A ^{3}He-GAP HEAT SWITCH FOR USE BELOW 2 K IN ZERO G

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ABSTRACT

We have designed and tested a compact heat switch that has a simple design and a very large ON / OFF ratio. The design uses concentric cylinders of copper that can be fabricated with higher precision and with thinner web thickness than other designs. It is assembled with a technique that carefully controls the narrow gap between adjacent segments. These features allow a very large surface area for conduction to be fitted into a small volume. The conduction medium is liquid or gaseous ^{3}He which is put into or taken out of the switch by a small nearby charcoal pump in order to avoid an external mechanical pump and a long pump line.

Measurements of its performance down to 1 K show an ON / OFF conduction ratio of ~4000.

INTRODUCTION

We have been developing a ^{3}He-^{4}He dilution refrigerator for space applications[1] that will require the use of heat switches to couple and uncouple various chambers from the system heat sink and from each other. In order to maintain the advantages of no moving parts and of operation by charcoal pumps which the dilution refrigerator exhibits, we want to have a heat switch which uses gaseous or liquid helium as a thermal conduction medium that is pumped out by a charcoal pump when isolation between the two halves of the switch is needed.

For these tests liquid and gaseous ^{3}He was used as the conduction medium. We felt that the higher vapor pressure of ^{3}He at 1 K would make it faster to pump out of the switch than ^{4}He. In addition, we wanted to evaluate the suitability of ^{3}He gas in anticipation of needing a switch to operate at 0.4 K where 4He has too low a vapor pressure to be used.

For our purposes it is necessary for the switch to be very compact and to have a large ON / OFF ratio. In addition, it is necessary for the OFF conduction to be very small. Because ^{3}He is not a very good thermal conductor, it is necessary to make the area across which the heat flows as large as possible and to make the distance the heat must flow through the helium as short as possible in order to achieve a good ON conduction. This suggests a design with a number of copper conductors of large surface area projecting from each end of the switch. These should then be assembled so that the surfaces from one end overlap those from the other end without touching them but with as small a gap as possible between them.

The compactness of the design is mainly a question of how thin the conductors can be made and how many of these plates can be squeezed into a given volume. For ease of machining and good mechanical stability of the resultant parts we felt that cylindrical geometry for the conductors was advantageous; it is extremely difficult to fabricate very thin, large plates of copper that will maintain their flatness and alignment to the degree necessary for this application.

Other designs of similar switches have either been able to relax the compactness requirement and use rather thick copper conductors[2,3], or they have been able to relax the low OFF conduction requirement and allow the conductors to touch in a few places[4]. This allows the gaps to be made smaller and allows the fabrication and assembly to be less critical.

HEAT SWITCH DESIGN

Figure 1 shows the design we have developed. It consists of a series of telescoping copper cylinders attached to each end of the switch in such a way that there is only a very narrow gap between adjacent cylinders when the two halves are assembled. The two halves are joined by a thin-wall stainless steel cylinder that serves to contain the helium but conducts very little heat between the two ends.

The overall length of the switch is 2.9 cm and the diameter of the housing is 1.5 cm. After

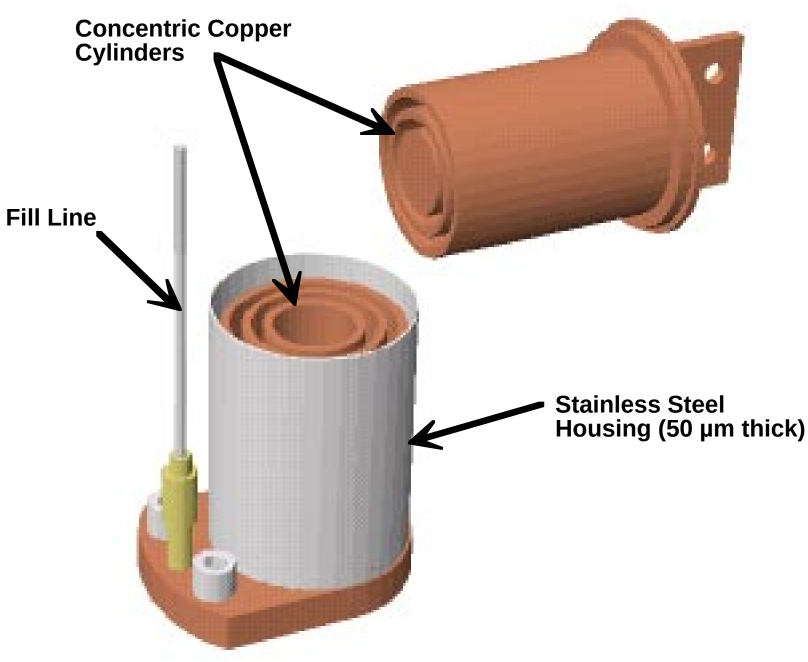

Fig. 1. Design of cylindrical heat switch.

assembly the gaps between adjacent cylinders are 0.01 cm and the total surface area across which heat flows is 26 cm^2. The wall thickness of the copper cylinders is 0.07 cm and their inner diameters are chosen to match standard reamer sizes with 1/16 inch increments. In this way the inner surfaces can be accurately reamed and the outer surfaces can be accurately turned on a lathe to achieve the precision needed to produce the close gap between cylinders that is desired when the cylinders are assembled.

The copper cylinders are silver soldered into shallow grooves in the copper end pieces. During this operation and also during the final assembly of the two halves of the switch the alignment of the parts is controlled by temporarily inserting a number of 0.01 cm diameter wires into the gaps between cylinders through small holes in the end caps; the holes in the top cap are later sealed with epoxy and the holes in the bottom cap become the access holes for helium to flow into and out of the gap spaces. These details are shown in a cross section view of the switch in Fig. 2.

When the helium is pumped out of the switch the only thermal path between the two ends is through the outer housing. Therefore, the housing was made from stainless steel and its wall thickness was made as thin as possible. We were able to make this only 50 μm thick by putting a thick-walled stainless steel tube of the correct inner diameter onto a tightly-fitting aluminum mandrel and then turning down the excess thickness on a lathe.

HEAT SWITCH TESTING

The switch was tested down to 1 K by mounting it on a ^{4}He pot that could be cooled to 0.9 K with no load on it. Pumping of the helium in the switch was provided by a large charcoal pump designed for other purposes. It was connected to the switch by a long pumping tube required in order to expedite the switch evaluation. These circumstances meant that it took

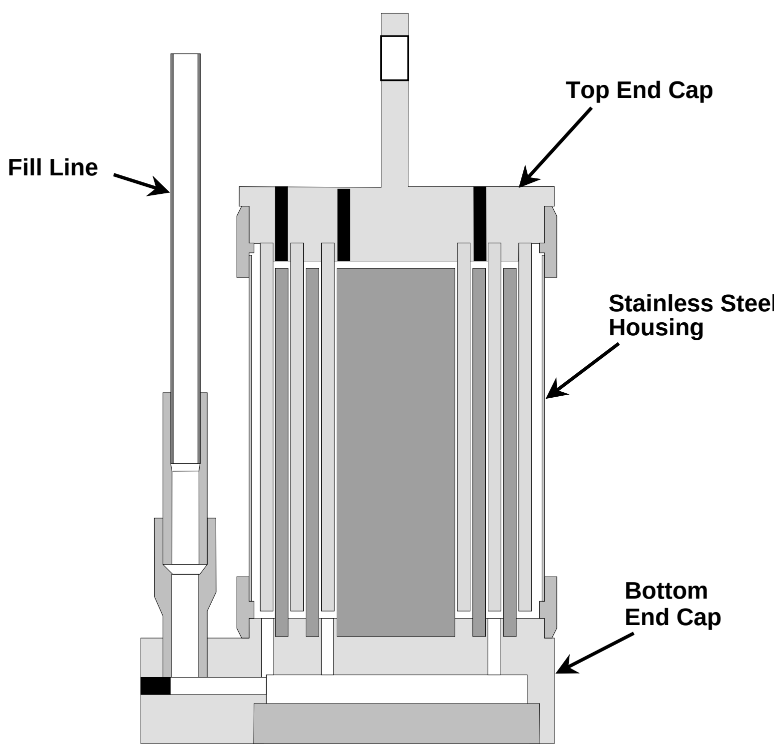

Fig. 2. Cross section of heat switch.

quite a long time to pump the helium out of the switch and that no meaningful conclusion could be drawn about the cycling speed of the switch.

Because this switch has a small thermal resistance in the ON state, it is necessary to be very careful in setting up the measurement in order to be sure that extraneous thermal resistances outside the switch aren't included in the switch measurement. In particular, it was observed in preliminary measurements that the thermal resistances of the bolted joints that connected the switch to the ^{4}He pot on one end and to a heater on the other end were almost as big as the thermal resistance of the switch itself in the ON state. For this reason the thermometers measuring the temperature drop across the switch were mounted directly on the end caps of the switch, not on the ^{4}He pot or the heater.

RESULTS

Measurements were made at 77 K, 4.2 K, 2.0 K, and 1.0 K. Conduction of the switch with ^{3}He gas was measured at all temperatures and with ^{3}He liquid in the switch at 2.0 K and 1.0 K. It was observed that the temperature of the switch increased as the applied power went up due to a warm-up of the ^{4}He pot. Similar effects occur at all our measuring temperatures but were most apparent at 1 K. One effect of this warm-up is shown in Fig. 3. Because the temperature of the switch is changing as power is applied, ΔT is no longer a linear function of Q. It is easy to show that if the thermal conductivity of a material is proportional to T, $\kappa(T) = kT$ (as is nearly true in this case), then the expression for heat flow across a large temperature difference is:

$$\dot{Q} = \frac{kA}{2L}\left(T_2^2 - T_1^2\right) \qquad (1)$$

where T_2 and T_1 are the temperatures at the ends of the heat flow, A is the area of the heat flow path and L is the length of the path. Figure 4 shows the good agreement of the data with the form of Eq. 1. The slope of the straight line is the factor $2L/kA$, so that the conductance of the switch, $\kappa(T)A/L$, is just $2T/(\text{slope})$. The ON conductance of the switch, k_3A_g/L_g, is then 4.37 x

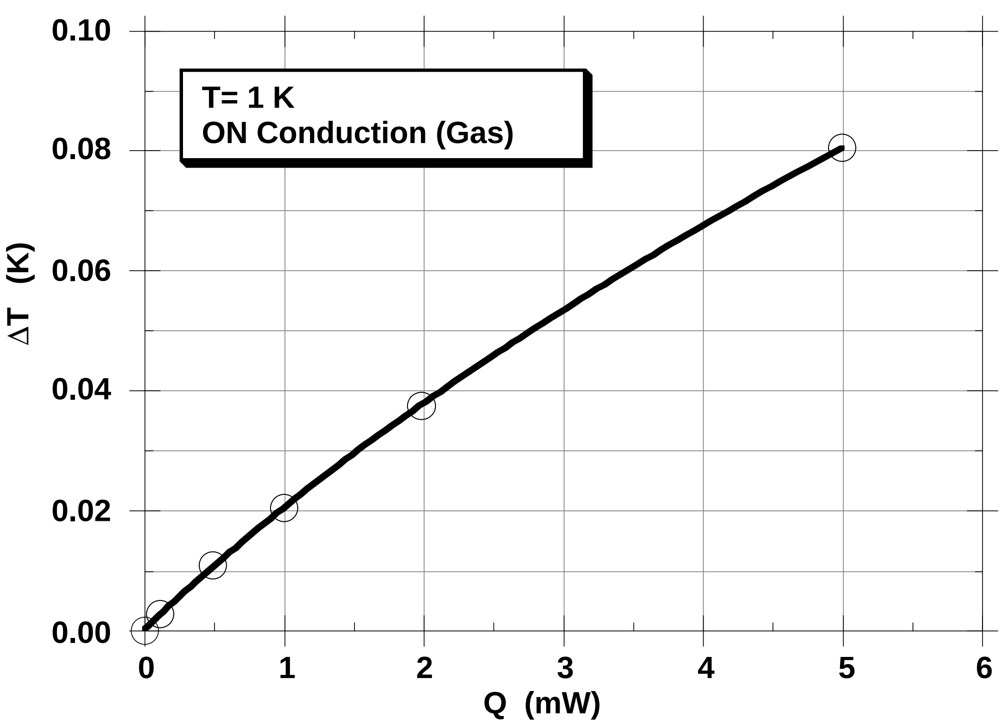

Fig. 3. Temperature differences at 1 K showing non-linearity due to warm-up.

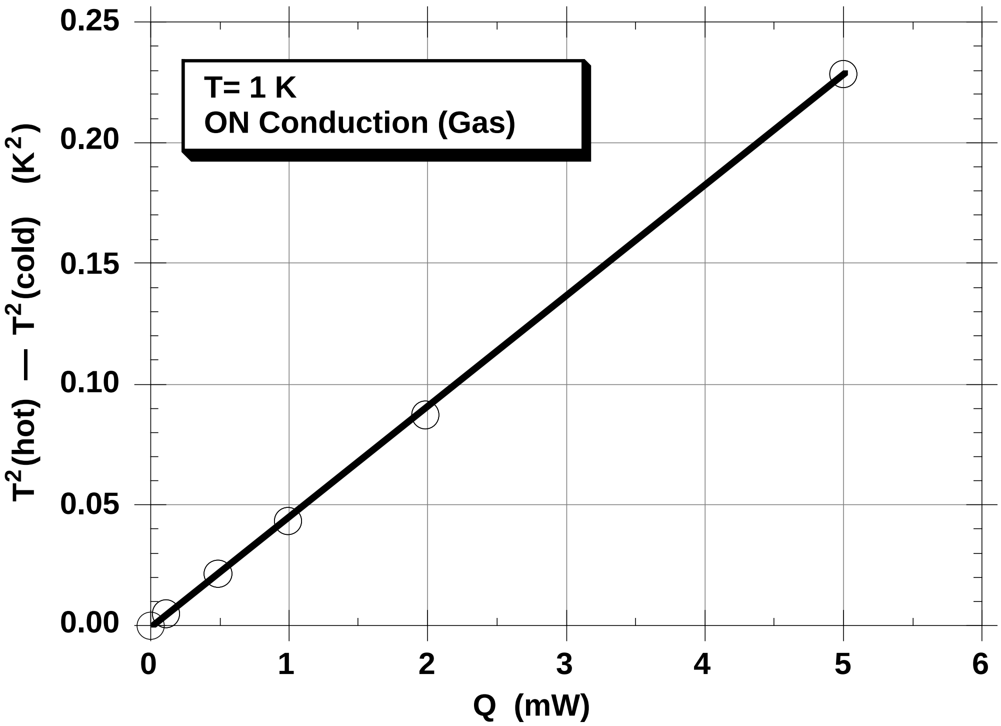

Fig. 4 Linearity of differences in T^2 for ON conduction.

10^{-2} •T W/K, where κ_3 is the ^{3}He gas conductivity, A_g is the surface area and L_g is the length of the gas gap (A_g/L_g = 20.7 m for our switch).

The gas pressure in the switch was monitored by a thermocouple gauge at room temperature. It was coupled to the low temperature region by a 0.3 cm dia. tube so that thermomolecular pressure corrections would need to be made in interpreting its measurements at the lowest pressures. For the measurements reported here, the pressure in the switch was between 60 and 260 Pa. At these pressures the conduction was essentially pressure independent. A test at 1 K showed a large increase in the conductance in going from below 0.1 Pa to 3 Pa pressure in the switch, after which the conductance increased very little with higher pressures.

It took many hours to pump the gas out of the heat switch at 1 K in the configuration we had. The pumping line between the charcoal pump and the heat switch was very long in order to expedite the test on our dilution refrigerator system. Calculations suggest that this pumpout time should not be nearly so long even with the excessively long pump line. Part of the problem might be the slow desorption of a monolayer of helium from the switch surfaces.

In order to measure the OFF conduction, the switch was pumped overnight at 4.2 K. This consistently gave the same, very low conduction value. Very low powers were applied in this case and the temperatures of the cold end of the switch and the ^{4}He pot changed very little during the measurement. The OFF conductance of the switch, $\kappa_s A_h/L_h$, is 1.20 x 10^{-5} •T W/K, where ks is the conductivity, A_h is the cross-sectional area and L_h is the length of the stainless steel housing (A_h/L_h = 1.6 x 10^{-4} m for our switch). At 1K the ON/OFF conductance ratio is 3640 for ^{3}He gas.

At 2.0 K the pumping speed of the charcoal pump on the ^{4}He pot could be controlled somewhat by heating the charcoal and the base temperature for the measurement didn't vary as much as in the previous case. At 4.2 K the ^{4}He pot was not pumped but it did contain liquid helium that was in contact with the 4.2 K bath by a heat-pipe refluxing mechanism. Because of this effect the pot only warmed from 4.26 to 4.49 K when 20 mW was applied to the heat switch.

At 77 K our calibrated germanium resistance thermometers are rather insensitive so we obtained only one measurement of the ON state at the maximum power we could safely apply, 100 mW. This produced a temperature difference of 0.15 K across the switch while causing the temperature to drift up at a rate of 0.06 K/min. We don't feel that this data point is more accurate than ±10%.

By applying pressures greater than 1.2 kPa at 1 K and greater than 20 kPa at 2 K, liquid ^{3}He could be condensed into the switch. The effect of the condensing helium could clearly be seen as a large load on the ^{4}He pot. We could be sure when the switch was full by noting when the ^{3}He pressure stayed constant at a value much greater than the vapor pressure for that temperature, indicating that both the switch and the filling line beyond the ^{4}He pot were filled with liquid. Interestingly, the conduction of the switch with liquid was only slightly greater than that with gas. The time needed to remove the liquid was much longer, however.

Figure 5 summarizes the measurements at all the temperatures for which we have data. Between 1 and 2 K the ratio of ON and OFF conductions are ~3600 for the gas and ~4300 for the liquid. The OFF conductions are just what we would expect for typical conductivities of our thin-wall stainless steel housing. At higher temperatures the ON/OFF ratio is not as good because the ^{3}He gas conductivity does not go up as fast with temperature as the stainless steel conductivity.

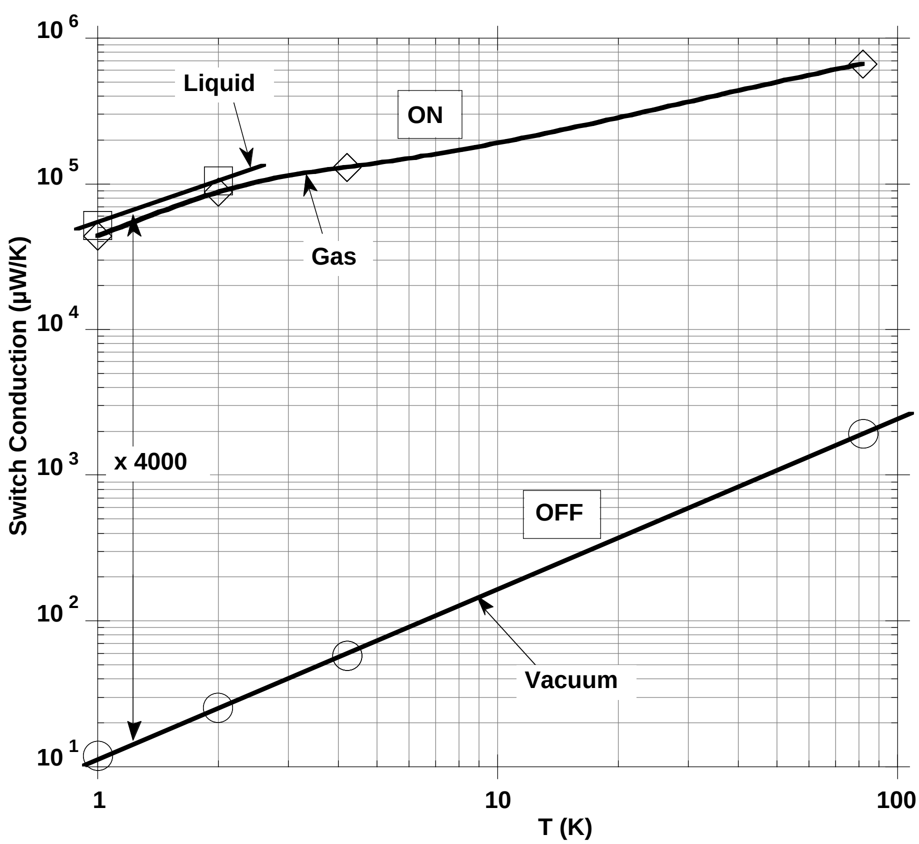

Fig. 5. Conduction of heat switch in OFF mode and in ON mode with both gaseous and liquid ^{3}He.

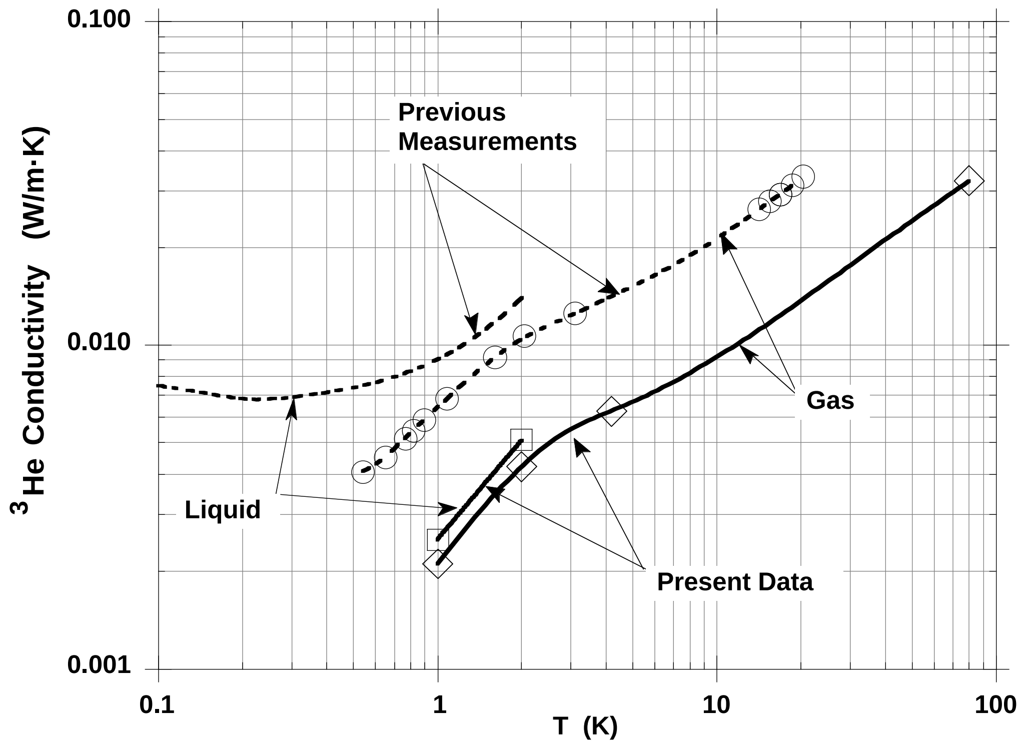

Fig. 6. Thermal conductivity of ^{3}He derived from present experiment.

ANALYSIS

The thermal conductivity of both ^{3}He liquid and gas as derived from our measurements are shown in Fig. 6. For comparison are shown previous measurements for liquid[5] and for gas[6]. The points for gas conductivity from 14 to 20 K are derived from viscosity measurements. The relationship[7] $\kappa = \varepsilon \eta C_v$ relates the conductivity, κ, to the viscosity, η, where ε = 2.50 for helium and $C_v = 3R/2M = 4160$ J/kg·K is the constant volume heat capacity where R is the molar gas constant and M is the molecular weight of ^{3}He.

Clearly, the conductivity results from our present data are about a factor of 3 too low. Since this discrepancy appears rather temperature independent over a wide temperature range, it is most likely due to an unexpected thermal resistance which has a temperature dependence that is similar to that of the helium. Many impure metals have conductivities that behave like this. In particular, if one estimates the effect of the silver solder at the end of the copper cylinders by assuming it has 1/100th the conductivity of copper and is 0.013 cm thick (much thicker than we would expect), it has enough thermal resistance to explain the discrepancy.

CONCLUSIONS

We have demonstrated the performance of a compact heat switch down to 1 K with both liquid and gaseous ^{3}He. Although it is quite compact, it has a very large surface area for conduction across a thin layer of helium, it has a very low conduction when OFF and the design prevents accidental touches between the conductors from opposite ends of the switch. The ratio of ON conduction to OFF conduction is ~4000 at 1–2 K, and we believe it would be 3 times higher if the silver solder joints at the ends of the copper cylinders were improved.

The use of this switch with liquid ^{3}He seems to have little advantage over gaseous ^{3}He at temperatures of 1 K and above. For lower temperatures we observed that the conduction is quite good with a gas pressure of 3 Pa (measured at room temperature, – it would be only 1.3 Pa in the switch because of the thermomolecular pressure drop[8] in our pressure-measuring tube). This means that the switch should be very useful with ^{3}He gas down to 0.35 K. At this temperature the vapor pressure of ^{3}He drops below 1 Pa and the gas conduction must start falling off rapidly. At temperatures below 0.35 K it would be necessary to use liquid ^{3}He in the switch. The heat load caused by the condensation of the liquid into the switch could be a problem, however, and it is not clear from our present results how easily the liquid could be pumped out of the switch at very low temperatures. At 1 K there seems to be a problem even pumping gas out of the switch. The determination of the seriousness of this problem awaits further measurements with a better pumping geometry.

In zero gravity the use of gas in the switch presents no difficulties. We believe that liquid could also be used in the switch for arbitrary directions of acceleration and zero G. Since the switch would be the coldest point along its pumping line, stray liquid would tend to evaporate at warmer points outside the switch and condense back into the switch. The most serious problem we would anticipate is that a refluxing flow could be established where liquid arrived at the hot charcoal pump, evaporated and the warm gas returned and heated the switch. This is a problem only if the liquid can flow directly to the pump without collecting in the pumping line and blocking it. If the pumping line is spirally wrapped around the switch then for any direction of force on the liquid stray liquid would have to collect somewhere in the line and the refluxing flow of gas would be blocked. In zero G the potential for this problem disappears.

The liquid could be pumped out of the switch without difficulty as long as the switch was at a high enough temperature for the vapor pressure to be able to push plugs of liquid toward the pump if such plugs were to fill the line.

ACKNOWLEDGEMENTS

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