Planck Engineering Breadboard Sorption Cooler Test Results Over Its Entire Operating Range

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The Jet Propulsion Laboratory (JPL) is developing a continuous hydrogen sorption cryocooler for the ESA Planck mission to measure the anisotropy in the cosmic microwave background. The sorption cooler is the only active cooling for one of the instruments and it is the first of a chain of three coolers for the other instrument on Planck. The cooler has been designed to provide a minimum cooling capacity of 1.1 W at a temperature below 20 K and with a temperature stability requirement of 100 mK over a compressor cycle (667 s) with an input power less than 520 W. The performance of the sorption cooler depends on many coupled operating parameters such as the temperatures of pre-cooling thermal shields (varying between 50 to 60 K) and the warm radiator (260 to 280 K). The breadboard sorption cooler has been tested to verify the design performance in terms of input power, cooling power, and cold end temperature as the thermal interfaces are varied over ranges expected for flight operation.

INTRODUCTION

Planck is a European Space Agency (ESA) to be launched in 2007 that will measure the Cosmic Microwave Background (CMB). Two instruments, the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI) will measure the CMB from 30 to 860 GHz. The Planck hydrogen sorption cryocooler will directly cool the LFI to 20 K while providing pre-cooling for the HFI cooler chain [1]. The sorption cooler consists of a six-element sorption compressor and a Joule-Thomson (JT) cryostat [2]. The cooler produces liquid hydrogen in two liquid reservoirs whose temperatures are stabilized by hydrogen absorption into three compressor elements. As with many future space cryogenic missions, the Planck sorption cooler depends on passive cooling by radiation to space. This is accomplished on Planck by V-groove radiators [1] with the coldest radiator required to be 60 K or below in order to provide the final pre-cooling stage for the JT cryostat. The radiator temperature, along with the inlet pressure and mass flow produced by the sorption compressor, determines the cooling power. The inlet pressure to the cryostat produced by the Planck sorption compressor is 5 MPa for an input power of less than 520 W. For the required cooling power the JT expander is chosen to produce a mass flow of 6.5 mg/s. These design choices result in a compressor cycle time of 667 s [2]. The actual liquid reservoirs temperatures are determined by the absorption isotherms of the hydride material used in the compressor elements. Thus the heat rejection temperature of the compressor elements during absorption and the final pre-cooling stage determine the cooler performance for a given design. The Planck sorption cooler requirements are summarized in Table 1.

EBB SORPTION COOLER

In order to validate the sorption cooler flight design an Engineering Breadboard (EBB) cooler was developed. The EBB cooler was built to be functionally equivalent to the flight design. The as-built EBB compressor is very similar to the flight design while the flight cryostat design is somewhat different. A separate cryostat design validation is currently ongoing. The EBB sorption compressor consists of six

Table 1. Planck Sorption Cooler Requirements

LR1 Temperature	< 19 K
LR2 Temperature	< 22K
Temperature Fluctuations	< 100 mK
Cooling Power	1102 mW
Input Power	< 520 W

Interface Flight Allowables

Warm Radiator	260-280 K
Pre-cooling stage	45-65 K

compressor elements, high-pressure stabilization tanks (HPST), and the low-pressure stabilization hydride bed (LPSB). Each compressor element includes a hydride actuated gas-gap heat switch that thermally couples or isolates the compressor element. The HPST consists of 5 one-liter tanks and serves to stabilize the high-pressure manifold. The LPSB, in addition to damping pressure oscillations in the low-pressure manifold, is used to store hydrogen gas so that the cooler can be shipped a pressure below atmospheric pressure. The two manifolds are separated from the compressor elements by check valves that control the flow into and out of the compressor elements.

Following the flight design, the EBB JT cryostat consists of a tube-in-tube heat exchanger, three pre-coolers, a porous plug J-T expander, and two liquid reservoirs. The major difference between the EBB cryostat and the flight design is the use of a discrete heat exchanger (DHX) that fixes the JT temperature and serves to keep the liquid dry-out point fixed [3]. The current development design will not use this element. The three pre-coolers are designed to operate at 160 K, 100 K, and 50-60 K. The two liquid reservoirs LR1 and LR2 provide cooling for the HFI and LFI instruments respectively. For the present EBB testing the JT expander produces 5.9 mg/s mass flow at 5 MPa, which is 10 % lower than the flight design of 6.5 mg/s. This impacts the input and cooling powers and these will be normalized in the data presented below.

TEST FACILITY

In order to realistically test the EBB sorption cooler under flight conditions a vacuum test facility was built. This facility allows the entire cooler to be mounted in a vacuum chamber that simulates the spacecraft interfaces. A schematic of the facility and cooler is shown in Figure 1. The chamber is relatively large, 1.5 m diameter and 2.5 m in length, so that the expected flight routing of the JT cryostat can be tested. To simulate the warm spacecraft radiator, each compressor is mounted to a thermally isolated aluminum plate with each plate cooled by a common chiller that can reach 233 K. With this chiller we are able to produce the full thermal range of the compressor elements in Table 1.

Above the compressor are two shrouds that thermally isolate the cryostat from the warm compressor. Mounted on the top of the outer shroud (100 K shroud) is a 300-liter liquid nitrogen tank. The tank serves as the cooling source for the 100 and 160 K pre-coolers in addition to cooling the shroud. For the current testing the first two pre-coolers operated at 165 K and 150 K due to inadequate cooling from the test facility. The effect of this is to add an additional amount of heat that must be removed by the 50 K pre-cooler, but does not affect the cooler performance. The inner shroud (50 K shroud) is cooled by the first stage of a CTI 1020 GM cryocooler to ~50 K while the second stage is attached to the 50 K pre-cooler. In our testing we were able to maintain the 50 K pre-cooler over its entire operational range. The components below the 50 K pre-cooler, JT expander, liquid reservoir, and discrete heat exchanger are thermally isolated within the 50 K shroud to a parasitic level of about 25 mW. The two liquid reservoirs are attached to separate copper mounting brackets. Each bracket is instrumented with a thermometer and a heater. The heater to each LR is used to simulate the instrument heat load. A four-wire measurement is used to determine the input power. At the high-pressure inlet to the discrete heat exchanger a heater and thermometer are placed. This heater and thermometer is controlled to a temperature nominally above the liquid temperature and below the exit temperature of the counter flow heat exchanger. By controlling this

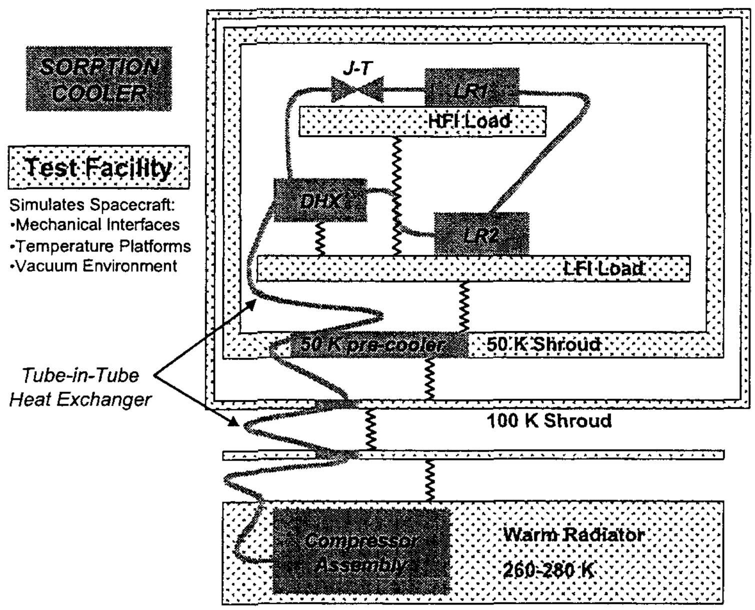

Figure 1. Schematic of the EBB Sorption Cooler and Test Facility

temperature, the excess cooling power of the cooler is removed and a stable dry-out point can be maintained. The total cooling power is determined by the amount input into LR1, LR2, and the heat needed to maintain the temperature at the discrete heat exchanger input.

TEST RESULTS

To date the EBB sorption cooler has been run for more than 1400 hours. All design requirements have been measured over the flight allowable range. A summary of the test data is given in Table 2. As can be seen, to first order the liquid reservoirs are only a function of the compressor chiller temperature and are independent of the pre-cooler temperature. The requirements listed in Table 1 for liquid reservoir temperatures are met for all test conditions. Figure 2 is a plot of LR2 temperature fluctuations and the pressure variation in the low-pressure manifold. The sawtooth behavior is due to compressor element switching and shows that the main temperature fluctuations are due to the compressor. Generally, temperature fluctuations are observed to vary from 250 mK to 400mK and do not meet the requirements of Table 1.

Table 2. EBB Sorption Cooler Performance

Radiator Temperature (K)	**260**			**270**				**280**		
PC3 Temp. (K)	**45.7**	**53**	**60.1**	**45**	**50**	**53**	**60.1**	**45**	**53**	**60**
LR1 Temp. (K)	17.32	17.33	17.36	17.72	17.74	17.76	17.79	18.30	18.30	18.26
LR2 Temp. (K)	17.31	17.33	17.32	17.70	17.69	17.69	17.69	18.29	18.29	18.25

Flow Rate (mg/s)	5.83	5.85	5.86	5.85	5.90	5.91	5.91	5.88	5.91	5.86
Calculated Cooling Power (W)	1.748	1.311	1.012	1.805	1.499	1.339	1.028	1.813	1.331	1.010
Measured Cooling Power (W)	1.633	1.236	0.941	1.702	1.422	1.264	0.964	1.701	1.241	0.926
Cooling Power Deviation (%)	-6.6	-5.7	-7.0	-5.7	-5.1	-5.6	-6.2	-6.2	-6.8	-8.3
Total Power Supplied (W)	370.7	370.5	370.7	363.8	363.8	363.8	363.8	358.0	358.0	358.1

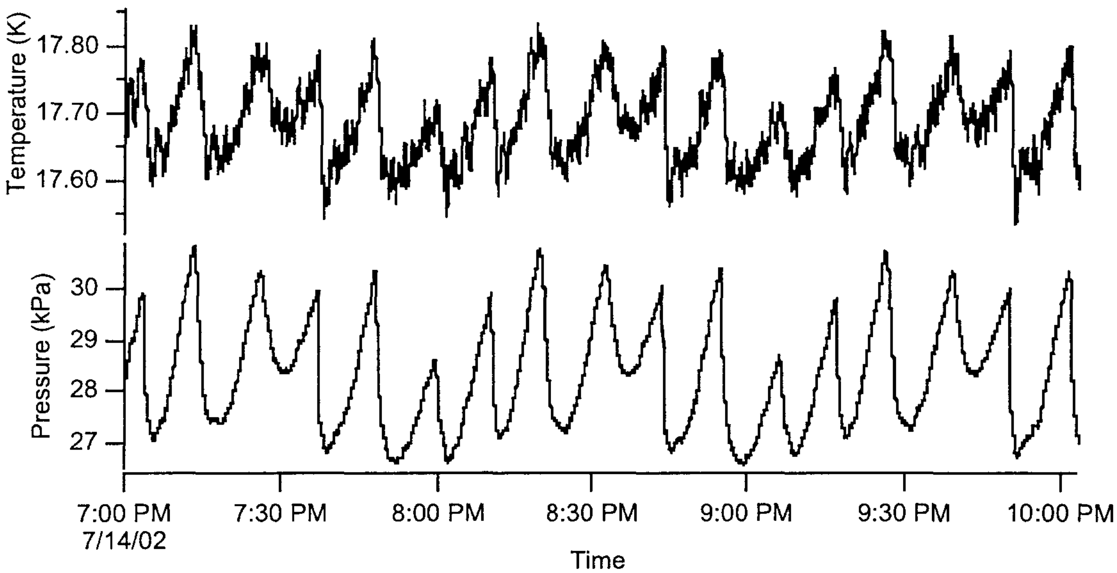

Figure 2. Plot of LR2 temperature and low-pressure manifold.

The cooling power, for the nominally constant mass flow in Table 2, is only a function of the pre-cooler temperature as expected. The measured values compare well to the calculated values. Again, the flow was 5.9 mg/s compared to the flight value of 6.5 mg/s. Thus, it is expected that with a properly selected JT expander the flight cooling power requirements will be met. Even at this reduced flow the requirement from Table 1 is met except at the 60 K pre-cooling temperature. The main uncertainties in the measurements are the values of the mass flow and the parasitics. From above, the parasitics are about 25 mW (2-3%) leaves a systematic difference of about 3-5 % between the calculated and measured cooling powers.

Input power is obtained from the sum of the heatup, desorption, gas-gap, and LPSB powers. Because the mass flow is 10 % lower than the flight design, the desorption power will be higher by about 17 W. The slight dependence of the power on compressor chiller temperature is due to a higher heat-up power at lower temperatures.

CONCLUSIONS

Planck EBB sorption cooler data have been measured over the flight allowable range of two key interfaces. Except for temperature fluctuations, the results indicate that the flight design will meet the requirements

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