# A ³He Gas Heat Switch for Use in a Cyclic Magnetic Refrigerator

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*We describe a heat switch which we have constructed to work in the range from 0.5K to 1.8K as a component of a cyclic demagnetization refrigerator. We measure a thermal conductivity of about 50 µW/K at 1.5K when the switch is in the 'off' state, and in excess of 10 mW/K at 0.5K in the 'on' state. The switching time into the conducting state is a matter of several seconds, while the transition to the insulating state achieves a factor of 100 reduction of conductivity within about 1 minute, followed by a slower reduction by another factor of 5 over an hour time scale. This paper describes some details of the construction, discusses the limiting factors in the thermal conductivity in the on and off states, and the switching times between these states. The requirements of the intended application are discussed.*

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## 1. INTRODUCTION

An important component of a cyclic demagnetization refrigerator is a set of heat switches which can alternate the thermal contact to a paramagnetic refrigerant from a pre-cooling heat sink or to a sample stage depending on the stage of the magnetic cycle. In the temperature range below about 0.5K, superconducting metal heat switches activated by a magnetic field work well. However, above this temperature range, phonon conductivity limits the switching ration between 'on' and 'off' thermal conductivity. Mechanical heat switches have been used by a number of experimenters, but it is hard to achieve a compact design with a high and repeatable 'on' state conductivity–in many designs, the performance degrades after many cycles of usage and is somewhat inconsistent, and it is hard to avoid mechanical vibration associated with opening and closing the switch. At somewhat higher

temperatures, switches utilizing the conductivity of both $^3$He and $^4$He gas have been used, but the performance deteriorates drastically at temperatures slightly above the point where superconducting switches become useful. We have constructed a switch using $^3$He gas which allows the use of a demagnetization stage operating between a pumped helium vessel at 1.8K and an intermediate thermal stage at 0.5K. Below this point, a second refrigeration stage can be operated using superconducting heat switches to achieve temperatures of a few mK. In order to achieve cooling powers suitable for a range of experiments customarily performed using $^3$He /$^4$He dilution refrigeration techniques, we would like to be able to deliver an average rate of cooling of about 1 mW at 0.5K, and to achieve reasonable thermal efficiency, we would like it to transfer this heat with a temperature drop of around 50mK. Further, we wish to have a heat leak of less than 50 $\mu$W through the switch during the part of the cycle when the paramagnetic salt is being re-magnetized at 1.8K. We have achieved such performance with the heat switch described in this paper.

## 2. CONSTRUCTION

A schematic diagram of the construction we have used is shown in Fig.1. Two concentric cylinders of copper with a 0.1mm gap between them at 7mm diam. are spaced by another cylinder of 0.1mm-walled copper-nickel tubing, providing a hermetic seal. $^3$He gas may be introduced into the 20mm long gap between the cylinders through a 30mm length of copper-nickel tubing, 0.75mm id and 1.1mm od, leading to a volume of 0.03 cm$^3$ containing approximately 20mg of activated charcoal. This whole assembly was filled to a pressure of 1.5 bar (absolute) with $^3$He gas through a small capillary which was pinched off after the filling. The pinched-off end was capped by an epoxy-filled sleeve afterwards to ensure mechanical stability. The charcoal-filled cavity had a small ruthenium oxide thick film resistor glued to the outside, which serves simultaneously as a heater and thermometer to regulate the adsorption or desorption of the $^3$He gas which provides the switching action. The mid section of the 1.1mm od capillary was thermally anchored to the 1.8K reservoir, to limit the thermal load resulting from elevating the charcoal reservoir to about 12K during the operation of the switch. There is considerable resemblance to the device of Torre and Chanin[1], but the use of $^3$He rather than $^4$He extends the working region much lower in temperature. The short length (about 10mm) of CuNi tube between the charcoal sorb and the 1.8K heat sink provides the thermal link to the 1.8K reservoir which drops the sorb temperature quickly once the heater current
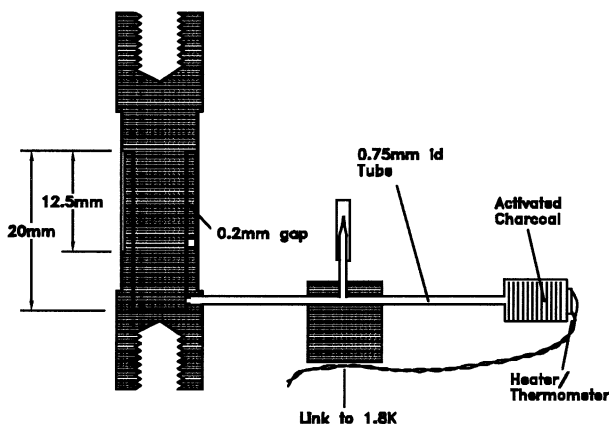
Fig. 1. Schematic construction

is turned off. About 2mW of power dissipation on the sorb container raises the temperature to about 12K, which is adequate to desorb enough gas for good conduction across the heat switch.

## 3.    CONDUCTION PERFORMANCE

### 3.1.    Experimental Performance

The thermal conduction of the heatswitch is shown as a function of temperature in Fig.2, in the on and off states.

### 3.2.    Metallic Conductivity

The ultimate limiting thermal conduction of the switch in the "off" state is the conductivity of the thin-walled CuNi tubing joining the two halves of the switch. Using $\kappa = 0.6 \times T^{1.5} \, mW \, cm^{-1} K^{-2.5}$ for the conductivity in the range from 0.5K to 20K, we have

$$\dot{Q} = \frac{A}{l} \int_{T_{low}}^{T_{high}} \kappa dT \approx 0.25 \frac{A}{l} T_{high}^{2.5} \ .$$

For our geometry, this yields $\dot{Q} = 10\mu W$ for the upper end at 1.8K.

There is also a smaller heat load of about half this magnitude into the higher temperature end of the heat switch when it is also near 0.5K, through the small pumpout tube connected to the 1.8K heat sink.
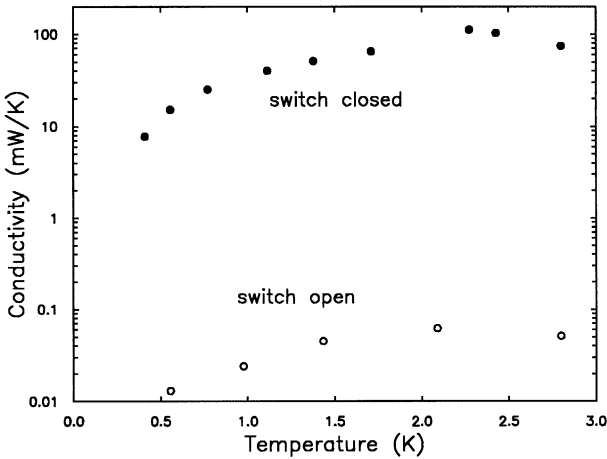
Fig. 2. Thermal conduction of the heatswitch as a function of temperature.

In the "on" state, the conductivity of the copper does not present a significant limitation to the conductivity. Using $\kappa = 1 \times T \; W \, cm^{-1} K^{-2}$ typical for pure copper without heat treatment, we find $\dot{Q}/\Delta T \approx 130 \; mW \, K^{-1}$ at 0.5K in our geometry, which could easily be improved by a factor of 100 by annealing.

### 3.3.    Gas Conductivity

Over most of the region of interest in the operation of this heat switch, the gas can be considered to be in the Knudsen regime, where the mean free path of a gas molecule is limited by the spacing between the copper walls (0.2 mm). Roughly (adequate for our estimates) the mean free path for the $^3$He can be related to the temperature and gas pressure through the formula $L = 4.8 \times 10^{-5} T/P$, with P in Torr, T in Kelvin, and L in cm. Thus at 0.5K and our gap of 0.2mm, the pressure at which the mean free path reaches that of the gap is $P = 1.4 \times 10^{-3}$ Torr. Below this pressure, the heat transfer per unit area is given by the kinetic theory formula[3]

$$\dot{Q}/A = \frac{a_0}{4} \frac{\gamma + 1}{\gamma - 1} \sqrt{\frac{2R}{\pi M}} \, p \frac{T_2 - T_1}{\sqrt{T}} \;.$$

In this formula, A is the area of each parallel surface, $a_0$ the accommodation coefficient for helium on the metal surfaces can be taken to be 1 because

the surfaces are covered with most of a monolayer of adsorbed helium in the range of operation, although for bare metal, it would be considerably lower. $\gamma$ is the specific heat ratio, which is 5/3 for helium. R is the gas constant, and M is the mass per mole of gas in grams. P is the pressure, $T_1$ and $T_2$ the temperatures of the two parallel plates of copper, and $T$ the effective temperature of the gas between them. In the "on" state of the switch, $T_1$ and $T_2$ are nearly equal and T may be assumed to be the average. For estimation purposes, we will assume the same for the "off" state where they may vary by a factor of as much as 4, and where the gas "temperature" may be ill defined, since there is no chance for the atoms in the gas to thermalize. Nonetheless, this would only make a factor of 2 difference in the estimated thermal contact. We note that the heat transfer is directly proportional to the pressure. Substituting numerical values at 0.5K, we discover that

$$\dot{Q}/A\,\Delta T = 0.7 \times P \; WK^{-1}cm^{-2}Torr^{-1} \; ,$$

and that at the pressure of $1.4 \times 10^{-3}$ Torr where the mean free path reaches 0.2 mm and for the nominal surface area of our copper surfaces we have $\dot{Q}/\Delta T = 4 \; mW/K$. This is a factor of 3 lower than the performance actually measured on the prototype switch. There are two factors which may help to explain this discrepancy. First, we have tried to increase the effective surface areas by sandblasting the surfaces to give them a rough texture before assembling the switch. This may well have increased the area of each surface by a factor of 2. Second, it is an oversimplification to believe that there is an abrupt transition from a regime of conductivity proportional to pressure until the mean free path reaches the gap, followed by a pressure independent regime. It is quite likely that there is another factor of two increase, although not strictly linear in pressure, as we pass through this region. In any case, the kinetic theory arguments give an approximate agreement with the "on" conductivity. It is also clear that it is necessary to reduce the pressure to about $10^{-6}$ Torr in order for the switch conductivity to be dominated completely by the residual metallic conductivity through the CuNi tubing.

## 4.   SWITCHING TIME

### 4.1.   Turn-on Time

The time required to turn the switch into the "on" state is a matter of a few seconds. Heat (approximately 2 mW) is applied to the activated charcoal sorb, and the gas is quite quickly desorbed. The process can be expedited by giving an extra pulse of heat for one or two seconds at the start of the switching.
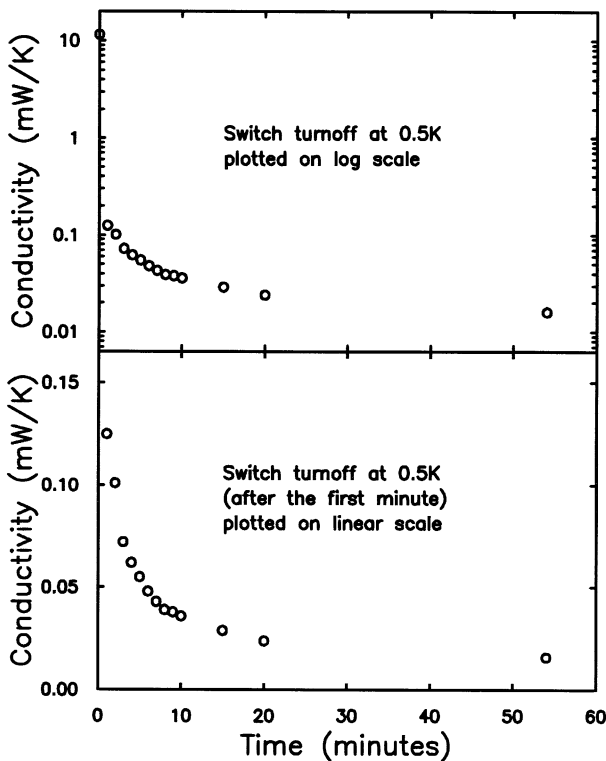
Fig. 3. Switching behavior at 0.5K, on semi-log and linear plots

## 4.2.    Turn-off Time

The switching into the "off" state is limited by the gas transport in the small gaps of the device. The conductivity changes rapidly by a factor of 100 within the first minute, by an additional factor of 3 within ten minutes, and ultimately by a final factor of two on the hour time scale. Three contributory factors to the switching time are the accessibility of the large surface area of the charcoal sorb, the dimensions of the gap between the copper pieces, and of the CuNi tube connecting to the sorb, and the adsorbed film of $^3$He gas on all the internal surfaces. Changes in the geometry of the switch have made major improvements in the transition time.

### 4.3.   Sorb Geometry

Our first effort used a single cylinder of activated charcoal, approximately 2.7 mm in diameter and 4 mm long. This resulted in a very slow pumpout time. We improved access of the gas to the surface by dividing the charcoal into 12 thin slices, each with a 0.5 mm hole through the middle. These slices were packed into a brass tube of length approximately 5 mm. Decreasing the distance which the gas was required to diffuse in from the surface seemed to make a major difference in performance.

### 4.4.   Gas Pumping Speed

As we are in the molecular flow regime for the entire range of interest for this problem, with the mean free path of the gas limited by the separation between walls, the pumping speed is pressure independent. We can consider the gas flow through the gap between the copper cylinders to be well represented by the formula for a rectangular tube of length $l$, and cross-section $a \times b$, all these dimensions in cm, for a gas of mass M grams/mole at a temperature T in Kelvin:

$$F = 9.70 \frac{a^2 b^2}{(a+b)l} (\frac{T}{M})^{1/2} \; liter \, sec^{-1} \; .$$

A similar formula holds for the cylindrical tube connecting to the sorb:

$$F = 30.48 \frac{a^3}{l} (\frac{T}{M})^{1/2} \; liter \, sec^{-1} \; .$$

For our case, the pumping speed in the thin gaps between the copper tubes $(2.5 \times 10^{-3} \; ls^{-1})$ is a factor of 10 better than that $(2.6 \times 10^{-4} \; ls^{-1})$ through the small CuNi tube. Since the pumping speed is independent of pressure in this regime, we may write

$$\dot{P} V_0 = FP \; .$$

Integrating and substituting numerical values gives us

$$P = P_0 e^{-\frac{F}{V_0} t} = P_0 e^{-1.4t} \; .$$

In principle, to decrease P by a factor of $10^4 = e^{9.2}$ would only require about 7 seconds. Clearly, something else is limiting the turnoff period. There are at least three reasonable candidates for the reduced rate. First, it may be necessary to make even more of the surface area of the activated charcoal

more immediately exposed to the helium vapor. This could be achieved by pulverizing the charcoal into very small grains. However, it could be that removing the heat of adsorption from the charcoal is in fact a limitation, and if this is the case, decoupling much of the charcoal from direct physical contact with the metal walls of the container could worsen rather than improve the pumping speed. A further possibility is that the surfaces are likely all coated with a monolayer or more of liquid helium when the pressure is maintained at several microns of pressure. How does the number of atoms in a monolayer on the copper surfaces compare with the number in the gas phase in the region of interest, near 0.1 micron of pressure? The quantity of helium in a monolayer on 30 cm$^2$ is about $7 \times 10^{-4}$ cm$^3$ at STP, whereas at 0.1 micron of pressure in the 0.2 cm$^3$ volume of the switch there is only about $1.5 \times 10^{-5}$ cm$^3$ at STP, so as the pressure drops through this range, the adsorbed gas represents a slowly evolving source several hundred times greater than in our original estimate.

## REFERENCES

1. J.P. Torre and G. Chanin, *Rev. Sci. Inst.* **55**, 213 (1984).
2. J.N. Haasbroek, *Thesis*, University of Leiden (1971).
3. See, for example, E.H. Kennard, *Kinetic Theory of Gases* (McGraw-Hill, New York, 1938).