2. Planck sorption cooler.

- Two completely *independent* cooler systems (Including electronics).
  - Provides 100% redundancy.
- Total mass per cooler (excluding electronics): ⩽53.3 kg.
- Total compressor volume (per cooler): ⩽1 m × 0.75 m × 0.25 m.

3. Maturity of sorption coolers

JPL has been a pioneer in the development and application of sorption coolers for space missions. A proof of principle sorption cooler was developed, built and tested in 1992 [4]. Following that a batch mode sorption cooler, BETSCE, was tested in space aboard the space shuttle in 1996 [5]. This cooler produced solid hydrogen at 10 K. The two Planck sorption coolers are the first continuous cycle sorption coolers to be used for a space mission.

4. Application of sorption cooler to space missions

Sorption coolers are attractive systems to provide cooling for instruments, detectors and telescopes when a vibration free system with no moving parts is desired. Since the pressurization and evacuation uses hydride beds that are simply heated and cooled sequentially with no moving parts like compressors or turbines, they tend to be very robust. The only caveat to "no moving parts" are the check valves that open and close passively and very, very slowly with negligibly small forces, thus essentially creating no vibrations on the spacecraft. This provides excellent reliability and long life. Also, since they employ Joule–Thomson cooling by a simple expansion through orifices, the cold end can be located remotely from the warm end. Finally, since the spacecraft's warm end is by design located away (thermally and spatially) from the payload, this allows for excellent flexibility in integration of the cooler to the cold payload (instrument, detectors and telescope mirrors) and the warm spacecraft.

5. Details of cooler operation

The sorption cooler is composed of a thermo-mechanical unit (TMU) and the electronics to operate the TMU. The primary focus of this paper is the TMU.

The sorption cooler (Fig. 3) performs cooling using Joule–Thomson (J–T) expansion employing hydrogen as the working fluid. The key element of the 20 K sorption cooler is the compressor, an absorption machine that pumps hydrogen by thermally cycling several sorbent compressor elements. The principle of operation of the sorption compressor is based on a unique sorption material ($La_{1.0}Ni_{4.78}Sn_{0.22}$), which can absorb large amounts of hydrogen at relatively low pressures, and which will desorb to produce high-pressure hydrogen when heated in a limited volume. Electrical resistance heaters accomplish heating of the sorbent while the cooling is achieved by thermally connecting the compressor element to a radiator at 270 K.

As a sorption compressor element (i.e. sorbent bed) is taken through four steps (heat up, desorption, cool down, absorption) in a cycle, it will intake low-pressure hydrogen and output high-pressure hydrogen on an intermittent basis. In order to produce a continuous

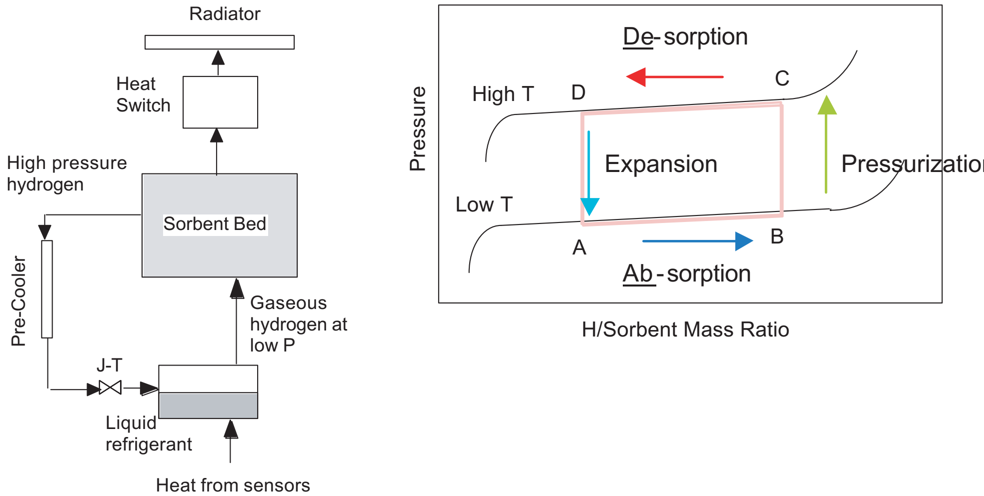

Fig. 3. Simplified Planck sorption cooler schematic.

stream of liquid refrigerant several such sorption beds are needed to stagger their phases so that at any given time, one is desorbing while the others are either heating, cooling, or re-absorbing low-pressure gas. In such a system, there is a basic clock time period over which each step of the process is conducted. Fig. 4 shows a more complete schematic of the cooler with all the major components and subsystems identified.

In order not to lose excessive amounts of heat during the heating cycle, a heat switch is provided to alternately isolate the sorbent bed from the radiator during the heating cycle, and to connect it to the radiator thermally during the cooling cycle. A single compressor element is comprised of two concentric cylinders closed with end caps. The inner of these tubes contains $La_{1.0}Ni_{4.78}Sn_{0.22}$ hydride material and the outer forms a vacuum jacket around the inner cylinder. This vacuum jacket is used as a gas-gap heat switch [6].

The compressed refrigerant hydrogen flows through the compressor to the high-pressure stabilization tanks (HPST) that are maintained at 4.8 MPa (48 atm.). The refrigerant than travels from the tanks through a series of heat exchangers attached to three V-groove radiators on the spacecraft (at 170, 100 and 60 K), which provide pre-cooling to approximately 60 K (Figs. 1 and 4), followed by expansion through the J–T expander.

Upon expansion, hydrogen forms liquid droplets whose evaporation provides the cooling power. The liquid/vapor mixture then sequentially flows through the first two liquid vapor heat exchangers (LVHX). The LVHXs are thermally and mechanically coupled to the corresponding instrument (LFI/HFI) interface. Finally

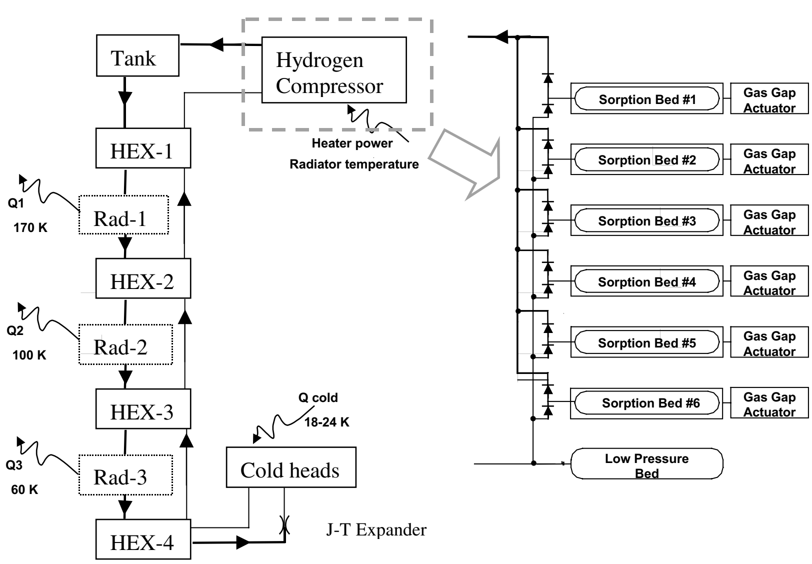

Fig. 4. Planck sorption cooler schematic, with the three pre-cooling radiators, four heat exchangers, the cold heads and the compressor. The arrows in front of each bed sorption bed are check valves, allowing flow only in the arrow direction.

the liquid vapor mixture flows through the third LVHX that is maintained above the hydrogen saturated vapor temperature to evaporate any excess liquid that reaches it to avoid flash boiling to help maintain a nearly constant pressure in the low-pressure plenum. Heat from the sensors evaporates liquid hydrogen and the low-pressure gaseous hydrogen is re-circulated back to the cool sorbent beds for compression.

Each compressor element is connected to both the high pressure and low-pressure sides of the plumbing system through check valves, which allow gas flow in a single direction only. To damp out oscillations on the high-pressure side of the compressor, a 4 l high-pressure stabilization tank (HPST) is utilized. On the low-pressure side, a low-pressure storage sorbent bed (LPSB) filled with hydride primarily functions to store a large fraction of the H_2 inventory required to operate the cooler during flight and ground testing while minimizing the pressure in the non-operational cooler during launch and transportation. The compressor assembly mounts directly onto the heat rejection radiator on the spacecraft.

6. Status of Planck sorption coolers

Two sorption coolers are currently being assembled for delivery for the Planck mission. The launch is scheduled for 2007. The two flight coolers are scheduled for delivery in early 2005. Prior to flight cooler delivery, in early 2004, a cryogenic qualification model of the piping and cold end assembly (PACE) is to be delivered to ESA for vibration and cryogenic testing. Since the PACE is very integrally coupled (mechanically and thermally) to the relatively flexible V-groove radiators and the instrument interfaces on the spacecraft, its thermal/structural performance is intimately dependent on these interfaces. Hence these tests will validate the structural and cryogenic performance of the PACE.

At the time this paper was written, for the first Planck flight cooler, all the compressor elements and the low pressure stabilization beds have been assembled, fully tested and delivered to the next level of assembly, the compressor assembly. The compressor assembly for the first cooler is almost assembled and getting ready for testing. The cold end for the cryogenic qualification model of the PACE has been assembled and the piping assembly has started. All systems are expected to meet the scheduled delivery dates.

7. Qualification of the Planck coolers, subsystems and components

To achieve an acceptable level of performance and robust operation with these hydride coolers during flight, detailed investigations have been performed on the sorbent materials and on all critical hardware components [7].

7.1. Component level

The primary long-term effect of operating the cooler is a slow aging of the hydride alloy. The key result of aging is a reduction in the storage capacity of the hydride alloy and a change in the shape of absorption/desorption isotherms. From the cooler standpoint the primary ramification of these changes is a slow degradation of cooler heat lift over time for a fixed input power or conversely a slow increase in required input power for a fixed heat lift requirement. The key parameters that affect the aging process are the level of high temperatures during desorption, time spent at these high temperatures and the number of cycles (concentration, temperature and pressure) experienced by the hydride during operation of the cooler. In terms of time spent at high temperature, the sorbent longevity has been verified for both the compressor alloy and the gas gap actuator alloy using accelerated life test cells containing these hydrides that were aged for a range of elevated temperatures. Acceleration is achieved by primarily subjecting the alloys to higher than expected temperatures to speed up aging. Extrapolation of aging rates at elevated temperatures to nominal levels, assuming constant activation energy for the reaction, allows for a faster collection of aging data as compared to simply aging the alloy at nominal temperatures. The effect of cycling was tested separately and discussed in the next section of this paper.

Check valves that isolate the high- and low-pressure sides within the sorption compressor are potential single-point failures as internal leaks would short circuit hydrogen flow to the Joule–Thomson (J–T) expander. To assess this risk, check valves were operated using hydrogen gas for over 43,000 pressure cycles at various orientations and temperatures and they exhibited no leaks or other changes. This qualifies them for 2X the number of cycles experienced during flight and ground testing. The filters that will be used to protect check valves and J–T expander from particles were tested in the same set up along with the check valves. The durability and reliability of low-power heaters used for the gas gap actuators were determined by accelerated temperature cycling.

All the critical components, e.g., check valves and filters, pressure transducers, isolation valves, warm getter, were vibration tested and thermally cycled (to at least the number of cycles experienced during ground testing, launch and flight) to qualify them for flight. All the welds used in the cooler were qualified by subjecting the samples, made with the same schedules that would be used for the flight coolers, to X-rays and pull tests. All the critical components and subassemblies were proof tested to qualify their structural designs. In addition, the low pressure storage bed (LPSB), high pressure stabilizer tank (HPST) and a compressor element (CE) with designs identical to those for flight were burst tested.

The 60 K charcoal filter was tested for its absorption capacity and found to trap about 3 orders of magnitude more capacity than needed for the flight coolers. The flow rates of the J–T expanders were characterized under prescribed conditions for flight by thermal cycling and cool downs to representative temperatures (~20 K). All cold end heaters were thermal-cycled to cryogenic temperatures (~20 K). The tubes in tube heat exchangers were characterized for their thermodynamic performance in subsystem tests. All the cold end sensors were irradiated with representative doses to qualify them for proton and gamma radiation. The LVHXs utilized in the flight coolers are identical to those tested in the EBB cooler.

Almost all the components used in the engineering breadboard (EBB) cooler were identical to those used for flight. This provided excellent qualification of these components at the system level.

7.2. Subsystem level

Three compressor elements (CE) were cycled to simulate temperature and pressure conditions that would be experienced by the flight CEs for 5000 cycles each. The gas gap actuators (GGAs) were cycled for 24,000 cycles in prototype units (the flight mission and ground testing is worth about 16,000 cycles). A pathfinder test that used a flight CE without the hydride in the CE and a flight GGA was used to qualify the GGA hydride size and the entire gas-gap system for maintenance of low pressure vacuum (~1 Pa) conditions during the off-state and medium pressure (~1 kPa) vacuum conditions in the on state [8].

7.3. System level (EBB cooler)

In order to validate the sorption cooler flight design, an engineering breadboard (EBB) cooler was developed [9,10]. Testing of the EBB cooler began in January 2002, and ended in May 2003. Throughout this period, the cooler was operated for a total of 4300 h, during which its performance was verified with respect to the flight requirements. The EBB provided a synergistic system test prior to the construction of the flight coolers. The results obtained in the 17 months of test campaign gave an extraordinary insight in operation of the sorption cooler, confirming the predictions and analysis [11], and validating the flight design. In addition, operation of the EBB was used to develop robust operational algorithms, which were implemented in the flight prototype electronics. Testing it with the EBB cooler also validated the prototype electronics. Fig. 5 shows pictures of the EBB cooler and its subsystems.

All the components for the flight cooler have been built to be functionally equivalent to those of the EBB, with a few exceptions. For this reason, the subassembly interactions and performance in the EBB are considered to be representative of those expected of the flight models.

All the lessons learned during the EBB tests have been included in the design and operation of the flight cooler. In addition, the EBB test validated the basic functionality of the test facility. The facility will remain essentially the same for the flight cooler testing, except for modifications required to accommodate the geometric configuration of the flight cooler. The enormous experience gained from the extensive EBB testing campaign greatly improved the reliability, robustness, and ability of the flight cooler to meet its requirements during testing and during flight.

8. Some important lessons learned from the EBB tests that were employed for the flight coolers

(a) Automatic J–T plug detection and defrost procedures: The software automatically detects a pressure rise due to a plug. It discriminates between a true plug and the flow reduction due to off-normal J–T operating conditions (warmer J–T during startup leads to lower than normal flow rates). And it finally energizes the defrost heater to eliminate the plug. The software then turns off the defrost heater which is then followed by a full recovery of flow.

(b) Cooler pressurization with conditioning mode: An elegant scheme was devised to achieve fast pressurization and establishment of normal cooling after a fresh cooler start or a restart after shutdown initiated by the spacecraft. The primary algorithm is based on an adaptive change in cooler cycle time to inject the maximum energy into the bed heaters safely and within the constraints of operating the cooler reliably. Compared to constant energy injection in normal mode, the conditioning mode with adaptive energy insertion speeds up the pressurization by about factor of three.

(c) Contamination mitigation by recharging the cooler with fresh H_2 after a few weeks of operation that flushes out any residual contaminants in the cooler.

(d) Coupled testing of the cooler (TMU) with the French supplied electronics characterized the electronics hardware and software components as a subsystem, tested their compliance with cooler control and

Fig. C. Photograph of 100 K and 55 K pre-coolers (PC2, PC3a, PC3b)

Fig. B. Photograph of EBB compressor

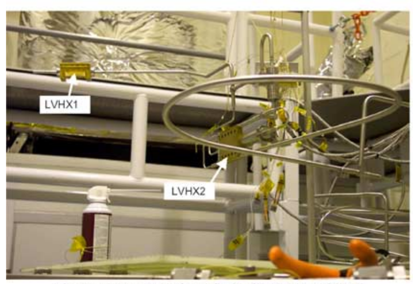

Fig. D. Photograph of pathfinder flight-like cold end

Fig. E. Photograph of Planck EBB test facility

Fig. 5. Engineering breadboard sorption cooler subsystems (clockwise: pre-coolers, compressor, test facility and cold end).

monitoring requirements and validated the Planck sorption cooler at system level (TMU+electronics).

8.1. Cooler thermodynamic performance modeling and comparison to test data

During the preliminary design phase an EXCEL based overall design model of the cooler was constructed to trade-off the various parameters associated with the functionality of this cooler. Once the design was optimized at the high level, a very sophisticated and detailed performance prediction model [11,12] was developed to support the design process and to evaluate the results of prototype testing. The performance of these coolers depends on many related operating parameters—with the temperatures of pre-cooling thermal shield and the warm radiator being only two of many—and they can only be assessed through a detailed modeling of each component coupling. This model predicts the time varying temperature, pressure and H_2 concentration gradients within the metal hydride beds, the H_2 flow rate, cooling power produced in the cold head, and the oscillations of the cold head temperature. Each component model has been parametrically described to allow trade off evaluation and the possibility to use it for different environmental and cooling requirements and for other sorption coolers.

The full validation of the model was obtained by comparison of the performance predictions to the experimental data for the engineering breadboard cooler built at JPL and described earlier in this paper. Some key performance requirements predicted for flight and measured by the EBB cooler, after normalization for flight to account for different boundary conditions and operating domain (like cooling produced and cold head temperature) are shown in Tables 1 and 2 below.

Table 1
Cooling produced versus predicted

Pre-cooler temperature (K)	Cooling predicted for flight, at 6.5 mg/s flow (mW)	Measured and normalized in EBB test (mW)
45	1828	1830 (±32)
50	1476	
53	1298	
55	1196	
60 (requirement)	986 (requirement)	1005 (±24)

Table 2
Measured cold end temperature versus predicted

Warm radiator (K)	Predicted LVHX1 temperature (K)	Measured and normalized in EBB test (K)
260	16.91	17.78
270	17.40	17.98
280 (requirement)	18.19	18.62

Excellent agreement was obtained between the predictions and the measured data.

9. Conclusions

Extremely successful testing of the EBB cooler demonstrated the viability of sorption coolers designed for space missions. Excellent agreement between predictions for the EBB cooler performance and the test results validated the flight cooler design. All important lessons learned from EBB testing were incorporated in the design, assembly and testing of the flight coolers. Excellent progress has been made in the construction of the coolers that will be delivered to ESA for the Planck mission. Based on the approach taken to design, build and test the flight coolers and the progress made until now, all indications are the Planck sorption coolers will operate successfully in flight and meet their requirements. Success of the Planck coolers will pave the way for a more widespread usage of such coolers for space missions.

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