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Heat switches for ADRs



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ABSTRACT

Heat switches are key elements in the cyclic operation of Adiabatic Demagnetization Refrigerators (ADRs). Several of the types of heat switches that have been used for ADRs are described in this paper. Key elements in selection and design of these switches include not only ON/OFF switching ratio, but also method of actuation, size, weight, and structural soundness. Some of the trade-off are detailed in this paper.

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1. Introduction – requirements

Because the Adiabatic Demagnetization Refrigerator (ADR) uses a cyclic process to obtain cooling, alternately magnetizing and demagnetizing a salt pill at high and low temperatures, efficient thermal switches are needed. Over the years thermal switches using heat flow through a gas, through a mechanical connection of high conductance materials, through a variable conductance metal, and others have been used. Gas conduction can be used to make contact to a higher temperature heat sink, for instance a liquid helium reservoir, for the ON state, and pumping this gas away turns the switch OFF. In a gas-gap heat switch (GGHS) the gas is contained within the switch and the pump is a material that acts as a getter for that gas. Mechanical heat switches may be activated manually, by an electric motor, by a piezoelectric device, by a magneto-strictive material or hydraulically. Examples of variable conductance metals include superconductors and magneto-resistive pure metals.

Switching ratio (the relative ON and OFF conductance) of a heat switch is a commonly used metric, but this is usually inadequate to capture the different temperature boundaries in the ON and OFF state. Rather, it is important to focus on the average heat flow, or even better, the average entropy flow in the ON and OFF state of the heat switch [1].

Switching ratio is not the only crucial factor in the choice of heat switch: considerations for the design of heat switches for ADRs include size, mass, structural integrity, actuation method, reliability, speed of actuation, and ON conduction relative to OFF conduction, including all associated parasitics, e.g., wiring, and external structural support that contribute to the overall system

thermal efficiency. As a practical matter, it is also very useful if the switch is very conductive at higher temperatures in order to speed cool down and avoid the use of another switch just for that purpose.

2. Gas heat switches

Originally used with the first ADRs [2], helium gas was alternately filled and pumped out of a vacuum can to heat exchange the magneto-caloric material with a surrounding helium liquid bath. This is a very simple method, but does require an external vacuum pump and requires more time to evacuate the vacuum can than an in situ getter. The GGHS, first proposed in 1973 [3] and developed by Nast et al. [4,5], allows a more compact heat switch with high pumping speed, decreasing the pump out time and decreasing the residual gas pressure within the vacuum can. If the gas is contained within the switch, then gas contamination of other parts of the instrument is avoided.

For ADRs operating below 10 K the gases of choice are usually ^3He or ^4He , however, for temperatures above 5 K, H_2 is a viable option. ^3He has a higher conductance below 10 K, so is usually favored over ^4He . Below about 0.2 K GGHSs are not usable since the saturated vapor pressure of even ^3He is too low to provide much conduction.

2.1. Typical construction techniques

To obtain a low residual conductance in the OFF state, the GGHS shell, which also contains the active gas, must have low thermal conductance between the warm and cold ends. In the ON state the switch must have a large surface area and a small gap between the warm and cold surfaces, which the relatively low thermal conductivity gas fills. These two requirements force the design into

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one having high thermal conductance metal (usually Cu) arranged in either in concentric cylinders or interleaved fingers, separated by a gap limited by manufacturability or robustness to handling or vibration.

The need for hermetic gas containment, both when the switch is cold and when the switch is warm in a vacuum or surrounded by air, forces the use of shell materials that have a low permeability to helium and other constituents of air. GGHS switch shells have been made from polymers (for instance, Vespel™) [6,7] or composites, which are then lined with, or overlapped with a low conductance metal foil, bonded in place with epoxy [8]. The foil liner must be defect-free – pin holes would provide a disastrously large leak path. For example, heat switches used in the X-ray Spectrometer (XRS) [7] and HAWC [8] and the Soft X-ray Spectrometer (SXS) [9] are filled with 3–10 std. cm³ of ³He. To meet a design life of 5 years and lose no more than 25% of the charge (and not spoil the guard vacuum in the dewar), requires a leak/permeation rate of $<5 \times 10^{-9}$ std. cm³/s. A comparable switch of Vespel™ without foil was measured to have a permeation rate at room temperature of 1×10^{-5} std. cm³/s, over three orders of magnitude worse than required. Adherence of the foil to the shell has also been an issue. Pockets between the foil and shell led to high OFF conductance in XRS when ⁴He was used. The ⁴He formed a superfluid film trapped between the foil and the Vespel™ shell. Substituting ³He was successful in solving this problem on XRS.

As an alternative to polymers and composites, all metal shells have been used. At higher temperatures the conductivity of titanium alloy Ti 15-3-3-3 is sufficiently low so that a simple cylinder can be used for gas containment. Also, to decrease the thermal conductance by increasing the effective length of the sleeve, a stainless steel bellows has been used with an external support structure of Vespel (see Fig. 1) or Kevlar fibers. Recently the SXS ADR team developed a reentrant heat shell using welded Ti 15-3-3-3 to achieve very low OFF conductance even at low temperature [9]. The Ti 15-3-3-3 has a superconducting transition at about 3.8 K which results in a very low thermal conductivity at low temperature [10].

In a GGHS with a heated getter, the pumping line connecting the getter volume to the body of the heat switch must have a low thermal conductance. Typical charcoal getter-ON temperatures are 7–14 K, while the switch itself may be operating in the ON state at 1.3 K. The connecting line must also have relatively high gas flow conductance so that the GGHS can be turned off in

a reasonable time. To accomplish both of these goals, a heat sink is added midway down the pumping line so that the vast majority of the getter heat is intercepted at the heat sink and returned to a warmer temperature. In the design for the XRS heat switch, this still resulted in 1–3 mW being dumped to the heat intercept, in this case the helium tank. The SXS design [9] (Fig. 2) improved on this by providing a larger pumping path and by decreasing the heat capacity of the hot elements to speed the warm up and cool down of the getter. These improvements led to a turn ON/OFF time of less than 1 min and a steady state heater power of 0.3 mW or less.

The amount of helium contained in the body of the switch and the size and type of getter material determine the turn ON and OFF temperatures. Fig. 3 demonstrates this. The data represent different pressures of ³He sealed into the switch at room temperature. As the amount of helium is decreased, the transition temperature between ON and OFF increases in temperature and the conduction in the switch in the ON state decreases. To facilitate the ON/OFF transition time and heat required, the usual amount of helium and getter material used provides for a working pressure that is in the transition region between molecular and viscous flow. Thus adding heat to the getter can raise the pressure and increase the conductance of the switch.

2.2. Pumping speed

A subtle effect that was not previously appreciated surfaced during testing on XRS [11]. The pumping speed of the getter depends on its temperature. At lower getter temperature the helium is less mobile and cannot reach open areas as quickly as when warmer. For the XRS getter, which was inadvertently partly contaminated, this forced a slow stepping-down of the getter temperature to allow the switch to fully turn off. Alternatively, more getter material can be used, but this increases the turn ON temperature for the getter, since the majority of the helium is more strongly bound to the surface of the getter. The amount of gas and getter material in a GGHS is balanced to allow a turn ON tem-



Fig. 1. Bellows-sealed gas-gap heat switch with external Vespel™ SP-1 support. The outer diameter of the top and bottom flanges are 38 mm.

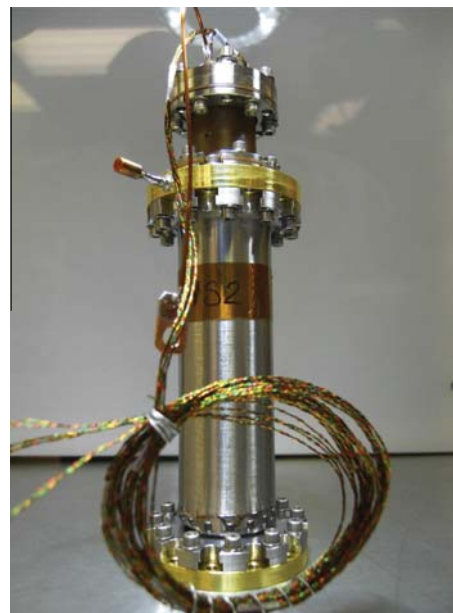


Fig. 2. SXS heat switch. The triple reentrant heat switch shell is made of Ti-15-3-3 alloy. The getter assembly is thermally isolated from the switch body and is at the top of the picture. Redundant thermometers and heaters are located at the top of the getter assembly. A large gauge copper wire is the thermal strap that carries the getter heat away from the switch.

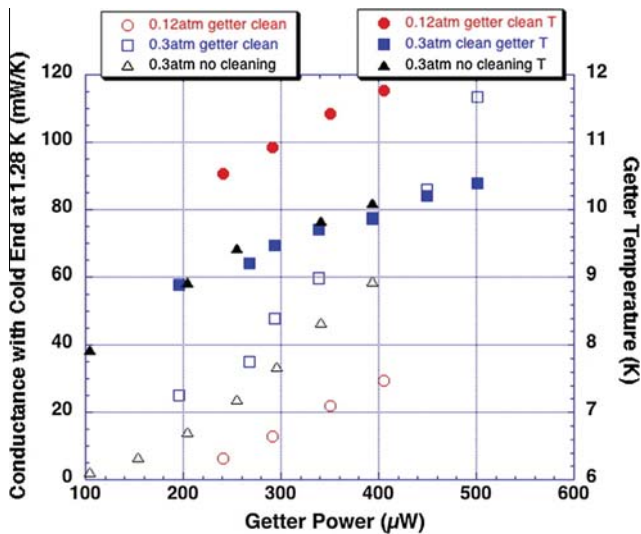


Fig. 3. Heat switch fill vs. conductance, getter temperature and heat applied. Data from Mark Kimball (unpublished). For some of the measurements the getter was cleaned by heating (50–70 °C) while evacuating it before filling with helium.

perature that is not too high as well as a turn OFF temperature that is high enough to be quickly reached when the getter heater is turned off.

The geometry of the XRS getter was partly responsible for its poor performance when contaminated. Zeolites adsorb gases by trapping them in atomic-sized spaces which can easily be shut off by small amounts of contaminants. GGHS getters produced using charcoal or graphite, which has a more open geometry, are not as susceptible to small levels of contamination.

The conductive elements of the GGHS also require engineering to provide high enough conductance of each finger or cylinder, while also providing the maximum surface area for gas conduction. Many times this requires the use of high purity copper. For support in extreme environments such as launch, the strength of each conductive element must also be considered. For SXS this is accomplished by tapering interleaved fins.

2.3. Passive gas gap heat switches

To simplify the operation of an ADR using fixed ON/OFF transition temperatures, an actively-heated getter may be replaced by a suitable passive getter anchored to the normally cold end of the heat switch. This method was first used by Duband et al. [12] as a method to speed cool down of a low temperature cooler, but not for cyclic operation at low temperature. Shirron et al. [13] and DiPirro et al. [14] developed the passive GGHS (PGGHS) to be used for self-actuated cyclic operation in ADRs. The principles of operation are as follows. The normally cold end of a heat switch contains a getter which rapidly adsorbs the active gas as this end of the heat switch is cooled by an ADR stage, turning the switch OFF. The switch turns ON when this ADR stage magnetizes to dump its heat to a higher temperature heat sink. The pressure in the switch is a very strong function of the getter temperature, and convenient gettering surfaces can be obtained for ^4He or ^3He (see Fig. 4).

A special case of the PGGHS is one in which the fins themselves are the adsorbing surface for the gas which condenses to form a thick film of liquid (^3He or ^4He) or solid (H_2) on the surface. The amount of gas in such a switch must be carefully chosen to not drip or fill the gap between the warm and cold surfaces when condensed. In this case the turn ON/OFF temperature is governed by the saturated vapor pressure of the gas.

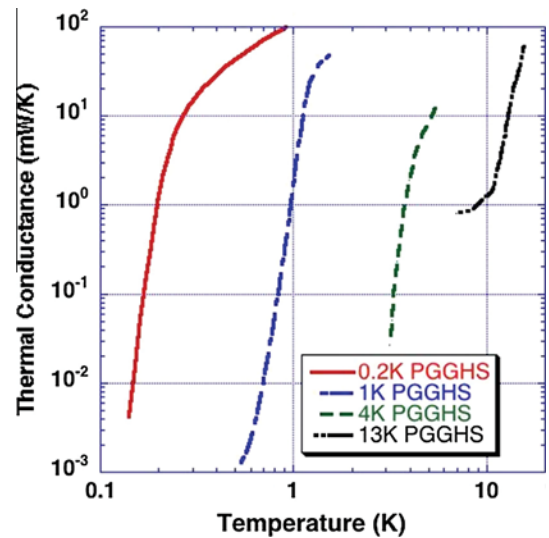


Fig. 4. Performance of various passive gas gap heat switches (from Ref. [14]).

Actually filling the gap with liquid was considered by several researchers [15,16] but the very slow rate of pumping of the liquid caused a very long turn off time, making these switches impractical [16].

3. Superconducting heat switches

An attractive type of heat switch that can be used at sub-Kelvin temperatures is the superconducting heat switch (SCHS). The switching element is a low temperature superconductor that normally has a very low thermal conductance when well below the superconducting temperature and a high thermal conductance at this same temperature when forced into the normal state by an applied magnetic field. Table 1 shows several pure metals [17,18] and the typical temperature where the thermal conductivity ratio is at least a factor of 100 between the normal and superconducting states. One can see from the table that the highest temperature for this ratio to be applicable is about 0.5 K. This sets the limit of the highest temperature of the warm end of this switch is for a practical OFF conductance. Conveniently this overlaps the applicability of the GGHSs and a complete 5–.03 K ADR system can be manufactured with just gas-gap and superconducting heat switches.

To preserve the thermal conductance of the system, the ends of the superconductor are terminated with a high thermal conductance material, such as high purity copper, to the thermal boundaries of the heat switch.

The magnetic field to turn the heat switch off is usually generated by a Helmholtz coil to maximize the uniformity of the field over the superconducting material while limiting the fringing field, which could generate eddy currents in the pure copper at the ends. A Helmholtz coil is used rather than a solenoid since it is important to provide a magnetic field perpendicular to the heat flow direc-

Table 1

Practical upper temperature for use of certain superconductors in heat switches. A perpendicular magnetic field is assumed.

Material	T_c (K)	H_c (mT)	T_{upper} (K)
Zn	0.85	5.3	<0.1
Al	1.2	10.5	0.1
In	3.4	29.3	0.5
Sn	3.7	30.9	0.52
Pb	7.2	80.3	0.5

tion. This limits the amount and direction of field lines that could become trapped inside the superconductor even after the external field has returned to zero. These field lines produce normal regions in the metal. If these lines extend from the cold to the warm ends of the heat switch, then the OFF conductance will be greatly increased. While the magnetic field destroys the superconductivity and raises the thermal conductance, it is also limiting the possible thermal conductivity due to the magneto-resistive effect [18]. Thus practical heat switches cannot obtain the highest ON conductance of a normal metal like copper. This also helps to explain why larger switching ratios are not obtained at higher temperatures for superconductors with a high transition temperature.

Lead, tin and indium have been used as the active element in the lowest temperature heat switch of the continuous ADR (CADR) [19]. Lead is the active element in the heat switch shown in Fig. 5. This switch construction is very rugged and is able to completely support the cold ADR stage. It is noted that the CADR requires the lowest temperature heat switch, in this case the superconducting heat switch needs to be ON at the lowest temperature and be OFF at the highest temperature.

3.1. Other considerations

The highest transition temperature element is niobium at 9.1 K. It would be expected that this would be a good candidate for a heat switch material, but its type-II behavior, trapping magnetic fields, makes it very difficult to obtain high switching ratios. Care must be taken with tin since it has a troublesome beta to alpha transition near room temperature, which can turn it brittle.

There is a small release of heat from a superconductor as it transitions from the normal to superconducting state. This needs to be considered when turning the switch OFF. For reasonably sized switches this heat is very small when considering the entropy of the attached magneto-caloric material.

4. Mechanical contact heat switches

Heat switches that work by making and breaking a mechanical high conductance contact are widely used in various laboratory and commercial apparatus. They are simple in concept: two different stages are connected or disconnected thermally by a movable contacting surface. In practice, the contact must have a considerable force or pressure between two very conductive surfaces [20,21], and the contact must be cleanly broken many times, which can also require considerable force to overcome stiction. Interstitial materials such as vacuum grease or indium foil, which are often



Fig. 5. Superconducting heat switch used in a CADR for temperatures below 0.35 K. The Helmholtz coil is stacked around a lead rod in the center of the picture. Gold-plated copper carries the heat between the top and bottom flanges. Vespel™-22 spacers provide mechanical support. The outer diameter of the heat switch is 38 mm.

used to enhance the conductance of pressed contacts, cannot be used for a contact that must be made and broken at low temperature. While other surfaces have been tested, gold-coated copper is the most widely used for its repeatability and high joint conductance.

Theoretically mechanical switches would have the benefit of complete thermal isolation in the OFF state. However, their size, mass, and alignment usually require supports across the gap, somewhat lessening this advantage.

4.1. Actuation

A wide variety of actuation methods have been used for mechanical heat switches. Most commonly used is an external actuator mechanism that can be operated by hand or motorized for automated actuation. External actuators need a hermetic feed-through and need careful thermal design and heat sinking to reduce parasitic heat loads from room temperature.

A reliable solenoid-actuated heat switch was developed for an ADR by Timbie et al. [22].

Hydraulic actuation through use of gas or liquid helium, which is most commonly used for low temperature valve operation, can transmit considerable force. However, the hydraulic line usually comes from a higher temperature and represents a very large heat leak if the warm end of the heat switch is below the superfluid ^4He transition.

In situ piezoelectric actuators have been tried, offering low dissipation and high force, but the displacement of a reasonably sized stack of piezoelectric transducers is very small, especially at low temperatures.

A larger displacement can be realized at low temperature and without dissipation by using magneto-strictive materials [23]. A modest magnetic field is required for this actuator which requires its own shielding for use with sensitive detectors.

The large forces involved in providing a separable contact require a rugged, and therefore, more massive structure than for a GGHS or superconducting heat switch. Activation techniques require use of a large mechanical advantage, further complicating the installation, and increasing the switch mass and size.

5. Other switches

There are other heat switch concepts that will be discussed briefly here. Mechanical heat switches based on the differential contraction of materials are generally not applicable at ADR temperatures since the coefficient of expansion is negligible for most materials in this region. Heating the switch to a higher temperature to produce an expansion is counter-productive.

The magneto-resistive effect in pure materials can change the thermal conductance by several orders of magnitude [24]. A switch fabricated from pure tungsten was tested with good thermal results [25] (Fig. 6), but the material was quite brittle, and the fields required to actuate this switch were several Tesla. The only way such large fields could be obtained without added excessive bulk and complexity to an ADR system would be to incorporate the switch into the bore of an existing ADR stage and activate it passively. An analysis using this technique has been performed, but as yet this technique has not been used in an ADR system. See also results from Bartlett et al. [26].

^3He - ^4He diode heat switches were proposed and constructed in the 1950s. They make use of the relatively high conductance of pure ^4He and relatively low conductance of ^3He - ^4He mixtures [27]. These effects work over a limited temperature range (about 1–2.1 K) and require the heat flush effect wherein the ^3He is forced to one end or the other of the heat switch by heat flow. Because



Fig. 6. Tungsten magnetoresistive heat switch which is sliced into a meander path (center of picture). Above the switch is a copper bus bar and below the switch is a mounting surface to an ADR stage.

this switch has practically no conduction until reaching low temperature, as a practical matter, another switch must be used to aid cool down from higher temperatures.

⁴He film heat pipe/heat switches have also been constructed and had good ON/OFF performance [28]. Unfortunately this type of heat switch also suffers from low conductance at higher temperatures, so must be augmented by another switch for cool down.

6. Summary

Low temperature heat switches are key ingredients for ADRs. A number of different types of heat switches have been designed, fabricated and tested for this purpose. Gas-gap, superconducting, and mechanically activated heat switches have been successfully tested for various roles in laboratory and space flight ADRs. Key elements in their selection for use include: temperature range, switching ratio, actuation methods, ability to withstand mechanical loads, size and mass.

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