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Performance of a fast response miniature Adiabatic Demagnetisation Refrigerator using a single crystal tungsten magnetoresistive heat switch

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ABSTRACT

The performance of a fast thermal response miniature Adiabatic Demagnetisation Refrigerator (ADR) is presented. The miniature ADR is comprised of a fast thermal response Chromium Potassium Alum (CPA) salt pill, two superconducting magnets and unconventionally, a single crystal tungsten magnetoresistive (MR) heat switch. The development of this ADR is a result of the ongoing development of a continuously operating millikelvin cryocooler (mKCC), which will use only magnetoresistive heat switches. The design and performance of the MR heat switch developed for the mKCC and used in the miniature ADR is presented in this paper; the heat switch has a measured Residual Resistivity Ratio of 32,000 ± 3000 and an estimated switching ratio (on thermal conductivity divided by the off thermal conductivity) of 15,200 at 3.6 K and 38,800 at 0.2 K when using a 3 T magnetic field. The performance of the miniature ADR operating from a 3.6 K bath is presented, demonstrating that a complete cycle (magnetisation, cooling to the bath and demagnetisation) can be accomplished in 82 s. A magnet current step test, conducted when the ADR is cold and fully demagnetised, has shown the thermal response of the ADR to be sub-second. The measured hold times of the ADR with just parasitic heat load are given, ranging from 3 min at 0.2 K with 13.14 μW of parasitics, to 924 min at 3 K with 4.55 μW of parasitics. The cooling power has been measured for operating temperatures in the range 0.25–3 K by applying an additional heat load to the ADR via a heater, in order to reduce the hold time to 3 min (i.e. approximately double the recycle time); the maximum cooling power of the miniature ADR (in addition to parasitic load) when operating at 250 mK is 20 μW, which increases to 45 μW at 300 mK and continues to increase linearly to nearly 1.1 mW at 3 K. To conclude, the predicted performance of a tandem continuous ADR utilising two of the miniature ADRs is presented.

1. Introduction

Adiabatic Demagnetisation Refrigerators (ADRs) use the process of magnetic cooling to reach millikelvin temperatures whereby cooling is achieved by reducing and controlling the entropy of a paramagnetic material; more specifically, the alignment of the electronic dipole moments of the magnetic ions within the material is controlled by the use of a magnetic field. The ideal process of magnetic cooling involves: (1) a magnetic field being applied and the dipole moments aligning with the field reducing the entropy of the paramagnet (in the ideal case magnetisation is isothermal and therefore the magnetisation energy Q_m is equal to TdS, where T is the temperature and dS is the change in entropy); (2) the paramagnetic material then being thermally isolated from its surroundings; (3) the magnetic field being reduced resulting in cooling. Fig. 1 illustrates the ideal process of magnetic cooling and shows how the entropy and temperature of the paramagnetic material vary with magnetic field.

The schematic of a single ADR is shown in Fig. 2; the paramagnetic material is suspended within the bore of the magnet via low thermal conductivity supports and is connected to the heat bath via the heat switch. In addition, there is a mechanical interface to the pill upon which samples/detectors to be cooled are mounted; this interface is commonly referred to as the cold finger.

Operation of a single ADR is based on the ideal process of magnetic cooling described above, but real world limitations mean that magnetisation is not isothermal because of the limited thermal conduction of the heat switch, and demagnetisation is not fully adiabatic because of the parasitic and sample/detector heat loads onto the paramagnetic material. The operational procedure (also known as recycling) of the ADR is therefore as follows: (1) magnetisation of the paramagnetic with the heat switch closed so that the magnetisation energy is extracted to the heat bath;

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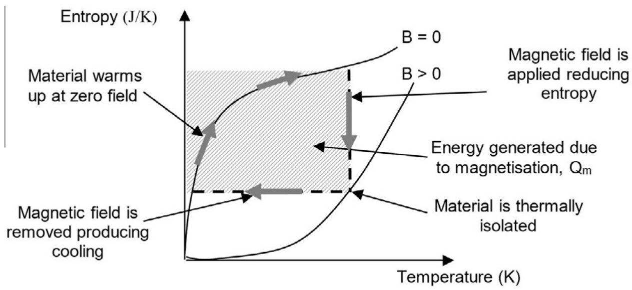

Fig. 1. Variation of entropy and temperature of a paramagnetic material during the ideal process of magnetic cooling.

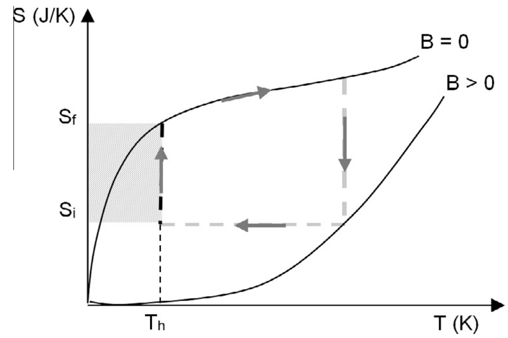

Fig. 3. Total energy that can be absorbed by a paramagnetic material at hold temperature T_h.

(2) a cooling period during which the paramagnetic is allowed to cool to the bath temperature via the heat switch; (3) isolation of the paramagnetic from the bath by opening the heat switch followed by demagnetisation. At this point, the ADR can be either: (1) fully demagnetised and a heater used to provide a stable cold finger temperature with time (by decreasing the heater power with time); (2) partially demagnetised until the required operating temperature is reached and then the remaining magnetic field removed at a rate such that the cooling produced from demagnetisation counteracts the heat flows into the salt pill, thereby maintaining a constant operating temperature; this can be achieved either manually or by the use of an automated control program. Of the two methods described, the partial demagnetisation is more favourable as it gives better thermal efficiency. In this case, the operating temperature (also referred to as the hold temperature T_h) can be maintained until zero magnetic field is reached. The total amount of energy Q_a that can be absorbed by the paramagnetic material when it is at the hold temperature is given by $nT_h(S_f - S_i)$ as depicted by the shaded area in Fig. 3, where n is the number of moles of the paramagnetic and S_i and S_f are the initial and final entropies.

The duration for which the paramagnetic can remain at the hold temperature is referred to as the hold time t_h. This is equal to the total energy that can be absorbed Q_a, divided by the total heat load (power) onto the paramagnetic which is comprised of the parasitic and sample/detector heat loads.

The performance of an ADR depends on the performance of each of its three main components. By individually developing and optimising each of these components, ADR technology can be taken forward to achieve smaller, faster and more efficient coolers. We describe below a fast thermal response miniature ADR, which not only uses a fast thermal response CPA pill [1] and fast ramping low current superconducting magnets, but which pushes the development of ADRs because of its use of a single crystal tungsten magnetoresistive (MR) heat switch. The design and performance of the MR heat switch is discussed in Section 2, we demonstrate the performance of the miniature ADR by presenting the experimental test results in Section 3 and the predicted performance of a continuous cooler utilising two of the miniature ADRs is given in Section 4.

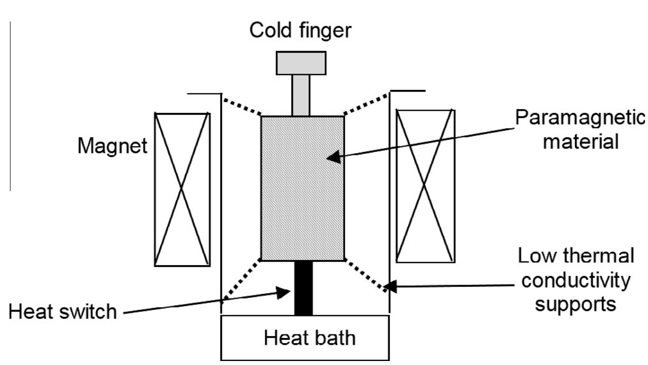

Fig. 2. Single ADR schematic.

2. Magnetoresistive heat switches

The heat switch plays a vital role in ADR operation; a high thermal conductivity in the 'on' state during magnetisation and cooling will enable a fast recycle time, whilst a low thermal conductivity in the 'off' state during demagnetisation and the hold time, will help minimise the parasitic heat load (the heat switch is typically the dominant contribution) and extend the hold time. Maximising the hold time and minimising the recycle time is desirable to maximise the duty cycle efficiency.

An indication of the performance of a heat switch is its switching ratio at a given temperature, which is the ratio between the on and off conductivities. Typical heat switches that are used in ADRs are gas-gap, superconducting and mechanical, all of which have their advantages and disadvantages. Gas-gap heat switches require high temperatures (7–14 K) to desorb the gas which is not ideal in a cold system and can be slow to switch between the on and off states due to the time taken to absorb the conducting gas. Whilst work has been done to reduce the switching time to the order of minutes [2], gas-gap heat switches cannot be used below ~0.2 K due to the gas vapour pressure being so low that heat transfer becomes inefficient. However, switching ratios of the order of several thousand can be achieved by gas-gap heat switches [3]. Superconducting heat switches have the disadvantage of only being effective over a narrow temperature range; Lead is commonly used in superconducting heat switches but to achieve a switching ratio of approximately 100, the heat switch has to be operated at or below 0.1 T_c which equates to 0.72 K for Lead. To achieve switching ratios of greater than 1000, it needs to be operated below 0.2 K, whilst switching ratios of tens of thousands are only achievable below 70 mK (0.01 T_c) [3]. Whilst mechanical heat switches are unparalleled when in the off state because they provide complete thermal isolation, they can be difficult to set up due to narrow clearances, unreliable because of their moving parts and cold welding can become an issue when the switches remain closed for long periods. The on state thermal conductance is also limited by the clamping force achievable between the switch and the object to be cooled.

An alternative to these conventional heat switches are magnetoresistive (MR) heat switches which have been investigated for use in ADRs since 2002, although until now, no usable ADR using an MR heat switch has been successfully demonstrated [4–6]. At the Mullard Space Science Laboratory (MSSL), development of

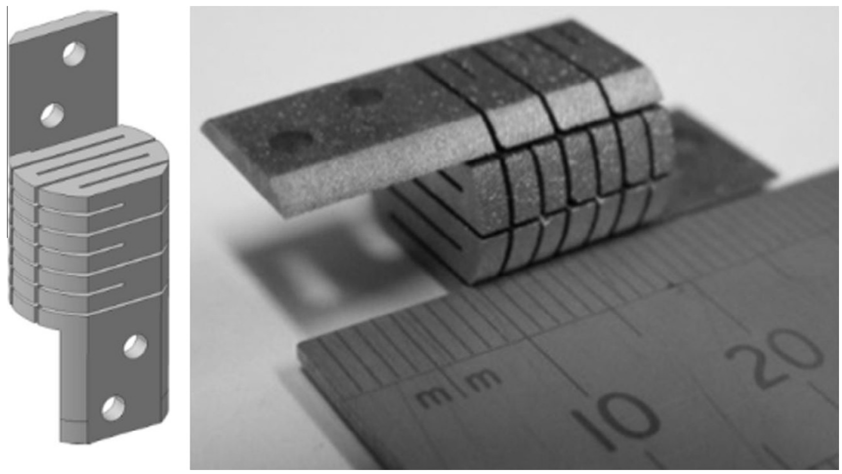

Fig. 4. Single crystal tungsten MR heat switch for the mKCC.

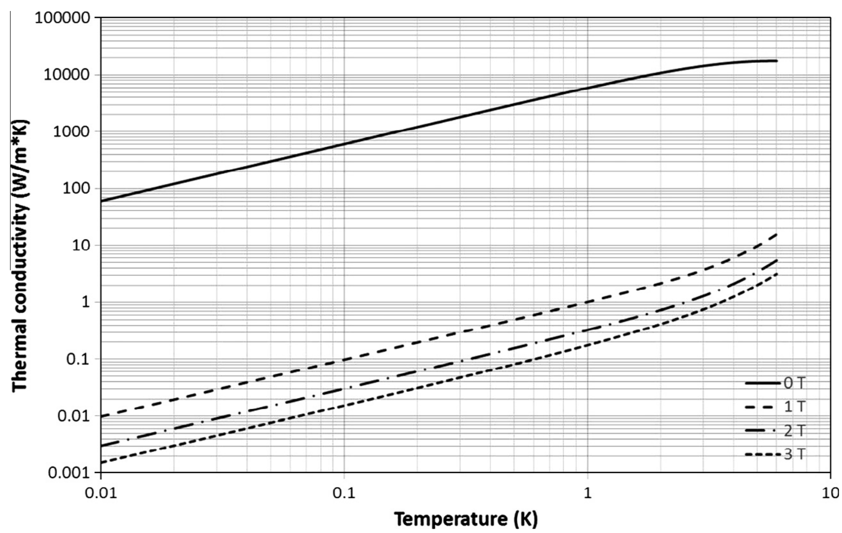

Fig. 5. Calculated MR heat switch thermal conductivity for 0, 1, 2 and 3 T magnetic fields.

tungsten MR heat switches has been ongoing since 2005 [7]. MR heat switches are solid state switches where heat is conducted by both electrons and phonons with the former being the dominant process. They are naturally in the high thermally conducting (on) state and are switched off by the application of a magnetic field perpendicular to the direction of heat flow, which suppresses the electronic conduction; the heat conducted due to the electrons decreases with increasing magnetic field, with the thermal conductivity ultimately being dominated by phonons. For detailed MR theory, refer to Hills et al. [8].

MR heat switches are ideally suited for use in ADRs because of their very high switching ratios (potentially 100,000 at 4 K [9]), that can be achieved over a large temperature range (>4 K to mK) and the fast switchover times between the on and off states which is only limited by the magnet ramp rate. In addition, an MR heat switch is tuneable i.e. as the magnetic field is varied the thermal conductivity varies, so therefore there is no sharp transition between on and off.

2.1. Single crystal tungsten MR heat switch for the millikelvin cryocooler

A MR heat switch has been developed as part of the millikelvin cryocooler (mKCC) project at MSSL. The mKCC [10] is a tandem continuous ADR which utilises two double ADRs (dADRs), both linked to a common cold stage via MR heat switches, and operated alternately; one dADR provides cooling whilst the other recycles. In order to provide continuous cooling, the recycle time of each dADR must be shorter than its hold time. For this type of continuous system, heat switches with high switching ratios are required for two reasons: (1) to minimise the parasitic heat loads to the cold stage i.e. to extend the hold time of the cold dADR by providing very low thermal conduction in the off state; (2) to minimise the recycling time of each dADR by providing high thermal conduction in the on state, which for a given sized system also allows for greater cooling power. With a target recycle time of each dADR of the order of 6–7 min, a fast switching, high switching ratio heat switch was important for the mKCC, and therefore a MR heat switch was the preferred choice.

The MR heat switch developed for the mKCC is shown in Fig. 4. It is wire EDM (electronic discharge machine) cut from a single crystal of tungsten (99.999% purity), is 12.5 mm in diameter and has a height of 32.3 mm (12 mm excluding mounting flanges). The slotted design [5], gives the heat switch an effective 1.5 mm square cross section and a free path length of 31 cm.

The Residual Resistivity Ratio (RRR) of the MR switch has been measured to be 32,000 ± 3000; the electrical resistivity at room temperature and 4.2 K were measured using an Agilent 34420A

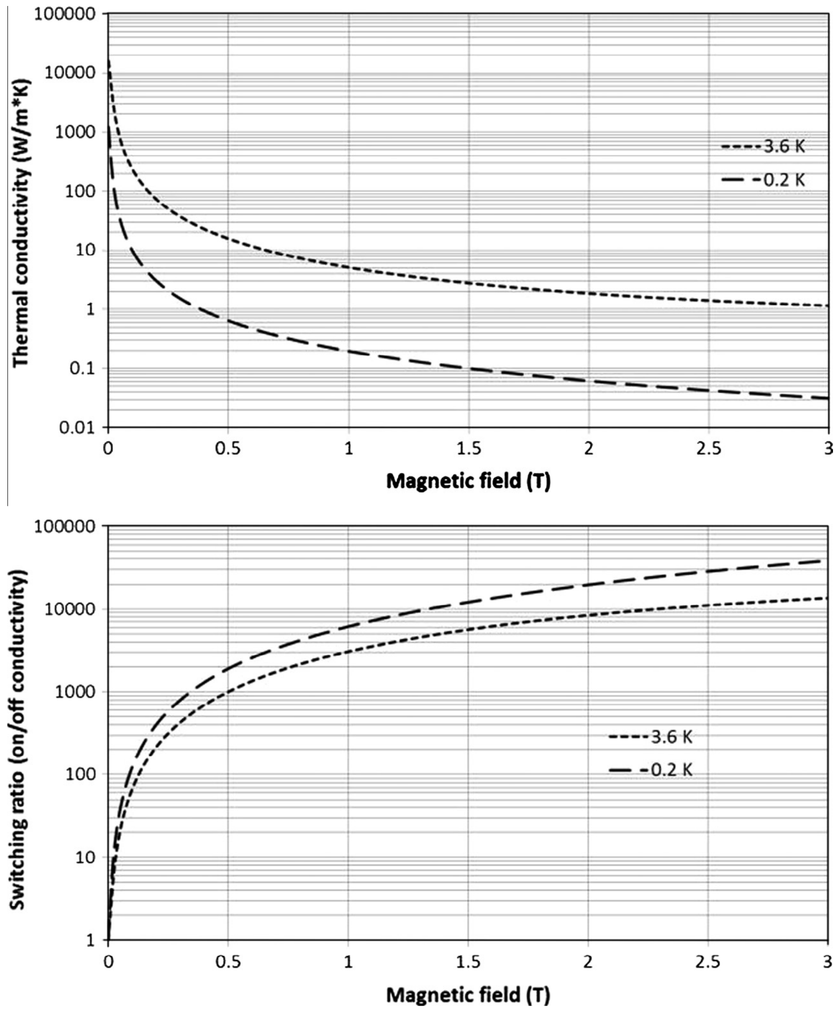

Fig. 6. MR heat switch performance at 3.6 K and 0.2 K. Top: Thermal conductivity as a function of magnetic field. Bottom: Switching ratio as a function of magnetic field.

nanoVolt/microOhm meter which is capable of measuring to 0.1 nV. The measurement was performed by passing a fixed current (0.1 A at room temperature and 5 A at 4.2 K) and measuring the voltage drop across the switch, with the electrical resistance calculated from Ohm's Law and subsequently the electrical resistivity. The room temperature electrical resistivity was measured to be $8.35 \pm 0.02 \times 10^{-8}$ Ωm and the 4.2 K resistivity measured to be $2.60 \pm 0.24 \times 10^{-12}$ Ωm.

Prior to assembling the miniature ADR, the mKCC MR heat switch could not be fully thermally characterised due to cryostat constraints. However, based on experiments and research conducted at MSSL on a range of tungsten heat switches, the thermal conductivity has been estimated. In Hills et al. [8], an equation is derived which allows the thermal conductivity (κ) below 6 K to be calculated as a function of magnetic field (B) and temperature (T) (see Eq. (1)). To estimate the performance of the mKCC heat switch, the parameters in Eq. (1) have been taken from the measured thermal conductivity of another MSSL heat switch with the same 1.5 mm square cross section, a free path length of 43 cm and a RRR of 20,000; it has been observed from experiments conducted at MSSL that there is little change in the thermal performance for tungsten heat switches with a RRR between 20,000 and 32,000 (subject of a future publication) and therefore the performance of the 20,000 RRR heat switch has been assumed to be a good approximation. Fig. 5 gives the calculated thermal conductivity of the mKCC switch at 0, 1, 2 and 3 T based on Eq. (1), where the constants $b0$, $a1$, $a2$, $a3$, $a4$ and n have the values 0.0328, 1.19×10^{-4}, 3.57×10^{-6}, 1.36, 0.000968 and 1.7 respectively. It should be noted that the calculated thermal conductivity of the mKCC switch presented in Fig. 5 has been validated by comparing the experimental results of the miniature ADR with modelled predictions (this is discussed in Section 3.3).

$$\kappa(T) = b_0T^2 + \frac{1}{\frac{a1+a2T^2}{T} + \frac{B^n}{a3T+a4T^4}} \quad (1)$$

From Fig. 5, the predicted switching ratios at 3.6 K and 200 mK are 9000 and 19,800 respectively when using a 2 T magnetic field to turn the switch 'off' and 15,200 and 38,800 respectively when using a 3 T field.

An advantage of the MR heat switch is the tuneable nature between the 'on' and 'off' states, with the thermal conductivity varying with magnetic field. This is particularly important for a tandem ADR whereby cooling of the continuous stage has to be switched from one ADR to the other – a smooth transition between on and off will minimise thermal fluctuations of the continuous stage by preventing sudden changes in thermal load. Fig. 6 (top) shows how the thermal conductivity varies as the heat switch is switched between 'on' (0 T) and 'off' (3 T) at 3.6 K and 0.2 K (i.e. the bath temperature and the lowest operating temperature of the miniature ADR). Fig. 6 (bottom) shows how the switching ratio varies with magnetic field. Due to the non-linear relationship

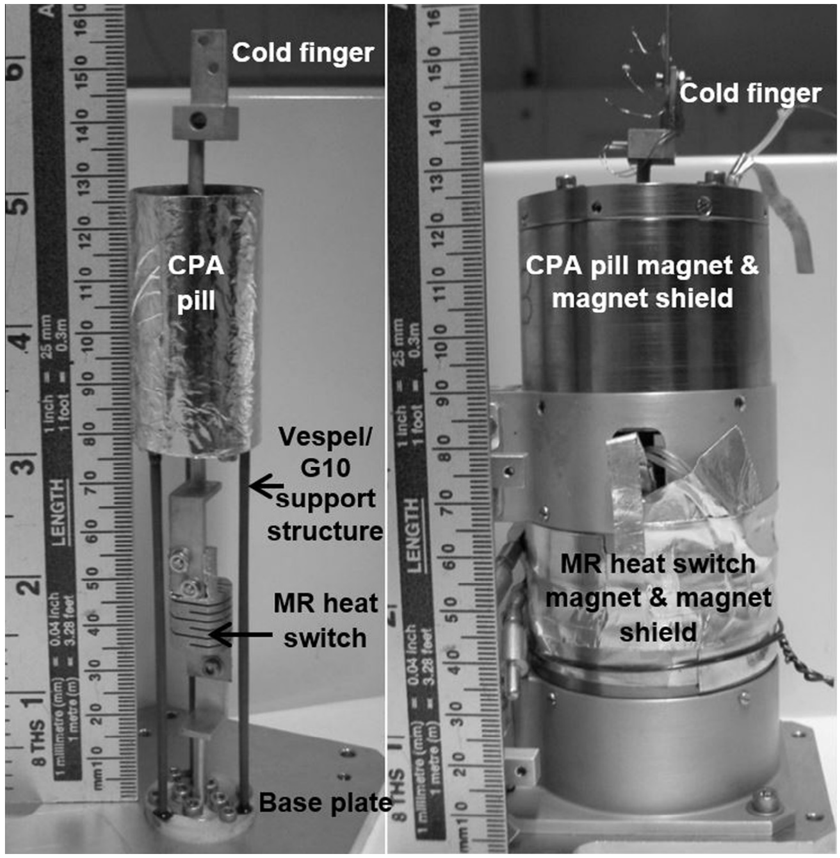

Fig. 7. Miniature ADR with tungsten heat switch. Left: ADR insert comprising CPA pill, MR heat switch and support structure. Right: Complete miniature ADR.

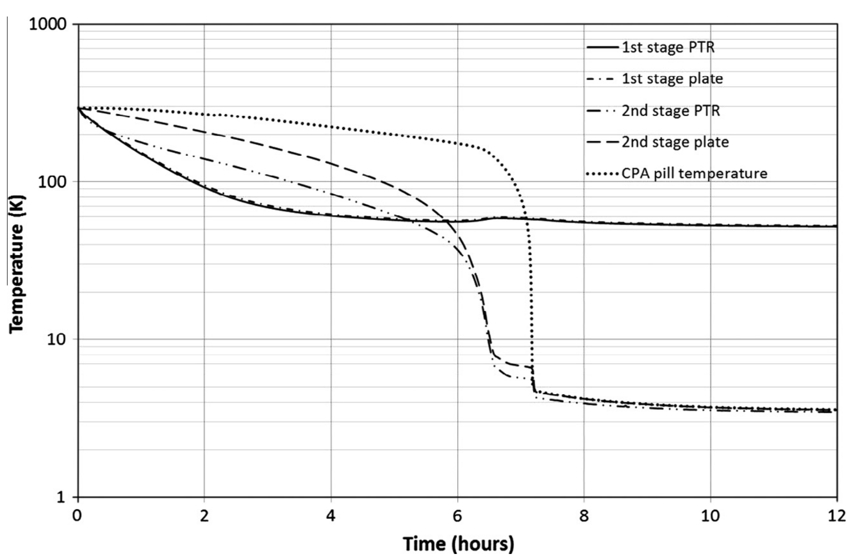

Fig. 8. Cool down temperature profiles of the PTR, base plates and CPA pill from room temperature.

between switching ratio and magnetic field, when turning the heat switch from 'on' to 'off', it can be seen that the thermal conductivity is reduced by a factor of at least 1000 with the application of just 0.5 T. When a fast ramping magnet is used to control the heat switch (such as those described below in Section 3), the 0.5 T is achieved in only 5 s.

3. Miniature ADR using a tungsten MR heat switch

As part of the mKCC development, a miniature ADR with a MR heat switch has been assembled and tested to demonstrate the performance and usability of the MR heat switch (shown in Fig. 7). The ADR is comprised of a fast thermal response Chromium

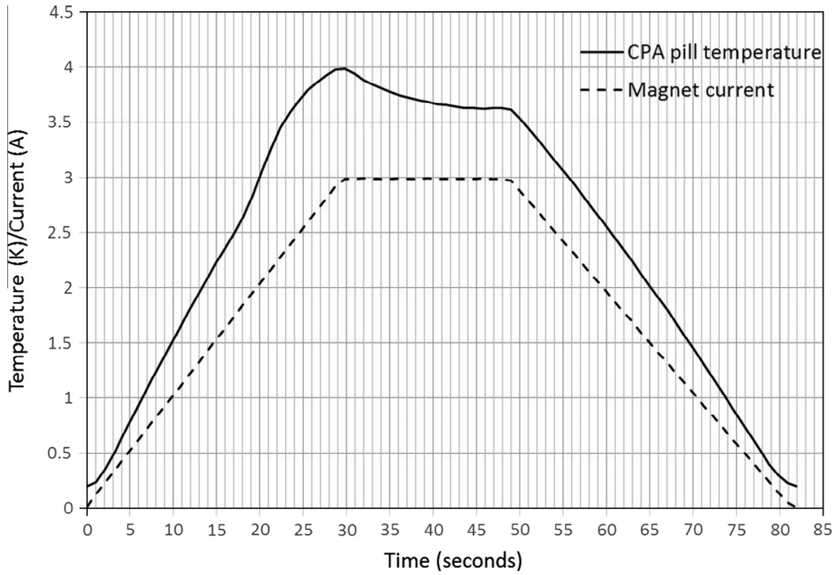

Fig. 9. Measured CPA pill temperature and magnet current profiles during recycling.

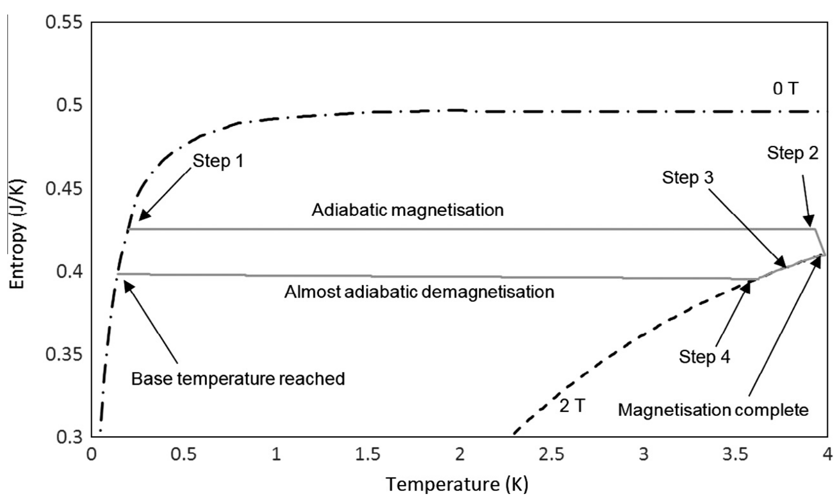

Fig. 10. Entropy-temperature diagram for miniature ADR cycle.

Potassium Alum (CPA) salt pill, a 7 layer single crystal tungsten heat switch (as shown in Fig. 4), two magnetically shielded superconducting magnets (one each for the CPA pill and the MR heat switch) and a low thermally conducting Vespel/G10 support structure, which suspends the CPA pill from the base plate whilst also providing strain relief for the MR switch. Two thermometers (a Ruthenium Oxide and a Cernox thermometer) were mounted onto the CPA cold finger along with a 10 kΩ heater.

The CPA pill was designed for the mKCC and is based on the prototype CPA pill design discussed in detail and presented in Bartlett et al. [1]. It has a 24 mm outer diameter, is 30 mm in length and contains 22 grams of CPA. Its thermal bus is made of gold plated copper and the contact area between the thermal bus and the CPA crystals is 87.36 cm^2. The superconducting magnets used are capable of ramping at 0.1 A/s with the CPA pill magnet operating at 2 T and 3.0 A (ramp time is 30 s) and the MR magnet operating at 3 T and 3.48 A (ramp time is 35 s). Both magnets are 30 mm in length and have an outer diameter of 43.6 mm. The inner diameter of the heat switch magnet is 26 mm, whilst the inner diameter of the CPA pill magnet is 28 mm. Each magnet has its own magnetic shield. For more information on the magnet design and shield performance refer to Bartlett et al. [10]. The miniature ADR has overall dimensions of 56 × 56 × 158 mm and a total mass of 1.48 kg, of which 1.32 kg is due to the mass of the magnets and magnet shields.

The miniature ADR shown in Fig. 7 was tested from a 3.6 K bath provided by a Cryomech Pulse Tube Refrigerator (PTR). In order to analyse the performance of the ADR and the MR heat switch, the testing and analysis has been broken down into three sections: (i) the cool down from room temperature to 3.6 K; (ii) the thermal response of the CPA pill during recycling and during a temperature step test; (iii) the hold time of the ADR at a range of temperatures from 200 mK to 3 K with no applied heat load and the maximum cooling power of the ADR at a range of temperatures between 250 mK and 3 K to give a hold time of 3 min. These are discussed in Sections 3.1, 3.2 and 3.3 respectively.

3.1. Cool down from room temperature

The testing of the miniature ADR was conducted in a large cryostat, 1.2 m high and 0.3 m in diameter. Both PTR stages have large copper plates, 6.35 mm thick, mounted onto them for interfacing

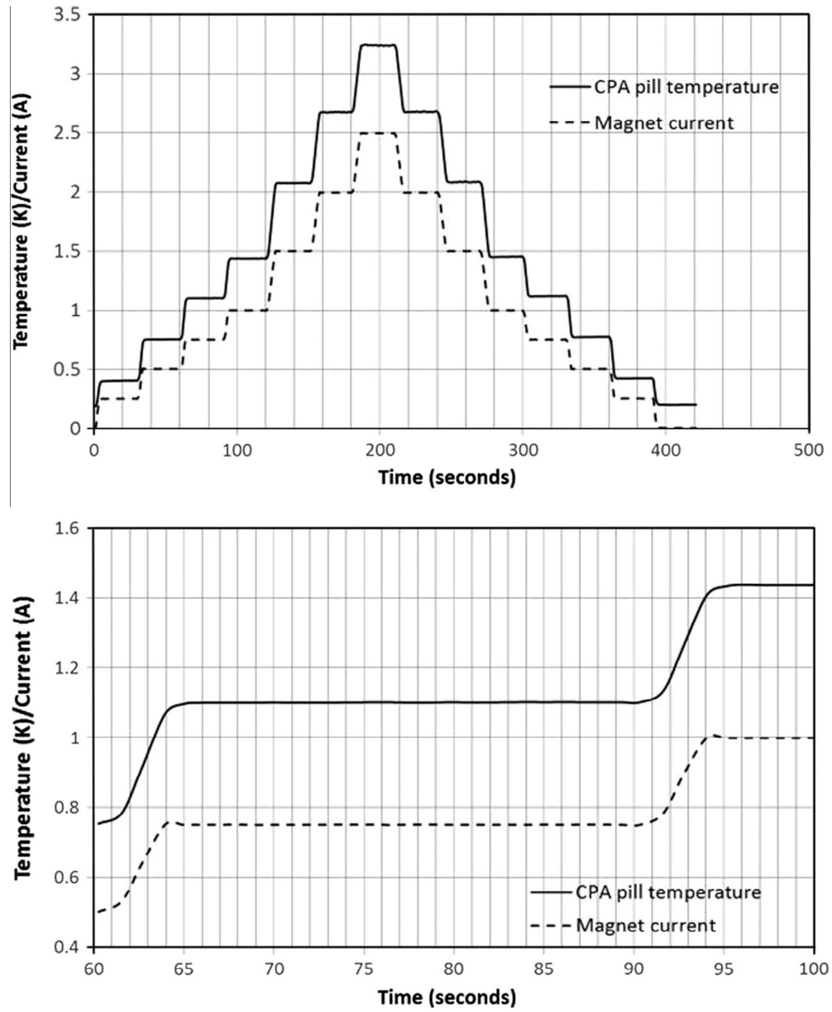

Fig. 11. Thermal response step test; Top: The temperature profile of the CPA pill as the CPA magnet current is stepped from 0 A to 2.5 A to 0 A; Bottom: A zoomed in view of the temperature and magnet current profiles in the 60–100 s time frame of the step test.

Table 1
Measured hold times of the miniature ADR.

Cold finger temperature (mK)	Predicted CPA crystal temperature (mK)	Calculated parasitic heat load (microwatts)	Measured hold time (min)	Modelled hold time (min)
200	190.1	13.14	3	3
250	244.2	13.13	11	11
300	296.0	13.11	17	17
400	397.8	13.05	30	30
500	498.6	12.98	43	42
800	799.5	12.67	85	84
1000	999.7	12.38	112	111
1500	1499.9	11.31	193	191
2000	1999.9	9.70	302	302
2500	2499.9	7.49	472	471
3000	2999.9	4.55	924	926

and are shielded by aluminium shields covered with multi-layer insulation blankets. Whilst the cool down time for a 0.5 W Cryomech PTR is typically a few hours with minimal thermal load, our test cryostat, because of the large thermal shields and base plates, has a baseline cool down time of 10.5 h (with no ADR or current leads). With the addition of 10 sets of current leads (the cryostat is set up for the full mKCC testing which uses 10 magnets) and the miniature ADR as described above, the cool down time is increased to 12 h. Fig. 8 shows the cool down of the ADR from room temperature to 3.6 K, along with the temperature profiles of the two PTR stages and the corresponding base plates mounted onto them. All temperatures were measured every 1.2 min with Cernox thermometers. As can be seen, there is a large temperature difference between the 2nd stage base plate and the CPA pill at higher temperatures, but once the CPA pill reaches 150 K, the thermal conductivity of the MR heat switch significantly increases, cooling the CPA pill from 143 K to 8 K in 30 min. The 2nd stage of the PTR reaches 4 K within 8 h, but it takes an additional 4 h for the 2nd stage plate to reach the base temperature of 3.6 K. During these last 4 h the MR heat switch keeps the CPA pill in good thermal equilibrium (within 10 mK) with the 2nd stage base plate. Therefore the MR heat switch does not appear to significantly affect the cool down duration from room temperature; instead any limitations appear to be due to the PTR itself and the large thermal load imposed on it by the cryostat.

3.2. Thermal response of the ADR

The thermal response of the ADR has been investigated by analysing the speed of the measured temperature response when the magnetic field is changed during recycling of the ADR and during a step test. As mentioned above, the temperature of the ADR is measured by a thermometer mounted onto the pill cold finger. The cold

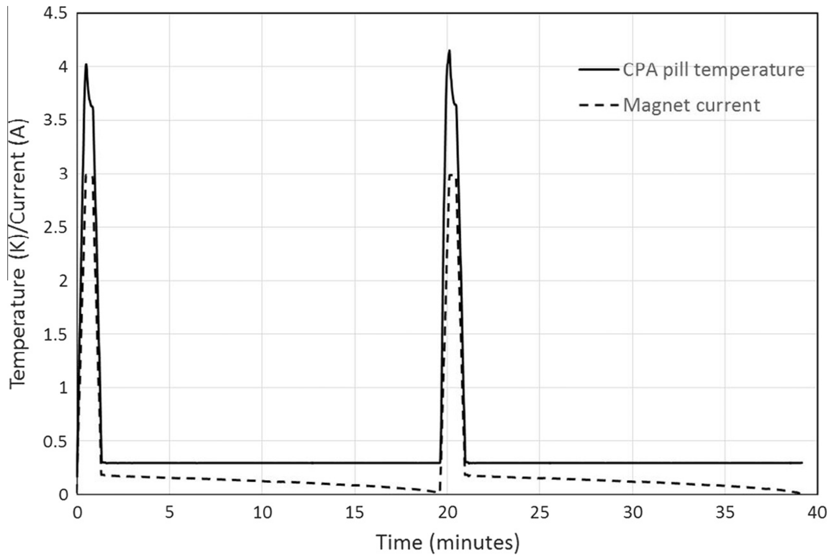

Fig. 12. Measured CPA pill temperature and magnet current during recycling and operation at 300 mK.

Table 2
Measured maximum cooling power to give a 3 min hold time at each cold finger temperature.

Cold finger temperature (mK)	Measured maximum cooling power (μW)	Parasitic heat load (μW)	Total heat load (μW)
250	20	13.13	33.13
300	45	13.11	58.11
400	85	13.05	98.05
500	122	12.98	134.98
800	240	12.67	252.67
1000	317	12.38	329.38
1500	511	11.31	522.31
2000	706	9.70	715.70
2500	900	7.49	907.49
3000	1094	4.55	1098.55

finger is vacuum brazed to the thermal bus (i.e. the wires within the pill), which in turn is in contact with the CPA crystals (this is discussed in detail in [1]). The temperature of the crystals will change immediately with respect to a change in magnetic field, therefore it is the response across the boundary between the CPA crystals and the thermal bus, i.e. the 'thermal lag' that is analysed. As discussed in [1], eddy current heating is produced in the copper thermal bus when subjected to a changing magnetic field, contributing a heat load of 17.84 μW when ramping the magnet at 0.1 A/s. However, this only affects the final ADR temperature by the order of tens of millikelvin for magnetisation and demagnetisation, and a millikelvin or less for the step test. These increases in temperature are insignificant when compared to the total change in temperature observed during recycling and the step test; eddy current heating can therefore be neglected when examining the thermal response of the ADR in these cases.

The ADR has been successfully recycled (magnetised, cooled to the bath and demagnetised) in 82 s. This has been achieved due to the fast thermal response of the pill, the fast ramping magnets, the switching ratio of the heat switch, and the ability to overlap the switching of the heat switch with the magnetisation/demagnetisation of the salt pill; a factor of 1000 reduction in thermal conductivity can be achieved within 5 s when switching from on to off, therefore the heat switch does not have to finish ramping before demagnetisation can begin. The miniature ADR recycling process (starting from 0.2 K) is broken down into the following steps: (1) Start demagnetisation of the heat switch magnet (i.e. to turn the heat switch on) and after 10 s, magnetise the CPA whilst the heat switch magnet continues to demagnetise – the CPA is still below the bath temperature and therefore magnetises almost adiabatically as the switch is not yet significantly conducting; (2) The heat switch magnet finishes demagnetising as the CPA reaches the bath temperature – the magnetisation energy is now extracted via the heat switch to the bath (non-isothermally); (3) Cool the CPA to the bath temperature and then start magnetisation of the heat switch magnet (i.e. to turn the heat switch off); (4) After 5 s demagnetise the CPA to its base temperature i.e. zero field (whilst the heat switch magnet continues to magnetise). Fig. 9 shows the current in the CPA magnet (3 A corresponds to a 2 T magnetic field) and the CPA pill temperature during a typical ADR cycle after operation at 0.2 K; the temperature increases almost linearly to a peak of 4 K during magnetisation, cools to 3.6 K and then demagnetises to the base temperature of 178 mK. It can be seen in Fig. 9 that the cold finger temperature responds practically instantaneously to a change in magnetic field; a change in magnetic field is mirrored within a second by a change in cold finger temperature. Fig. 10 shows the temperature and predicted entropy of the CPA during recycling, with each of the recycling steps listed above highlighted on the diagram. The 178 mK measured base temperature of the ADR equates to a CPA crystal base temperature of 143 mK, due to the thermal boundary resistance between the copper thermal bus and the CPA crystals (as explained in Section 3.3).

During magnetisation from 0.2 K (when most of the magnetisation energy goes into warming the pill to the bath temperature) and cooling, the estimated peak heat load to the bath is 45 mW, with an average heat load of 19 mW. The total energy extracted to the bath is 0.474 J. Initially, when the ADR is first recycled from the 3.6 K bath temperature, the peak temperature is 4.16 K, resulting in an estimated peak heat load of 65 mW, an average heat load of 32 mW and a total of 1.56 J being extracted to the bath. These values have been calculated using the measured CPA temperature and the predicted thermal conductivity of the heat switch and support structure.

Investigating the thermal response further, a current step test has been conducted after full demagnetisation, during which, the CPA magnet current was increased in 0.25 A steps from 0 A to 1 A, and 0.5 A steps from 1 A to 2.5 A (at a rate of 0.1 A/s), every 30 s with the temperature response of the CPA pill measured at

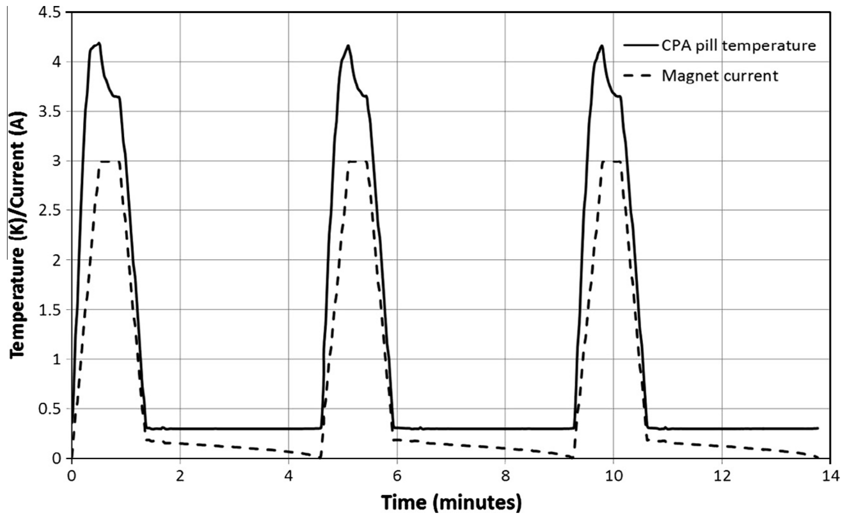

Fig. 13. Measured cold finger temperature and magnet current during recycling and operation at 300 mK with a 45 μW applied heat load.

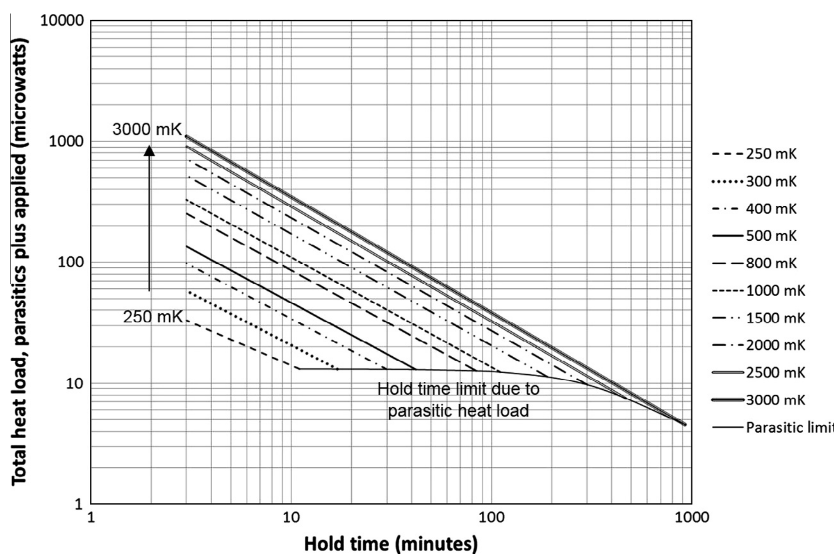

Fig. 14. Relationship between hold time, total heat load and operating temperature for the miniature ADR.

approximately 1 s intervals (the logging times vary between 0.9 and 1.1 s due to the computer program). The complete step test is shown in the top part of Fig. 11, with a zoomed in view of a couple of the steps shown in the lower part of Fig. 11. From the graphs, it appears that changes in the CPA pill temperature track the changes in the magnetic field; because the CPA pill temperature is read and logged at approximately 1 s intervals, any delay in the thermal response of the pill appears to be sub-second.

3.3. ADR hold times

To fully characterise the ADR, the hold times have been measured with just the parasitic heat loads and then with an additional applied heat load so as to reduce the hold time to 3 min (i.e. approximately twice the recycle time). This was to give an indication of the potential maximum cooling power of the ADR. The operating temperatures were controlled by using an automated servo control program.

The base temperature of the ADR (from a 3.6 K bath) is 178 mK and therefore the lowest operating temperature is considered to be 200 mK. Table 1 gives the measured hold time at a range of hold temperatures from 200 mK to 3 K, along with the estimated total parasitic heat load onto the CPA, which is comprised of the heat load due to the MR heat switch (calculated using the data from Fig. 5), the support structure (calculated using published material data) and radiation. In addition, the predicted CPA crystal temperature is given, with the temperature difference being due to the thermal boundary resistance between the CPA crystals and the thermal bus/cold finger. The thermal boundary resistance has been calculated using Eq. (2), where dQ/dt is the heat flow across the boundary, A is the contact area, T_1 is the temperature of the thermal bus, T_2 is the temperature of the CPA crystals and β is the thermal transport parameter, which has a value of 4×10^{-4} watt cm^{-2} K^{-3} [1].

$$\frac{dQ}{dt} = \frac{\beta A}{3}\left(T_1^3 - T_2^3\right) \tag{2}$$

The final column of Table 1 presents the modelled hold times of the ADR, which can be seen to have good agreement with the measured results. This thereby validates the assumption that the calculated thermal conductivity of the mKCC heat switch as presented in Fig. 5, is a good approximation of the actual thermal conductivity.

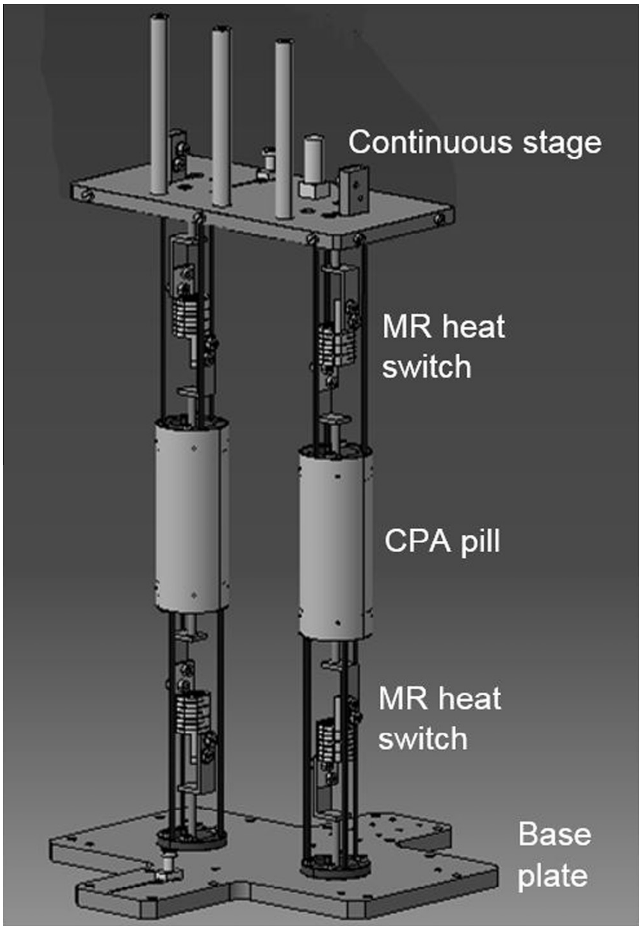

Fig. 15. The single millikelvin cryocooler (smKCC) ADR insert.

Table 3
Predicted cooling power of the smKCC based on the miniature ADR performance.

Operating temperature (mK)	Measured cooling power of miniature ADR (μW)	Calculated peak heat load from recycling ADR in smKCC (μW)	Estimated cooling power of smKCC (μW)	
			Lower limit	Upper limit
250	20	17.13	2.87	16.87
300	45	17.12	27.89	57.89
400	85	17.06	67.94	136.94
500	122	16.99	105.01	216.01
800	240	16.69	223.32	457.32
1000	317	16.39	300.61	612.61
1500	511	15.32	495.68	1000.68
2000	706	13.71	692.29	1396.29
2500	900	11.50	888.50	1773.50
3000	1094	8.57	1085.43	2178.43

The model used is a dynamic 0.1 s time step mathematical thermal model [11], which has been developed, tested and compared to several different MSSL ADR systems with good results. It incorporates all material thermal conductivities and heat capacities (based on published data). It calculates the parasitic heat loads within the system along with the effects on the CPA pill entropy and temperature throughout the recycle and hold times. The model also calculates the thermal boundary resistance between the CPA crystals and the copper thermal bus and therefore predicts the CPA crystal temperature. It is the same model as proved in Bartlett et al. [1], but a MR heat switch is used in the model instead of a mechanical heat switch.

As can be seen from Table 1, the measured hold time at 200 mK is 3 min with a parasitic heat load of 13.14 μW. The hold time increases to 17 min at 300 mK (as shown in Fig. 12) with a similar parasitic heat load of 13.11 μW. The dominant parasitic heat load is due to the MR heat switch which accounts for approximately 82%, therefore reducing the heat load from the MR heat switch would have a large impact on the hold time; doubling the path length of the heat switch would halve its thermal conduction and therefore almost double the hold time.

Table 2 gives the measured maximum cooling power of the miniature ADR at a range of operating temperatures from 250 mK to 3 K. The maximum cooling power was ascertained by applying power through a 10 kΩ heater mounted on the cold finger and adjusting the power until a hold time of 3 min was measured. A hold time of 3 min was chosen as this is just over twice the recycle time and if used as part of a tandem continuous cooler (see Section 4), this is expected to be the maximum hold time needed; the hold time has to just exceed the recycle time but also has to allow for a switch over time between ADRs. Due to the hold time measured at 200 mK being only 3 min with parasitic heat load, no additional heat load could be applied. As can be seen in Table 2, the maximum cooling power of the miniature ADR when operating at 250 mK is 20 μW, which increases to 45 μW at 300 mK and continues to increase linearly to nearly 1.1 mW at 3 K. It should be noted, that the relationship between total heat load and hold time is not linear for a given operating temperature. This is due to the thermal boundary resistance within the CPA pill, which results in a greater temperature difference between the cold finger and CPA crystals as the heat load is increased; since the cold finger temperature is fixed, this results in a lower CPA crystal temperature and hence lower available entropy, thereby resulting in a lower maximum cooling power than may be expected from the results presented in Table 1.

Fig. 13 shows the measured cold finger temperature as the ADR is recycled and operated at 300 mK (with a 45 μW applied heat load) three times in a period of just under 14 min. The dotted line is the measured magnet current which again demonstrates the responsiveness of the miniature ADR. The figure clearly shows that the hold time is longer than the recycle time, thereby supporting the tandem continuous ADR design.

Tables 1 and 2 have shown the measured hold time of the miniature ADR (with parasitic heat load only) and the measured maximum cooling power to give a hold time of 3 min. Using these results and the mathematical thermal model, the relationship between the hold time, the total heat load (parasitics plus applied) and operating temperature has been calculated for the miniature ADR and is shown in Fig. 14; for a given operating temperature, the relationship between hold time and total heat load follows a power law. The minimum hold time shown relates to the parasitic heat load plus the maximum applied power, giving a hold time of 3 min. The maximum hold times shown refer to the measured hold time with parasitic load only, which decreases with increasing operating temperature.

4. Continuous cooling using the miniature ADR

As stated previously, the miniature ADR has been developed and tested as part of the mKCC development program. Whilst a hold time of 3 min and a recycle time of 82 s give a duty cycle of 67%, the 3 min hold time may not be practical for some applications. However, as in the mKCC design, two of these miniature ADRs connected to a common cold stage via additional MR heat switches, can be used to make a small tandem continuous ADR as shown in Fig. 15; one ADR recycles and is isolated from the cold stage whilst the other is connected to the cold stage and provides cooling. This has been named the single millikelvin cryocooler (smKCC) and will be the next phase in the assembly and testing of the mKCC. The smKCC will provide continuous cooling from 4 K to 250 mK, have dimensions of $56 \times 120 \times 228$ mm (excluding the millikelvin shield) and a mass of 4.67 kg, of which 3.96 kg is due to the mass of the magnets and magnet shields and 0.3 kg is due to the mass of the continuous stage.

In the smKCC, the cold miniature ADR, whilst providing usable cooling power for any detector/experiment mounted on the continuous stage, will have to absorb heat from not only the parasitics from the bath (via the heat switch, support structure and radiation), but also the parasitic heat load from the recycling ADR via the continuous stage. From Fig. 9, which shows the temperature profile of the miniature ADR during recycling, it can be seen that the peak temperature is 4 K, which will correspond to the recycling ADR peak heat load needed to be absorbed by the cold ADR. The maximum cooling powers for a single miniature are given in Table 2 above, and therefore the cooling power of the smKCC has been calculated by taking the measured cooling power of a single ADR and subtracting the calculated maximum heat load from the recycling ADR. This is presented in Table 3 as the lower limit of the cooling power. An estimated upper limit of the cooling power is also given, calculated using the thermal model discussed in Section 3.3 and is based on minimising the margin between the recycle and hold time of the ADRs; in a tandem ADR, the hold time of each ADR only has to just exceed the recycle time. The lower limit cooling power is based on a recycle time of 82 s and a hold time of 3 min, which gives a factor of 2 margin. Reducing the hold time to 90 s so that it just exceeds the recycle time, allows the smKCC to have a higher cooling power, which is given as the upper limit in Table 3. As mentioned for the miniature ADR, the cooling power could be further increased by reducing the parasitic heat load contribution from the MR heat switches; doubling the path length of the heat switch would almost halve the total parasitic heat load (from the bath and recycling ADR) and because the magnets are 30 mm high and the height of the mKCC heat switch is only 12 mm without the mounting flanges, this could be implemented without changing the overall dimensions of the smKCC – a heat switch that has double the path length would only be 24 mm high (without flanges) and would therefore still fit.

The smKCC is currently under construction (September 2015). Results are expected by the end of 2015 and will be the subject of a future publication.

5. Conclusions

A miniature ADR which uses a single crystal tungsten magnetoresistive heat switch has been successfully built and tested as part of the mKCC development program, with the tests demonstrating that MR heat switches are a good alternative to conventional heat switches such as gas-gap, superconducting and mechanical heat switches. As well as providing high switching ratios over a large temperature range, MR heat switches have fast switching times with the only limit being the magnet ramp rate. In addition they are 'tuneable', with the thermal conductivity varying with magnetic field so that there is no sharp transition between 'on' and 'off'. This smooth transition has the advantage of preventing sudden changes in thermal load and in the case of the mKCC, minimising any thermal fluctuations on the continuous stage as cooling is switched from one ADR to the other . The tungsten MR heat switch used in the miniature ADR has a RRR of 32,000 ± 3000 and an estimated switching ratio of 15,200 at 3.6 K and 38,800 at 0.2 K and can be switched between 'on' and 'off' in 30 s, although a change in thermal conductivity of a factor of 1000 can be achieved within 5 s.

The performance of the ADR has been demonstrated through fast recycling, thermal response and hold time tests. The recycle time (magnetisation, cooling to the bath and demagnetisation) of the ADR was measured to be 82 s. By conducting magnet current step tests, the thermal response of the ADR has been ascertained to be sub-second (within the reading time of the thermometry). The hold times of the ADR were measured with only parasitic heat loads at a range of operating temperatures from 200 mK to 3 K; the measured hold time at 200 mK is 3 min with a parasitic heat load of 13.14 μW with the hold time increasing to 17 min at 300 mK with a similar parasitic heat load of 13.11 μW. A 43 min hold time was measured at 500 mK (12.98 μW parasitic load) with the hold time increasing to 924 min at 3 K with a 4.55 μW parasitic load. By applying an additional heat load to the ADR via a heater in order to reduce the hold time to 3 min (i.e. approximately twice the recycle time), the cooling power was measured for operating temperatures in the range 250 mK to 3 K; the maximum cooling power of the miniature ADR (in addition to parasitic load) when operating at 250 mK is 20 μW, which increases to 45 μW at 300 mK and continues to increase linearly to nearly 1.1 mW at 3 K. Combining two miniature ADRs to form a single millikelvin cryocooler (smKCC) which is a tandem continuous ADR, is the next stage in the mKCC development program. Based on the measured hold times of the miniature ADR and using mathematical thermal modelling, the predicted cooling power of the single smKCC has been calculated to be up to 16.87 μW at 250 mK, up to 57.89 μW at 300 mK and again increasing linearly with temperature to give up to 2.1 mW of cooling power at 3 K. The smKCC is currently under construction (September 2015) and will undergo testing in autumn 2015. The results will be presented in a future publication.

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