5-Stage Continuous ADR for Future X-Ray Missions

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1.1 Introduction

There are two main challenges that are common to the majority of future X-Ray missions: 1) the need to cool detectors to low operating temperature (in the 50 millikelvin range) and the relatively large heat load they dissipate (2-5 microwatts), and 2) the need to reject heat from the low temperature cooler to a cryocooler operating in the 4-5 K range. The challenge arises from the fact that most low temperature coolers, including adiabatic demagnetization refrigerators (ADR) and sorption refrigerators, are inherently single-shot systems. That is, they produce cooling for a period of time (the "hold time"), and are then "recycled". Recycling involves warming the coolers to the heat sink temperature of 4-5 K and offloading heat. Because recycling disrupts science observations, it must be conducted quickly (~1 hour), while the hold time must be much longer (~1 day). This requires the cooler to store heat for a long period of time and reject it quickly. In other words, for a reasonably sized cooler, the amount of heat it can absorb during the hold time is very limited (1-2 microwatts of detector heat load is a practical limit), and the peak heat reject rate is high (>40 mW, depending on the cooler's efficiency).

Scaling existing coolers to meet the hold time and cooling power requirements for future X-Ray missions results in relatively large masses (20-30 kg), and long recycle times when their heat rejection rates are limited to the capability of existing cryocoolers which are used as heat sinks. Instead, **we propose the use of a continuous ADR (CADR) for future missions**. The CADR is a proven cooler concept that provides continuous cooling at very low temperature and eliminates the need for a hold time requirement. By operating on a short cycle period, it achieves 1-2 orders of magnitude higher cooling power per unit mass and low heat reject rates. **It has demonstrated 5-6 microwatts of cooling power at 50 mK, and peak heat reject rates of less than 10 mW at 4.5 K.** This technology is enabling for instruments with large format detector arrays – such as the X-ray Microcalorimeter Spectrometer (XMS) planned for the European Athena mission – where lead conduction constitutes the majority of heat dissipation at low temperature, and provides the highest possible observing efficiency (100%) of any cooler.

A 4-stage CADR has being built and tested at NASA/Goddard Space Flight Center that has the performance cited above. Its mass is <8 kg. Extensive testing over the last 10 years, and recent flight qualification testing of a related 3-stage ADR for Astro-H has raised the CADR's TRL to 6.

For future missions, an additional stable temperature at 1 K or less is needed as an intermediate heat sink for the detector wiring and/or detector amplifiers, so a 5-stage CADR is proposed, as shown schematically in Figure 1.2-5. **A 5-stage CADR will have the capability of continuous cooling at 50 mK and 1 K, and of meeting the cooling requirements of all currently conceived X-ray missions.**

1.2 ADR Configuration and Requirements

1.2.1 4-stage CADR Prototype

The 4-stage CADR that forms the basis for the 5-stage version is shown schematically in Figure 1.2-1 and as-built in Figure 1.2-2. This unit has been extensively tested with a liquid helium heat sink at 4.2 K, and with a simulated cryocooler interface at 4.5 K.

Each stage in the chain is constructed in the same manner as conventional single-shot ADR stages: a "salt pill" containing a solid magnetic refrigerant is located in the bore of a superconducting magnet, and connected to a heat sink by a heat switch. Not shown are low conductance suspension assemblies that physically support, but thermally isolate, the salt pill from the magnet.

Based on the magnetocaloric effect, increasing the magnet's field will warm the salt pill or give off heat; while decreasing the magnetic field causes the salt pill to cool or absorb heat. Whether the salt pill warms or gives off heat is determined by whether the salt is thermally isolated (i.e. adiabatic) or thermally linked to a heat sink, which is controlled by the heat switches. The coordinated action of magnetization and demagnetization with appropriate heat switch closing and opening drives a 4-step process in which 1) the salt is magnetized and warms to its upper temperature, 2) the heat switch is closed and further magnetization causes the salt pill to generate heat which flows to the heat sink, 3) after opening the heat switch, the salt pill is demagnetized and cooled to its lower temperature, and 4) the salt pill is demagnetized as it absorbs heat from some load. After the magnet reaches zero current, this process repeats. In short, this process involves absorbing heat at low temperature and rejecting heat at high temperature.

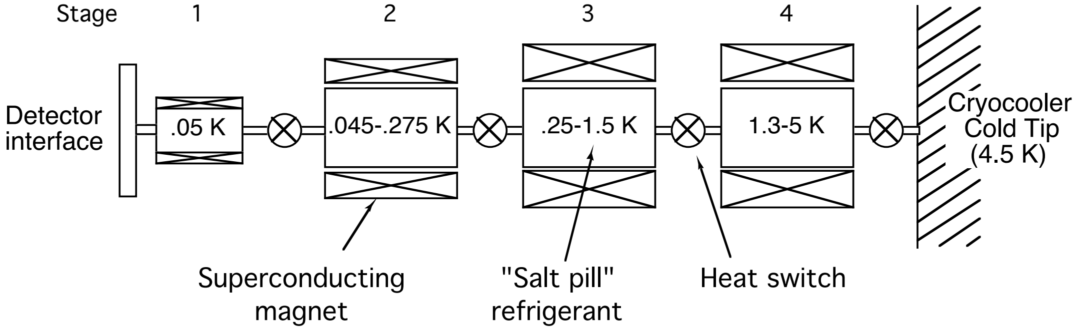

Figure 1.2-1. Schematic of the 4-stage CADR.

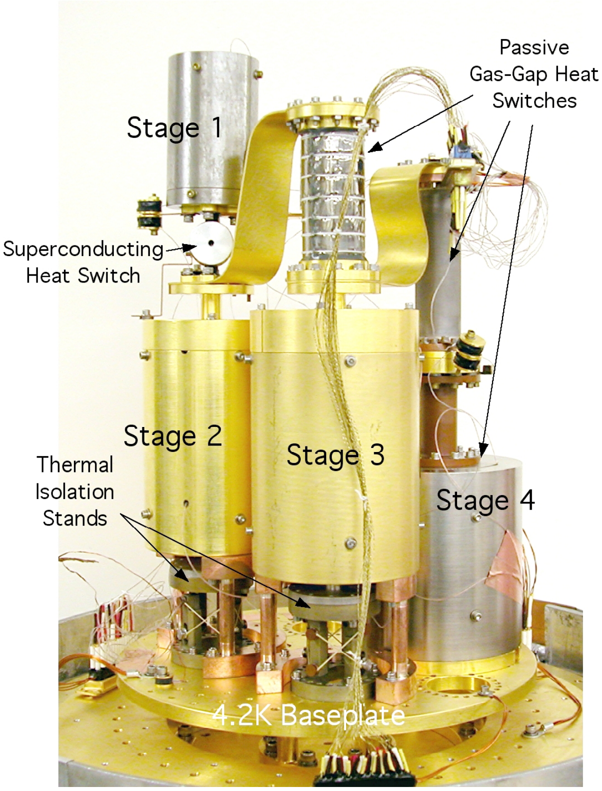

Figure 1.2-2. Prototype 4-stage CADR.

The CADR uses this process with 1 or more upper stages to repetitively offload heat from a "continuous" stage (stage 1 in Figure 1.2-1), and cascade it to a warm heat sink. Stage 1 continuously absorbs heat from the detector system, and periodically transfers it to the 2nd stage when the 2nd stage is at the low end of its range. That heat is transferred stepwise up through the ADR chain as described above. Figure 1.2-3 shows the temperatures of the 4-stages of the CADR as it produces continuous cooling at 50 mK and rejects heat to a 4.5 K heat sink.

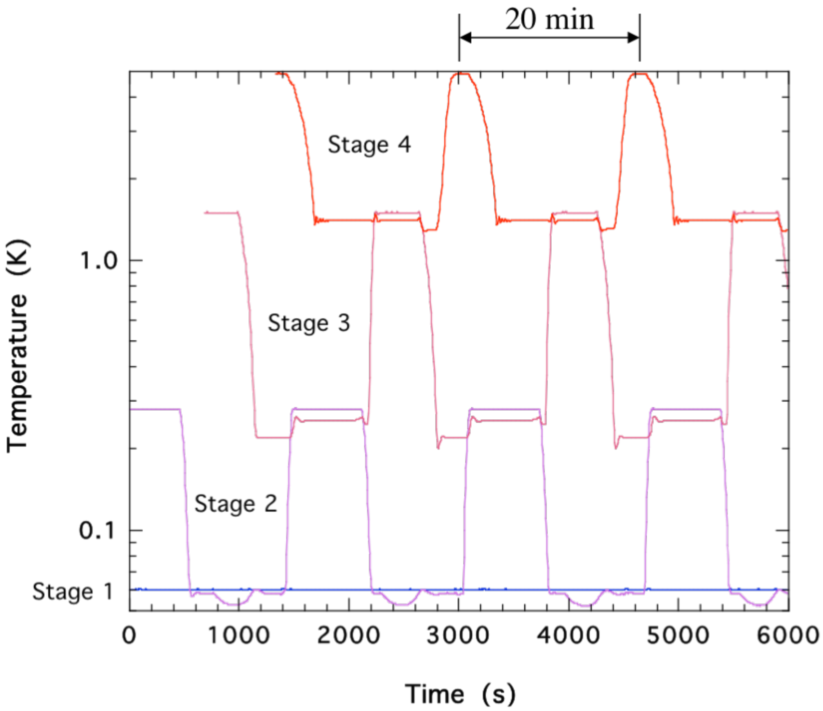

Figure 1.2-3. Temperatures during operation of the 4-stage CADR.

The advantages of continuous operation are that detector operations are never interrupted, eliminating the need for a hold time requirement. Instead, the recycling interval for the ADR is dictated by internal design parameters such as heat switch conductances and salt pill heat capacities, and external parameters such as the cooling power of the cryocooler. In practice, the cycle period is about 20 minutes. The mass of refrigerant for each stage is dictated by the time interval over which it must absorb heat and the heat load. Reducing the interval reduces the mass of refrigerant required, or increases the amount of heat that can be absorbed.

Another important benefit is that internal parasitic heat loads are much more efficiently absorbed, enabling the CADR to achieve significantly higher thermodynamic efficiency. This directly translates to lower time average heat rejection, and reduced power requirements for the cryocooler.

While the CADR requires more stages than a conventional ADR spanning the same temperature range, its stages are significantly smaller. Equally important, the magnetic field needed by each stage scales with its operating temperature range. The relatively small salt pill masses and low fields significantly reduces the size and mass of the magnets and magnetic shields. Since the stages closest to the detectors use the lowest fields, it is possible to meet the stringent magnetic fields requirements of detector systems like those on IXO/XMS with very modest shield masses.

Table 1.2-1 Summarizes the design of the 4-stage CADR. These masses include magnetic shields that achieve basic attenuation of internal fields as needed to prevent undesirable interactions between stages.

Table 1.2-1 – 4-stage CADR design summary.

Stage	Refrigerant mass	Temperature range	Magnetic field	Stage mass
1	40 g of CPA	50 mK	0.2 T	0.5 kg
2	100 g of CPA	45 mK to 0.275 K	0.5 T	1.7 kg
3	100 g of CPA	0.25 K to 1.35 K	1.5 T	2.4 kg
4	70 g of GLF	1.2 K to 5 K	4 T	3.1 kg
			Total	7.7 kg

The 4-stage CADR has already demonstrated cooling powers well in excess of the IXO/XMS cooling requirement. As seen in Figure 1.2-4, the CADR has achieved continuous cooling of 6 μW at 50 mK, and temperatures as low as 35 mK. The proposed 5-stage CADR for IXO will actually improve this capability, through the addition of a constant temperature stage, by reducing parasitic heat loads and allowing more rapid cycling of the cold stages.

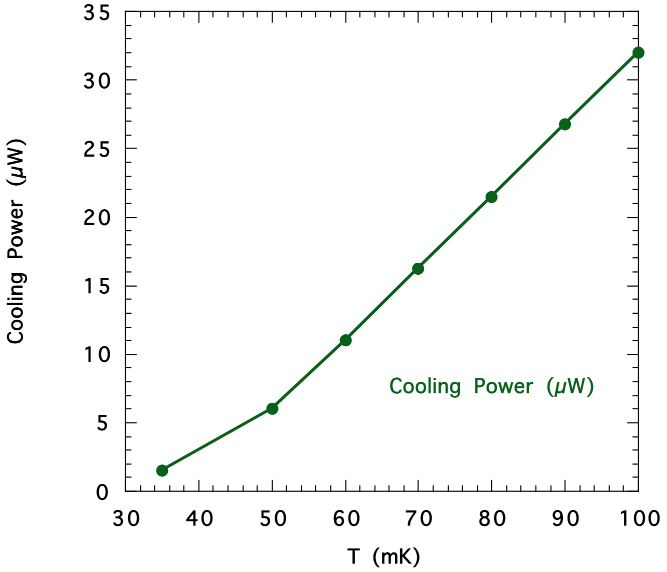

Figure 1.2-4. Temperatures during operation of the 4-stage CADR.

1.2.2 5-stage CADR for Future X-Rzy Missions

Figure 1.2-5 shows the proposed configuration for a CADR that can provide continuous cooling at 50 mK and 1 K.

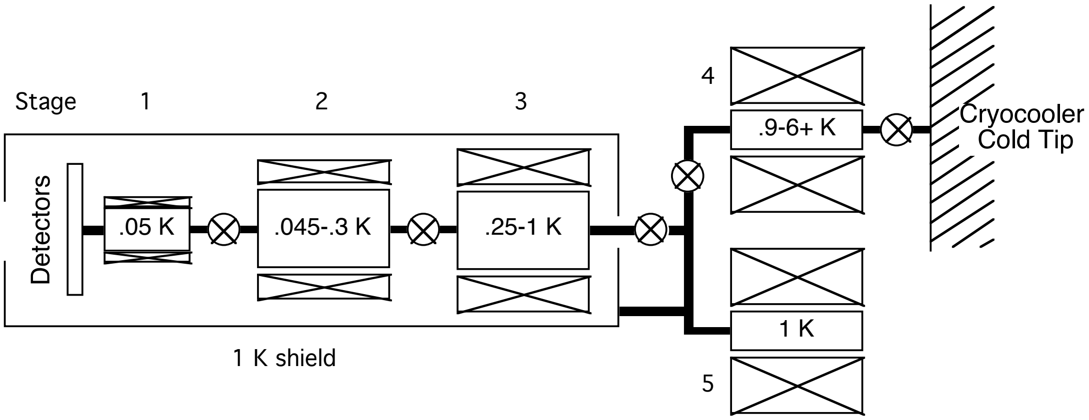

Figure 1.2-5. Schematic of the 5-stage CADR.

The added 5th stage will regulate the temperature of a shield surrounding the colder ADR stages and the detector assembly at 1 K. It will also act as a constant temperature heat sink for the chain of 3 stages that cool continuously at 50 mK. The 4th stage operates only to transfer heat accumulated by the 5th stage to the heat sink.

In this configuration, the 3-stage chain operates asynchronously from cycling of the 4th stage. This allows both to cycle at optimal rates to meet the cooling power requirements and peak heat loads limits to the cryocooler. In the 4-stage prototype, the 4th stage could be recycled more rapidly that the lower 3 stages. Synchronizing their operation constrained the heat dumps to the heat sink to be less frequent, and to involve higher peak and lower time-average heat rejection. Decoupling the recycling operations will allow the 4th stage to cycle more rapidly, thereby generating higher cooling power at 1 K and lower peak heat reject rates.

This configuration also allows the 3-stage chain to reject heat to a lower temperature (1 K vs 1.2 K) and to be thermally stationed off 1 K, instead of 4.5 K. This will reduce the magnetic field and shielding requirements for the 3rd stage, and significantly lower the parasitic and radiative heat loads to the cold stages. These two factors will increase the usable cooling power of the 1st stage by about 1 μW, and produce a modest mass reduction of about 0.3 kg.

The design of the 5-stage CADR is summarized in Table 1.2-2 and expected performance are summarized in Table 1.2-3. The latter includes a comparison of performance with the current requirements for the XMS instrument should it be included on Athena. Note that the cooling power of the 1 K stage is two orders of magnitude larger than the projected heat loads from detector wiring. This might seem to imply that the 5th stage is overdesigned, but in reality the 5th stage must be sized to absorb the full entropy capacity of the 3rd stage, which greatly exceeds the amount of heat absorbed from detector wiring. If excess margin is evident after final optimization of the detector and CADR systems, either the mass of stage 5 can be reduced, or, more beneficial, stage 5 can be regulated at a lower temperature to reduce the detector load at 50 mK.

Table 1.2-2 – 5-stage IXO/XMS CADR design summary.

Stage	Refrigerant mass	Temperature range	Magnetic field	Stage mass
1	40 g of CPA	50 mK	0.2 T	0.5 kg
2	100 g of CPA	45 mK to 0.275 K	0.4 T	1.5 kg
3	100 g of CPA	0.25 K to 1.35 K	1.0 T	2.1 kg
4	70 g of GLF	1.2 K to 5 K	4 T	3.1 kg
5	70 g of GLF	1 K	1.5 T	2.3 kg
			Total	9.5 kg

Table 1.2-3 – IXO/XMS Requirements and expected performance of the 5-stage CADR.

Parameter	Athena (formerly IXO) /XMS Requirement	5-stage CADR Expected Performance
Detector temperature	50 mK	50 mK
Detector interface temperature	45 mK	45 mK
Detector temperature stability	2 μK rms	<10 μK rms
Intermediate temperature node		<1 K
Cooling power at 50 mK	3 μW	7 μW
Hold time	31 hours	Continuous cooling
Recycle time	<10 hour	N/A
Cooling power at 1 K (with 4.5 K cryocooler)	40 μW	~1 mW
DA temperature stability	<1 mK in 10 minutes	<0.5 mK
Heat sink temperature		4.5 K
Heat load on heat sink		<10mW

It should also be noted that the current CADR system has not yet demonstrated the level of temperature stability required for the XMS detectors. Unlike conventional ADRs where temperatures and heat flows are inherently stable, the CADR's internal cycling generates changes in heat flow within the 1st stage that can cause temperature disturbances. With simple PID control of the 1st stage's current to stabilize temperature, these disturbances can be as large as 100 μK depending on how fast the cycle is being run. This implies that a trade can be made between cycle speed – and hence cooling power – and temperature stability. This is the case, but for prior development of the CADR, the emphasis has been on obtaining the required stability without compromising cooling power.

To do this, the control system uses real-time knowledge of the thermodynamic state of the ADR (which can be calculated from analytic functions from temperatures and magnet currents) and internal heat flows as calculated from heat switch conductances and temperature gradients. This has been very successful, achieving stabilities throughout the CADR cycle of better than 10 µK rms, and limited only by the resolution of the temperature bridges used (~5 µK rms). The readout circuits in the flight electronics for Astro-H have demonstrated resolution and control at better than 0.5 µK rms, a key advance for demonstrating the stability needed for XMS.

1.2.3 5-stage CADR Control Electronics

The ADR control (ADRC) electronics for Astro-H were used as a basis for estimating the mass, power and size of comparable electronics for the 5-stage CADR for IXO/XMS. Although the Astro-H is a 3-stage single-shot cooler, its control methodology is based on functionality that was developed for the 4-stage CADR. For IXO, it would only need to be scaled is size, board count and power for the larger number of stages. This scaling reflects the different duty cycles of each stage, as well as the smaller magnetic fields used (requiring lower charging/discharging voltages). The ADRC includes all circuits needed for temperature measurement, magnet control, and recycling algorithms. Table 1.2-4 lists the relevant parameters for a scaled ADRC. Powers include a 70% efficiency in converting from spacecraft bus supply.

Table 1.2-4 – ADR control electronics for a 5-stage CADR based on the Astro-H ADRC.

Size	29.2 cm x 31.8 cm x 36.0 cm	
Mass	16 kg	
Power (W)	Stage 1	10.2
	Stage 2	11.8
	Stage 3	15.0
	Stage 4	13.4
	Stage 5	15.0
	Total	65.4

1.3 5-stage CADR Technology Roadmap

A technology development roadmap was originally established for the CADR under NASA's Constellation-X program, and revised more recently to reflect IXO/XMS target implementation dates. The plan leverages concurrent development of multi-stage ADRs for other projects – principally Astro-H – to first achieve flight-worthy demonstrations of all component technologies and relevant sub-assemblies. In parallel, the goal of any future development of a full-scale 5-stage CADR and control electronics is to demonstrate compliance, with adequate margin, of all XMS cooling requirements, using components that have been qualified at the mechanical and structural level..

The following milestones (with ROM costs and durations) were established to identify critical advances needed in demonstrating a cooler that meets all of the interface and performance requirements for IXO. Initial funding was obtained under NASA/GSFC's IRAD program, but there is no current funding for this effort.

1.3.1 5-stage CADR Demonstrator - $1.2 M, 2 years

The goal is to demonstrate a CADR with the ability to continuously cool at 2 distinct temperatures (50 mK and 1 K), and the control electronics needed to achieve the temperature stability requirements of future missions, using the requirements for IXO/XMS as a baseline. Initial tests would focus on developing control algorithms for cycling the 5 stages and thermodynamic efficiency, as well as more basic measurements of cooling power and heat rejection rates.

The CADR will be tested in a facility with a commercial cryocooler, whose capabilities exceed those of flight coolers. This gives margin on performance that allows more rapid development and characterization of the CADR.

The effort would build on partial completion of a 5-stage CADR under NASA/GSFC IRAD funding, but expanded in scope to include electronics development. The electronics would be based on the ADRC (ADR control electronics) developed for Astro-H which controlled 3 stages. The majority of the electronics effort will be in programming the FPGA to coordinate cycling of all 5 stages. A fallback position is to assembly commercial electronics that have also successfully been used to control the 4-stage CADR

Cost basis: GSFC has a long history of fabrication and testing of ADR components and systems. Since no new test facilities are needed, the costs reflect only the production of, assembly, and labor for testing the magnets, shield, salt pills, heat switches, and suspension systems, as well as the structure for mounting. Costs for the electronics are based on the production costs of the breadboard ADRC boards, and the labor for assembly, testing and programming.

1.3.2 Combined CADR/cryocooler/detector system demonstration - $1.0M, 1 year

This effort would demonstrate operation of a detector system cooled by the 5-staeg CADR, using a flight-quality cryocooler as a heat sink. This would be a high-fidelity test intended to identify interactions between subsystems (microphonics, magnetic fringing fields, temperature fluctuations) that can severely degrade detector performance. It would essentially duplicate testing that is currently being conducted for Astro-H, but with the CADR replacing the 3-stage Astro-H ADR and the core array of XMS microcalorimeters being developed at Goddard replacing the Astro-H detector array.

Goddard has performed instrument-level and mission-level design studies for Con-X/IXO, considering all 4K class cryocoolers developed under NASA's Advanced Cryocooler Technology Development Program. Through these studies, Goddard has established collaborative working relationships with the cooler developers (Lockheed, NGST, Ball, and Creare) and an understanding of the requirements for, and limitations of, operating the CADR with each of these coolers. Consequently, Goddard is in a position to work with any cryocooler supplier to accomplish a CADR/cryocooler demonstration.

Cost basis: It is assumed that both the detector system and cryocooler are separately funded, since their development is beyond the scope of this effort. The costs associated with the CADR testing mainly reflect labor costs for assembly, disassembly and operation of the test dewar, including integration of the CADR, detector and cryocooler systems. These are complicated by the need to maintain the dewar as a clean (Class 1000) facility.

1.3.3 Engineering Model and Flight Model CADR Builds and Flight Qualification - $3.5M each, 1.5 years each

Assuming selection of the CADR for a future mission, it would be prudent to implement a program in which both EM and FM models are built. This has proved vital to Astro-H in allowing early mitigation of interface issues, development of production processes, determining the amplification of launch loads and subsequently modifying designs to compensate, and developing automated control algorithms for the ADR.

Cost basis: The cost of producing each CADR system is a scaling of the actual costs of building the EM ADR for Astro-H, considering the larger number of components and complexity of the magnetic shielding needed for future detectors and amplifiers, like TESs and SQUIDs, that are far more sensitive to magnetic fields than the JFET-based silicon microcalorimeters used for Astro-H.