SPICA/SAFARI Sub-Kelvin Cryogenic Chain

L. Duband[1], J.M. Duval[1], N. Luchier[1] and S. D'Escrivan[2]

[1]CEA / INAC / Service des Basses Températures, Grenoble 38054 France
[2]CNES, Toulouse 31401 France

ABSTRACT

SPICA, a Japanese led mission, is part of the JAXA future science program and is planned for launch in 2018. SPICA will perform imaging and spectroscopic observations in the 5 to 210 mm waveband. The SPICA payload features three instruments, one of which, SAFARI, is developed by a European based consortium.

SPICA's distinctive feature is to use an actively cooled telescope down to 4 K. In addition SPICA is a cryogen-free satellite and all the cooling will be provided by radiative cooling (L2 orbit) down to 30 K and by mechanical coolers for lower temperatures.

The satellite will be launched warm and slowly reach its operating temperatures once in orbit. This warm launch approach allows to suppress any large liquid cryogen tank and to use the mass saved to launch a large diameter telescope (3.5 meters). This 4 K cooled telescope allows significantly reduced thermal radiation, offering superior sensitivity in the infrared region.

The cryogenic system that enables this warm launch/cooled telescope concept is a key issue of the mission. This cryogenic chain features a number of cooling stages comprising passive radiators, Stirling coolers and several Joule Thomson loops, offering cooling powers at typically 20, 4.5, 2.5 and 1.7 K.

The SAFARI detectors require cooling to temperatures as low as 50 mK, and thus the SAFARI instrument cooler will be operated from these heat sinks. It is composed of a small adiabatic demagnetization refrigerator (ADR) pre-cooled by a sorption cooler. This hybrid architecture allows a lower weight cooler able to reach 50 mK. Because the sorption cooler/ADR combination is probably the lightest solution to produce sub-Kelvin temperatures, it allows the stringent SAFARI mass budget to be met.

INTRODUCTION

The SpicA FAR infrared Instrument (SAFARI) is an imaging Fourier Transform Spectrometer (iFTS) designed to give continuous wavelength coverage in both photometric and spectroscopic modes from around 34 to 210 ìm, one of the richest ranges of the electromagnetic spectrum emitted by astrophysical objects. SPICA's science objectives[1] can only be achieved by increasing dramatically the sensitivity with respect to IXO, AKARI or HERSCHEL. To meet these objectives requires to develop more sensitive detectors but also to reduce to the maximum extent the background photon noise generated by the telescope itself. For wavelengths less than 200 μm, this leads to a telescope temperature below 6 K (5 K as a goal). For the detectors there are currently four competing technologies: Transition Edge Sensor (TES), Kinetic Inductance Detector (KID), Silicon bolometers and Photoconductors. With the exception of the photoconductors, these technologies require sub Kelvin cooling possibly down to 50 mK. This is a temperature outside the range of helium

Cryocoolers 16, edited by S.D. Miller and R.G. Ross, Jr.

evaporative cooling. Indeed one can show that from a practical point of view the absolute minimum temperature achievable with this technique remains above 160-180 mK. Thus for this last cooling stage and for a space application, there are only two possible solutions, the dilution cooler and the adiabatic demagnetization refrigerator (ADR).

An open-cycle space compatible dilution[2] refrigerator has been developed by Institut Néel and Air Liquide and is currently used in the ESA Planck space mission (~100 nW @ 100 mK). A closed cycle dilution refrigerator is currently under development and with this new concept a temperature close to 50 mK has been achieved[3]. There are still several technical challenges to be solved and the technological maturity must be improved, but this solution could be attractive in the future.

An ADR employs a very efficient technology to cool down to a few milliKelvin. Moreover, it is gravity independent and has no moving part. It fulfils the main reliability requirements of space missions. Several ADRs can then be chained to cover an extended temperature range[4,5,6]. For the 50 mK range this technology certainly has a very high maturity level. One of the drawbacks is the mass, which becomes very large as the temperature range is raised.

The design of the sub-Kelvin cooling chain must be made in light of the mission constraints. In that respect the current trend in space cryogenics is the elimination of liquid cryogen cryostat in favor of mechanical coolers, which is precisely the case for SPICA[7], allowing among other things, to extend considerably the mission duration. However this new philosophy comes with a number of technical challenges. For instance the mechanical coolers feature a limited cooling power and in certain cases cannot accept large peak powers (JT loop for instance). In general this is not the case for the liquid cryogen for which a large number of cold joules are available (latent heat) and thus can accommodate the peak power (at the cost of autonomy reduction). Consequently it is necessary to come up with clever thermal architectures in which all available cooling sources may be used in order to optimize the heat dissipation at each temperature stage.

In addition, mass has become a critical driver and a clear objective of the future space instruments is to maximize the amount of on board science within the overall mass allocation. This has a direct impact on the cryogenics for which one of the motto is now the lighter the better. Of course, the mass issue has to be balanced with the efficiency issue when necessary.

DESCRIPTION OF THE SAFARI CRYOGENIC CHAIN

In order to save mass, we propose for SAFARI an alternate approach to the multistage ADR system. In this approach[8], the most demanding stage, in terms of mass (first ADR stages), is replaced by a ^{3}He sorption cooler that is substantially lighter than the ADR. As an example, the HERSCHEL sorption cooler heart weighs less than 300 grams[9]. Then from this 300 mK stage, only one ADR stage is required to achieve temperature lower than 50 mK. This system will be a one shot system: the cooler is recycled and then provides cooling powers for a given time at the two temperatures, 300 mK to intercept parasitic heat loads and cool detector front end electronics and 50 mK for the detectors. Once the system is out of "cold joules" it can be recycled again and indefinitely as long as the upper heat sinks are available. The current specifications for SAFARI is to provide 1 μW useful heat lift at 50 mK and simultaneously 15 to 20 μW at 300 mK for an autonomy of 30 hours and a recycling time less than 10 hours.

This concept has been demonstrated in the laboratory and temperature as low as 20 mK has been achieved. A detailed description of this first prototype is given elsewhere[8]. For this paper we focus on the operation of the sorption stage.

The main challenge with the sorption cooler is the need to thermally cycle the sorption pump between a few K and possibly 45 K[4]. Each cycling is required to remove a given amount of energy: if this is done quickly, large peak powers are to be dealt with. For HERSCHEL this is not a problem since the cryogen tank contains about 2500 litres of superfluid helium. In the present case the limited cooling powers available require that 1) the thermal architecture takes advantage of all available cooling resources and 2) the timing of the cycle is set such that the instant loads never exceed these cooling powers.

The SPICA cooling chain features several Stirling and Joule Thomson coolers as depicted in Figure 1. The available heat sinks for the SAFARI instrument are 1.7 K, 4.5 K and 20 K with

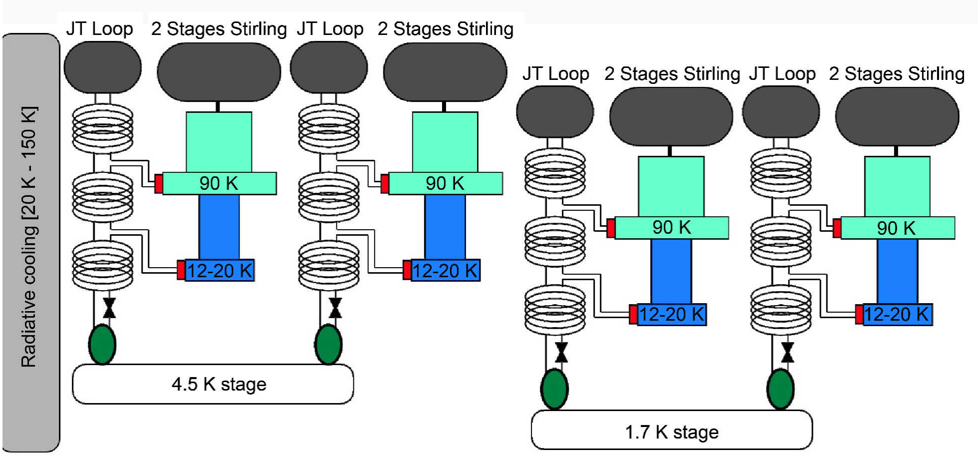

Figure 1. Schematic of the SPICA cryogenic chain

respective cooling power of 5, 10 and 30 mW. These numbers may evolve in the future, but they were used as the basis for the sub-Kelvin cooler design.

SUB-KELVIN COOLER ARCHITECTURE

For our first design we decided to take advantage of all available thermal resources and the architecture foreseen is shown in Figure 2. In this case the cooler mechanical structure is at 4.5 K. All heat switches (with the exception of the 300 mK switch) are mechanically held to this structure, and then thermal paths are provided between the switch and its associated component. One clear advantage is that the interfaces with the other heat sinks are only thermal.

The "condensation" switch to the evaporator (HS4) is thermally connected to the 1.7 K and thus the only penalty paid due to the 4.5 K structure is through the Kevlar suspension system. To reduce the parasitic heat loads from the Kevlar cords (evaporator and ADR), a solution could be to

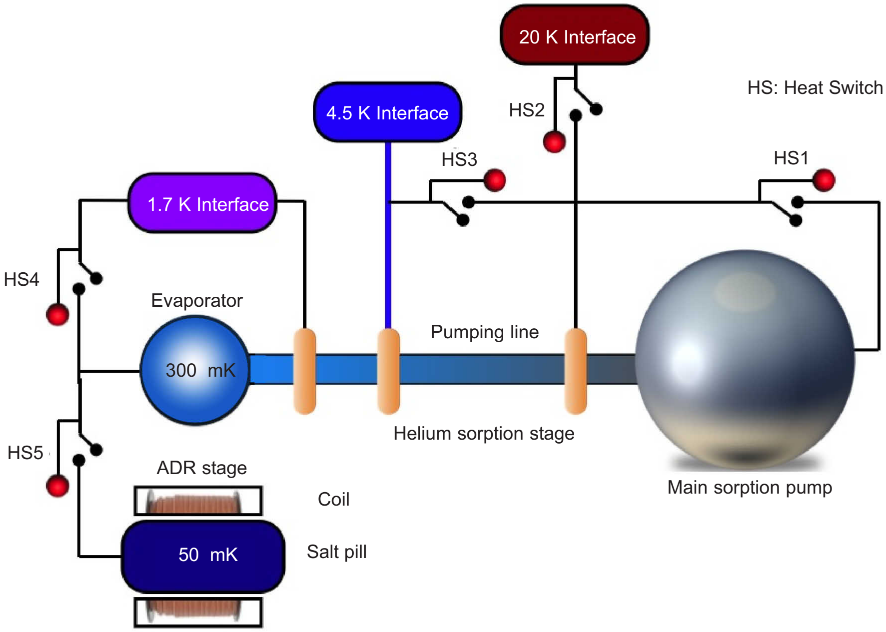

Figure 2. Initial sub-Kelvin cooler thermal architecture

Table 1. Heat Switch States

	State of heat switches				
Action	**HS1**	**HS2**	**HS3**	**HS4**	**Comments**
Sorption Pump heated to 45 K	OFF	ON	OFF	ON	hot gas from the pump is cooled to 20 K and then to 4.5 K
Pump cooled down from 45 to 20 K	ON	ON	OFF	OFF	Efficient adsorption (pumping) occurs once Tpump ≈ 20 K
Pump cooled down from 20 to 4.5 K	ON	OFF	ON	OFF	Evaporator drops to 300 mK.
Low T phase (once ADR magnetized)	ON	OFF	ON	OFF	

thermally shunt the cords at 1.7 K. This will be evaluated in view of the salt pill mass and of the added complexity of the suspension system.

In this arrangement, the sorption cooler is first recycled. This recycling process involves two phases. During the first phase, the sorption pump is slowly raised to 45 K and maintained there until the right thermodynamic conditions are reached (mostly an evaporator temperature as close as possible to the 1.7 K heat sink). During this phase, the hot gas is cooled and the corresponding energies are rejected to the heat sinks (20 K, 4.5 K and 1.7 K) and finally the gas is liquefied (1.7 K). Then in a second phase the pump is cooled down first to 20 K and then to 4.5 K, and the energies related to the heat capacities and the heat of adsorption are removed at these temperature stages. Table 1 depicts the phasing of the various heat switches.

RECYCLING PHASE AND PEAK POWER ISSUE

Although the energies are distributed to the heat sinks, all thermal links between the cooler interfaces and the heat sinks must be precisely controlled to avoid any peak dissipation in excess of the available resources. Each of these links includes a heat switch. For that purpose one could use a hybrid gas gap heat switch[10] where it is possible, by construction, to obtain several levels of conductance. Although this solution remains a possible option, we decided for the present work to use standard gas gap heat switches operated in the ballistic (or molecular) regime. In this regime the thermal conductance is directly proportional to the internal pressure of the switch (see Figure 3). Since the temperature of the miniature sorption pump sets this pressure, it is possible in principle to control the conductance by temperature regulating this component.

In order to demonstrate and validate the recycling of a helium sorption stage with limited resources, a so-called demonstrator was designed and built. This unit has been sized according to

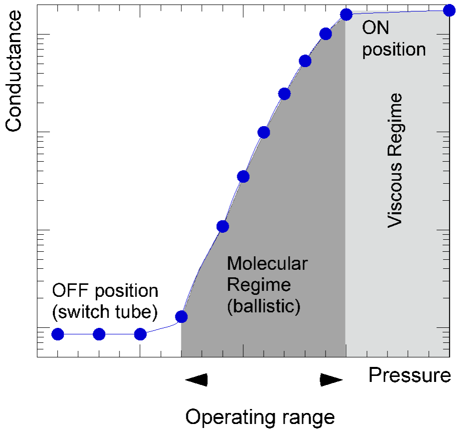

Figure 3. Heat switch conductance versus internal pressure

the SAFARI needs and it turned out that a 6 liters STP unit similar in size to the HERSCHEL cooler would fit (direct benefit from the HERSCHEL heritage[9]). This demonstrator features 4 heat switches, a pumping line with 3 heat intercepts and a support structure (see Figure 4). All interfaces can be temperature regulated to the required level. The whole system is mounted on the cold plate of a 1.2 K pumped helium cryostat. The objective of this system is to measure (and control) the flowing powers while the cooler is recycled. The principle is straightforward: each thermal interface is thermally connected to the helium cryostat cold plate by a calibrated copper link. Each link has been sized so that the heating power required to maintain 4.5 K, for instance, is about twice the available cooling power specified for SAFARI (20 mW in this case). When there is no dissipation, the temperature controller inputs 20 mW to this interface via a heater, and as soon as heat is flowing to this interface, the temperature controller adjusts the input power accordingly. By difference it is then possible to extract exactly this flowing power.

It took several experiments to tune the heat switches and finally we were able to demonstrate a full recycling within the specified resources. For clarity purpose we have reported in Figure 5 only the temperature of the main pump and the dissipation on the 3 interfaces. For this particular experiment the temperature of the miniature sorption pumps on the switches were adjusted manually, which explains the switchback graph. On this graph it can be seen that the input power to the pump was raised too quickly and lead to a slight overshoot at the 4.5 K interface. Nevertheless this experiment demonstrates we can recycle the cooler while controlling the heat dissipations.

While this thermal architecture works, a 20 K thermal bus inside the instrument is not perceived as something attractive for integration reasons and stray light issues. Thus we developed a second approach. In the case of HERSCHEL the mission duration is set by the cryostat lifetime and consequently by the efficiency of the cryogenic systems. Consequently the objective was to have the most efficient cooler and to obtain the longest hold time for any recycling, or in other words to condense as much helium as possible for a given energy dumped on the main tank. Because the superfluid cryostat is cooled to about 1.7 K and because the thermal links to this reservoir have a finite conductance, it was important in this case to raise the temperature of the main sorption stage to 45 K to obtain over 90% condensation efficiency at 1.9-2 K. However for SAFARI the approach is different; first, the condensation temperature is 1.7 K. This leads to a lower saturated vapor pressure and thus a larger amount of helium desorbed from the activated charcoal for a given pump temperature.

Then a smaller fraction of liquid is lost during the cool-down phase from 1.7 K to 300 mK. Finally, there are no consumables and the drivers for the cryogenics are the instant loads and the timings.

Based on this new approach, our calculations show it is indeed possible to limit the temperature of the sorption stage to 30 K instead of 45 K. The thermal architecture is then significantly

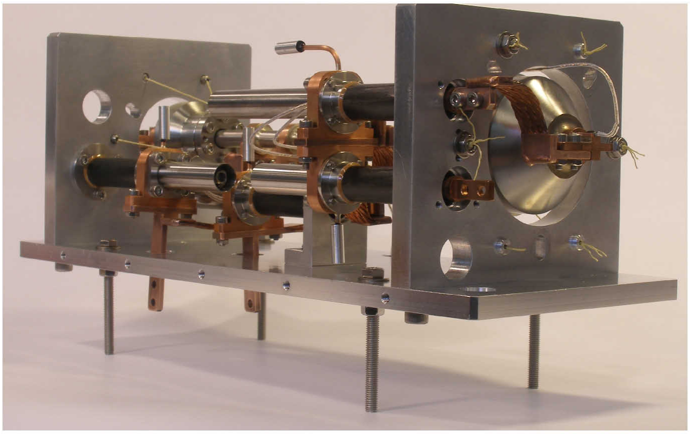

Figure 4. Helium sorption cooler prototype (demonstrator)

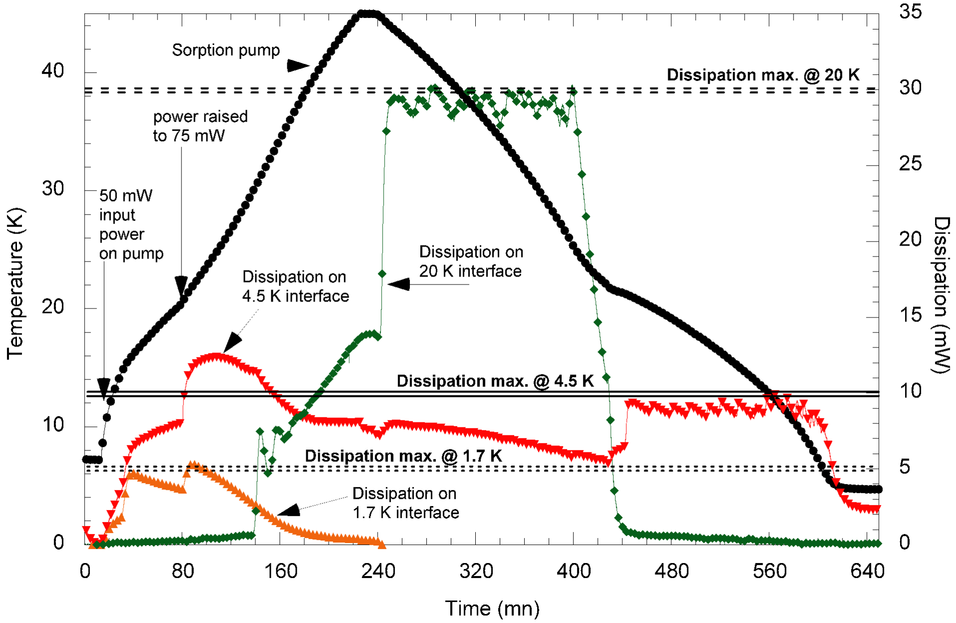

Figure 5. Typical recycling phase – Case 45 K and 3 thermal interfaces

simplified: the 20 K interface is not necessary anymore and two switches out of 5 are suppressed (see Figure 6). It should be pointed out that the 20 K interface is not used directly by the cooler, but we still need to heat sink the ADR current leads to it.

Of course there is a cost in terms of efficiency, and the modeling indicates an autonomy reduction of about 20% for the cooler, meaning that for the same autonomy the heat lift at 300 mK is reduced by about 20%. On the other hand the recycling time is decreased by almost 30%. Consequently the overall benefit of this second architecture is substantial.

The demonstrator was used to validate this choice. This is shown in Figure 7 where we have reported the autonomy reduction as a function of the pump temperature. The autonomy obtained

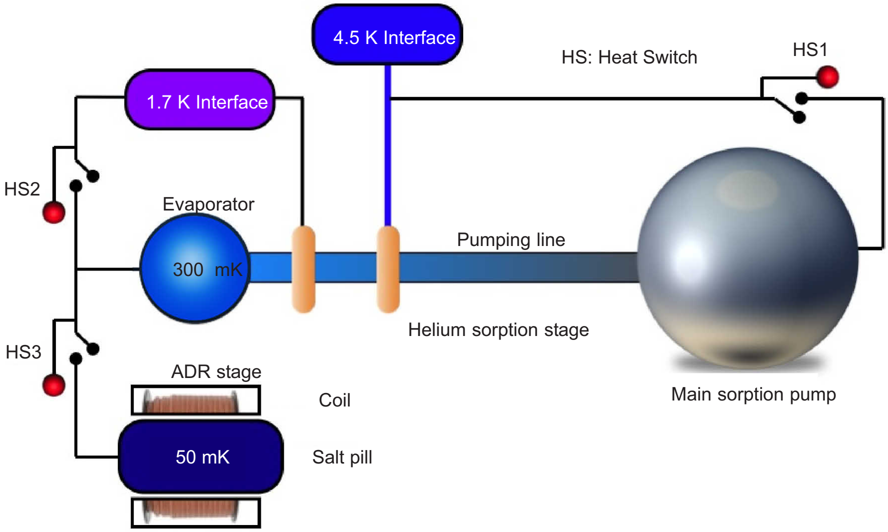

Figure 6. Final sub-Kelvin cooler thermal architecture

with a pump at 45 K has been normalized to 100% (in fact a test was made with 50 K and did not show a significant difference). This figure shows that indeed a pump at 30 K only impacts the autonomy by less than 20% in accordance with the modeling.

The demonstrator was then modified accordingly. The pumping line remains the same, but the 20 K shunt becomes inactive and the associated heat switches are disconnected. Several recycling phases were then performed with this new architecture and our laboratory drive electronics were modified to be able to control the dissipation at each interface. Several options were possible for this control and we selected what seems the simplest one: to adjust the conductance of the heat switch (HS1) as a function of the temperature of the main sorption pump. In other words for a given pump temperature, a given input power is sent to the miniature sorption pump. This requires calibrating the heat switch in the molecular regime, but once it is done the recycling can be performed automatically. This technique works fairly well as shown in Figure 8. The specified limits for the dissipation are slightly overshot but the difference remains below 10% and is just a matter of precise tuning. For comparison purpose we have reported in this figure the dissipations measured during the recycling of a HERSCHEL sorption coolers. In this case the cooler is thermally connected to only one heat sink (the superfluid tank) but features two copper links to this interface[9]. This explains why two peaks are reported on the figure. This graph shows that we are now able to reduce the peak powers by more than two orders of magnitude. Of course since the energy to be removed remains the same, the recycling time is strongly dependent on the available resources, mostly at 4.5 K (see Figure 8) and thus any increase in cooling power is most welcome. In any case, the recycling phase was one of the challenges that needed to be solved for this concept to be considered.

The detailed design of the SAFARI cooler will probably be initiated in fall 2010. In the meantime we have been working on a similar system dedicated to the IXO mission. Although the thermal interfaces and associated resources are different (10 mW @ 2.5 K and 100 mW @ 15 K), the overall concept is the same, and the experimental results will benefit directly the SAFARI developments. The IXO sub-Kelvin cooler has been designed, parts are available and the cooler is currently being assembled. The full system is expected to be available in June 2010. An extensive test campaign will follow.

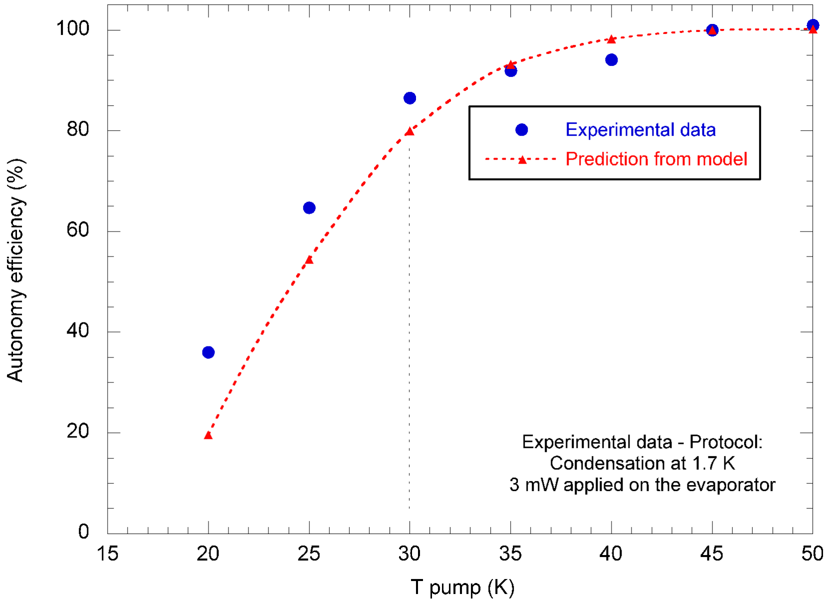

Figure 7. Autonomy reduction versus pump temperature

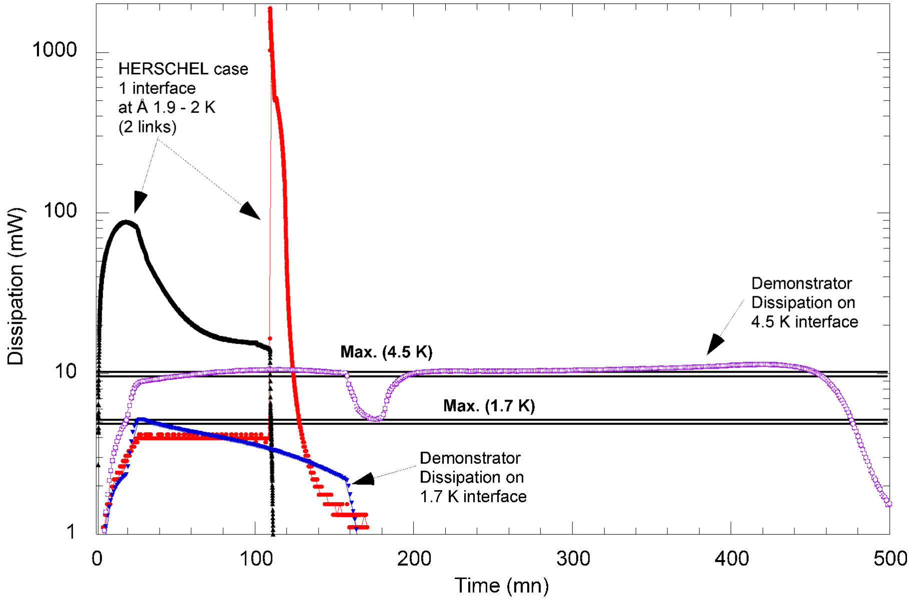

Figure 8. Typical recycling phase – Case 30 K and 2 thermal interfaces (Comparison with HERSCHEL cooler)

CONCLUSION

We have successfully demonstrated operation of a sorption unit with limited resources at the upper heat sinks. This was one of the last challenges to be solved and the results enhance our confidence in the ability of this concept to meet the requirements of several future space instruments needing temperature below 100 mK.

In addition work has been carried out to simplify the thermal architecture of the SAFARI cooler. Supported by experimental data, the architecture has been reworked and uses now only two interfaces and three heat switches.

An engineering model of the SAFARI cooler is expected to be build end of 2010 – early 2011. However in the meantime, the first fully integrated sorption / ADR cooler is currently being assembled and should be available for tests this summer 2010; this unit is dedicated to the XMS instrument on board the IXO mission.

ACKNOWLEDGMENT

We thank the French Space Agency (CNES) for the funding of this work. We thank L. Clerc for his expert technical work during the assembling phase, the setup of the test cryostat and his contribution to the test campaign.

REFERENCES

1. ESA Assessment Study Report "SPICA Revealing the origins of planets and galaxies" *ESA/SRE [2009]6* (Dec 2009)
2. Triqueneaux, S., Sentis, L., Camus, P., Benoit, A. and Guyot, G., "Design and performance of dilution cooler system for the Planck mission," *Cryogenics*, Vol. 46 Issue: 4, April 2006, pp. 288-297.
3. Martin, F., Vermeulen, G., Camus, P. and Benoit, A., "A closed cycle ^{3}He-^{4}He dilution refrigerator insensitive to gravity," *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 623-627.

4. Shirron, P., Canavan, E., DiPirro, M., Francis, J., Jackson, M., Tuttle, J., King, T., Grabowski, M., "Development of a cryogen-free continuous ADR for the constellation-X mission," *Cryogenics*, Vol. 44, Issues: 6-8, June-August 2004, pp. 581-588.
5. Bartlett, J., Hardy, G., Hepburn, I.D., Brockley-Blatt, C., Coker, P., Crofts, E., Winter, B., Milward, S., Stafford-Allen, R., Brownhill, M., Reed, J., Linder, M., Rando, N., "Improved performance of an engineering model cryogen free double adiabatic demagnetization refrigerator," *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 582-590.
6. Shinozaki, K., Mitsuda, K., Yamasaki, N.Y., Takei, Y., Masui, K., Asano, K., Ohashi, T., Ezoe, Y., Ishisaki, Y., Fujimoto, R., Sato, K., Kanao, K., Yoshida, S., "Development of double-stage ADR for future space missions" *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 597-602.
7. Sugita, H., Sato, Y., Nakagawa, T., Yamawaki, T., Murakami, H., Matsuhara, H., Murakami, M., Takada, M., Takai, S., Yoshida, S., Kanao, K., and SPICA pre-project team, "Cryogenic system design of the next generation infrared space telescope SPICA," *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 566-571.
8. Luchier, N., Duval, J.M., Duband, L., Camus, P., Donnier-Valentin, G., Linder, M., "50 mK cooling solution with an ADR pre cooled by a sorption cooler," *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 591-596.
9. Duband, L, Clerc, L., Ercolani, E., Guillemet, L. and Vallcorba, R., "Herschel flight models sorption coolers," *Cryogenics*, Vol. 48, Issues: 3-4, March-April 2008, pp. 95-105.
10. Duband, L., "A thermomechanical heat switch," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp. 561-568.