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The Planck sorption cooler: Using metal hydrides to produce 20 K

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Abstract

The Jet Propulsion Laboratory has built and delivered two continuous, closed cycle, hydrogen Joule–Thomson (J–T) cryocoolers for the ESA Planck mission, which will measure the anisotropy in the cosmic microwave background. The metal hydride compressor consists of six sorbent beds containing $LaNi_{4.78}Sn_{0.22}$ alloy and a low-pressure storage bed of the same material. Each sorbent bed contains a separate gas-gap heat switch that couples or isolates the bed with radiators during the compressor operating cycle. $ZrNiH_x$ hydride is used in this heat switch. The Planck compressor produces hydrogen gas at a pressure of 48 bar by heating the hydride to ~450 K. This gas passes through a cryogenic cold-end consisting of a tube-in-tube heat exchanger, three pre-cooling stages to bring the gas to nominally 52 K, a J–T value to expand the gas into the two-phase regime at ~20 K, and two liquid–vapor heat exchangers that must remove 190 and 646 mW of heat, respectively. Gas evaporated from the liquid phase is recovered by three hydride beds at ~0.3 bar and 270 K. Each cooler was designed to provide 1 W cooling at ~20 K for a total input power of 470 W, excluding electronics. The performance of these coolers is mainly a function of the compressor interface and final pre-cooling stage temperatures. We present results from the testing of these two coolers for the input power, cooling power, temperature, and temperature fluctuations over the flight allowable ranges for these interfaces.

Keywords: Intermetallics; Hydrogen storage materials; Hydrogen absorbing materials; Metal hydrides

1. Introduction

Planck is a European Space Agency (ESA) mission that will launch in late 2007 to measure the temperature anisotropy of the Cosmic Microwave Background (CMB) at high angular resolution. Two instruments, the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI) will measure the CMB from 30 to 957 GHz. Both instruments need to be cooled to cryogenic temperatures to optimize their signal-to-noise ratio. The LFI instrument requires a temperature of 20 K that is provided by direct cooling through the sorption cooler. The HFI instrument needs its sensors cooled to 0.1 K. This is accomplished using two additional coolers: a 4 K mechanical Joule–Thomson cooler; and an open-cycle dilution cooler. The sorption cooler provides pre-cooling for the 4 K mechanical cooler [1].

As with many space cryogenic missions, the Planck sorption cooler depends on passive cooling by radiation to space. This is accomplished on Planck by three V-groove radiators [1]. The final V-groove is required to be between 45 and 60 K to provide the required cooling power for the two instruments. At 60 K, with a working pressure of 48 bar, the two-sorption coolers produce the 990 mW of required cooling power for the two instruments.

2. Sorption cooler description and operation

To provide complete redundancy for the mission, two sorption coolers were built and delivered. Flight Model 1 (FM1) was delivered to ESA in May 2005, while Flight Model 2 (FM2) was delivered in August 2005. The two coolers are functionally identical. Each consists of a sorption compressor (SCC) and a piping assembly and cold-end (PACE). The as-built compressors are identical while the two as-built PACEs are mirror images of each other with some minor differences in the lower piping sections. Fig. 1 shows the FM1 configuration. Due to the commonality of the two coolers; the following description applies to both coolers.

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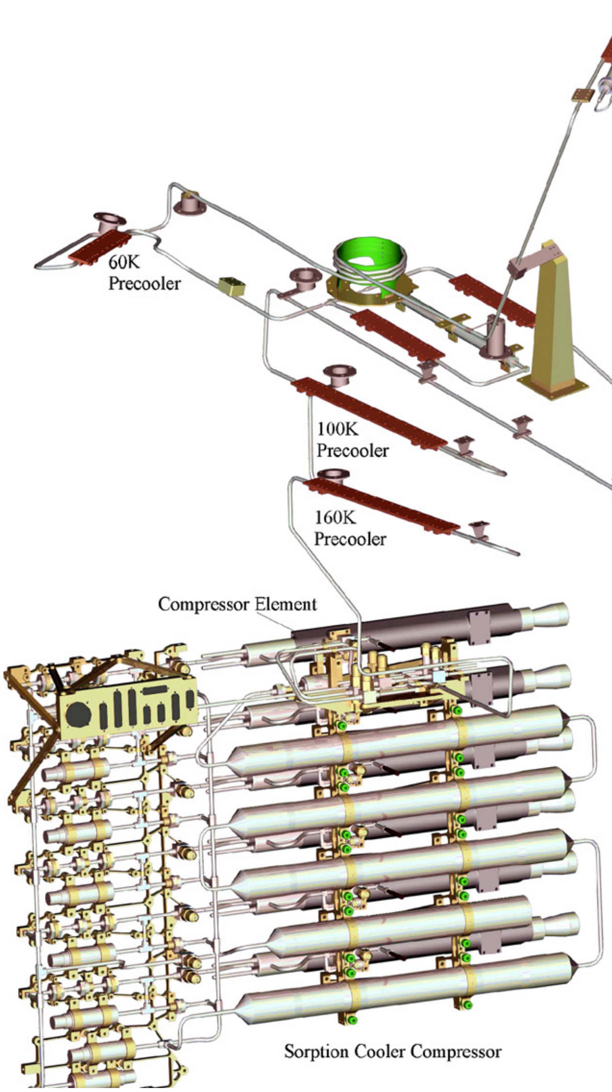

Fig. 1. Model of the FM1 sorption cooler. The FM2 sorption compressor is identical, while the piping sections (PACE) is a mirror image. The PACE pre-coolers attach to the spacecraft V-grooves. The sorption compressor attaches to the warm radiator panel.

2.1. Sorption cooler operation

The Planck sorption cooler performs cooling using Joule–Thomson (J–T) expansion with hydrogen as the working fluid [2]. The hydride compressor is the key element, which produces gas at approximately 50 bar and also pumps the returning gas by absorption at a pressure of ∼0.5 bar. Fig. 2 shows the principles of the cooler operation. Each sorption compressor element (CE) is taken through four-cycle steps of operation: heatup (pressurization), desorption, cooldown (expansion), and absorption. In order to produce a continuous stream of liquid refrigerant and to satisfy the mission requirements, six compressor elements are required. At anyone time, an element is in the heatup, desorption, and cooldown phases. Three compressor elements are used in the absorption phase for a total of six compressor elements.

In this system, there is a basic cycle time over which each step of the process is performed. The typical cycle time is on the order of 700 s. Resistance heaters provide the heating of the hydride while cooling is achieved by thermally connecting the compressor element to a radiator at approximately 270 K. In order not to lose excessive amounts of heat during the heatup and desorption cycles, each compressor element is equipped with a hydride actuated gas-gap heat switch. The heat switch is a vacuum space that is filled by heating the hydride. The hydride used for the heat-switch is ZiNi and is described in detail in [3]. During the cooldown and absorption phases, the gas-gap hydride is heated, and the compressor element is thermally coupled to the radiator.

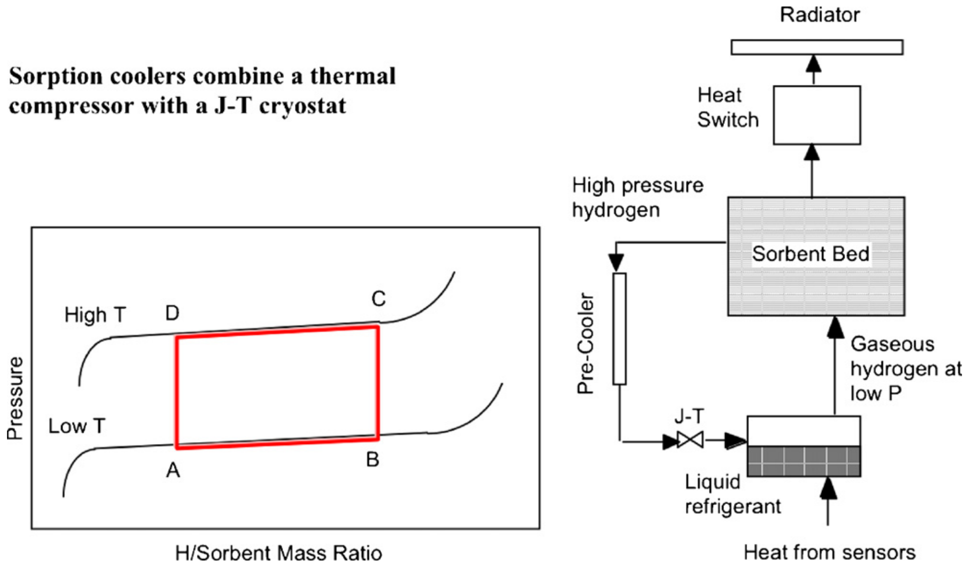

Fig. 2. Schematic showing cooler operation. On the left are shown the working isotherms of the hydride. Points B–C is the heatup cycle; C–D the desorption cycle; D–A the cooldown cycle; A–B is the absorption cycle. On the left is depicted the main parts of the sorption cooler and the warm radiator heat sink.

The hydrogen refrigerant, evolved from the desorption CE, flows to the high-pressure stabilization tanks (HPST) at a nominal pressure and flow rate of 48 bar and 6.5 mg/s. The refrigerant then travels from the tanks through a series of heat exchangers that pre-cool the gas to approximately 60 K, followed by expansion through the J–T expander. Upon expansion, the hydrogen forms liquid droplets whose heat of evaporation provides cooling for the two instruments. The refrigerant returns through the heat exchangers to the absorption CEs at a pressure of 0.5 bar. The temperature of the two-phase liquid, and thus the instrument temperatures, are determined by the absorption properties of the hydride, which are in turn determined by the radiator temperature. Each of the six compressor elements is connected to both the high-pressure and low-pressure sides of the plumbing through check valves, which allow gas-flow in only a single direction. On the low-pressure side, a storage sorbent bed, using the same hydride, functions to set the gas concentration of the six compressor elements by changing the temperature of the hydride with resistive heaters. This sorbent bed also functions to store hydrogen gas evolved as the cooler ages.

The PACE consists of a tube-in-tube heat exchanger, three pre-cooler stages, a porous plug J–T expander, and two liquid–vapor heat exchangers (LVHXs). The three pre-cooling stages, PC1, PC2, and PC3, attach to the three V-grooves, and are nominally at 160, 100, and 52 K, respectively. PC3 consists of three interfaces to the V-groove, PC3A, PC3B, and PC3C, to distribute the heat removed from the gas stream to different locations on the 3rd V-groove. The temperature of the last pre-cooler, PC3C, determines the cooling power. Between PC3C and the J–T, a high efficiency heat-exchanger pre-cools the gas stream. After the J–T, the two-phase mixture passes through the two LVHXs. LVHX1, is required to remove 190 mW while LVHX2 removes 646 mW. The vapor pressure, and hence the temperature of the LVHXs, is established by the three absorption compressor elements.

A temperature stabilization assembly (TSA), using PID control, is placed between LVHX2 and the instrument interface to reduce temperature fluctuations. The TSA consists of two thermal resistors on each side of the control stage. One hundred and fifty milliwatts for temperature control power is allocated. This is in addition to the 836 mW required for the instruments, for a total of 986 mW.

The requirements for the Planck sorption cooler are given in Table 1 as a function of the interface flight allowables. The performance of the cooler depends on two interface temperatures. The first is the interface to the compressor elements, which determines the cold-end temperature, and to second order, the input power. The second, the temperature of the final pre-cooling, PC3C, determines the cooling power and the input power. For a constant pressure of 48 bar, the cooling power varies from 1 W at 60 K, to 2 W at 45 K.

2.2. Hydride compressor

In this section, we focus on the unique features of a sorption compressor. Basically, the sorption compressor serves two main purposes: (1) produce a hydrogen gas pressure of ∼48 bar for a

Table 1
Planck sorption cooler requirements

LVHX1 temperature	<19 K
LVHX2 temperature	<22.5 K
LVHX1 temperature fluctuations	<450 mK
LVHX2 temperature fluctuations	<100 mK
Cooling power	>986 mW (646 mW for LFI, 190 mW HFI, 150 mW for TSA
Input power (excluding electronics)	<426 W (BOL)
Interface flight allowables	
Warm radiator	262–282 K
Final pre-cooling stage	45–65 K

Table 2
Results for flight models one and two for a warm radiator interface temperature of 282 K and a final pre-cooling temperature of 60 K

	LVHX1 temperature (K)	LVHX2 temperature (K)	LVHX1 fluctuations (mK)	LVHX2 fluctuations (mK)	Cooling power (mW)	Input power (W)
Requirement	<19.02	<22.5	<450	<100	>996	<426
Flight Model 1	18.4	19.7	374	91	1050	387
Flight Model 2	18.63	20.73	442	159	1116	387

flow rate of 6.5 mg/s within the limits of the required input power, and (2) by absorption pumping, maintain the low-pressure manifold so that the temperature and temperature–fluctuation requirement at the instrument interfaces is met. In addition, these requirements must be met over the lifetime of 2 years. $La_{1.0}Ni_{4.78}Sn_{0.22}$ hydride is most suited for the above requirements due to its isotherm and aging properties [4]. For the production of 48 bar, the hydride temperature will be ∼465 K. This temperature is below the temperature where excessive disproportionation that would lead to premature aging would occur [4–6]. In addition, the power required to heat the hydride and to maintain it at the desorption pressure must be low enough to satisfy the input-power requirement. Regarding the instrument temperature and fluctuation requirements, the hydride must have its absorption pressures below 0.3 bar for a hydride temperature of 282 K.

Of special importance is that the isotherms have minimal slope across a wide composition range both for the high- and low-pressures of the compressor. If the isotherms are not relatively flat at 465 K, the input power will be prohibitively large. Likewise, to limit the instrument fluctuations, the absorption plateau must also be flat, while the unheated CE sorbent beds are filling with hydrogen at a rate of 6.5 mg/s. Of equal importance is the thermal behavior of the CE that, along with isotherm properties, determines the temperature fluctuations. Thermal conductivity of $La_{1.0}Ni_{4.78}Sn_{0.22}$ powder is poor and the heat of absorption cannot be removed easily. For this reason, aluminum foam was used in packing the hydride to increase the thermal conductivity [2,7]. Even with the use of aluminum foam, temperature gradients as large as 30 K exist in the hydride for nominal operation. The poor thermal conductivity is also the reason why three absorption CEs are necessary to meet requirements. The required mass flow, 6.5 mg/s, is split between the absorption CEs, which results in the heat of absorption being removed through the three elements.

The lifetime of the hydride is determined by the number of cycles undergone by a compressor element. As the hydride degrades, the isotherms become narrower and the plateau slopes increase [8]. As discussed above, the cooling power varies from 1 to 2 W over the flight allowable of the final pre-cooling temperature. To increase the lifetime of the cooler, the mass flow can be reduced from the 6.5 mg/s at 60 K to about 5 mg/s at 45 K and still provide the required cooling power. With less mass flow, a longer cycle time can be used, which will increase the lifetime of the hydride. The same amount of mass is being used (or equivalently the same plateau width), only at a slower rate. As the plateau width narrows, decreasing the cycle time to prevent temperature fluctuations above the requirement will become necessary. In order to decrease the cycle-time, more heatup power is required. In addition, the desorption power will increase because of the increased slope of the isotherms. At lower pre-cooling temperatures, the required pressure is less, and in turn, the input power is lower.

3. Results

Both coolers, FM1 and FM2, were tested over the flight allowable parameter ranges with the complete results discussed elsewhere. Table 2 shows the results for the two coolers for a warm radiator interface of 282 K and a final pre-cooling temperature of 60 K. Requirements were met for all test conditions except for the temperature fluctuations. From Table 2, the FM2 fails to meet requirements for the LVHX2 interface, 159 mK versus a requirement of 100 mK. This occurred for other interface conditions for both coolers. The lack of compliance with these requirements is due to gravitationally induced two-phase flow. A waiver was granted for this requirement because two-phase flow effects are not expected to occur in the micro-gravity conditions of space. These issues have been discussed in Ref. [9]. Total test time for each cooler was greater than 1000 h.

3.1. Temperature and fluctuations

The maximum instrument interface temperatures occur for the interface conditions of Table 2. For the FM1 and FM2, LVHX1 was 18.63 and 18.4 K, respectively. Both coolers satisfy the requirement of <19.0 K. Fig. 3 is a plot of the low-pressure manifold of the compressor and the cold-end temperature.

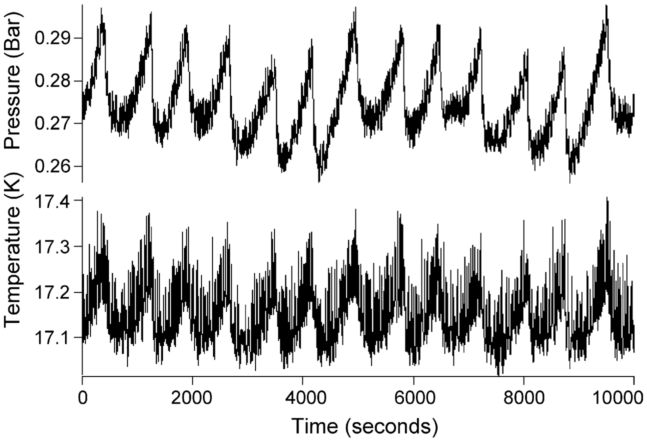

Fig. 3. Plot of low-pressure manifold and cold-end temperatures. Periodic shape is due to cycling of compressor elements. Higher frequency noise seen in the temperature is due to two-phase fluid flow.

Clearly, the two track each other closely, which will be the case for two-phase liquid. The periodic rise-and-fall of the pressure/temperature is due to filling of the absorption isotherms. When a bed begins absorption, the pressure/temperature drops abruptly, and then slowly rises as the CEs fill. The higher-frequency variations are due to two-phase liquid behavior in the cold-end. Note that the relative magnitude is much larger in the cold-end temperature than in the compressor low-pressure manifold.

3.2. Cooling power

The cooling power will be a minimum for the conditions of Table 2. The requirement of 996 mW is satisfied for both coolers and for all other test conditions.

3.3. Input power

The majority of the input power consists of the heatup power and the desorption power provided to the compressor elements. This requirement is met for the conditions of Table 2 and all other test conditions.

4. Conclusions and current status

Flight acceptance testing of the two JPL sorption coolers has been performed. The coolers met all requirements except for temperature fluctuations. The higher level of temperature fluctuations is due to gravity pooling leading to two-phase plug-flow events. A waiver was granted based on the fact that gravity pooling will be absent in micro-gravity.

The two coolers have been delivered to ESA and have just recently undergone spacecraft level testing, with the results being similar to the JPL results.

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