Evaluation of Hydride Compressor Elements for the Planck Sorption Cryocooler

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ABSTRACT

Hydrogen sorption cryocoolers are being developed for the European Space Agency Planck mission to provide nominal 19 K cooling to instruments for measuring the temperature anisotropy of the cosmic microwave background with extreme sensitivity and resolution. The behavior of the metal hydride sorbent beds used in the compressor dominates both the performance and reliability of these sorption cryocoolers. The compressor elements have been designed to minimize their input power requirements and to enhance durability during extended temperature cycling while in operation. The Lanthanum-Nickel-Tin alloy $LaNi_{4.78}Sn_{0.22}$ in the sorbent beds circulates and compresses the hydrogen refrigerant gas while the ZrNi alloy is used to provide variable pressure in the gas-gap heat switches for each compressor element. Characterization tests have been performed on the compressor elements built for an engineering breadboard (EBB) cooler to evaluate the behavior of both the sorbent bed and gas-gap switches under conditions simulating flight operation. These results provide a basis for predicting EBB cooler performance and to identify any design deficiencies prior to fabrication of the flight compressor elements. In addition, experiments were done on compressor elements that had been operated up to several thousand cycles to assess degradation in the sorbent hydride and reduction in the effectiveness of the gas gap switches in reducing parasitic heat losses

INTRODUCTION

The Jet Propulsion Laboratory (JPL) is developing hydrogen sorption cryocoolers to provide cooling below 19 K to the instruments on the Planck spacecraft, which is scheduled to launch in 2007. Descriptions of the cryogenic systems for the Planck mission have been published[1,2]. Laboratory testing of a full-scale Engineering Bread Board (EBB) version of the Planck sorption cooler was started[3] in January 2002. The present paper presents a comprehensive description of the design and performance of the hydride compressor elements that were utilized in the EBB cooler[3]. After final iterations, the components will be built for integration into the flight coolers.

DESCRIPTION OF COMPRESSOR ELEMENTS

The compressor assembly for a Planck sorption cooler[2] has six identical compressor elements (CEs) each containing 615 grams of the hydride alloy $LaNi_{4.78}Sn_{0.22}$ in its sorbent bed. The CEs are independently heated and cooled through a series of heat-up, desorption, cool-down, and absorption steps to provide compression and circulation of the hydrogen refrigerant gas during closed-cycle Joule-Thomson (J-T) process that generates liquid hydrogen at ~18 K in the cryostat. The CEs are directly mounted to a radiator that is sized to reject the heat from the input power and exothermic hydrogen absorption by the alloy at 270 K +10 K/-20 K. Gas gap heat switches[4,5] are used to facilitate heat transfer between the sorbent bed and the radiator while minimizing thermal mass during the heat-up and desorption phases. Although the first version of the Planck compressor element was described previously[2,6], several modifications have been made to make the unit more robust during launch vibrations, reduce thermal gradients in the sorbent bed, etc. An exploded view of components for the compressor elements used in the EBB cooler is given in Fig. 1. The central portion of the outer tube is aluminum metal type 6061-T6, the foam is also 6061 aluminum at ~11% of its bulk density, the button is A286 stainless steel (SS), and all other components in contact with hydrogen are made from 316L stainless steel. To minimize sources of contamination and enhance impurity removal, all surfaces of the 316L SS were electropolished giving bright surfaces. The outer surface of the inner tube assembly and both surfaces of the aluminum portion of the outer tube were electroplated with a gold film of nominal thickness of 0.7 μm to reduce thermal emissitivity in the gas gap volume.

A cross sectional view of the assembled compressor element is shown in Fig. 2 and illustrates the 0.75 mm gas gap separation between the inner and outer tubes. The thickness of the wall for the inner tube is 1.22 mm except at the weld zones on the ends where it is 1.52 mm. The porous filter tube ensures that hydride powder contained in the Al foam does not migrate from the sorbent bed during the temperature and pressure cycling. Tight physical contact of the Al foam with the inner surface of the tube wall provides heat transfer from the sorbent bed to the gas gap. The sorbent bed is supported to the outer housing only at the ends using the supports shown in Fig. 1. All assembly joints are made using automatic orbital-tube welding under argon/3% H_2 gas.

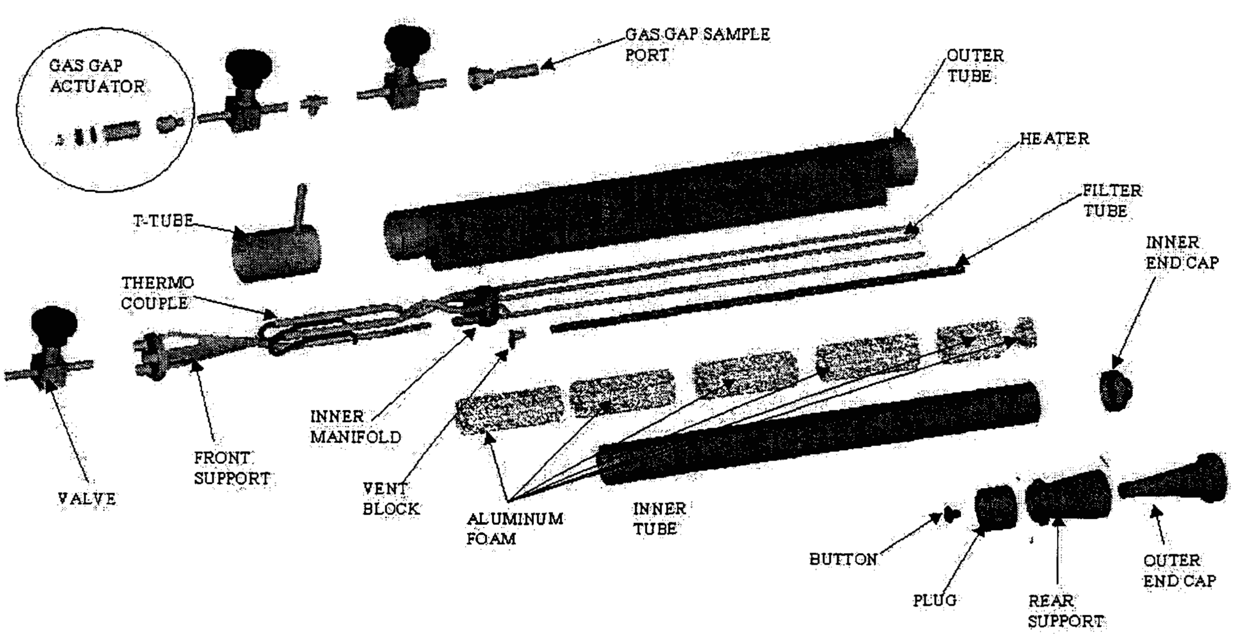

Figure 1. Exploded view of the components used in the compressor elements of the Planck Engineering Bread Board (EBB) cooler. Powder of the hydrogen sorbent alloy $LaNi_{4.78}Sn_{0.22}$ fills the voids in the aluminum foam pieces.

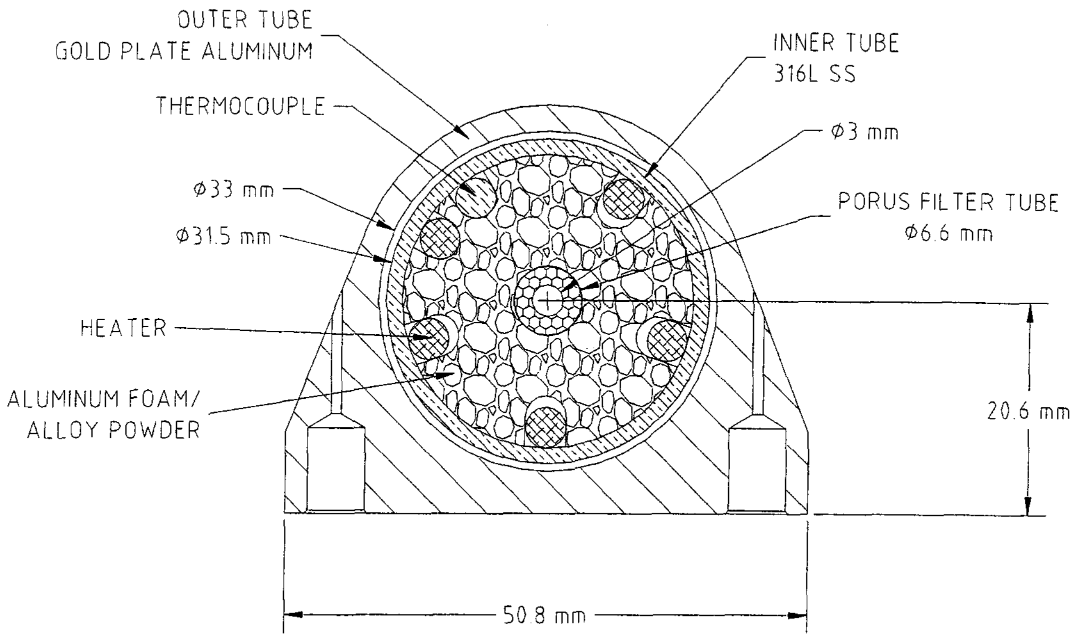

Figure 2. Cross sectional view of the EBB compressor element showing the gas gap spacing of 0.75 mm between the gold-plated inner bed that contain the sorbent alloy and the outer housing, which is gold plated on both surfaces.

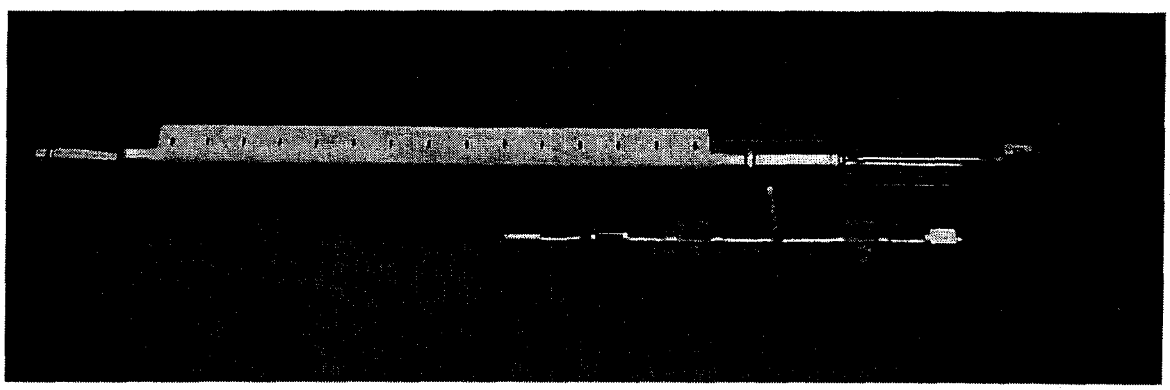

Figure 3. Photograph of an assembled EBB compressor element with a ZrNi hydride gas gap actuator installed.

Eight compressor elements were fabricated and assembled: Six for the EBB sorption cooler, one for vibration/shake testing, and one spare. A photograph of the spare CE with a gas gap actuator (GGA) attached is shown in Fig. 3.

The assembly of the CEs occurred in three phases after the fabrication of the various components and processing of the $LaNi_{4.78}Sn_{0.22}$ and ZrNi alloys for the sorbent bed and gas gap actuator bed, respectively. First, the inner bed is filled with $LaNi_{4.78}Sn_{0.22}$ alloy powder and a closure weld performed with all processing occurring in an argon atmosphere (<1 ppm O_2 and <2 ppm H_20) glove box. After a uniform powder distribution is achieved in the sorbent bed, the alloy is activated by vacuum baking above 525 K and reacted with purified hydrogen gas yielding hydride compositions in agreement with independent isotherm measurements. The inner bed assembly was next sent to Epner Technology (Brooklyn, NY) for gold electroplating. The gas gap actuators, which are shown in Fig. 1, were assembled following previously described procedures[4,5,7] using strips of high purity ZrNi cut with a diamond saw. Their external heaters were directly brazed to the GGA cap to provide stable thermal contact[7]. The resulting stability and reproducibility of each GGA unit was verified by performing a minimum of ~1000

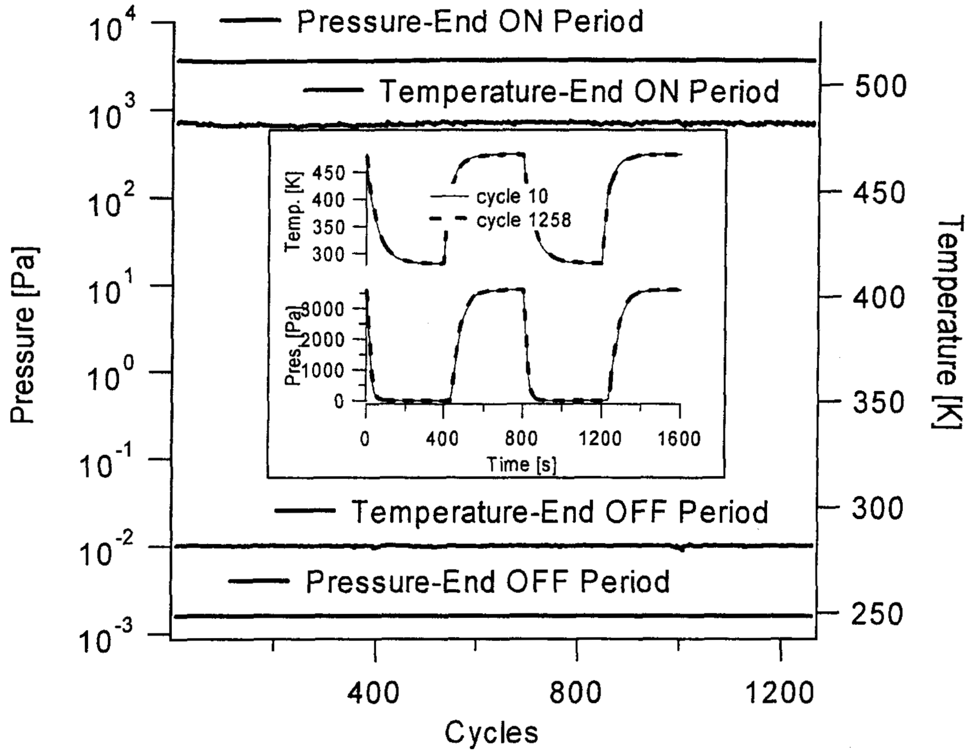

Figure 4. Performance of a ZrNi hydride actuator during initial temperature cycling prior to installation on a compressor element. The insert shows that both the temperature and pressure profiles have not changed between 10 and 1258 cycles.

temperature cycles over the expected operation range. Typical results obtained for one of the GGA units is shown in Fig. 4. No degradation in the upper and lower pressure values or the absorption and desorption kinetics was found. Similar results were obtained from all GGAs that were installed on EBB compressor elements. A manual valve was used to isolate activated and charged GGA with its initial hydride content of $ZrNiH_{1.5}$. The third phase was sequential integration of gold-plated inner bed assembly to the outer tube assembly and a GGA unit, which was followed by an extended hydrogen gas fill and evacuation process. The inner bed was heated to ~670 K with its internal heater while distilled water heated to ~360 K was circulated through a chiller plated mounted on the outer shell, which was covered in an insulation blanket. The gas gap volume was alternatively filled with purified hydrogen at ~1 bar pressure and evacuated with a turbomolecular pumping station. These fill-evacuate cycles were repeated until the mass spectrum from a residual gas analyzer (RGA) indicated no hydrocarbon species above instrumental background levels (i.e., usually over 100 cycles were required to obtain sufficient cleaning) in the vacuum state.

PERFORMANCE TESTING OF INTEGRATED COMPRESSOR ELEMENTS

In order for the Planck sorption cryocooler to meet its performance goals[2], numerous requirements are imposed[8] on the compressor elements. The heated sorbent beds need to provide hydrogen gas at 50 bar pressure and an average mass flow rate of 0.065 mg/s with a total (i.e., heat-up, desorption, and gas gap) input power of <410 W at end-of-life (i.e., two years of operation during ground tests and flight). During absorption, the beds must maintain hydrogen pressure below 0.59 bar (445 Torr) for a radiator temperature of 270 K. The ON-state pressure for the gas gap must exceed 800 Pa (6 Torr) and its OFF-state pressure go below 0.7 Pa (5.2 mTorr) with switching times below 250 s. Past studies[6,9] with the first prototype Planck CEs demonstrated that the sorbent bed met its beginning-of-life (BOL) requirements using an external

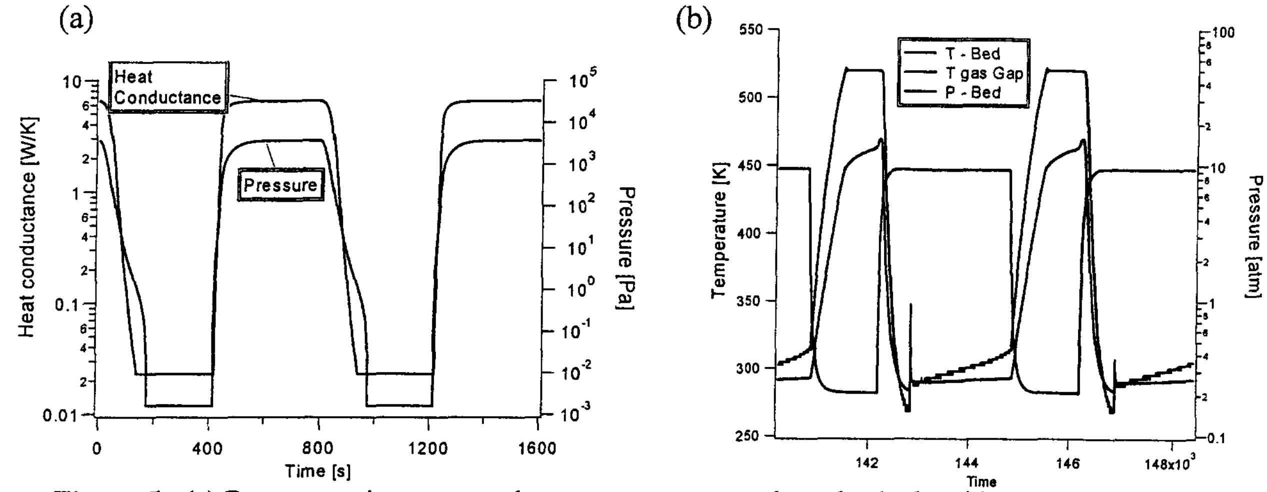

Figure 5. (a) Representative measured gas gap pressure cycle and calculated heat conductance for a heat switch during initial cycling tests of an EBB compressor element. (b) Behavior of the gas gap actuator temperature (T gas gap), sorbent bed temperature (T-bed), and sorbent bed pressure (P-bed) during two cycles of compressor operation.

gas manifold and vacuum pump for the heat switch. In addition, life cycling tests showed[4,7] that actuators composed of $ZrNiH_{1.5}$ also satisfied the requirements for heat switches. However, the behavior of the complete Planck compressor elements with hydride gas gap actuators had not been evaluated. These measurements have now been performed on seven of the EBB compressor elements.

An individual EBB compressor element was installed into a dedicated vacuum test chamber equipped with separate gas lines for the sorbent bed and gas gap volume, a circulation loop to an external refrigerator capable of cooling the CE chiller plate to 278 K, and hermetic electrical connections for the heaters and pressure and temperature sensors. The sorbent bed gas line was attached to the gas manifold described by Pearson, et al.[9] for controlled gas absorption and desorption that closely simulates behavior in the operating cryocooler. LabView software controlled the heaters, electropneumatic valves and pressure control valves as well as recorded the data from the sensors.

The relationship between the pressure and temperature in the gas gap with the parameters for the CE sorbent bed is illustrated in Fig. 5. The change in thermal conductance across the gas gap as a function of pressure is shown in Fig. 5(a) while the time constants for temperature variations during the ON-OFF and OFF-ON switches are given in Fig. 5(b) along with sorbent bed pressures during two heating/cooling cycles. The hydride-actuated gas gap heat switches clearly meet their performance requirements during both transitions.

A detailed comparison of the sorbent bed temperature and hydrogen mass flow rate during the desorption step is given in Fig. 6. The initial flow oscillations at the start of desorption are artifacts from the outlet flow controller system and were not seen during cooler operation[3] using the J-T expander. The input power during the desorption process in Fig. 6 was 158 W and outlet pressure was held at a constant 50.7 bar. While the flow varied during the desorption process, the average was close to the goal of 6.5 mg/s (i.e., 4.34 sl/m). The maximum temperature did not reach 465 K at the end of desorption.

Representative hydrogen absorption behavior observed from the same CE is shown in Fig. 7 where the shell temperature is maintained within 2 K of the chiller plate value of 278.5 K throughout the absorption. The hydrogen flow rate is around 1.42 sl/m (i.e., 2.1 mg/s) as specified[2,8] for boil-off gas from the liquid hydrogen reservoirs from Planck cooler operation at its nominal heat load. The temperature measured by the thermocouple in the hydride sorbent bed is 7-8 K above the shell temperature due to the limited thermal conductance of the powder/Al foam matrix to remove the heat from the exothermic absorption process. While the bed temperature remains fairly constant the pressure rises noticeably during the last third of the

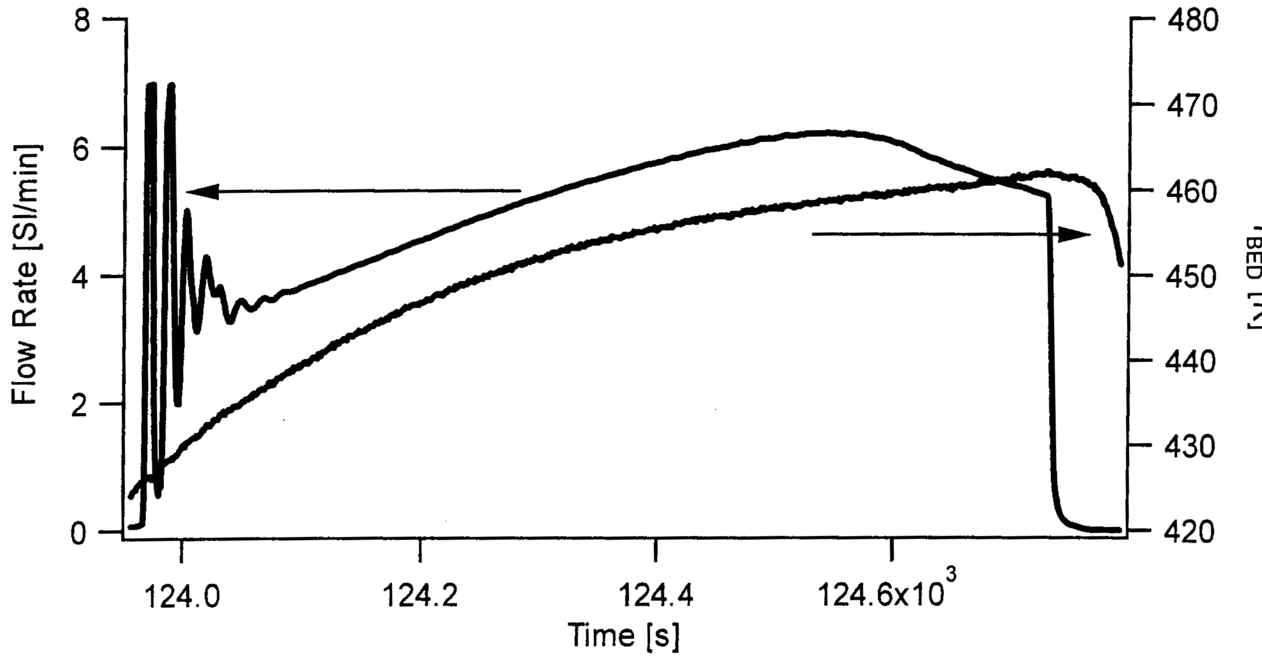

Figure 6. Representative behavior observed for hydrogen flow rate and sorbent bed temperature (T_{BED}) during the desorption phase of compressor operation. Input power was 158 W and desorption pressure was kept at 50 bar.

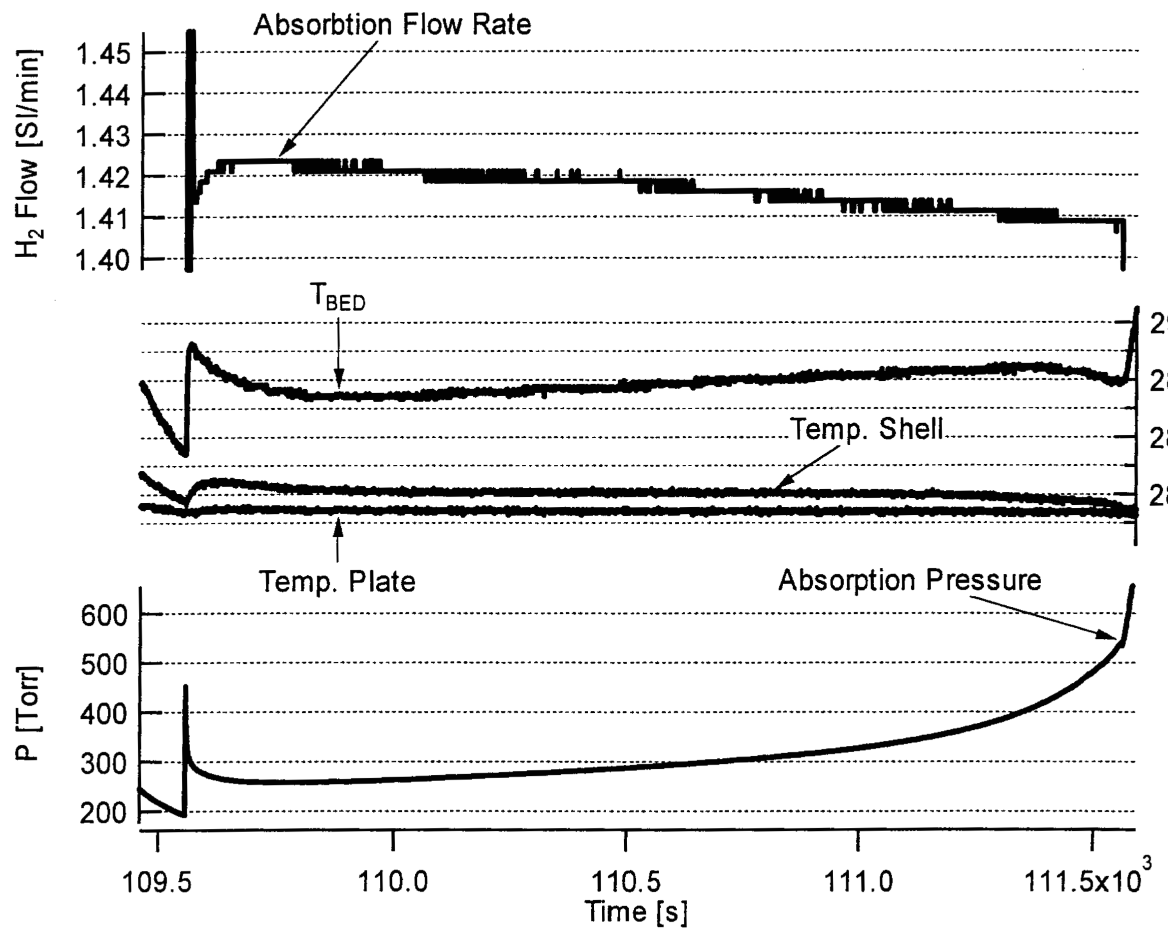

Figure 7. Representative behavior of the temperature in the hydride sorbent bed (T_{BED}), outer shell surface (Temp. Shell), and cooling plate (Temp. Plate) along with the pressure in the sorbent bed during the absorption phase.

absorption. The pressure and temperature spikes at the beginning and end are again artifacts from the control system. These are not seen during EBB cooler operation[3].

Seven compressor elements were each subjected to 50 – 100+ cooler simulation cycles to assess their initial behavior. Although there were some variations in the flow rate, temperature, and pressure profiles due to differences in starting hydride compositions and chiller plate temperatures, overall agreement in average mass flows, input power, pressure values, and gas gap parameters was observed.

VIBRATION TESTING OF A COMPRESSOR ELEMENT

After completion of its initial performance cycling tests, the CE designated for vibration testing was transferred into the glove box where the gas gap actuator assembly was removed and replaced with a VCR plug. This assembly was mounted on a custom vibration test fixture and instrumented with several force transducers/accelerometers. The hydrogen pressure in the sorbent bed was 0.42 bar and the hydride stoichiometry was determined to have been $LaNi_{4.78}Sn_{0.22}H_{4.3}$ from quantitative desorption measurements following the vibration tests.

The EBB compressor element was subjected to sine sweep and random vibration in each of its three principle axes at qualification levels expected during system random testing and launch on an Ariane V rocket[1]. The vibration tests were completed with no structural failures occurring although metal-to-metal impacting was detected during the high level runs and some minor modal frequency shifts were noted in the sine surveys.

Various post-vibration tests confirmed that no damage has been produced by these shake tests. X-ray radiography indicated no redistribution of the hydride in the sorbent bed and no displacements or cracks of the support structures at either end of inner tube assembly. A series of helium leak tests were performed of the gas gap volume (i.e., external leaks with the unit in a helium filled bag, the inner bed pressurized to 52 bar at ambient temperature, and the inner bed heated 470 K with a helium pressure of 52-55 bar) where no leaks were detected above the background level of $\sim 10^{-9}$ atm-cc/s. Further performance and cycling tests are planned to see whether there are any other changes although preliminary tests appear consistent with pre-vibration behavior.

LONG TERM OPERATION DEGRADATION AND CONTAMINATION

The Planck compressor elements will undergo ~20,000 cycles between 270 K and 470 K during ground testing and flight operation[2]. The degradation of the sorbent and gas gap hydrides has been a concern since the conception of the Planck sorption cryocooler and considerable efforts have been made to evaluate their behavior during accelerated aging studies[3-7,9,10]. The CE design includes storage margin that accounts for anticipated[2] rates of hydride degradation. The stoichiometric alloy (i.e., [Ni + Sn]/La ratio = 5.0) used in the EBB-CE sorbent beds has recently shown[7,10] smaller rates of degradation than the material used[3,7,9] on the earlier Life-cycle compressor elements (LCEs). To date there has been no indication of hydride degradation on the performance of the EBB compressor elements during their characterization tests or initial operation of the EBB cooler[2].

Three LCE units were thermally cycled up to 5000 times as reported previously[9]. The hydrogen gas from these sorbent beds has been recently analyzed by RGA and mass spectrometry. The dominant impurity was methane in the concentration range of 200-370 ppm relative to the total hydrogen content. There was also evidence of moisture and a species at mass peak 28 amu (i.e., either N_2 or CO) present at variable levels in the different beds. The beds had been initially filled with research grade hydrogen gas (i.e., 99.999+% purity) that was further purified by flowing it through a Nanochem chemical purifier and a carbon cold trap cooled in liquid nitrogen prior to admitting into the hydrogen gas filling station. Hence, the impurities in the LCE gas seen after cycling were probably generated from residual hydrocarbons on surfaces of filters, foam, and other components even though vacuum and purge gas cleaning was performed during activation. The hydride may act as a catalyst for the conversion of condensed impurities into methane, water, and CO. Since all these molecular species will form solids well above the temperature of liquid hydrogen, they would likely cause plugging at the J-T expansion valve. The Planck sorption coolers contain chemical purifiers/getters and a carbon trap cooled to 50 K to removed these condensable species from the hydrogen gas before entering the cold system and the J-T valve region[2,9]. However, the cycling of the LCE beds and individual EBB CEs was done without any filtering or gettering to remove impurities from the hydrogen. The remaining issue is how large to size these devices for the flight coolers that can remove the impurities effectively during the nominal two years of flight operation? A methane level of 43 ppm was observed in the EBB CE used for the vibration tests after only 68 cycles. It is thus likely methane formation is most rapid at the beginning of cycling when the residual hydrocarbon is the highest. A combination of initial cycling, evacuation and refilling with pure hydrogen may prove to be a viable means of eliminating long-term creation of methane and the other species. This supposition will be examined during future tests of both individual EBB compressor elements and the EBB cooler during extended operation.

During the time period between the completion of the characterization tests of the individual EBB compressor elements and start of the initial cooler operation, the two manual valves for the gas gap volume (see Figs. 1 and 3) remained close isolating the ZrNi hydride from the rest of the gas gap. When the pressure was checked for each CE, the pressures in these latter volumes range from 70 Pa to 700 Pa (i.e., 0.5 – 5.0 Torr) following ambient temperature storage between two and six months. Several tests, including RGA determination of gas composition, identified that hydrogen was responsible for essentially this entire pressure rise. Since the OFF state pressure in the gas gap must lie below 1.3 Pa (~10 mTorr) to minimize excessive parasitic heat leaks[4,5] to the outer shell and radiator, the magnitude of hydrogen pressure increase is a serious issue. Because the $ZrNiH_x$ gas gap sorbent was configured to work in the middle of its plateau region[4,7] during heat switch cycling, it can accommodate a certain amount of additional hydrogen without significant performance impact. However, its capacity is limited and increasing the mass and size of the actuator will require additional power to activate the heat switches. Consequently, quantitative assessment of amount of hydrogen has become imperative before the design of the compressor elements is finalized and the flight units fabricated.

Measurements of the rate of pressure increase in the gas gap volumes of two of the EBB compressor elements have been done under various conditions. The outer shell was maintained between 290 K and 296 K while inner bed was held at fixed temperatures from 293 K to 540 K and the pressure rise with time was recorded. Tests were made with the sorbent bed under vacuum, helium (0.6 – 35 bar), and hydrogen (0.5 – 55 bar). The observed rates for the quantity of gas produced in units of standard cubic centimeters per second (scc/s) are nearly independent of the pressure and gas composition in the sorbent bed, but are strongly temperature dependent. The rates range from 4×10^{-8} scc/s at 293 K to 9×10^{-6} scc/s at 525 K. These values are consistent with hydrogen outgassing and permeation rates reported[11-14] for stainless steel and other metals. These tests are still in progress and additional measurements are planned to determine the total hydrogen contents in the electroplated gold films, the nickel underlayers, and host 316L SS and Al metals. The results will be reported elsewhere in the future. The information on hydrogen contents in the structural materials and outgassing/permeation rates will be used to properly size the gas gap actuators and made any other modifications to ensure efficient heat switch performance during the planned operational life of the Planck sorption cooler.

CONCLUSIONS

The second generation of compressor elements for the Planck sorption cryocoolers has been successfully fabricated for use the EBB system. The hydride gas gap actuators have been found to work efficiently and reliably. The CE sorbent beds deliver and absorb hydrogen within the performance specifications. The results from the vibration tests and post shake measurements confirm that the basic structural design and component fabrication processes are sufficiently robust to withstand the expected launch conditions. Formation of methane has been observed during the temperature cycling of the CEs and this impurity must be removed from the hydrogen gas stream before entering the region of the J-T expansion valve. While the coolers have cold carbon traps for this purpose, improvements in cleaning processes are also being investigated for use on the flight units. Outgassing of hydrogen gas into the gas gap volumes has been detected and alternative methods to minimize its impact through of larger actuator beds or incorporation of supplemental valves will be considered after the total magnitude of gas has been established.

ACKNOWLEDGMENTS

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