PERFORMANCE, RELIABILITY AND LIFE ISSUES FOR COMPONENTS OF THE PLANCK SORPTION COOLER

R. C. Bowman[1], M. Prina[1], M. E. Schmelzel[1], C. A. Lindensmith[1], D. S. Barber[1], P. Bhandari[1], A. Loc[1], and G. Morgante[2]

[1]Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA

[2] Instituto Te.S.R.E.- CNR
Bologna, 40129, Italy

ABSTRACT

Continuous-duty hydrogen sorption cryocoolers are being developed for the European Space Agency (ESA) Planck mission. To achieve an acceptable level of performance and robust operation with these hydride refrigerators during flight, detailed investigations have been performed on the sorbent materials and on critical hardware components. The sorbent longevity has been verified for both the compressor alloy and the gas gap actuator alloy. 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. Check valves were operated using hydrogen gas for over 43,000 pressure cycles at various orientations and temperatures without leaks or other changes. The filters that will be used to protect check valves and J-T expander from particles were tested. The temperature gradients along the tubular heater elements for the compressor beds were evaluated to assess their impact on the dynamics of compressor element heating and hydrogen desorption. The durability and reliability of low-power heaters used for the gas gap actuators were determined by accelerated temperature cycling.

INTRODUCTION

Planck (http://astro.estec.esa.nl/SA-general/Projects/Planck/planck.html) is a space observatory that will image the temperature anisotropies of the Cosmic Microwave Background (CMB) radiation over the entire sky at extreme sensitivity and resolution [1]. Planck will provide much new information on several key cosmological and astrophysical issues and will test theories of the early universe and the origin of cosmic structure. To achieve these objectives,

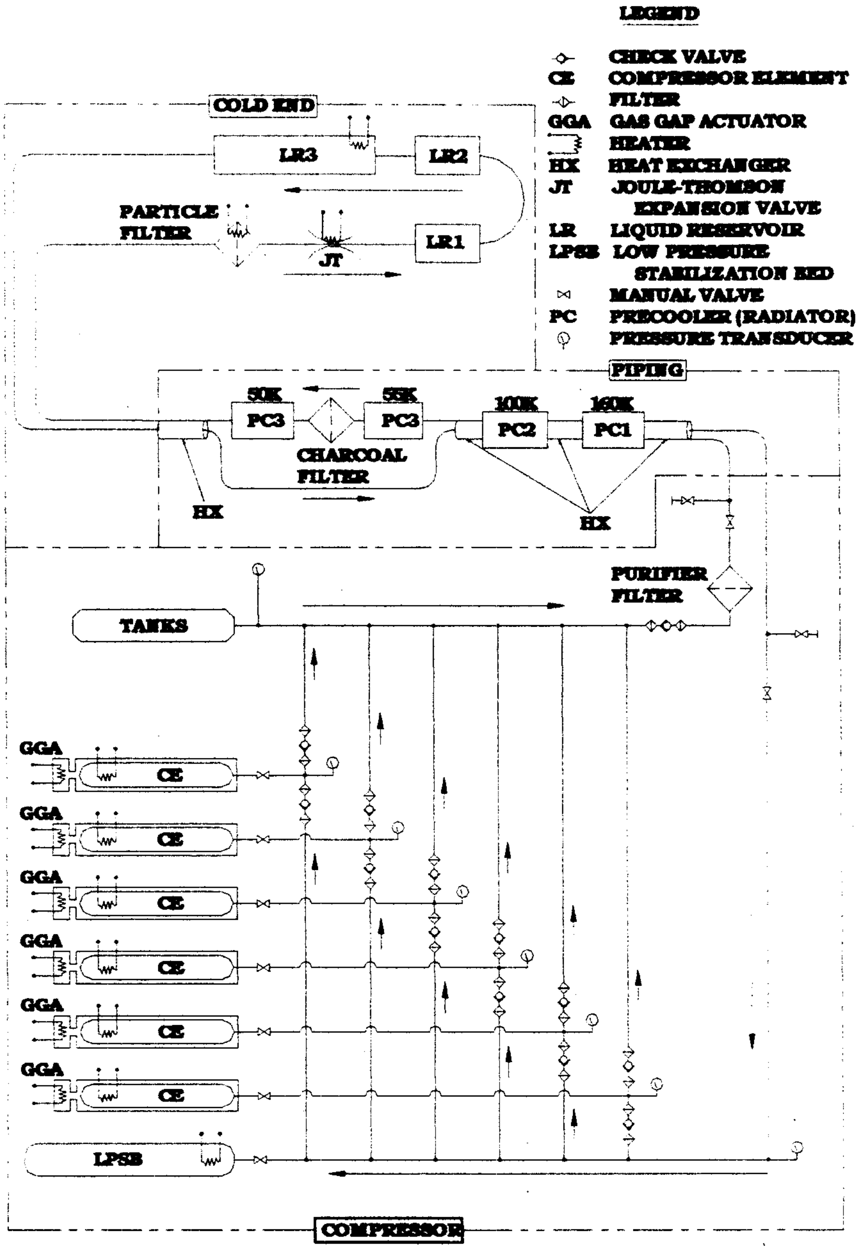

FIGURE 1. Schematic diagram of the JPL 19 K sorption cryocooler for Planck that identifies major components. The arrows denote the flow direction for the hydrogen refrigerant.

state-of-the-art broadband detectors covering the frequency range ~30 to ~1000 GHz must be operated at cryogenic temperature [1-3]. The Jet Propulsion Laboratory (JPL) is developing hydrogen sorption cryocoolers [3] to provide cooling at 19 K for the Planck instruments. A schematic of the cooler is shown in FIG 1. The compressor contains six Compressor Elements (CE) filled with $LaNi_{4.78}Sn_{0.22}$ alloy that provide continuous circulation of hydrogen at the appropriate pressure and flow rate. Each CE uses a gas gap heat switch to isolate the sorbent during heating and desorption while permitting heat removal during cool down and absorption. The Gas Gap Actuator (GGA) uses $ZrNiH_{\sim 1.5}$ to reversibly vary hydrogen pressure between <1.3 Pa and >1.3 kPa by alternately heating and cooling this hydride [4]. Hydrogen flow in the cooler is directed by passive check valves that are protected by porous sintered disc filters to prevent leaks by entrapped particles. Since the Planck sorption coolers must operate a minimum of two years, including 18+ months in orbit, the performance and reliability of all components and materials need to be demonstrated. The present paper provides summaries of experimental results obtained for the hydrides selected as the CE and GGA sorbents, the check valves, low- and high-pressure line filters, and heaters for the CE and GGA sorbent beds. Studies on the Planck cold end components are described in a companion paper by Sirbi, et al. [5].

DEGRADATION OF COMPRESSOR ELEMENT SORBENT HYDRIDE

The alloy $LaNi_{4.78}Sn_{0.22}$ provides the optimal combination of hydriding properties that satisfy the performance requirements for a 19 K hydrogen sorption cooler [3, 6]. Furthermore, this hydride is fairly stable towards degradation effects during cyclic operation between 280 K and 500 K as recently reported [7]. While long-term CE cycling experiments are in progress at JPL to assess degradation [8, 9], it is impractical to obtain end-of-life performance within the allowable development time before delivery of the Planck flight coolers. Thus, accelerated aging tests were performed on the same alloy as used in the long-term CE cycling tests [8] by continual heating at maximum hydrogen content for pressures up to ~21 MPa and T > 465K. Representative changes in the hydrogen absorption and desorption isotherms measured at 294 K are shown in FIG 2a while the dependence of the decrease in plateau width (i.e., loss of reversible storage capacity) and mid-plateau desorption pressure are plotted in FIG 2b. Significant rises with increasing temperature are observed for both properties. The dashed lines in FIG 2b represent a thermally activated degradation process with a mean activation energy of ~200 kJ. More detailed analyses of the degradation behavior of this hydride are in progress and will be reported elsewhere in the future. These results imply that the amount of degradation from this hydride during cooler operation can be accommodated within the design margins [6] providing bed temperatures do not routinely exceed 470 K. An improved $LaNi_{4.78}Sn_{0.22}$ alloy has been recently produced which shows smaller changes during accelerated aging tests. This new material will be use to fill sorbent beds for the flight coolers.

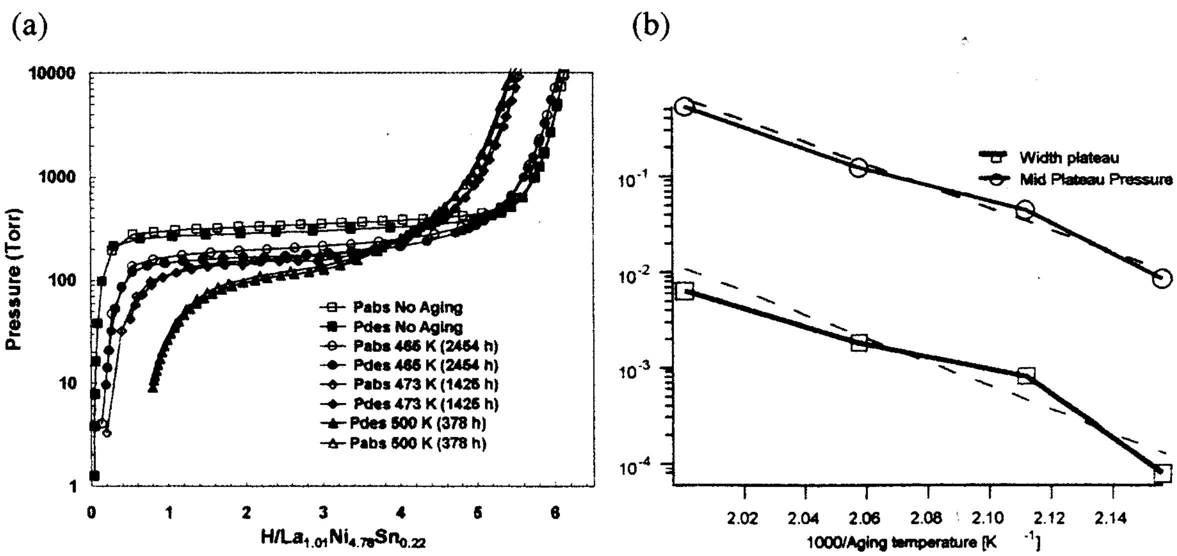

FIGURE 2. (a) Hydrogen absorption (open symbols) and desorption (filled symbols) isotherms for activated and aged $La_{1.01}Ni_{4.78}Sn_{0.22}$ hydride measured at 294 K; (b) Rates of change for the decrease in plateau width and mid-plateau pressure at different aging temperatures.

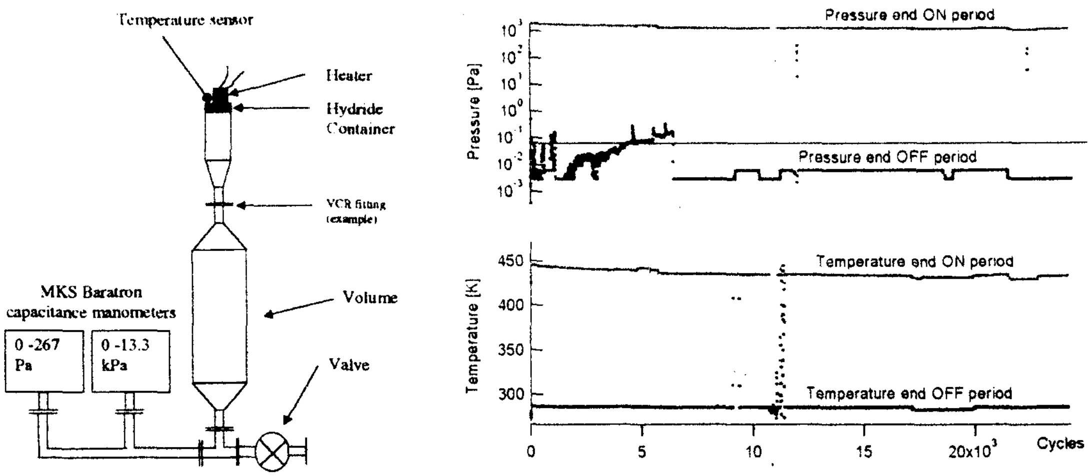

FIGURE 3. Schematic of the ZrNi hydride gas gap actuator with its testing system for temperature cycling along with ON and OFF pressures obtained at temperature extremes over 25,000 cycles.

CYCLING BEHAVIOR OF HYDRIDE GAS GAP ACTUATORS

Gas-gap heat switches provide variable thermal conduction between two objects by the changing the pressure of a gas between their surfaces. Prina, et al. [4] reported initial development of such devices for the Planck CEs using metal hydrides for the GGA. From a combination of performance and temperature cycling experiments with the system shown in FIG 3, $ZrNiH_{1.5}$ has been selected as the sorbent material for the Engineering Bread Board (EBB) and Flight coolers. Representative temperature cycling data for one the test $ZrNiH_{1.5}$ GGA units are also presented in FIG 3. Pressure changes greater than five orders-of-magnitude are found as the temperature is varied between 280 K and 440-450 K during more than 25,000 cycles. Examination of the $ZrNiH_{1.5}$ powder by x-ray diffraction after completion of these tests revealed no sign of hydride degradation or phase separation that had been observed [10] from $ZrNiH_x$ treated at temperatures above 650 K. There were also only minimal changes in the hydrogen absorption and desorption rates, which imply minimal contamination issues with this design and assembly process. Problems with detachment of the GGA heaters, as well as variations in thermal conductance to the powder, were seen on some units – especially those operating at higher temperatures. Thus, a different type of heater, which was physically more robust, was directly brazed to the GGA cap. Accelerated temperature cycling between 280 K and 500 K reveal stable operation and no detachments after ~25,000 cycles. The new GGA units that have been fabricated for the EBB compressor all completed a minimum of 1000 cycles without failures – demonstrating their reliability and stability. Extended life cycling of Flight-like GGA versions are planned to start by late summer, 2001.

UNIFORMITY OF COMPRESSOR ELEMENT HEATERS

Custom tubular electrical heaters (Idaho Laboratories Corporation, Idaho Falls, ID) are inserted into the CE sorbent beds [3,8] to produce up to 200 W power for heat up to ~465 K and desorption of hydrogen gas at an outlet pressure of 50 bar. Since these heaters are critical components for operation of the cooler, their design contain substantial margin with respect to durability and predicted life for the expected operating temperatures and power loads. The long-term behavior and possibility of failure are issues being addressed in the CE life-cycling studies [8, 9] that simulate nominal cooler operation. In addition, methods are needed beyond simple continuity verifications of lead-wire resistances to ensure correct heater function before each is assembled into the CE. An optical technique was devised to monitor the temperature profile of operating heaters after they had been transformed into the desired geometry [3,8] for insertion into the CE. An infrared (IR) image radiometer (Inframetrics Model 760) was positioned to record temperature profiles when power was applied to the heater assembly. Digital images were stored on a computer for processing and later analysis. A thermocouple was placed at the tip of the heater to measure temperature directly. While this approach had limited quantitative capabilities, the IR images showed the heaters to be fairly uniform along their lengths with a maximum ΔT of ~20 K. The hottest temperature regions were at the bends and tips of the heater assemblies. Since any defective heater could be quickly identified and discarded, the IR camera and heater support were transferred into an argon atmosphere glove box to screen the heaters prior to fabrication of the compressor elements for the EBB cooler. The argon prevented oxidation of the outer surfaces of the 316L SS heater sheaths that had been observed after heating in air. All of the tested heaters passed the IR screening and had similar temperature distributions to those previously evaluated in air. Subsequent operation of the assembled EBB compressor elements have not shown heater failures or large deviations between each other during all the heating cycles performed to date.

TESTING OF CHECK VALVES

As indicated in FIG 1, hydrogen flow through the sorption cooler is directed by a series of passive check valves that separate the lines into a high-pressure (i.e., 5.0 MPa) manifold before the J-T expander and a low-pressure (i.e., ~0.05 MPa) manifold after the J-T. The performance of the chosen check valves is very important to maintain steady and controlled flow as the CE beds transition between the absorbing and desorbing phases of the sorption compression cycle. In addition, these valves must be leak free, possess low pressure drops, not degrade in hydrogen gas, and not be sources of contamination that could migrate to either the sorbent beds or cold end components. The NUPRO "CW" Series all-welded check valves with their maximum working pressure range of 20.6 MPa and cracking pressure <14 kPa were selected for the Planck cooler. While these valves (shown in FIG 4) are mainly constructed of 316L stainless steel, a Viton seal is bonded to the poppet. Thus, there is a concern of compatibility problems with hydrogen gas at the highest potential operating temperatures of ~ 373 K for these valves.

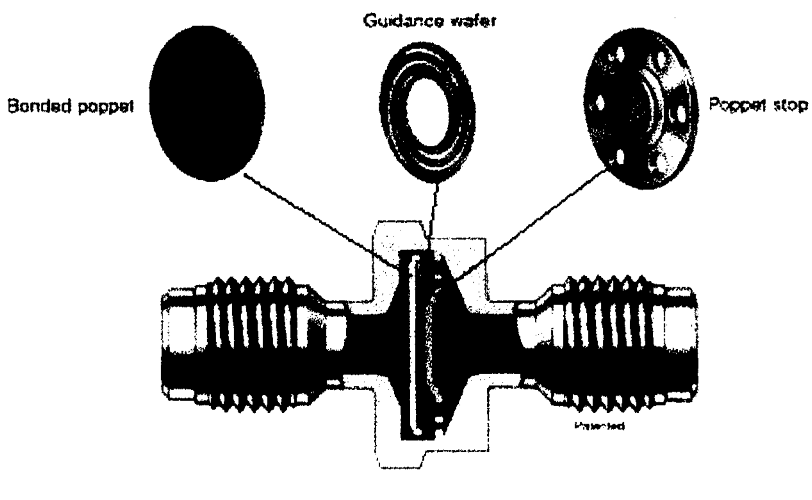

FIGURE 4. NUPRO "CW" Series all-welded check valves for the Planck cooler.

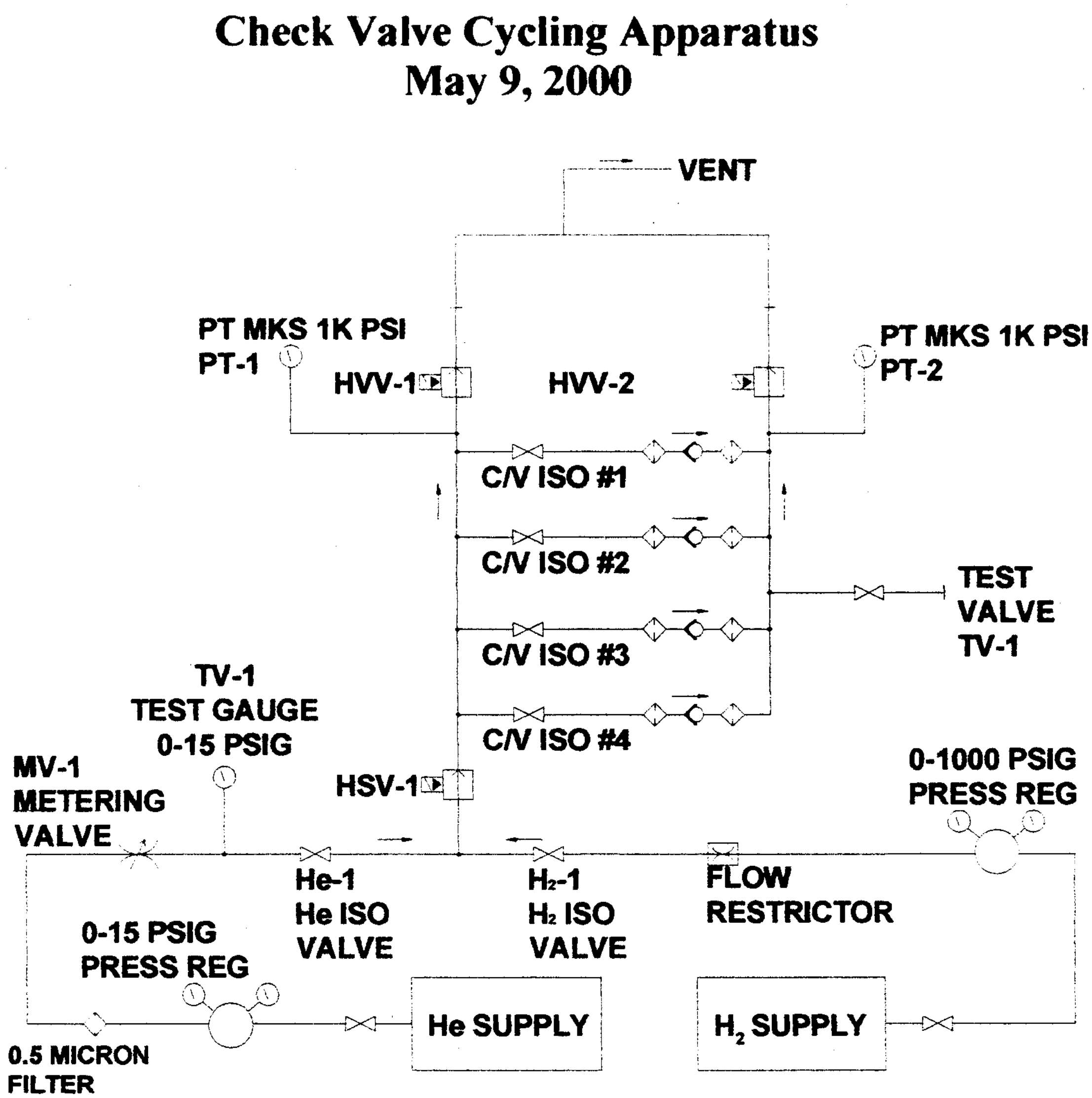

FIGURE 5. Schematic of the test station developed to assess the performance of the "CW" series check valves and filters.

To evaluate the NUPRO "CW" series check valves for mechanical integrity in the Planck EBB and flight coolers, temperature conditioning/accelerated cycling tests based on predicted flight operating temperature ranges and expected mission cycles were done. The check valves have been characterized by performing through-leakage, cracking and reseat pressures. All cycling was performed using hydrogen gas of industrial grade purity with in-line particulate filters (i.e., Mott 6610-17-Inline sintered disc filters rated for 10 μm-particulates) but without chemical purification filters. A schematic diagram of the test apparatus is shown in FIG 5. Two gas supplies provide the two major capabilities of the apparatus: (1) Cycle the check valves at high pressure (i.e., > 5.0 MPa) with hydrogen gas every 60 seconds and (2) Evaluate the cracking pressures at low pressure (i.e., < 0.1 MPa) with helium. A computer operating with LabView software controlled the sequencing of the actuated valves HSV-1, HVV-1, and HVV-2 to pressurize and vent hydrogen simultaneously to four check valves during cycling. Cracking pressures were manually determined for each check valve when helium first formed bubbles in isopropyl alcohol using a Staham 0-35 kPa (0-5 psid) range differential pressure transducer to record the breakthrough pressure. Back flow leak tests were performed by first pressurizing the downstream of the check valves with 5 MPa hydrogen followed by venting the upstream gas and monitoring the pressure gauge PT-2 overnight (~ 12 h).

Check valve test units CV-1 and CV-2 were mounted horizontally in the test apparatus. Units CV-3 and CV-4 were mounted vertically with flow direction down (i.e., gas pressure for sealing the check valve works against gravity). Heaters were attached to CV-1 and CV-2 for testing/cycling at elevated temperatures (i.e., 295 K – 443 K) while CV-3 and CV-4 were emerged in Neslab model RTE-221 refrigerated bath for cold temperature cycling (T = 253 K). After all four check valves were pressure cycled 10,000 times at ambient temperature, CV-1 and CV-2 were cycled 30,000 times while heated to 373 K and CV-3 and CV-4 were simultaneously cycled 30,000 times while cooled to 253 K. The four valves were next cycled an additional 2,000 times at ambient temperature. Cycling was periodically stopped to allow measurement of the cracking pressures and back flow leak rates. None of the check valves failed or starting leaking during or after the cycling and their cracking pressures did not change significantly over time. The cracking pressure varied more or less randomly over the range 0.03-0.83 kPa (0.004-0.12 psid) where the requirement for the Planck cooler is a cracking pressure < 6.9 kPa (1.0 psid). Valves CV-1 and CV-2 were cycled an additional 1,250 times at 443 K without changes or leaks. Valves CV-3 and CV-4 were removed from the test apparatus and soaked at 233 K for 120 h to see if performance was degradation by lower temperatures possible when the cooler not operating during flight. The initial cracking pressures at ambient temperature were 0.12 kPa and 2.4 kPa, respectively, but there were no leaks. Cracking pressures after 1000 more cycles at ambient were 0.04 kPa for both units indicating no permanent effects from storage at 233 K.

Each check valve has undergone over 43,000 cycles showing no negative impact from either their orientation with respect to gravity or temperature from 253 K to 443 K. Since the check valves on the Planck flight coolers will complete only ~16,000 cycles during their entire operational life, the CW series check valves are deemed to be sufficiently reliable and robust. Finally, there was no indication of hydrogen incompatibility on the performance of the check valves during these tests.

EVALUATIONS OF FILTERS

A number of sintered 316L SS porous filters are located in the Planck cooler lines to prevent particulates from reaching the check valves or J-T expander as shown in FIG 1. To satisfy the differing pressure drop constraints [3,6] on the high-pressure (i.e., ~5.0 MPa) and low-pressure (i.e., < 0.05 MPa), two types of filters are required. For the low-pressure side, a NUPRO type FW Series filter with a 7 μm-size rating was chosen. A Mott 5 μm filter (Part No. 5000-1/4-5000 sccm) was selected for the high-pressure manifold. The pressure drops were measured on samples of each type of filter using the check valve test apparatus in FIG 5. A nitrogen gas aspirator was added to produce vacuum on the downstream side of the filter while hydrogen flowed through the filters at various rates. The measured pressure drop (ΔP) across the low-pressure NUPRO filter was 21 Pa (0.16 Torr) at an outlet pressure of 47 kPa (352 Torr) and H_2 flow rate of 1.9 slm (2.9 mg/s) where the cooler requirement is $\Delta P < 3.5$ kPa (26 Torr) for these conditions. The measured mean ΔP across the high-pressure Mott filter was 3.3 kPa (0.48 Psia) at an outlet pressure of 5.0 MPa (735 Psia) and a nominal H_2 flow rate of 5 slm (7.5 mg/s) where the cooler requirement is $\Delta P < 10.3$ kPa (1.5 Psia). Thus, acceptable performance has been verified for both filters.

CONCLUSIONS

Detailed characterizations have been performed on the sorbent materials and on critical hardware components for the Planck sorption cryocooler. Check valves were operated using hydrogen gas for over 43,000 pressure cycles at various orientations and temperatures without leaks or other changes. The sintered porous filters that protect check valves and J-T expander from particles found to have acceptable pressure drops at proposed cooler operating conditions. The temperature gradients along the tubular heater elements for the compressor beds were evaluated to assess their impact on the dynamics of compressor element heating and hydrogen desorption. The durability and reliability of low-power heaters used for the gas gap actuators were determined by accelerated temperature cycling. Acceptable sorbent longevity has been verified for both the compressor alloy and the gas gap actuator alloy. Further evaluations are continuing on the sorbent hydrides, heaters, and gas gap actuators to better define any performance limitations and sources of degradation or failures. This information will be incorporated in the final designs and fabrication of the Planck flight sorption coolers.

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