A Thermo-Mechanical Heat Switch

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ABSTRACT

A thermo-mechanical heat switch has been developed. This concept, based on a gas gap heat switch that relies on the presence or absence of gas between two interlocked parts, also features a magnetically driven part. This part can be moved within seconds from one position to the other allowing very fast switching time between a 'fully-on' conductance and a 'partly-on' one. This limited 'on' conductance can be tuned. In addition, it allows one to partly mechanically decouple the switch end, and thus improve the mechanical strength of the switch. The design and preliminary thermal results are presented.

INTRODUCTION

Cryogenic heat switches are one of the key technologies in many space cryogenic systems. With the exception of the ultra low temperature range, for which specific techniques must be employed, two types of switches are generally used. The first is mechanical switches, whereby the thermal conductance is directly linked to the quality of contact between two surfaces, and the second is gas gap heat switches, whereby the conductance is due to the absence or presence of gas between two interlocked parts. In most cases, particularly at liquid helium temperatures, the gas gap heat switch is selected for its high reliability (no moving parts) and excellent 'on' thermal conductance. We have built literally several dozens of gas gap heat switches with a very high success rate. To further improve the selection process, a dedicated test program was set up on these components in the framework of the HERSCHEL program.[1] This selection program features geometrical, thermal, and vibration tests that allow individual items of the batch to be ranked. Once the switch is qualified, its sensitive structural characteristics require great care during mechanical integration so as to not distort the switch free-end and thereby create contact between the switch's close-tolerance internal parts. To address this last point, a highly flexible high-purity copper braid is generally used for the link between the switch end and whatever it is connected to.

Although this technology works, assuming the above precautions are taken, we came up with an alternative design[2] to improve the integration aspects. In addition, this design allows for control of the 'on' conductance and features an extremely fast switching time. A first prototype has been built and tested, and the concept has been experimentally demonstrated. The design has been further improved, and several new prototypes have been assembled. This work is supported by the French space agency (CNES), and the new prototypes have been sized based on the specifications described later, given by CNES.

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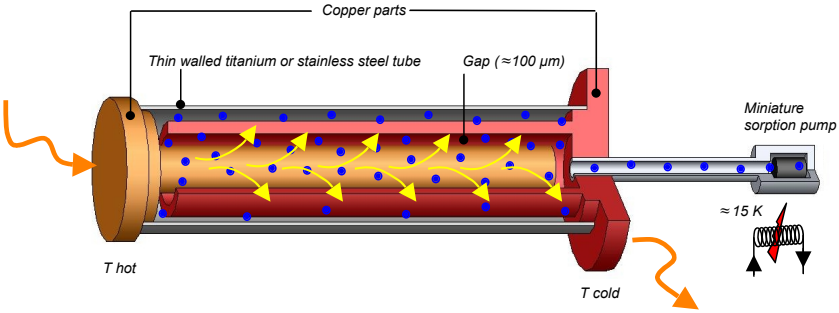

Figure 1. Schematic of a standard gas gap heat switch (dots depict the gas)

DESCRIPTION OF THE SWITCH

The operation of standard gas gap heat switches has been described in numerous papers and the reader is referred to the relevant publications.[3, 4] In its most common form, this switch is made of two interlocked copper parts separated by a small gap (typically 100 µm), and held together by a thin-walled stainless steel or titanium tube (see Fig. 1). This tube provides the thermal isolation in the 'off' position. A miniature adsorption pump controls the presence ('on' position) or absence of gas ('off' position) inside the switch. Obviously, and as mentioned previously, any excessive displacement of the switch end (in excess of roughly 100 µm) can bring into contact the copper parts and increase the 'off' conductance. In practice, not only must the displacement be larger than 100 µm, but the force must be large enough to get substantial contact (the contact thermal conductance depends on the force). In the case of the HERSCHEL coolers, and because we were sensitive to microwatt or even fraction of microwatt loads, special care was taken during integration. As mentioned, to avoid as much as possible any mechanical constraints on the switch end, one common solution is to use highly flexible copper braids.

In the newly proposed concept, a moving part is added. Different geometries are possible, and in the one chosen here, the internal copper rod is the moving part. This part (part B in Fig. 2) can be set back from the switch hot end or displaced and brought into contact with the latter. In the absence of any gas inside the switch ('off' position), when the moving part is not in contact with the switch end, the thermal conductance is only due to the switch's envelope tube, which is typically made out of stainless steel or titanium. Because there is a decoupling between the thermally active moving part and the switch hot end, constraints on the latter, and thus some imposed displacement, can be tolerated without impacting the 'off' conductance.

Then, once the miniature sorption pump is heated to roughly 15 K and that gas is released inside the switch, the internal pressure becomes large enough so the viscous regime is reached. In this case, the heat transfer is inversely proportional to the distance between the parts A/B and B/C.

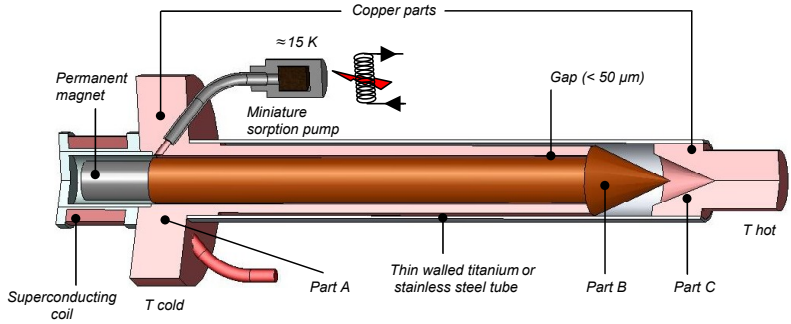

Figure 2. Schematic of the thermo-mechanical switch

Figure 3. Picture of the switch prototype featuring the small superconducting coil (left)

Thus, displacing part B between its two extreme positions changes significantly the 'on' conductance of the switch. This displacement can be made almost instantaneously, and thus the conductance of the switch can be varied very quickly between the 'partly-on' position and the 'fully-on' position. The facing surfaces of the moving part and fixed end can be made such they can tolerate the radial displacement of the switch end. Although the end surface (B to C) is much lower than in a standard switch, it is compensated by the fact that the gap is also much smaller. This gap between A and B can even be reduced to almost zero, since in this case, with the two parts in contact, the performance is further improved.

The moving part features a permanent neodymium magnet bonded to one of its ends. Facing this magnet, a small superconducting coil made of NbTi wires is mounted on the external switch envelope. This magnetic arrangement allows the internal copper part to be moved back and forth. A picture of the switch is given in Fig. 3.

When the switch is 'fully-on,' the objective is to lower as much as possible the distance between the moving part B and the two fixed parts A and C, or rather, to maximize the term Area/Distance. For the case A/B, the length along which the exchange through the gas will occur is large (large surface), and the gap can be left at values on the order of 25-50 microns. It would be feasible, by construction, to reduce this gap; however, it is useless, as the limitation comes from the gap between B and C. In addition, as discussed further, keeping the A/B gap to several tens of microns can in fact improve the performance.

The main technical challenge is indeed between parts B and C. In theory, assuming the ends are machined so as to obtain an excellent surface finish and that the parts are perfectly aligned, one can expect a gap on the order of a micron or less. In practice, we have not been able to reach such a low value, and as shown further, the gap remains on the order of 20 µm. It should be noted also that, at some point, the performance becomes limited by the copper itself. With the first prototype built to validate this concept, the measured gap was of the order 30-40 µm, and thus the switch described in this paper was sized assuming a gap of 35 µm.

In the end, two accommodating attributes were introduced into the design:

1. The design and assembly technique was set such that parts B and C could be aligned very well, and then the switch end part could be assembled last using an electron beam weld
2. The contact surface areas were made larger (as described below)

Three versions of the switch have been built. In the first one, the end of the copper moving part is cylindrical, and the facing surfaces are flat (ease of machining). In the second version, the end and its facing surface have a conical shape. The cone not only provides a larger surface area (35% in this case, because the full surface is not used), but it should also allow for the self-centering of the moving part, and possibly yield a lower gap. And, this is why we decided not to further reduce the gap A/B: leaving some clearance should ease the centering of the cone. Finally, the last version is again cylindrical with a flat surface, but is made out of aluminium 6061 for two reasons: 1) a reduction in mass for the moving part, and 2) the use of dissimilar material (copper/aluminium) to prevent potential galling issues. The first reason is related to the mechanical strength of the switch; at some point, for space application, it will be necessary to demonstrate these switches can survive a typical launch vibration test. Obviously, the fact that the inner part is now mobile can be a problem. One potential solution is to supply enough current to the coil so that the magnetic system can hold the moving part in position. In this case, the lighter this part is the better.

Table 1 : Heat Switch main characteristics

Overall dimensions	Ø 40 mm x L 128 mm
Weight (including coil)	139 g (Cu version)
Stainless steel tube	11.8 ID x 12 OD (mm) 70 mm active length
Gap (full ON* and partial ON) (*estimated)	35 µm / 4 mm
Mass of moving part	Cu version: 38 grams Al version: 13 grams
Charge pressure at room T (^{3}He)	0.12 MPa

And, if it turns out the performance penalty due to the lower thermal conductivity of aluminium is acceptable, then this last version would be a very good candidate. Once in orbit, the mass of the moving part does not matter anymore, and a very limited force is required to move this part. For this set of prototypes, the switch tubing is made of stainless steel to ease the assembly phase. Finally, to further gain on the 'on' conductance, the switches are charged with helium-3 gas.[5] Table 1 summarizes the switch main characteristics.

The proprietary software model developed for our standard gas gap heat switch has been modified, and a dedicated version has been produced for the thermo-mechanical switch.

EXPERIMENTAL RESULTS

Once the switches are charged with helium and permanently sealed, the miniature sorption pump is equipped with one carbon thermometer and a heater. Each switch is then mounted in a helium test cryostat (see Fig. 4). A Cernox thermometer and a heater are mounted on the hot end, and a second cernox is placed on the switch base. Electrical connections with the small superconducting coil are then made. This simple setup allows us to fully characterize the performance of the device. The switches are mounted in a horizontal position, and one feature of the test cryostat is that it can be operated in any orientation between –90° to 90° (cryostat is vertical at 0°). Thus, we can test the switches in various positions and, in particular, upside down. The magnetic circuit has been sized to provide enough force to move and maintain the inner part against gravity.

The first tests were focused on the magnetic engine, and the behaviour was in accordance with predictions. The moving masses were 38 and 13 grams for the copper and aluminium versions, respectively. The calculated current for the copper version was 265 mA, to be compared with 250 mA measured experimentally (switch vertical). And, as expected, the current required to sustain the aluminium version was found to be 80 mA (≈ 250/3). The coil is driven and measured using a 4-wire mode, and the dissipation was checked to be zero (no resistance). Surprisingly, in the horizontal position, the current required to move the part is about the same. We suppose, then, that the friction force is of the same order as the gravitational force. Of course, in this case (horizontal), the current can be reduced back to zero after a very brief pulse.

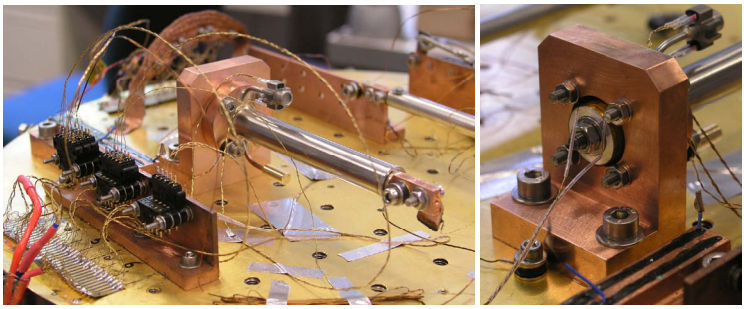

Figure 4. Prototype switch mounted in the test cryostat (left). View of the back side of the switch (right)

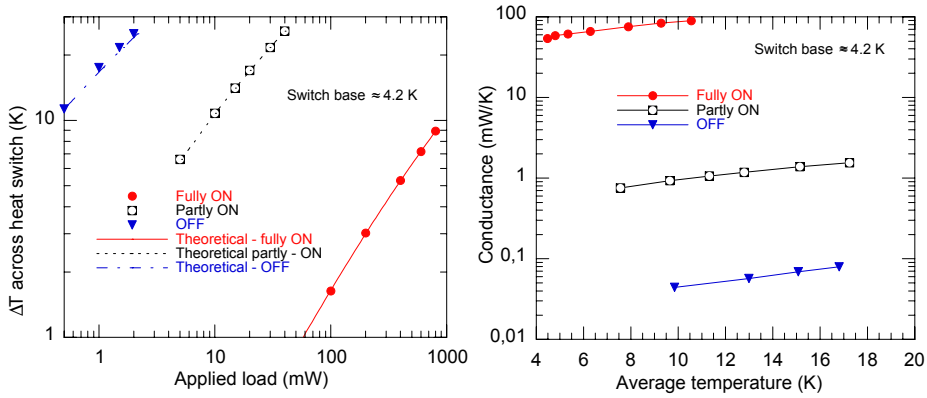

Figure 5. Thermal performance for the Cu-Cu version with flat cylindrical end

Thermal Conductance

The first prototype—copper rod with cylindrical flat end—was characterized. The results are displayed in Fig. 5 for each position ('off', 'partly-on' and 'fully-on') along with the predicted performance calculated taking into account the remarks below. In a second curve, the conductance is represented as a function of the average temperature; it should be noted that in some cases this temperature is the average between a temperature close to 4.2 K and one above 20 K. Thus, the curve should be considered with care. The measurements were done with the switch horizontal, but it was checked that the orientation has no effect on the performance for this switch. These experimental data have been analyzed, and in particular, for the two 'on' positions. The analysis leads to two results. First of all, compared to our previous prototype, we have obtained a slight gain on the end gap, which is 18 µm. Second, the model predicted a lower conductance for the 'partly-on' position. However, in the model the 'on' conductance is equal to the sum of several terms including the conductance through the tube envelope. For this term, it is assumed the thermal gradient is distributed along the full length of the tube. In fact, and this was already confirmed by our previous results, the switch behaves as if the gradient is limited more or less to only the distance between parts A and C at the hot end. Indeed, the distance between the tube and the outer surface of inner copper part A is about 400 µm, and thus it is conceivable that conduction through the gas impacts the gradient. These parameters were then adjusted in the model to reflect the experimental data. The experimental performance is given in Table 2 along with the specifications from CNES.

Next, the experiments were repeated with the two other prototypes (copper rod with conical end, and aluminium rod with flat cylindrical end) (see Fig.6). Besides a slight gain for the 'on' position (see further), the conical version was found to be sensitive to orientation. Indeed, with the switch vertical—hot end downward—we noticed an increase in conductance in the 'on' position. The reason, in this case, is that the cone self-centres, and thus the ratio area-over-distance is increased. The performance is not changed if current is supplied to the coil (adding a downward force). The switch was then brought back horizontal, and it was indeed found that the current pulse moves the rod toward the conical end, but due to its own weight, the rod slides back slightly when the current is removed.

Table 2 : Thermal performance

	CNES Specification	**Experimental result**
Fully ON @ 4.2 K	> 20 mW/K	≈ 50 mW/K
OFF @ 4.2 K	< 20 µW/K	≈ 20 µW/K*
Partly ON	0.1< spec < 1 mW/K	0.5 mW/K

(:if stainless steel was replaced by titanium Ta6V for the tube, this result would decrease to about 15 µW/K. Stainless steel was chosen for greater convenience).*

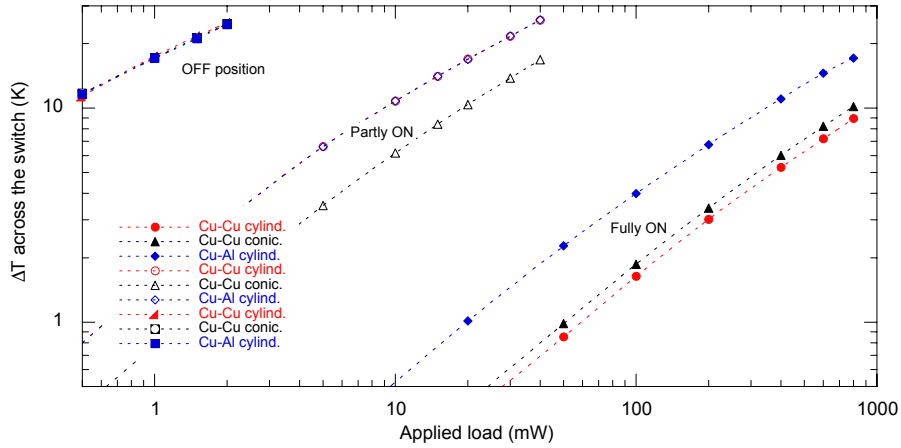

Figure 6. Thermal performance for all versions (switches horizontal) (lines are guide for the eyes)

Then, injecting a continuous current pushes the rod back, and the conductance is increased, yet not quite to the level obtained in the vertical position (see Fig. 7).

In the best case, the gain compared to the cylindrical flat-end version is about 25%, against 35% expected. This difference is attributed to the fact that the surface finish of the conical version was not as good as with the flat ends. The 'partly-on' position is also different, simply due to geometrical reasons: when the rod is pulled back, the conical part still has measurable gaseous conduction to the facing cone. Of course, as expected, the 'off' (no gas) position remains the same for all versions. The curves in Fig. 7 summarize the results obtained for the 'fully-on' position for the various versions.

Switch Kinetics

The heat switch kinetics were then evaluated. All switches behaved in a similar way, and we have reported in Fig. 8 the results obtained with the conical-end version. The miniature sorption pump was kept at 20 K to guarantee a fully-established viscous regime, while 40 mW was applied to the switch hot end. The results are spectacular: the switching time between the 'partly-on' to 'fully-on' position is of the order of 5 seconds in this case. Switching back to the other position takes slightly longer, since the thermal conductance is lower, and the applied load sets the timing. Then, to switch to the 'off' position takes several minutes, as with a standard gas gap heat switch.

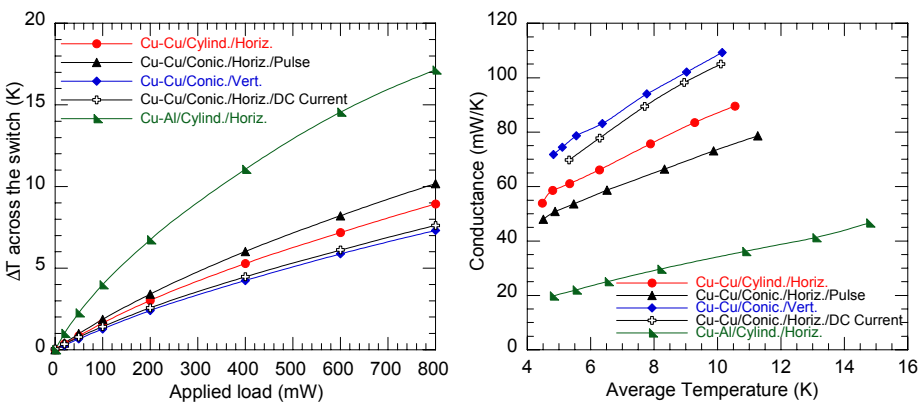

Figure 7. Performance comparison between all versions tested for 'fully-on' position.

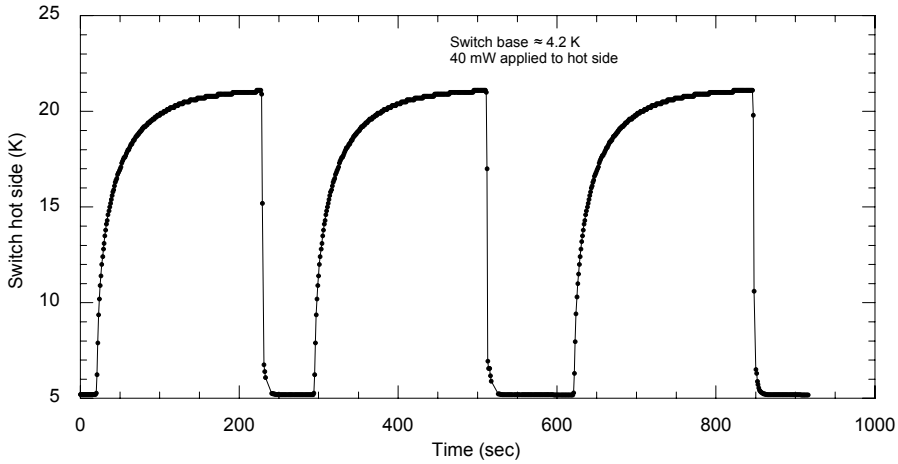

Figure 8. Switching time (prototype with copper conical-shape rod)

This 'turn-off' time is defined by the thermal conductance between the miniature sorption pump and the switch base, and this conductance is usually chosen in order to obtain a good balance with the power required to maintain the pump at 20 K.

Switching Temperature

To determine the switching temperature, a power was applied to the hot end of the switch while the miniature sorption pump temperature was reduced in steps from 20 K or so. Once the conductance starts to decrease, the temperature of the hot side increases and eventually reaches the value associated with the stainless steel tube conductance. The measurements have been made for both positions, 'fully-on' and 'partly-on' (see Fig. 9). In fact, there is not a single switching temperature, but rather two thresholds: one first temperature below which the gas heat transfer is molecular and is negligible in comparison to the transfer through the external tube, and a second temperature above which the viscous regime is fully established.

It is interesting to note on the plot that the decreasing of the conductance occurs at a higher temperature for the 'fully-on' position. This is due to the fact that the viscous regime depends on the mean path of the gas molecules. When the mean free path grows to be larger than the typical dimension (gap), the heat transfer becomes molecular and depends on pressure (and thus on the miniature sorption pump temperature). In the 'fully-on' position, the gap is of the order of 20 µm, and in the 'partly-on' one it is 4 mm.

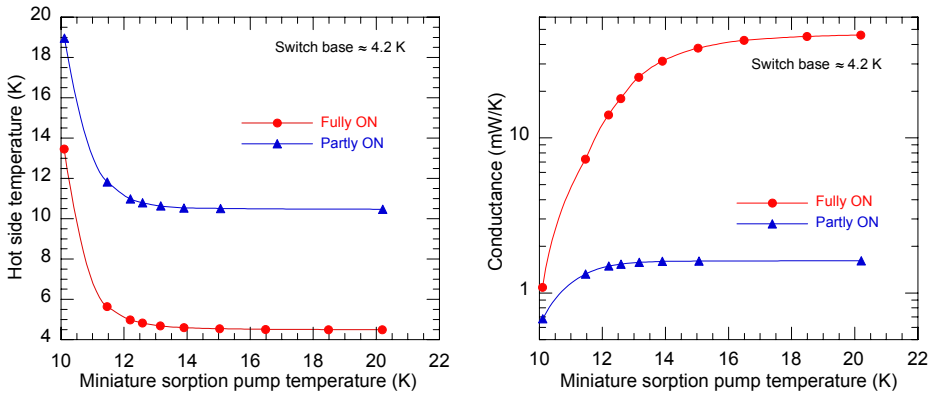

Figure 9. Switching temperature (prototype with copper conical shape rod)

Consequently since the mean free path is directly linked to the miniature pump temperature, it will become larger than 20 µm first, and then at some point larger than 4 mm. This is clearly seen in the curves.

The switching temperature is slightly below 10 K. This is lower than for our typical gas gap heat switches (12-15 K), simply because the internal volume of the switch is larger (permanent magnet, large gap for the moving part). Since the charge pressure and the amount of charcoal have been kept the same, it is indeed quite natural that the activated charcoal temperature must be lower to adsorb this additional gas.

These results are in good agreement with the model, which predicts 9 K and 17 K, respectively, for the 'off' and 'fully-on' positions.

CONCLUSION

We have developed and patented a new concept for a gas gap heat switch. In this concept a moving part is added, which provides interesting features. For instance it allows one to partly mechanically decouple the switch hot end, and thus to ease the integration of these items. It offers an intermediate 'partly-on' position that can be tuned to basically any value, along with a very fast switching time between this position and the 'fully-on' position. It can be noted that, depending on the application, the switch can be used without any miniature sorption pump, if the ratio between the 'fully-on' and 'partly-on' positions fulfills the requirements. In this case, the switch could be operated with virtually no power dissipation.

The thermal operation of the switches has been experimentally demonstrated. In a next phase, their mechanical performance will be investigated. The switches will be vibration tested, and these tests will be followed by a second thermal test campaign to check their integrity.

Finally, a test setup is being designed to measure the impact of real-time side loads on the switch performance.

ACKNOWLEDGMENT

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REFERENCES

1. Duband, L., "Herschel flight models sorption coolers," *Cryogenics*, vol. 48 (2008), pp. 95-105.
2. Patent ref PCT/FR2007/001040.
3. Gifford, W.E., Kadaikkal, N. and Acharya, A., "Simon helium liquefaction method using a refrigerator and thermal valve," *Adv. in Cryogenic Engineering,* Vol. 15, Plenum Publishing Corp., New York (1970), p. 422.
4. Torre, J.P. and Chanin, G., "Heat switch for liquid-helium temperatures," *Rev. Sci. Instr.*, Vol 55 (1984), p. 213.
5. Duband, L., Collaudin, B. and Jamotton, P. "Sub-Kelvin sorption coolers for space applications," *Cryocoolers 11,* Kluwer Academic/Plenum Publishers, New York (2001), pp. 567-576.