# 50 mK Continuous Cooling with ADRs Coupled to $^3$Helium Sorption Cooler

**J.M. Duval[1], N. Luchier[1], L. Duband[1], A. Sirbi[2]**

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

## ABSTRACT

CEA/SBT has well established knowledge and recognized experience in sorption coolers reaching 200 to 300 mK. Combining sorption cooler developments with adiabatic demagnetization refrigerators creates the possibility to reaching temperatures below 50 mK with a limited mass budget (less than 5 kg for a 1 µW cooler). In the framework of an ESA contract we are developing such a cooler for continuous cooling at 50 mK based on this technology. The cycle chosen is described and discussed. Mass and efficiency optimization is being done and a trade-off is presented. Experimental results on a one-shot cooling system reaching a temperature of 30 mK are also shown.

## INTRODUCTION

Cooling below 100 mK is a necessity for future space science missions where detectors sensitivity is an issue. For example, instruments designed for the XEUS[1] mission or for the SPICA[2] mission require a temperature close to 50 mK. Adiabatic demagnetization refrigerators (ADR) can fulfill such requirements in a space environment. Indeed, ADR has the potential to cool efficiently from more than 4 K to less than 50 mK.[3] However, an important aspect of ADRs is that the higher the base temperature, the larger the magnetic system has to be (see Figure 1).

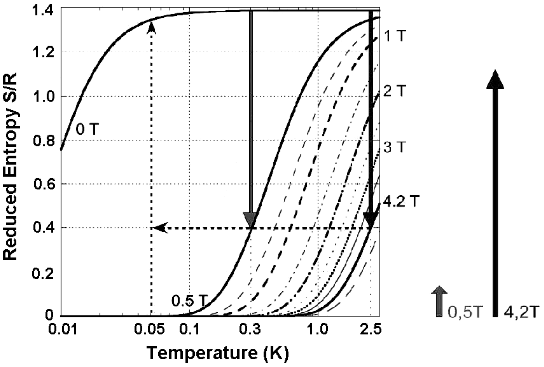


**Figure 1.** Entropy as a function of temperature and magnetic field.

*Cryocoolers 15*, edited by S.D. Miller and R.G. Ross, Jr.

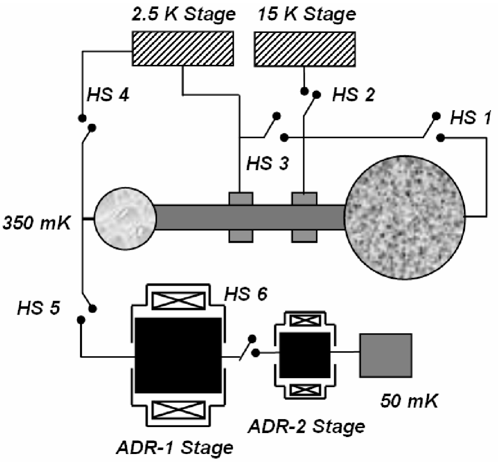


**Figure 2.** Sketch of the proposed solution for 50 mK continuous cooling.

The basic idea[4] of our design is to couple a continuous double-stage ADR to a sorption cooler: the sorption stage provides temperatures down to 400 – 300 mK, and the ADR allows 50 mK to be reached. The advantage of the sorption fridge lies in its low mass: less than 1 kg for a cooler reaching 300 mK, from 2.5 K.[5] Unfortunately, the sorption cooler's lowest temperature is limited to about 220 mK. However this cooler can be used in combination with an ADR to provide cooling down to 50 mK. In our design, continuous cooling is made possible by the use of the last stage ADR acting as a thermal buffer during the cycling of the previous stage as is described below.

Following the general architecture proposed for the missions mentioned above, we are assuming that at least two heat sink temperatures are available (2.5 K and 15 K). Obviously the thermal architecture will 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 allow 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 in Figure 2. We emphasize here that this architecture is selected based on the limited cooling power available at 2.5 K. If this cooling power was significantly increased, the number of heat switches could be reduced.

## DESIGN OF THE SORPTION ADR

### Advantages in Mass and Field

The main advantage of the coupling between the sorption cooler and ADRs is a significant reduction in mass: indeed for the active components, that is excluding the support structure, the mass can be limited to a couple of kilograms. Obviously the mass is further reduced when taking into account the structure: a lighter component to be mechanically held certainly requires a lighter support structure.

A second advantage of the combind cooler approach is related to the fields required for the ADR: the autonomy at low temperature is directly linked to the entropy difference between the maximum magnetic field and the zero field states as shown in the Figure1. The higher the magnetization temperature (heat sink) is, the higher the magnetic field needed for a given autonomy for a given salt quantity. This is demonstrated in Figure 1 for two heat sink temperatures, 2.5 K and 0.3 K; indeed the require field drops from 4.2 Tesla to 0.5 Tesla (this value is only used for illustration purpose). Apart from the need for heavy coil(s), a high magnetic field can impact the detectors or any sensitive elements. They must be shielded and again at the cost of additional mass.

Our design is represented in Figure 2. The helium 3 sorption cooler can be connected via heat switch 1, 2, 3 and 4 to the 2.5 K heat sink or the 15 K heat sink. By closing heat switch 5, the salt pills CPA1 can be in thermal connection to the cooler, or in contrary, thermally isolated. The pill of the ADR2-stage is kept at the constant nominal temperature of the cooler. Heat switch 6 is closed once ADR1-stage drops below 50 mK, at which point it is used to recycle ADR-2.

### Heat switches

The study of the efficiency of the coolers shows that it is directly related to the performance of the heat switches. Indeed, if a single stage ADR is close to the Carnot efficiency, the efficiency of a chain of cascaded ADRs depends mostly on the performance of the switches used: the inefficiencies of the ADR cycle come from the heat flowing through the heat switches in their off position and also from the temperature difference when the switches are in their on position.

For temperatures above 300 mK, gas gap heat switches have been extensively studied at CEA/SBT,[6] and their reliability has been demonstrated during the qualification phase for the Herschel and Planck programs. Gas gap heat switches are limited to temperatures above 200 mK, because the liquefaction of helium 3 at these temperature makes them unsuitable. For temperatures below 200 mK, the most commonly used heat switches are magnetoresistive or superconducting switches. Superconducting ones require much lower magnetic field (typically 50 mT compare to 2 to 3 T for the magnetoresistives). Our focus is therefore on superconducting switches, which are proven techologies.[7,8,9]

### Asymetric Cycle ADR

Details of the proposed cycle are represented in Figure 3. The sorption cooler is used to cycle the first stage ADR (ADR1) which in turn is used to cycle ADR2. A major contribution the first stage ADR (ADR1) has to deal with is the thermal load due to the heat switch (HS5) operating between the sorption cooler evaporator and ADR1. Typically, the heat flow through our gas gap heat switch in the off state between 2.5 K and 50 mK is on the order of 8 μW. This number does not vary much with the cold temperature. The cost associated in terms of efficiency is linked to the entropy creation, which is proportional to the inverse of the cold temperature. To limit this contribution we propose an asymmetrical timing approach in which this heat switch never operates between 2.5 K and 50 mK. In this approach, ADR1 is used as a heat intercept between the 2.5 K and the 50 mK stage during the sorption fridge recycling (phase A). The temperature of the ADR1 in this heat intercept position can be optimized to increase the efficiency of the overall cooler and is typically

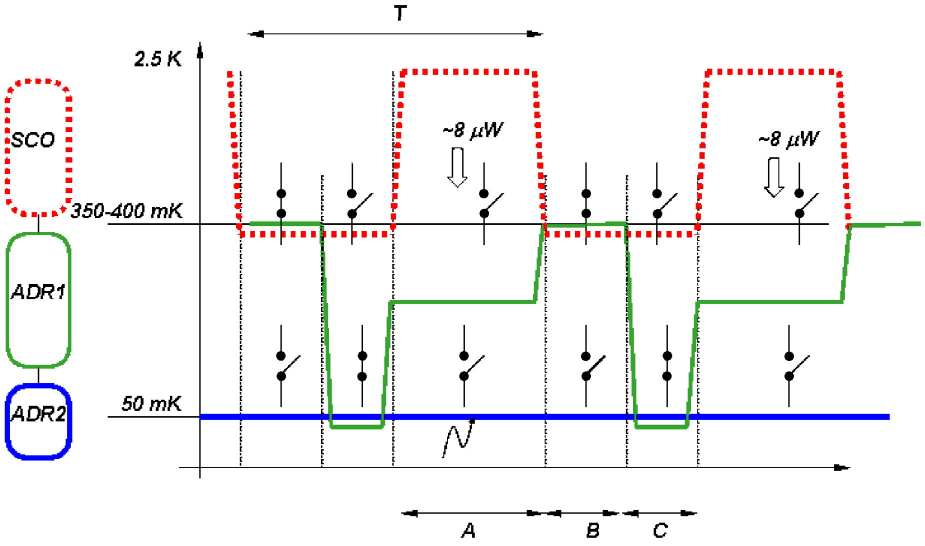


**Figure 3.** Sketch of the temperature variations of the sorption cooler evaporator (SCO), the first and second stage ADR (ADR1 and ADR2) during the designed cycle.

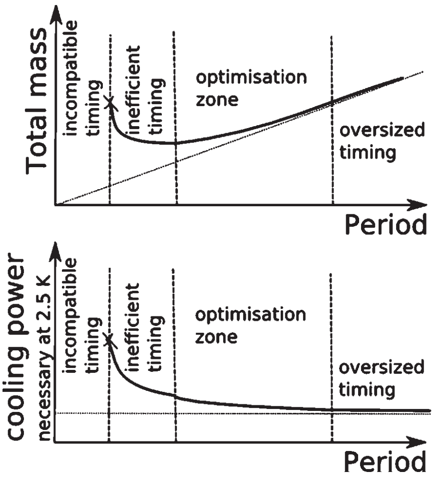


**Figure 4.** Design of a 50 mK continuous cooler. Mass and cooling power required at 2.5 K as function of total period. The full and real optimisation of the cycle is an iterative procedure, during which the reasoning presented above and results of experiments has to be taken into account.

on the order of 250 mK. During phase B, ADR1 is recycled using the sorption cooler evaporator as a cold source. The temperature of the helium 3 cooler is maintained at 350 mK while ADR1 is cold and recycling ADR2 (phase C).

On the 50 mK stage side, ADR2 provides the nominal cooling power during phase A and B. After this time, the first stage ADR (ADR1) takes over (phase C). ADR1 is sized to deal with the gross cooling power during phase C plus the energy needed to recycle ADR2 and the parasitic coming from the heat switch HS 5.

### Size, Cycle Time and Efficiency

In the above paragraph, the management of the temperature of each stage during the cycle has been discussed. Other parameters to optimize are the relative durations of each period — A, B and C — and the total period of the cycle.

For a given period, the optimization of the respective time of each phase should maximize the efficiency of the cooler. As an approximation, the duration of phase A is approximately a half of the total period, while the phase B and C are about a quarter of it. Refining these numbers will be done when precise numbers for heat switch performance and heat losses through the supporting structure are available.

The total period is a parameter which influences both the total mass and the efficiency of the system as seen on the plot of Figure 4. This diagram is for discussion purposes only. For a too short cycling period, the time for turning off the switches or for ramping the magnet would be so short that the energy dissipation would be excessive and would lead to an inefficient design. For a more reasonable cycling period, increasing this period leads to an increase in the mass and volume of the cooler. A compromise needs to be made between efficiency and mass. Unfortunately, the efficiency of the cooler cannot be increased indefinitely. For an infinitely long cycle, the efficiency will still be limited by the finite heat switch conductivity and by the efficiency of the helium 3 cooler, which is notably limited by the exothermal process of the adsorption. The designer has to choose the best trade-off between these two criteria.

In our preliminary design, a total period duration of 6 hours has been chosen. The designed prototype fulfils mass and efficiency requirements. This period may be optimized during the validation and the benchmarking of the full set-up. The design has not been finalized.

**Table 1.** Breakdown of masses for the whole system.

| Item | Mass (g) |
|---|---|
| Sorption cooler | 800 |
| ADR1 system | ~2550 |
| ADR2 system | ~600 |
| Heat switches (x2) | ≈150 |
| Support brackets | ≈300 |
| **Overall system (SCO + ADR)** | **≈4400** |

### Mass and Design

In Table 1, the estimated masses are summarized for a continuous cooler operating between 2.5 K and 50 mK and with an additional heat sink at 15 K. They have been calculated from estimation of energies exchanged and salt quantities and magnetic fields for the ADR.

The sorption cooler is sized based on the Herschel heritage.[5] Additional thermal connections through heat switches are used to take advantage of the 15 K heat sink. The sizing of the ADR is made based on a total period of 6 hours. The coils have been designed assuming a maximum current of less than 5 amps. The magnetic design has been made in order to have a magnetic field lower than 0.1 mT at the detector position (25 cm from the coil center). Additional shielding could be applied using cryoperm or a superconducting shield near the detector to reduce the magnetic field by several orders of magnitude. The mass estimate for the prototype is compiled in Table 1.

## OTHER POSSIBLE DESIGNS

### Intermediary Temperature Stage

For other detectors or instrument designs, an intermediate stable temperature between 300 mK and 1.0 K may be required. This stable temperature can be advantageously used to stabilize the temperature of the detectors, to heat sink the numerous wires, or to cool some additional electronics. This intermediate stage could be obtained with the addition of a partly independent ADR stage[10] or with the addition of an ADR stage and a heat switch as shown in Figure 5. The disadvantages in terms of complexity and additional mass have to be balanced by the gain in efficiency and the availability of this cold source. With this design, the asymmetric cycle may not be useful and a more classical cycle can be used.

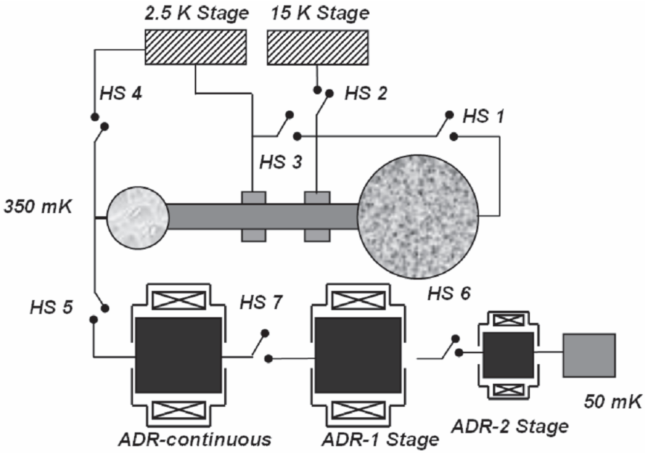
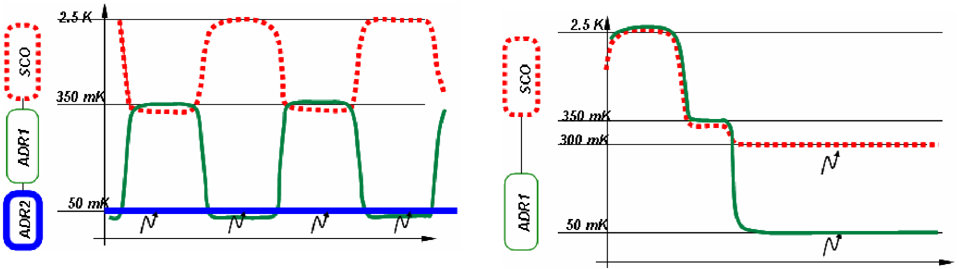


**Figure 5.** Diagram of a solution with continuous cooling at 300 mK.



(a) (b)

**Figure 6.** Schematic comparison of: (a) continuous cooler, and (b) one-shot cooler.

### Continuous and One-Shot Cooling

This paper mainly focuses on the description of a cryogenic cycle able to provide continuous cooling at 50 mK. We want to point out that a one-shot system (Figure 6) based on the same architecture (SCO + ADR) can also be a solution to fulfil many cryogenic needs at 50 mK. The low mass and low magnetic field advantage of our coupled ADR solution is still valid for a one-shot solution.

The paradox with the continuous system is that when we think of a cooler operating at 50 mK continuously, we tend to associate this feature with temperature stability. This is certainly true for the 50 mK stage, but not for the upper stages which are permanently recycled and shuttled back and forth between various temperatures. On the contrary, for the single-shot system, the thermal environment is disturbed during the recycling process, but once the ultimate temperatures are reached, all temperatures settle down. Also, the benefit of the single-shot system is that an intermediate temperature could be provided by the sorption cooler. Indeed the first stage can be sized to recycle the second stage and still hold enough “cold joules” to provide additional cooling power at this intermediate temperature. Finally, the one-shot system is also simpler from a technical point-of-view (no need for the superconducting switches and for one of the ADR stages).

We showed previously that one advantage of the continuous solution is the minimization, possible to a certain extend, of the mass of the system by reducing the cycling period. The sizing of the one-shot cooling depends directly on the duration of the cycle. As long as the required autonomy and/or heat load remains reasonable, the difference in term of mass between the one shot and continuous system for the hybrid solution is not significant. Concerning the need in terms of cooling power at 2.5 K, it depends mostly on the duty cycle required in the case of a one-shot cooler.

## EXPERIMENTAL RESULTS

Our preliminary experiments are geared toward the demonstration of the feasibility of the continuous 50 mK cooler. The sorption cooler and gas gap switches are mature technologies and have already been demonstrated and qualified, notably for the Herschel coolers. Our focus is therefore on the ADR and on the superconducting heat switches. The experiments presented here demonstrate the adequate design of the first-stage ADR, and as a side result, the feasibility of the one-shot cooler. We expect that the second-stage ADR should not raise any problem considering its similarity with the first stage.

For our preliminary test, a double stage helium cooler[11], which was available in our lab, has been used. The ADR stage was magnetized by a large laboratory magnet able to produce the magnetic field desired (up to 0.8 T). The paramagnetic stage is a 70 $cm^3$ CPA pills grown on copper wires as has been described by Timbie et al.[12]

The focus of the experiment was to demonstrate the feasibility of a pill being recycled at 300 mK by a sorption cooler and then providing a sufficient cooling power at 45 mK. A typical cooldown is shown in Figure 7. The salt pill has first been magnetized to 1.2 T and its temperature stabilized at 320 mK. The salt pill has then been demagnetized to about 0.1 T, and then a simple PID algorithm

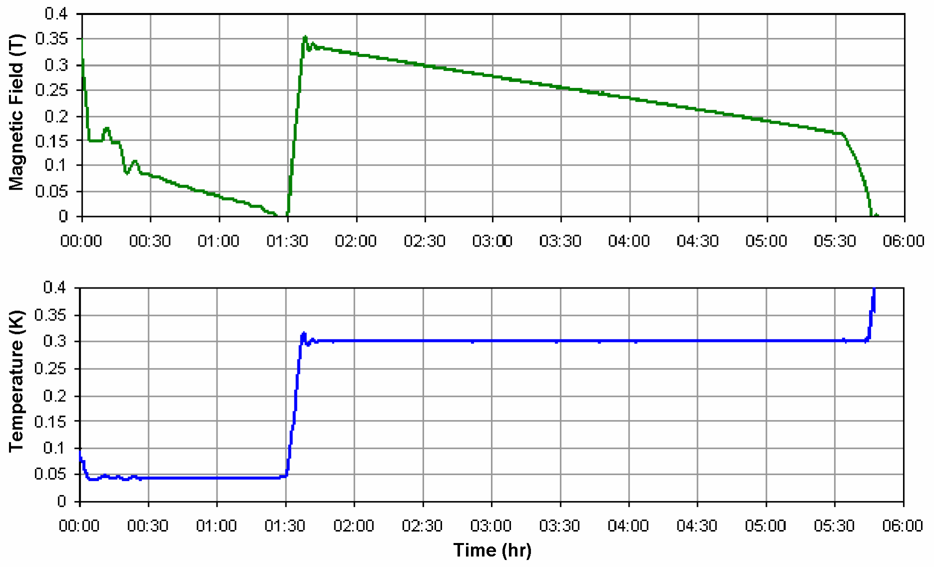


**Figure 7.** 80 minutes temperature regulation at 45 mK with 5 μW applied load followed by a regulation at 300 mK with a 6 μW applied load. Regulation stopped because of external parameters.

has been used to maintain a 45 mK temperature while a cooling power of 5 μW was applied. After this phase, the magnetic field was increased to 0.33 T so that the pills temperature reached 300 mK where the temperature was regulated for more than 8 hours with an applied load of 8 μW. The magnetic field was still at more than 0.15 T and the regulation could have lasted longer. The demonstration of the cycle of the first ADR was therefore achieved.

In another experiment, the magnet was demagnetized fully to 0.0 T and a temperature of 20 mK was measured. Considering the PID control, the results shown are from our initial work and many parameters can be adjusted to improve temperature stability.

Measurements on the heat link between the copper thermal bus and the salt have been made using a heater, and a temperature gradient on the order of 1 mW/K was measured at a temperature of 50 mK. In fact during the regulation, the pills temperature was about 40 mK while the measured temperature was 45 mK.

Thus, operation of a single-shot ADR coupled to a sorption cooler has been demonstrated. This system will now be used as the upper stage for the 50 mK salt pill.

## CONCLUSION

A light weight cooler providing continuous cooling at 50 mK with a cold source at 2.5 and 15 K has been designed. A special focus has been put on the cycle phase to improve the overall efficiency. Experimentally, the first stage, including a helium 3 sorption fridge and a one-stage ADR has been tested and provides enough cooling power below 50 mK to give us confidence in our design and to be able to propose a one-shot 50 mK cooler. A coldest temperature of 20 mK has been measured. Our work will now focus on the superconducting heat switches and on the assembly of the different components.

## ACKNOWLEDGMENT

Part of this work is now supported by ESA/ESTEC n$^0$ 21226/07/NL/EM 50 mK continuous cooling. We wish to thank Jean-Louis Durand for the experimental work and he expertise in the design and setup. Thanks also to Guillaume Donnier-Valentin and Philippe Camus of Institut Néel for providing coils and for the discussion on the design.

## REFERENCES

1 Perkinson, M. et al., "XEUS Payload Accommodation Challenges and Trade-offs," *36th COSPAR Scientific Assembly* (2004), p. 249.

2. Griffin, D.K. et al., "Thermal design of the SPICA/ESI instrument," *Proceedings of SPIE*, vol. 6275 (2006), p. 6275.

3. Shirron, P.J. et al., "A Multi-Stage Continuous-Duty Adiabatic Demagnetization Refrigerator," *Adv. in Cryogenic Engineering*, Vol. 45B, Kluwer Academic/Plenum Publishers, New York (2000), pp. 1629-1638.

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. "A Thermal Switch for Use at Liquid Helium Temperature in Space Borne Cryogenic Systems," *Cryocoolers 8*, Plenum Press, New York (1995), pp. 731-741.

7. Bunkov, Y.M., 1989. "Superconducting Aluminum Heat Switch Prepared by Diffusion Welding," *Cryogenics*, 20(9) (1989), pp. 938-939.

8. Ho, P.C. and Hallock, R.B., "A Compact Design for an Indium Heat Switch," *Journal of Low Temperature Physics*, 121(5) (2000), pp.797-802.

9. Schuberth, E., "Superconducting Heat Switch of Simple Design," *Review of Scientific Instruments*, 55 (1984), pp. 1486-1488.

10. Shirron, P.J., "Development of a Cryogen-Free ADR for the Constellation-X Program," *Cryogenics*' 44 (2004), pp. 581–588.

11. Duband, L. "Double Stage Helium Sorption Coolers," *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 561-566.

12. Timbie, P.T., Bernstein, G.M. and Richards, P.L., "Development of an Adiabatic Demagnetization Refrigerator for SIRTF," *Cryogenics*, vol. 30 (1990), pp. 271-275.