In-Flight Performance of the HERSCHEL Sorption Coolers – One Year of Operation

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ABSTRACT

HERSCHEL, the fourth 'cornerstone' mission in the ESA science program, was launched on 14 May 2009 from Kourou, French Guyana. With a 3.5 m Cassegrain telescope it is the largest space telescope ever launched. HERSCHEL is performing photometry and spectroscopy in the electromagnetic spectrum for wavelengths 55-672 μm. This bridges the gap between earlier infrared space missions and ground-based facilities.

HERSCHEL's payload consists of three instruments built by international scientific consortia: HIFI (Heterodyne Instrument for the Far Infrared), PACS (Photo-conductor Array Camera & Spectrometer) and SPIRE (Spectral and Photometric Imaging REceiver). Two of these instruments, SPIRE and PACS, use bolometric detectors cooled to 300 mK. The HERSCHEL cryogenic subsystem relies on passive cooling down to liquid nitrogen temperatures for both the cryostat & telescope. It features a 2367 liter superfluid helium tank that vents to space and provides the instruments with cooling at four interface temperatures between 1.6 K and 15 K. Two dedicated sorption coolers are then used to lower the PACS and SPIRE bolometer temperatures to below 300 mK. These units are single shot devices and need to be recycled on a regular basis. Their typical hold time is over 48 hours for less than 2 hours recycling time. To date these systems have been in operation for approximately a year. As of April 2010, over 150 re-cycles have been successfully performed and the performance of these coolers is stable and fully in line with predictions.

INTRODUCTION

In May 14th 2009 13:12 UTC the Ariane 5 ECA lifted off from Kourou spaceport (French Guyana) with two satellites onboard: HERSCHEL and PLANCK. After about 30 minutes the satellites were successfully released and began their journey to the L2 Lagrange point 1.5 million km away from the Earth. This marked the beginning of a new adventure for many scientists around the world, but for the European cryogenic community this event was the culmination of over a decade of effort to design and manufacture technological "cutting edge" components for both satellites.

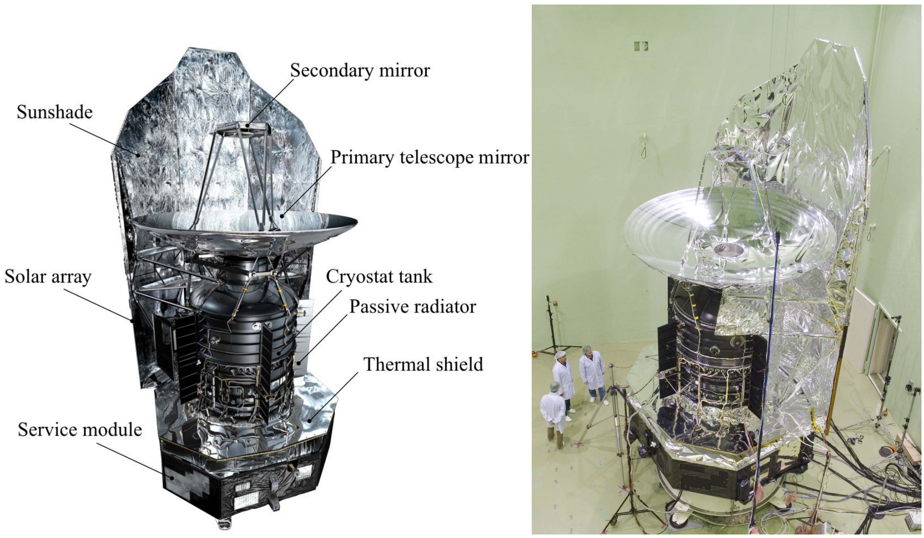

Figure 1. Overall view of the HERSCHEL spacecraft. Left: the 'payload module' with the cryostat housing the instrument focal plane units, the telescope, the service module with warm electronics, and the sunshield sunshade. Right: HERSCHEL being prepared for acoustic testing in the Large European Acoustic Facility in ESTEC in June 2008, providing a good view of the telescope (Photo ESA)

HERSCHEL[1,2] is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. It embarked three instruments, HIFI[3], PACS[4] and SPIRE[5], the latter two feature detectors operated at subKelvin temperatures. An overview of the spacecraft and of the cryostat and instruments are given in Fig. 1, 2 and 3.

SPIRE consists of a three-band imaging photometer and a two-band imaging Fourier Transform Spectrometer (FTS). The spectral bands covered range from about 200 to 670 microns. The SPIRE focal plane unit is approximately 700x400x400 mm in size, and is supported from the 10 K optical bench by thermally insulating mounts. The focal plane instrument includes the optics, five detector arrays cooled down to 300 mK, detector pre-amplifiers, the sorption cooler, filters, and several mechanisms.

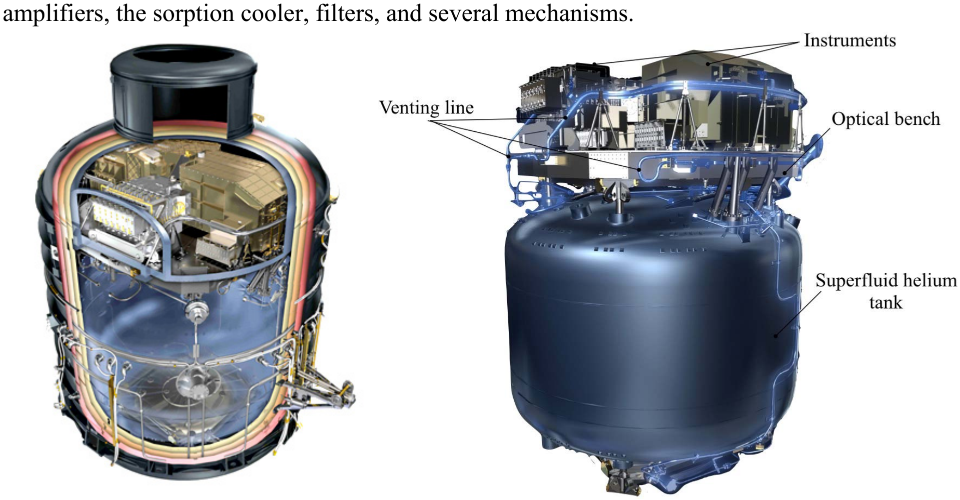

Figure 2. Overal view of the HERSCHEL cryostat with the instruments mounted on the optical bench on top of the main helium tank. The focal plane cover and the three vapour-cooled shields inside the cryostat vacuum vessel are also shown on the left

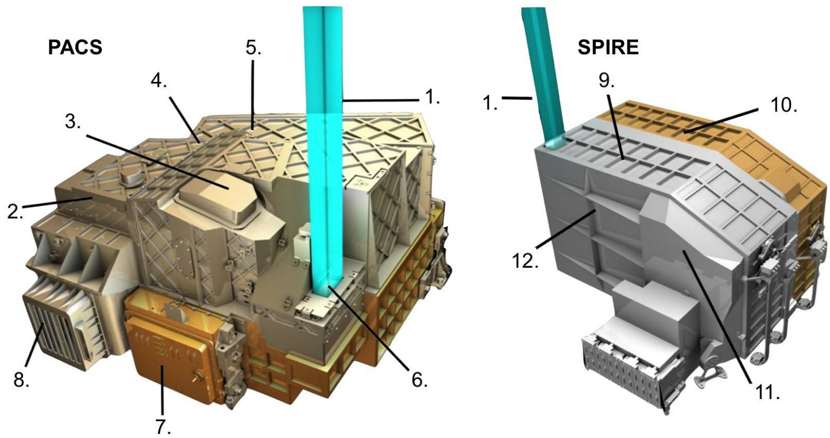

Figure 3. Overall view of the PACS and SPIRE instruments: 1. Telescope Beam, 2. Photometer optics, 3. Chopper, 3. Slicer optics, 5. Collimator grating, 6. Entrance aperture, 7. sGe:Ga Detector, 8. Bolometer unit (incl. cooler), 9. Photometer, 10. Spectrometer, 11. Detector array, 12. Mirror.

PACS is both a camera and a low to medium resolution spectrometer for wavelengths ranging from 60 to 210 µm. It features two bolometer arrays (cooled at 300 mK) for the photometer—designed for three different wavelength bands: 60-90, 90-130 and 130-210 microns, and two Ge:Ga photoconductor arrays (operated at about 1.7 K) covering the wavelength range between 57 and 210 microns in three consecutive bands for the spectrometer.

Both PACS & SPIRE instruments are thus complementary, covering the far infrared spectrum from 60 to 670 microns.

DESCRIPTION OF THE THERMAL ARCHITECTURE

The cryogenic chain[6] comprises a combination of passive cooling down to about 80 K and a large superfluid helium tank holding 2367 liters that provides a base temperature close to 1.6 K. Final instrument related cooling down to 290 mK is provided by two helium sorption coolers. A sunshield, also carrying the fixed solar array, protects the cold payload from solar heat input and allows the whole telescope to be passively cooled to a temperature below 90 K.

The instruments are mounted on an optical bench, which was aligned on the ground to the telescope. The cryostat provides several temperature interfaces for the evacuation of heat from the instruments. These temperature interfaces are at 1.6 K (referenced as Level 0) via direct conductive cooling to the liquid helium, 2 K – 6.5 K (level 1), 10 K (level 2) and 15 K (level 3) via gas cooling to the helium vent line. The cooling power required by the instruments was a critical driver for the design of the cryostat. Indeed this requirement sets the minimum mass flow rate needed for venting in orbit, and hence the minimum parasitic load on the helium tank (see Fig. 5). While it would have been easy to design Herschel for a lifetime greater than 5 years, this would have led to instruments being “blinded” by excessive straylight coming from a “warm” Level 1 interface. Therefore, the lifetime design was always a compromise between instrument performance and in-orbit observation time. Once the venting line exits the payload module, the cold flowing gas is further used to cool down 3 thermal shields, which are arranged in a Russian dolls configuration. On November 2009 the first direct measurement of the amount of remaining helium was carried out. The result, together with thermal modeling, indicates a predicted mission lifetime somewhere in the range 3.5 to slightly above 4 years.

The description and operation of the sorption units has been described in numerous papers.[7] Schematically, they feature an evaporator into which liquid helium 3 is condensed and then pumped down, a pumping line, a sorption pump, and two gas gap heat switches to control the temperature gradient and provide the necessary thermodynamic conditions.

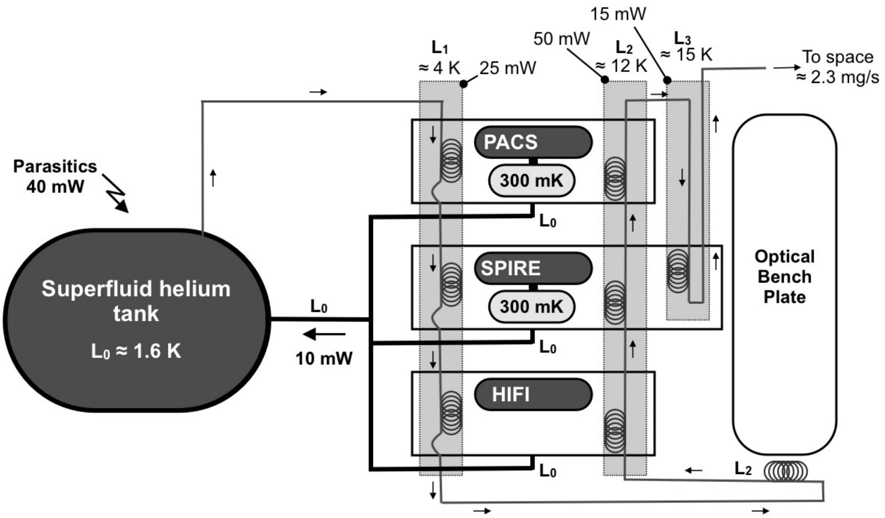

Figure 4. Thermal architecture**.** 90 mW are evacuated by the enthalpy of the vent line and only 10 mW are dissipated directly to the superfluid helium. 40 mW are due to the cryostat's own parasitics

The sorption units have no moving parts and can be operated with heaters. They require a temperature below the helium 3 critical temperature (≈ 3.3 K), and thus direct thermal paths are provided to the superfluid helium tank. During cooler operation, the heat flowing to the tank from the sorption pump and from the evaporator are significantly different. In particular during the recycling phase, it is crucial to keep the evaporator temperature as cold as possible to increase the condensation efficiency and reduce the liquid fraction lost during cooldown. Consequently two thermal interfaces and thus two thermal busbars are provided to allow efficient distribution of the heat flows. Additional 1.6 K direct links are also provided for the detector enclosure to reduce the parasitic heat flow to the 300 mK stage through the supporting structures.

Each link consists of a pod, which plunges in the Main Helium II Tank (HTT) (Fig. 5). The pod is a hollow structure made of copper into which the superfluid film crawls and increases significantly the thermal conductance. Then a flexible high conductance copper strap insures the thermal connection to the cooler or detector box interfaces.

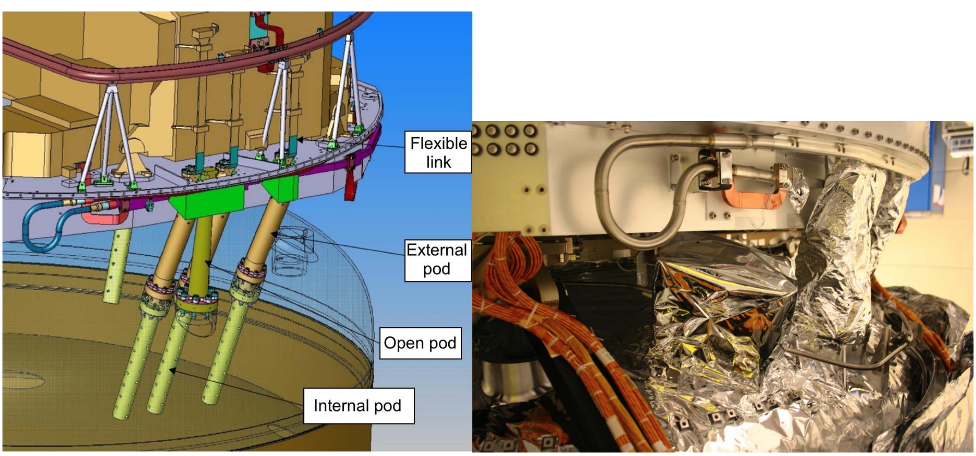

Figure 5. Left: Cryostat top cover with the pods and copper straps. Right: idem fully integrated in cryostat (pods covered with MLI)(Photo ESA)

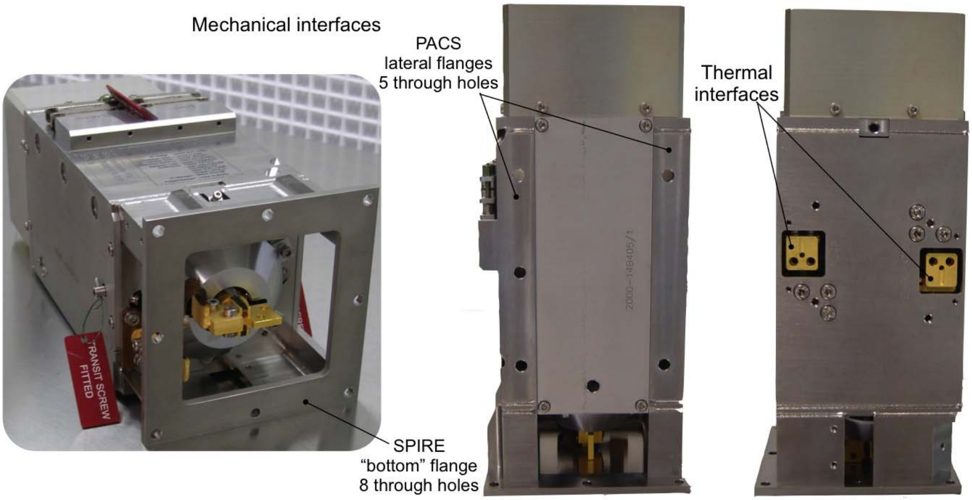

Figure 6. Mechanical and thermal interfaces of the sorption cooler

INTEGRATION OF THE COOLERS

The mechanical integration of the coolers is straightforward since the interfaces are simple and robust; both coolers interface with the instrument via their stiff titanium structure (see Fig. 6). However integration with the thermal interfaces called for a careful design. Indeed the cooler features two copper flanges each directly connected to the gas gap heat switch. These switches are fixed by one end and behave like cantilever beams. Thus, the two thermal interfaces must not be submitted to any mechanical constraint to avoid any displacement that could cause the heat switch OFF position to degrade. The maximum allowable unsupported mass on the copper flanges is limited to 50 grams to prevent inertial loads during launch and mechanical qualification from plastically deforming the components in the interface. The maximum static loads is limited to less than 50 N to account for any static misalignment or CTE mismatch between the cooler and the cold straps in any direction.

Due to constraints on the relative orientation of the SPIRE cooler with respect to the gravity vector during cooler recycle in ground testing, the length of the straps between the cooler interface and the spacecraft cryostat had to be longer than would otherwise be desirable. One impact of this design constraint was the need to include intermediate busbar supports between the spacecraft and cooler thermal interfaces to limit the loads on the cooler (Fig. 7).

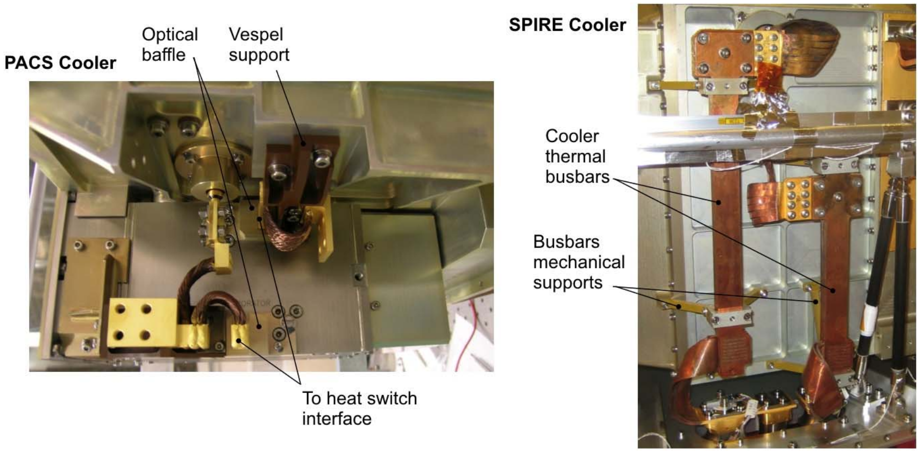

Figure 7. Cooler integration. Left : PACS. Right: SPIRE

For PACS however the straps are routed directly from the 1.6 K pods to the cooler. Consequently a set of pieces was added to decouple the thermal and mechanical aspects. The design is straightforward: the level 0 strap is mechanically supported by a Vespel part before it reaches the heat switch interface, and then from this point, a flexible link is provided for the thermal path (Fig. 7). In addition, this design includes an optical baffle to reduce the stray light. For the straps to the detector boxes, tripods (or bipods) made of carbon fiber reinforced plastic (CFRP) tubes provide the mechanical support. Of course these additional structures introduce a direct thermal path between the L0 (1.6 K) and L1 (4.5 K) interfaces. These cumulated contributions were measured and account for less than 700 µW, an acceptable value.

Prior to delivery and integration in the instruments, each cooler went through its own acceptance program (ILT for Instrument level tests) including full functional tests, calibration, and environmental testing: thermal test, mechanical tests (including cryogenics vibration of the FPU's)(see ref 2). After delivery to the Herschel-Planck Prime contractor, a sequence of validation and acceptance tests was performed on the satellite[8]. The instrument part of these integrated tests (IST for Integrated System tests) were very similar to the instrument tests (ILT), to compare the performance of the instruments on the satellite. Consequently the coolers underwent extensive testing prior to flight.

IN FLIGHT PERFORMANCE

The HERSCHEL cryostat was filled to almost 100% with 333.5 kg (± 3%) of superfluid helium just before launch in order to maximize the mission lifetime. On May 22nd, 2009, nearly a week after launch and with the cryocover still closed, a first recycling of the SPIRE sorption cooler was successfully performed with the cooler reaching 293 mK. The PACS unit was tested for the first time on June 8th and reached a lowest temperature of 278 mK due to the absence of loading from the detectors and a level 1 temperature colder than nominal (spacecraft not at thermal equilibrium yet and consequently higher mass flow rate in the venting line). These performances are in line with the ground-based tests carried out prior to launch by the instruments teams.

One interesting feature is that during ground testing the coolers could not be set at the right angle to avoid any convective effect, and thus the energy balance was somewhat altered. For all the recycling performed in space, indeed all convective effects are gone and the coolers behave as in vertical position on ground.

HERSCHEL is a multi-user observatory open to the scientific community. The observation time is thus shared and SPIRE and PACS "own" a guarantee time of 60%. In this scenario for each instrument, the cooler is recycled and provide the required temperature for a given time. Then operations are switched to the other instrument. For both instruments the cooler hold time measured are all in excess of 46 hours, meeting the requirement that two full days of operation be possible after one cooler recycling.

The hold time measured in orbit is larger than on ground for the following main reasons:

- The thermal link to the Helium (HTT) is far better in flight as the open pods bypasses the copper pods.
- The effect of the convection (losses on evaporator) is gone.

Cooler recycling

SPIRE and PACS use different philosophies for the recycling of the cooler. The SPIRE algorithm is based on a feedback-controlled software process executed in the SPIRE Digital Processing Unit (DPU). The algorithm uses the temperatures of the Sorption Pump, Evaporator and Heat Switches to monitor to status of the recycle and sets the current to the Heat Switches and the Sorption Pump heater accordingly to effect the recycle. The software maintains various timeout counters to handle specific error conditions. The PACS's process uses input powers and timing (for instance 27 mA are sent to the main sorption pump for a set duration)(see Fig. 8).

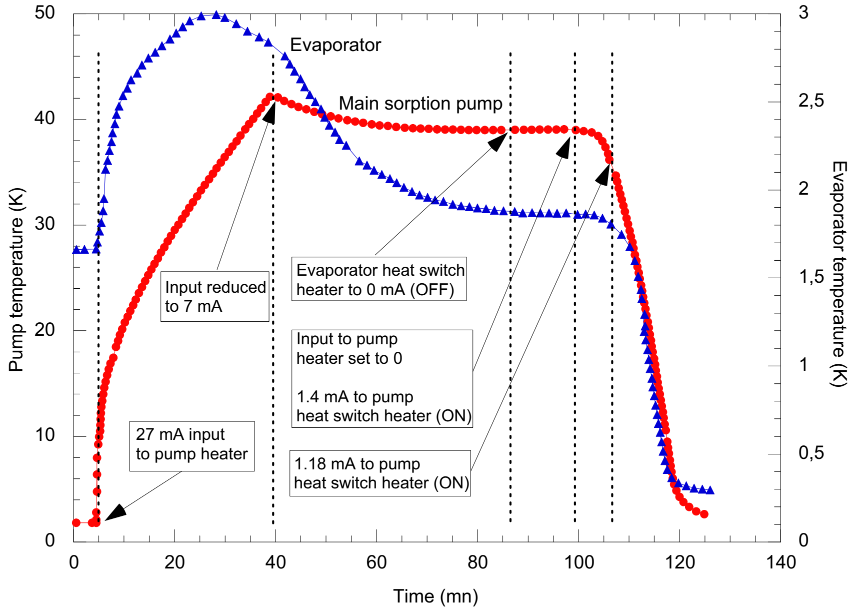

Figure 8. Typical in-flight recycling phase (PACS unit, heater input power based)

Both methods work fine as long as the cooler has been thermally characterized first and behaves as before. If any thermal conductance was changed, obviously the SPIRE process would be the way forward, since it guarantees the correct thermodynamic conditions, and thus the best condensation efficiency.

The sorption cooler pump and evaporator are both connected to the helium tank (HTT) through heat switches and thermal straps (open pods). During each cooler recycling, the energy stored in the pump is released in the helium when the pump heat switch is closed, which provides a large temperature excursion of the interface point (up to 5/6 K each time). The impact on the HTT temperature is also visible, on the order of mK at the beginning of the mission, increasing slowly as the tank depletes. The temperature of the tank is fairly stable as depicted in Fig. 9. Figure 10 shows the temperature of the sorption cooler pump and evaporator L0 interfaces for a quasi parallel recycling of both PACS and SPIRE.

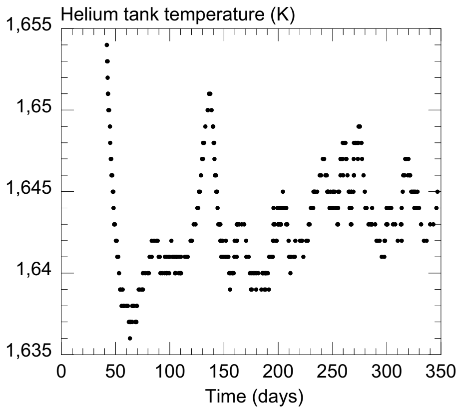

Figure 9. Evolution of HTT temperature

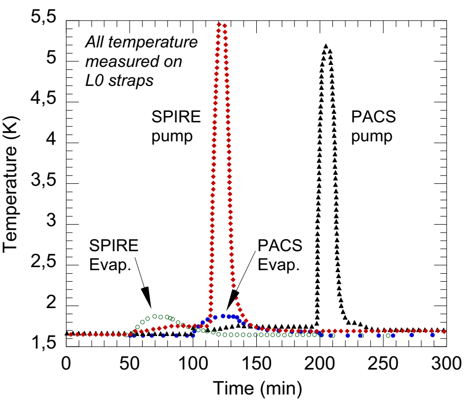

Figure 10. PACS/SPIRE parallel recycling

Indeed the benefit of two thermal bus to the HTT for each cooler is clearly seen on Figure 10. While the temperature of the link to the pump varies substantially, the evaporator links temperatures remain well below 2K.

Ultimate temperature and stability

To date over 150 cooler recycles have been performed and the ultimate temperatures recorded fall within specifications. The temperatures recorded for both units are reported in Figure 11 and 12. For the SPIRE this temperature corresponds to the temperature once the cooler has stabilized (see Fig. 13). Indeed for the SPIRE unit a peculiar behavior of the temperature is seen on most cycles just after the evaporator reaches temperatures below 300 mK (Fig. 13). Its temperature drops down to about 285 mK and then drifts up to ≈ 286.5 mK, after which the temperature drifts slowly as expected and at a rate smaller than measured on ground. This 1.5 mK or so step is still not understood. These coolers were extensively tested on the ground, and this behavior has never been recorded during the several tens of cycles performed. In addition there seems to be no thermal signature on the main sorption pump, indicating that this effect is probably not related to physisorption nor to any additional input load. We suggest that the liquid inside the porous material rearranges itself once the filling fraction reaches a given value and although the liquid temperature remains the same, the external temperature changes due to a change in the Kapitza resistance.

The evaporator temperatures reported for PACS are distributed on a wider range because the dissipation at 300 mK depends on the operating mode of the detectors (less sensitive for SPIRE).

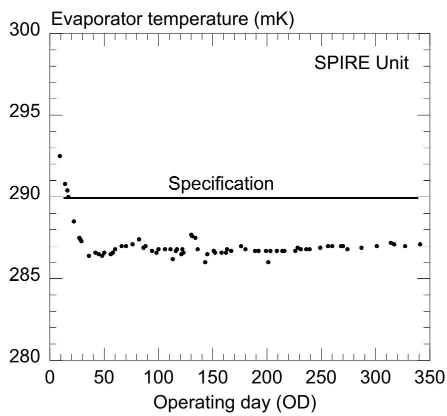

Figure 11. SPIRE ultimate temperature

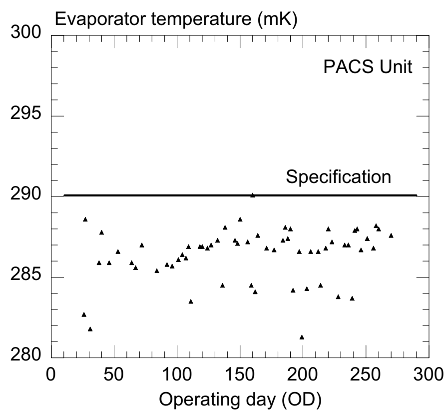

Figure 12. PACS ultimate temperature

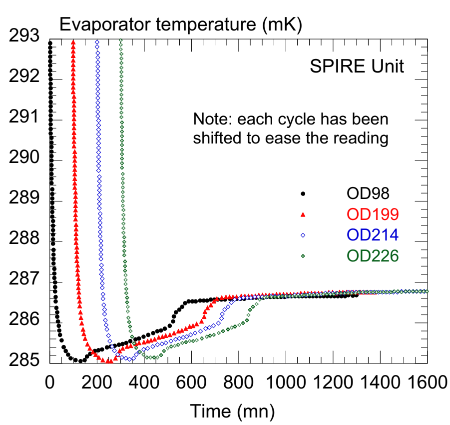

Figure 13. Evaporator temperature after recycling

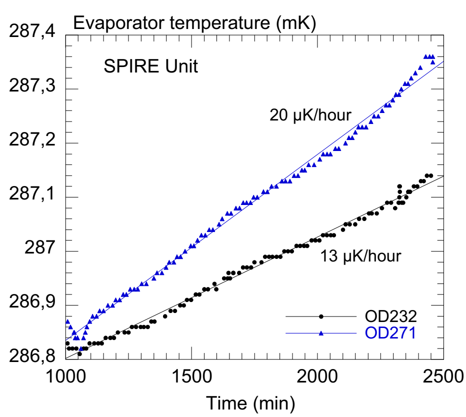

Figure 14. Typical temperature stability

The long-term temperature stability depends of course on what is occurring with the detection chain (operating mode). However, for many cycles we can extract the period of operation during which the cooler is slowly drifting, probably due to its internal physics (activated charcoal filling up, depletion of liquid, etc…). This drift displayed on Figure 14 for two typical cycles on SPIRE (Operating day 232 and 271) is found to be between 13 μK and 20 μK per hour, lower than what was measured in the laboratory (≈ 25 μK/h – to specification). Note that this is the drift measured at the cold tip of the cooler not at the detector level.

Hold times

Although both coolers are similar, the power dissipated at 300 mK is different for SPIRE and leading to differences in hold times. In particular the hold time of the PACS unit reaches values in excess of 70 hours on a regular basis. According to our thermal modeling, the load from the detectors (incl. support structure) is probably of the order of 7 μW (10 μW specified).

The thermal load onto the SPIRE cooler is significantly higher than on the PACS cooler due to the following reasons:

- There are five separate detector arrays requiring cooling power at 300 mK in the SPIRE design compared with two in the PACS instrument
- The five detector arrays are separated by large physical distances and therefore the length of the interconnecting busbars operating at 300 mK is significantly larger in the SPIRE design. This leads to the need to incorporate five intermediate Kevlar suspension supports between the cooler and the detector arrays which have a negative impact on the parasitic heat loads
- The SPIRE detector arrays are feed horn coupled compared to the detectors whereas the PACS are a bare, filled arrays. The mass of the SPIRE feed horn assemblies drives the total mass of structure supported at 300 mK and consequently leads to a larger parasitic heat load due to a larger required cross-section of Kevlar
- Finally the PACS instrument is positioned first on the L1 venting line

As mentioned previously the operating mode has a clear impact on the cooler autonomy. This is shown on Fig. 15 for the PACS unit where it can be seen that indeed the hold time correlates with the photometer operating time.

The hold time reported for SPIRE (Fig. 16) is fairly steady with a sharp increase for the early tests. As shown on the figure, this increase was simply due to the temperature of the HTT being not at its operating point yet. The data point for which the hold time falls below 46 hours are due to operations for which the cooler was stopped before running out of liquid.

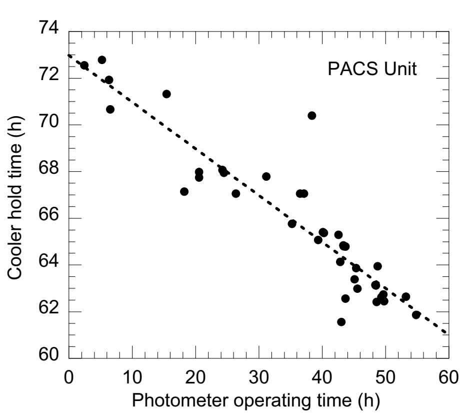

Figure 15. PACS cooler hold time

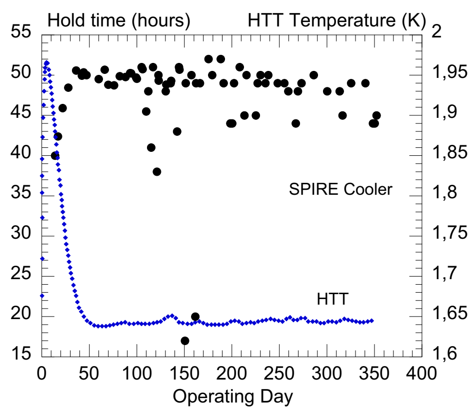

Figure 16. SPIRE cooler hold time

CONCLUSION

The HERSCHEL satellite was successfully launched on May 14th 2009. The Herschel payload consists of three instruments built by international scientific consortia, HIFI, PACS and SPIRE. Both instruments SPIRE and PACS feature detectors operating at 300 mK. This cooling is effected by two helium sorption coolers developed at CEA-SBT. These coolers have been in operation for almost a year and have demonstrated sound performances. They are very reliable cooling stages with potentially “unlimited life”. The latter will be limited by the lifetime of the HERSCHEL cryostat expected to fall within 3.5 to 4 years.

ACKNOWLEDGMENT

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