Progress in the Development of the IXO 50 mK Sorption-ADR stage

J.M. Duval[1], N. Luchier[1], L. Duband[1], T. Tirolien[2]

[1] CEA / INAC / Service des Basses Températures, Grenoble, France
[2] ESA / ESTEC, Noordjwick, the Netherland

ABSTRACT

The nominal temperature of the new generations of detectors for the next space mission International X-ray Observatory (IXO) is expected to be around 50 mK. The coupling of a ^{3}He cooler with an ADR provides an elegant cooler in this temperature range with low mass and few interfaces. As part of an ESA contract to develop such a solution, we designed an efficient assembly based on low thermal interfaces at 15 K and at 2.5 K. The cooler is sized to provide simultaneously net heat lifts of 1 µW at 50 mK and 10 µW at 300 mK for an autonomy exceeding 24 hours. The design of an engineering model is presented, as well as mechanical analysis and simulated results. The influence of the interface parameters are discussed together with different cycling scenario possibility.

INTRODUCTION

ESA awarded CEA the contract ESA/ESTEC n^0 21226/07/NL/EM 50 mK Continuous Cooling to design, manufacture and test a 50 mK cooler using two heat sinks at 2.5 and 15 K. Based on the cooling need and observation procedure for this mission, it appeared that a continuous solution is not necessarily useful and we switched our focus from a design optimized for continuous cooling[1] to a cooler able to provide a cold phase of more than 24 hours. Our optimization is a balance between the mass aspect, the main thermal requirements for this cooler (cooling power, temperature, available power at heat sink) and the stray magnetic field. In this article, the design of our engineering model is presented, followed by experimental results and finally a discussion on cycle optimization.

Sorption Cooler

The design for the 50 mK cooler presented here is based on our Herschel heritage, for which mission we provided two sorption coolers for the PACS and SPIRE detectors on the Herschel mission. These coolers can provide low temperature of about 300 mK by pumping on a liquid ^{3}He during the cold phase. The pressure variations are obtained by modifying the temperature of a charcoal pump using their high adsorbent quality. Following the cold phase, a recycling phase is necessary to condense the liquid ^{3}He in the evaporator. During this phase the charcoal pump is warmed up to a temperature of about 45 K. This technology is limited to temperature higher than 250 mK and therefore an additional stage is required to provide 50 mK cooling[1].

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

Heat Switches

Several heat switches are required to thermally connect and isolate the different parts of the coolers (heat sinks, evaporator to ADR). For all these heat switches, gas gap technology is used. We already designed and used such heat switches at different temperature ranges[2] with a great reliability, ease of use and efficiency (ON/OFF ratio).

DESIGN OF THE SORPTION ADR

For the one-shot 50 mK cooler, an ADR stage is connected to a sorption cooler stage through a gas-gap heat switch. In the cold phase, the ADR stage provides a stable temperature of 50 mK, while the sorption cooler provides a temperature of about 350 mK. The nominal cooling powers are 1 µW and 10 µW respectively on the ADR stage and on the sorption stage. By coupling these two different stages, we can take advantage of the low mass of the sorption cooler while reaching temperature as low as 50 mK with the ADR stage. This concept has been described by Luchier, et al.[3]

The basic idea[4] of our design is to couple an ADR stage to a sorption cooler: the sorption stage provides temperatures down to 400 – 300 mK and the ADR allows to reach 50 mK. The advantage of the sorption unit lies in its low mass: less than 500 grams for a cooler reaching 300 K from 2.5 K[5]. Unfortunately, the sorption cooler lowest temperature is limited to about 200 mK. However this cooler can be used in combination with an ADR to provide cooling down to 50 mK.

Based on requirements from the ESA contract, two heat sinks are available at 2.5 K and 15 K with respectively 10 and 100 mW of available cooling power (peak values).

Obviously the thermal architecture shall take advantage of the available cooling power at 2.5 K and 15 K. In particular during the recycling process of the sorption unit, the upper stage will remove a large fraction of the energies involved and thus allows a better management of the available cooling power at 2.5 K. Various thermal architectures have been evaluated and the selected one is shown on the sketch Figure 1. For this set architecture, several recycling schemes have been

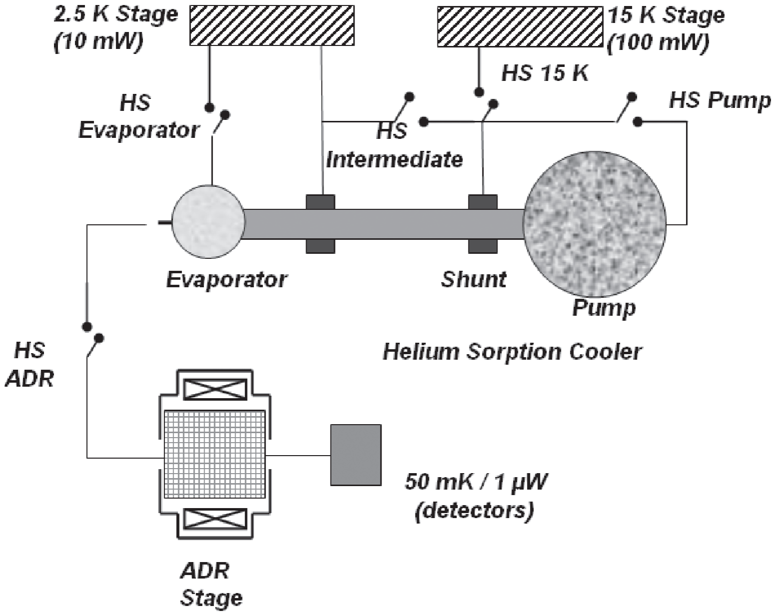

Figure 1. Sketch of the 50 mK Sorption – ADR stage

studied and are described further in this article.

ENGINEERING MODEL OF THE SORPTION-ADR

An engineering model based on the previously discussed concept has been designed and is presented in Figure 2. It features a compact design to fit in a 350 x 175 x 125 mm^3 box. The structure is thermally anchored on the 2.5 K interface, and the 15 K interface is simply connected to one end of the 15 K heat switch. To limit heat losses on the ADR stage, the salt pill support is divided in two parts, with the connecting parts thermally anchored to the sorption evaporator. On the low temperature side, a carbon tube is used to maintain the Chromium Potassium Alum (CPA) salt pills, and this rod is mechanically attached to the structure using Kevlar string. This model is now fully built (Figure 3) and will be assembled for thermal testing in 2010.

Coil, Current and Current Lead and Magnetic Shielding

The coil is designed to be used with a maximum current of 5 A. As will be shown later, this maximum current is achieved only during the recycling phase and is kept below 1 A during the cold

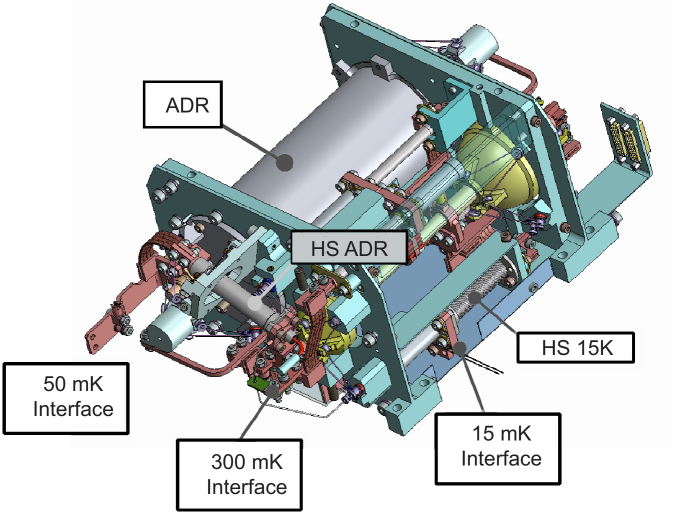

Figure 2. 3-D view of the 50 mK Sorption – ADR

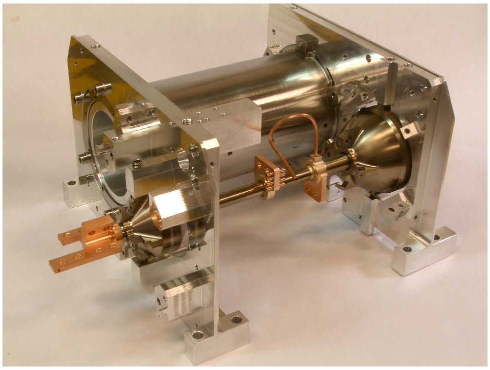

Figure 3. ADR stage and pills supporting structure

phase. The magnetic shield is made of iron cobalt, and it has been optimized to provide an efficient shielding at a low mass. The magnetic specification for the detectors is not yet known because it depends largely on the detectors technology and on the shielding at detector level which are not yet known. For our prototype, the largest magnetic field achieved during the recycling phase is less than 10 mT. However, during the cold phase of the cycle, this magnetic field is less than 0.1 mT (Figure 4). More stringent requirements can be obtained with a redesign of the magnetic shield at the cost of an increased mass. Also, the position of the detectors, with respect to the ADR stage, could be reevaluated. For this project, the detectors are imagined close to the axis of the ADR stage, which has some advantages in term of integration, but is the worst case in terms of stray magnetic field. In summary, the magnetic requirements have a strong impact on the weight of the cooler, but we believe that any reasonable requirements can be met with a small redesign that would have a low impact on the overall system.

The coil is based on a standard NbTi thin wire. Current of 5 A with such magnetic field are far from their limit. During the qualification of the coil in a helium bath, quench occurred at a current of 11 A. Nevertheless, protection using a combination of a diode and a resistor is implemented in the unlikely scenario of a quench. We worked together with the KIT (Karlsruhe Institute of Technology) to implement MgB_2 wires for the current lead between the 15 K stage and the 2.5 K. These wires have been characterized[3] and are perfectly suitable for this application (large margin in terms of critical current / temperature, low dissipation and low conduction. The soldered connections between MgB_2 and NbTi have been experimentally measure, and we expect dissipation at this interface of less than 0.1 mW at 2.5 K.

Mass Breakdown of the Engineering Model

The main advantage of the coupling between the sorption cooler and ADR is a significant gain in mass: indeed for the active components, that is excluding the support structure, the mass can be

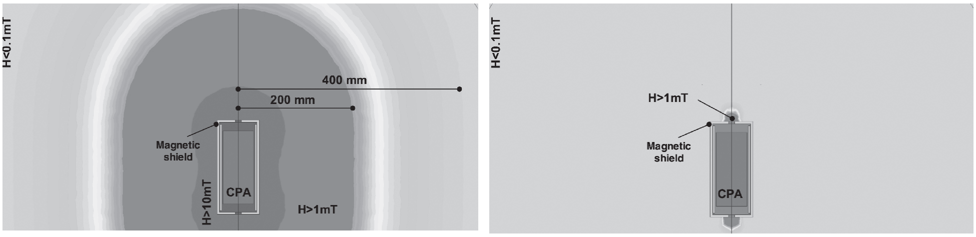

Figure 4. Simulation of magnetic field. Left at maximum field, right: at maximum field of the recycling phase.

Table 1 System Mass Breakdown

Item	Mass (g)
Sorption cooler	270
Salt (CPA) and its pill	780
ADR coil and mandrel	770
ADR shield	1620
5 heat switches	420
Straps	260
Structure	800
Cover	550
Miscellaneous (Pulleys, capstans, …)	630
Overall system (SCO + ADR)	**≈ 6100**

limited to a couple kilograms. As can be seen on the Table 1, the ADR is maintained at a relatively low mass by limiting its range of temperature between the recycling temperature and the cold temperature. Finally, the total mass of this cooler is around 6 kg.

Mechanical Analysis

Resonant frequencies of the engineering model have been calculated to verify that our prototype is able to fulfill the constraints of a typical launch environment. The resonant frequencies have been calculated using structural calculations (Figure 5), and they are all above the 100 Hz requirement, with the two lowest ones being the displacement of the salt pills (Figure 6). Due to its relatively high suspended mass, the salt pill defines the limit of the mechanical design. The resonant frequencies are high enough, and depending on the final requirements, the suspended mass could possibly drastically decrease.

CYCLING SCENARIOS

As stated in the introduction, the sorption cooler needs to be recycled before it can provide any net heat lift at 300 mK. During this recycling phase the sorption pump is heated to about 45 K and the helium is condensed in the evaporator. Similarly, for the ADR stage, it is necessary to magnetize the salt and to evacuate the associated energy on a warmer stage, here on the sorption cooler evaporator. This magnetization can be done at different timing of the recycling phase of the cooler, leading to the different cycling scenarios.

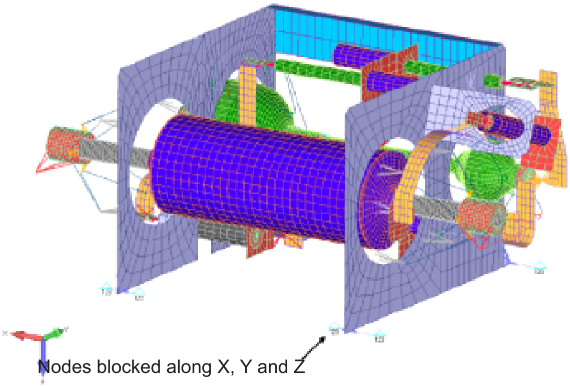

Figure 5. Mechanical Calculations

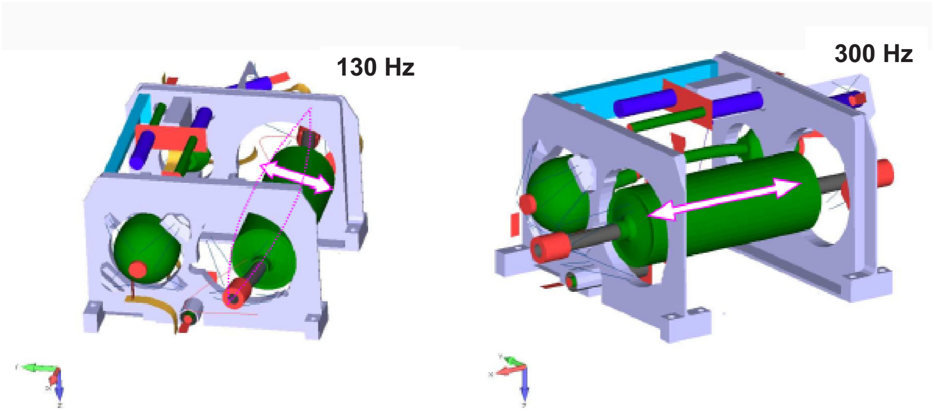

Figure 6. Two Lowest Resonant Frequencies

General Cycling Scheme

Because of the limited amount of cooling power available the heating and cool down of the sorption pump is a relatively long process[6], much longer than for what happens on the Herschel satellite for which the large superfluid helium tank allows to dump energy at a very high rate. To determine the best possible conditions and to optimize quickly the recycling parameters, it was necessary to develop a full simulation of our cooler. This simulation has been partially validated using previous laboratory experiments and will be refined after the first tests. The results obtained with our simulation with different recycling scheme are presented below. For the study presented here, we assume the cooler has already been cycled once. Indeed for the first cycle, the sequence of operation is slightly modified because of the warmer ADR initial temperature. During the subsequent cycles, the ADR stage remains below this initial temperature as discussed below.

The general cycling scheme is presented on Figure 7. Phase A corresponds to the cold phase and is designed to be longer than 24 hours. Phases B, C, D and E compose the full recycling process. The pump is first heated to 45 K (phase B) while the ^{3}He condenses in the evaporator. Then, the pump is first cooled down to 15 K (phase C) and finally to 2.5 K (phase D). The variations of the evaporator temperature are sketched in the dotted line of Figure 7. To limit the losses on the ADR during the beginning of the recycling process, the magnetic field is ramped to its maximum value at the beginning of phase B. This step is advantageous because it limits the thermal gradient and more importantly because a heat loss on the ADR at low temperature has a more important cost than a heat loss at high temperature: the entropy is proportional to the inverse of the temperature. Then, the conductive losses from the evaporator and the suspension system induce a slow increase of its temperature. During phase C, the evaporator temperature falls below the ADR temperature, and the complete recycling of the ADR can start. Different schemes are possible as described below. In all these schemes, the phase B and beginning of C are similar.

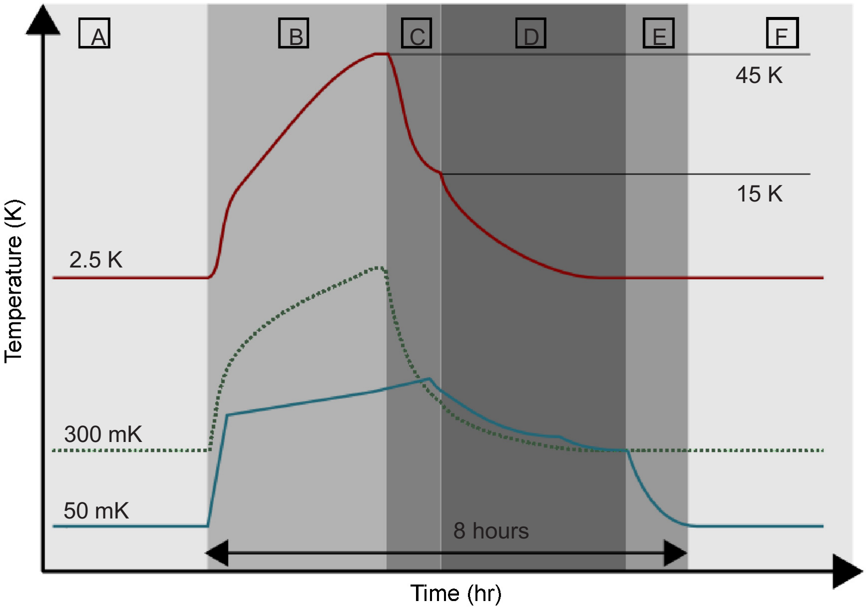

Figure 7. General Cycling Scheme

Recycling Schemes for the ADR

In a direct recycling scheme, the ADR is thermally connected to the evaporator once its temperature is above the latter. Because the ADR has been magnetized at the beginning of the cycle, it acts as a thermal load on the evaporator until it reaches an optimum temperature that we call the magnetizing temperature. At this point, the ADR heat switch is opened, and the ADR is demagnetized until it reaches 50 mK for the regulation to start. This recycling is described in Figure 8. This basic cycle is not the most efficient thermally speaking because it is more efficient to recycle the ADR, i.e., transfer energy at a lower temperature.

We propose a second cycle (C2) for which the ADR heat switch is kept open while the pump temperature falls from 45 to 15 K. During this phase, the temperature of the ADR is maintained close to the evaporator temperature by decreasing the magnetic field. This will limit heat transfer. When the pump reaches 15 K, the ADR heat switch is closed, and the magnetic field is ramped again. According to our calculation, this scenario gives an additional 2 µW of available cooling power on the sorption stage for 24 hours.

This modification can be extended further by recycling the ADR only when the pump temperature reaches 2.5 K. While the third scenario (C3) may seem to be the most efficient, it does not take advantage of the full cooling potential of the warm temperature heat sink (100 mW vs. 10 mW), thus leading to a longer recycle time. The advantage in terms of ADR efficiency is cancelled by a longer recycling period which leads to lower duty cycle efficiency.

A fourth intermediary cycle can be used. In this scenario (C4), one takes advantage of the recycling at 15 K as in the (C2) scenario, but then the ADR heat switch is opened until the pump reaches 2.5 K at which point the ADR is magnetized again. This scenario is slightly more complicated than the previous one but is more efficient and a gain of about 3 µW over the direct scenario is expected. This scenario will therefore be experimented. We expect a cooling power above 15 µW at 300 mK with more than 1 µW at 50 mK on the ADR stage. A balance between these numbers can be found depending on the real need of the mission. The expected performance is seen in Figure 9.

To summarize, we described four possible cycles, with consequences in terms of efficiency, duty cycle efficiency and recycling time. These cycles are compared in Table 2. For all these cycles, the calculation was done to obtain a nominal cooling power of 1 µW at 50 mK. The recycling time is indicated, but these numbers are approximate as some parameters, including notably the time for switching from one phase to the other are not known with a sufficient precision. The most attractive one seems to be the (C4) scheme because of the highest thermal performances expected. The pre-

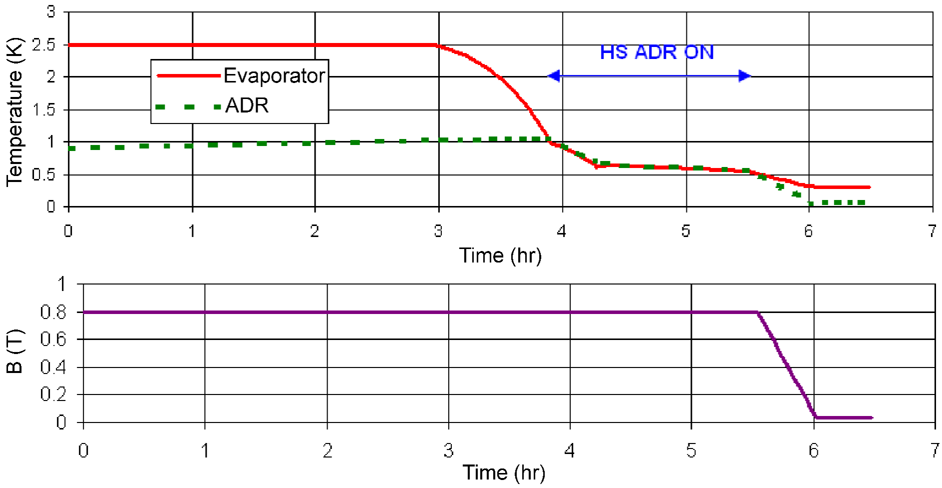

Figure 8. Simulated Recycling Plots in the 'Direct' Scenario

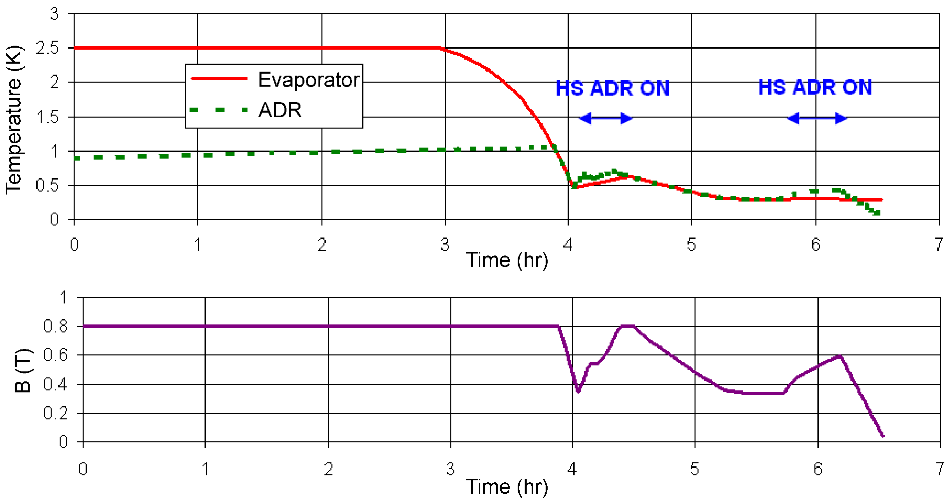

Figure 9. Simulated Recycling Plots in the C4 scenario

Table 2 Comparison of the Different Cycles with Calculated Available Cooling Power

	Direct	C2	C3	C4
Expected cooling power at 300 mK (24 hours)	14 µW	16 µW	20 µW	17 µW
Expected cooling power at 50 mK (24 hours)	1.1 µW	1.1 µW	1.1 µW	1.1 µW
Calculated recycling time	7:30	7:30	9:20	7:40

dicted autonomy of the sorption cooler exceeds the specifications of 10 µW. The cycle will be refined to reach an optimum between the sorption and the ADR autonomy.

CONCLUSION

A light cooler providing 1 µW of cooling power at 50 mK and 10 µW at 350 mK with a cold source at 2.5 and 15 K has been designed. It is expected to provide a cold phase over 24 hours with less than 8 hours recycling time. A special focus has been put on the cycle phase to improve the overall efficiency. An engineering model has been designed and built and mechanical simulations show no resonant frequencies below 120 Hz. Thermal simulations of different recycling schemes have been done, and a C4 scheme has been chosen to be implemented for the thermal tests planned in the coming months. Based on the first experimental results and on the refinement of the specifications, our design will be adapted to provide the best thermal performances with the lowest mass.

ACKNOWLEDGMENT

Part of this work is now supported by ESA/ESTEC n^{0} 21226/07/NL/EM 50 mK continuous cooling.

This project greatly benefited of the experimental skills of Jean-Louis Durand, the expertise in mechanical calculation of Eric Ercolani and the great design work of Laurent Guillemet. We wish to thank them all.

Thanks to Guillaume Donnier-Valentin and Philippe Camus of Institut Néel for providing coils and for the discussion on the design, and to Sonja Schlachter and Wilfried Goldacker of KIT for their work on MgB2 wires.

REFERENCES

1 Duval, J.M., Luchier, N., Duband, L., and Sirbi, A. “50 mK Continuous Cooling with ADRs coupled to Helium-3 Sorption Cooler,” *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp 505-512.

2. Duband, L., “A thermal switch for use at liquid helium temperature in space borne cryogenic systems,” *Cryocoolers 8*, Plenum Press, New York (1995), pp. 731-741.

3. Luchier, N., Duval, J.M., Duband, L., Camus, P., Donnier-Valentin, G., Linder, M., “50 mK cooling solution with an ADR precooled by a sorption cooler," *Cryogenics*, Vol. 50, Issue: 9, September 2010, pp. 591-596.

4. Luchier, N., and Duband, L. “Small Adiabatic Demagnetization Refrigerator for Space Missions,” *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), pp. 561-566.

5. Duband, et al., “HERSCHEL Sorption Cooler Qualification Models,” *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), pp. 543-551.

6. Duband, L., Duval, J.M., Luchier, N., and D’Escrivan, S. “SPICA/SAFARI Subkelvin Chain,” *Cryocoolers 16*, ICC Press, Boulder, CO (2011), (this proceedings).