Heat switches providing low-activation power and quick-switching time for use in Cryogenic Multi-stage Refrigerators

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Abstract.

An adiabatic demagnetization refrigerator (ADR) is a solid-state cooler capable of achieving sub-Kelvin temperatures. It neither requires moving parts nor a density gradient in a working fluid making it ideal for use in space-based instruments. The flow of energy through the cooler is controlled by heat switches that allow heat transfer when on and isolate portions of the cooler when off. One type of switch uses helium gas as the switching medium. In the off state the gas is adsorbed in a getter thus breaking the thermal path through the switch. To activate the switch, the getter is heated to release helium into the switch body allowing it to complete the thermal path. A getter that has a small heat capacity and low thermal conductance to the body of the switch requires low-activation power. The cooler benefits from this in two ways: shorter recycle times and higher efficiency. We describe such a design here.

INTRODUCTION

One of the few—if not only—options to cool a detector in space to sub-Kelvin temperatures is an adiabatic demagnetization refrigerator. This solid-state cooler uses the change in entropy of a paramagnetic salt with a decreasing magnetic field to cool a detector attached to the pill. When the external field is near zero the individual magnetic moments within the pill self-align and therefore no further change in entropy may occur: no more cooling power. At this point the stage must be recycled by allowing heat to flow from it to a heat sink while the external field is increased. The bridge between the pill and heat sink is called a heat switch.

In the most simplistic terms a heat switch is a device that allows heat to flow through it when it is "on" and limits heat flow when "off". This can be done mechanically, allowing two surfaces to come in contact when on and separated them when off; using a superconducting wire, in the normal state the wire allows heat to flow but limits it when in the superconducting state; or by injecting or removing gas between interlaced sets of fins where one set is attached to one switch end and the other to the opposing end. The latter switch is knows as a gas-gap heat switch (GGHS) and is discussed further.

A GGHS uses a material that getters the working gas when cooled below some temperature. To turn the switch on the getter is heated above an activation temperature and gas leaves the getter and fills the volume between the finger sets. Thus heat flows down one set of fingers, transverses the gas, and continues through the second set of fingers to the opposite switch end. A cut-away view of a switch is shown in figure 1.

The switch described here is based upon a switch design used on the Astro-E and Astro-E2 missions [1]. The differences are the material used in the shell body, the geometry of the internal conduction fins, and the getter assembly. These differences are described below.

DETAILS OF THE SWITCH

Conduction Fins

Since the internal fins are a major portion of the thermal path through the switch a reasonably high thermal conductivity material is needed. For the present design we take a section of high-purity copper rod and machine it into a smaller diameter center region and two end flanges. Next, we use a wire electric discharge machining system (Wire EDM) to cut a well-defined path that traverses through the center region of the switch. This single cut produces two pieces; each containing one set of fins. Figure 1 shows a cross-section of the switch including the fins.

Originally we cut fins with a uniform thickness along their length. This is an easy geometry to produce with the Wire EDM and provides a reasonably large surface area for the thermal transport when gas fills the switch body. However, due to this geometry, individual fins have a resonant frequency with a moderate quality-factor

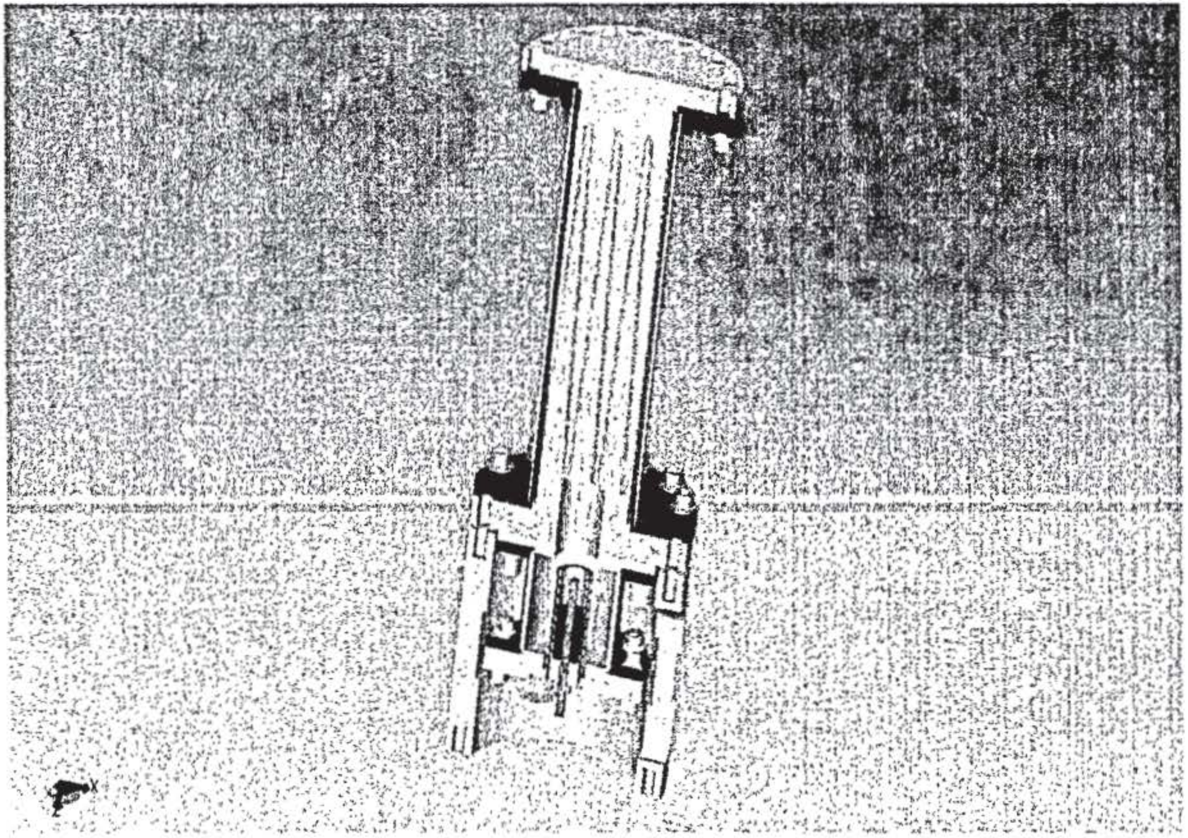

FIGURE 1. A cut-away model of a gas-gap heat switch (GGHS). The long-thin section is the interlaced fins surrounded by a hermetic outer shell. The getter assembly is the region toward the bottom of the figure. The getter material—activated charcoal in this design—is pierced by a copper pin. Below $\sim 6.5\ K$ gas is adsorbed within the charcoal and the switch is "off". Heat applied to the copper pin via a resistive heater drives the getter above an activation temperature where the gas is released and fills the gap between the interlaced fins. This "on" state allows heat to flow from one end of the switch to the other.

that lies within the frequency range of vibrations generated during a rocket launch. While fins knocking into one another during a launch is not problematic—as long as there is no permanent deformation—it was decided that raising the resonant frequency of the individual fins was the proper thing to do. Therefore the latest fin design involves cutting the solid spool of copper into triangular shapes. The surface area is nearly the same as fins that have a uniform thickness along their length but with a higher resonant frequency due to a stiffer geometry. Vibration testing of actual heat switches agrees with the mechanical modeling and proves that the tapered fin design has resonant frequencies outside the range typically experienced during a rocket launch.

Shell

The shell that surrounds the fins serves two purposes: it is a structural element of the switch and confines the gas when the switch is in the "on" state. Therefore it must be strong enough to support itself and the innards containing the conduction fins. This is balanced by the requirement that when the switch is "off" the heat flowing along the shell's length is minimized. This last requirement is the most difficult to achieve in practice.

Our latest switches use one of two classes of materials for the outer shell. Switches requiring the smallest possible heat leak while in the "off" state use composite shells. Here the use of uni-directional T300 carbon fiber or γ-alumina ceramic fibers provides substantially lower heat conduction than previous designs that use metallic bodies. Both T300 and γ-alumina are porous to helium gas at room temperature and therefore require that we bond a 0.0005 inch thick layer of titanium foil to the innermost composite surface. We find two layers of either composite material, wrapped at ± 30 degrees from axis of the tube, is sufficiently strong to support the switch's mass and provide a stable interface for both innards containing the conduction fins. The diameter of the shell is a trade-off between reducing the area through which heat can flow in the "off" state and the diameter of the fins contained within it. The latter directly limits the cross-sectional area used for conduction when the switch is "on". This is one of the trades performed when designing these switches.

Once a composite tube is produced it is mated to two flanges; one at each end, In the current design these flanges are copper and contain a thin circumferential groove with dimensions 0.040 wide by 0.150 inches deep.

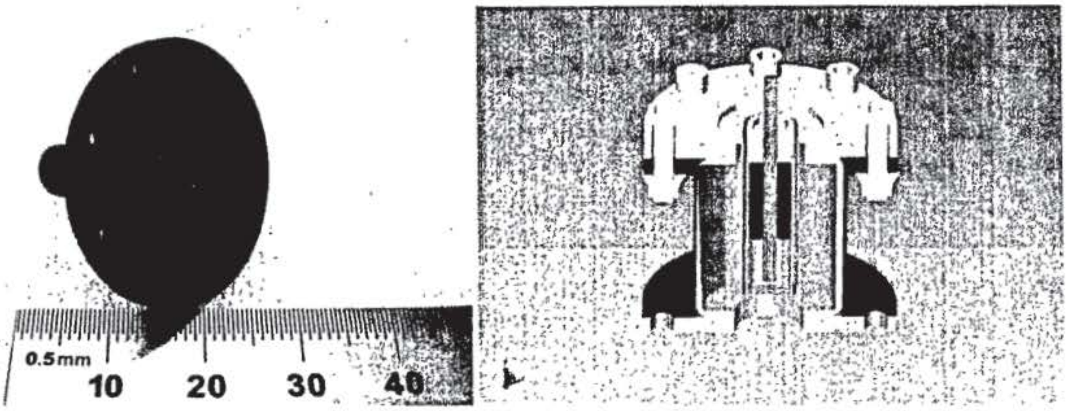

FIGURE 2. Our latest getter design. The charcoal getter is epoxied to a copper pin in the center. Heat applied to the pin raises the temperature of the charcoal and liberates helium gas. The getter is thermally stood off from the remainder of the getter assembly by a reentrant titanium tube. This provides the isolation needed to activate the switch with a relatively small power. Not shown in the figure are the two thermometers and two heaters attached to the free-end of the copper pin.

This groove accepts a composite tube that has been coated with a thin band of epoxy on the end. Once a flange is mated to each end the assembly is put into a fixture to align the flanges parallel to one another as well as determine the flange separation. The shell and flange subassembly is left in the fixture while the epoxy cures overnight.

A second design uses thin titanium shells with a larger diameter for the switch body compared to the composite-body version. Here we trade a higher heat flow when the switch is "off" for fins with a larger surface area. This allows a larger heat throughput when the switch is "on". This shell is made from titanium 15-3-3-3 cut from a billet using wire EDM. The sidewall thickness directly determines the "off" conduction and the current shells are 0.005 inches thick. This thin sidewall is close to the limit where a shell can support a pressure differential of one atmosphere across it. A thinner sidewall may implode during the pumpout step during the filling of the switch body with helium. Once the tube is created it is brazed to two 17-4PH stainless flanges. It would seem natural to mate the titanium tubes to titanium flanges, however, an indium seal is used to mate the innards containing the conduction fins to the shell flanges using an indium seal. Titanium oxide prevents a reliable indium seal and dictates we use another material. 17-4PH stainless steel has a coefficient of thermal expansion comparable to copper and makes a fine choice for the shell flanges.

Getter

The getter material is a piece of activated charcoal roughly 0.150 and 0.375 inches in diameter and length respectively. This is epoxied to a copper pin that is then brazed into slug of titanium that has been e-beam welded to a thin titanium tube. The tube is a reentrant design that provides thermal isolation between the copper pin and the remainder of the getter assembly in a compact design. This thin reentrant tube geometry is the reason relatively small power can be applied to the getter to activate the switch. When the switch is turned "off" heat drains from the charcoal through the thin titanium tube to a flange that has been thermally strapped to the ultimate heat sink. This flange is electron-beam welded to a stainless-steel bellows with another flange on the opposite end. This sub-assembly forms a hermetic seal when it is mated to the switch body. The convolutions of the bellows are purposely thin and have a cross-sectional thickness of 0.003 inches to minimize the heat transfered from the getter assembly to the heat switch innards. The convolutions are so thin that they cannot support their own weight. Therefore we surround the bellows with a Vespel support that has a flange on both ends and a side-wall thickness of 0.010 inches.

Figure 2 shows a cutaway model of the latest getter design. Not shown are the heaters and thermometers that are epoxied onto the free end of the copper pin. Note the large opening directly below the getter region. This provides a direct view of the getter into the switch interior and is largely responsible for the quick turn-off time not usually experienced with gas-gap heat switches. A second benefit to the low-impedance path from the getter to the switch interior is detailed in the section titled "Gas desorption effect".

The low mass of the getter and the thermal isolation of the charcoal pill from the remainder of the assembly allows the switch to be fully activated with as little as 0.200 mW of power. The data shown in figure 3 used a constant 0.280 μW to activate the switch.

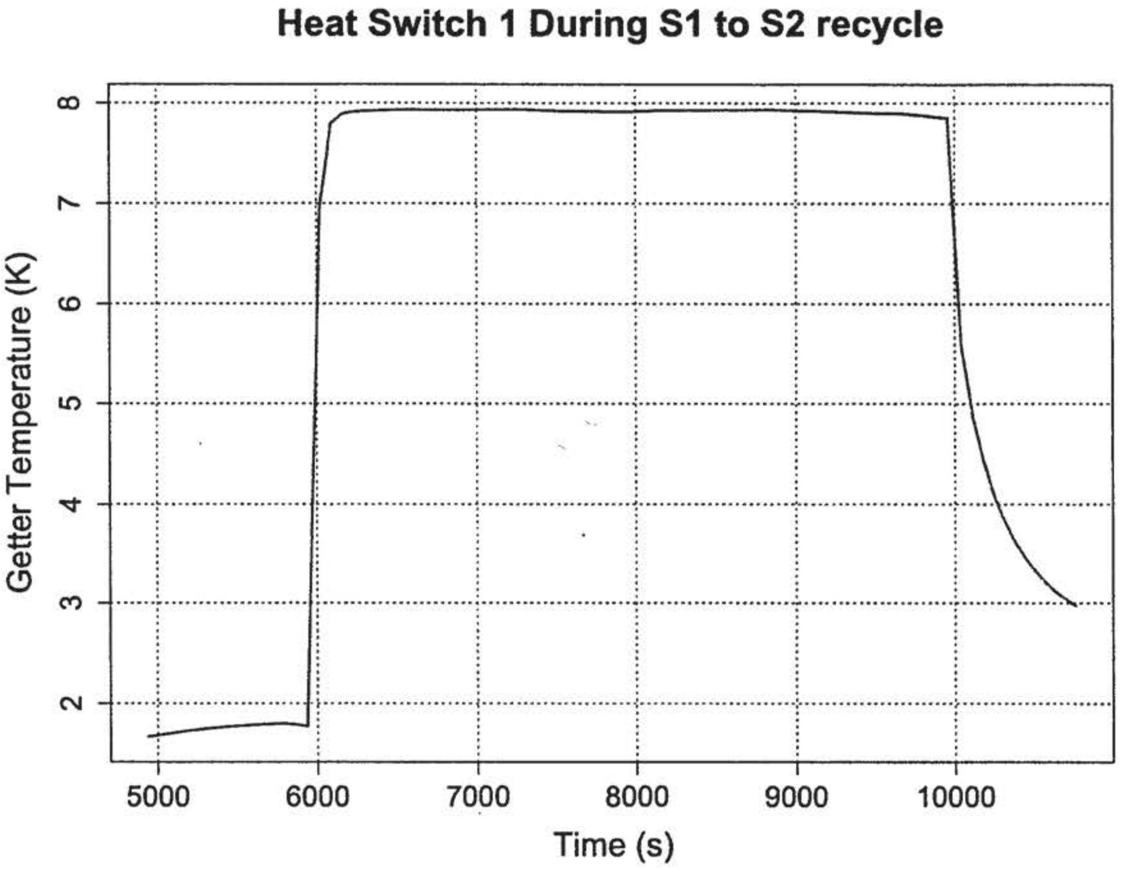

FIGURE 3. Temperature profile of the copper pin that pierces the charcoal getter when 0.280 μW of heat is applied to it. This particular switch separates the first and second stages of the Astro-H 3-stage ADR. During the time the switch is "on" the ends of the heat switch are at 0.8 and 0.72 K. The time axis is seconds after the current data file is started.

Gas desorption effect

In the past we have seen an effect in multi-stage refrigerators when one of two stages connected by a heat switch is rapidly warmed. The warming of one end of the switch may liberate gas that has condensed at that end causing the switch to partially turn on. The end result of this is a small flow of heat to the colder stage that lasts until the gas is adsorbed onto another cold surface or the getter itself. This effect may present itself as an oscillation in temperature at the cold end of the switch. Switches with a configuration that positions the getter remote from the switch body may be more susceptible to this effect. Here the connection between the getter and the switch body is typically a high-impedance line. When the switch is turned "off" some gas may adsorb onto surfaces away from the getter.

The design of this heat switch allows a low-impedance view into the interior of the switch since the getter assembly is intimate to the switch itself. Thus, when the switch is turned "off" and the getter begins to cool, the majority of the gas is adsorbed into the getter. Tests of this heat switch design have not produced the signature of gas being liberated from surfaces other than the getter.

PERFORMANCE

The particular switch described in this section is a composite-shell version in use between the two low-temperature stages of the Astro-H 3-stage ADR. At room temperature there is 0.5 atmospheres of ^{3}He contained within the switch.

Figure 3 shows a plot of getter temperature vs. time with 0.280 μW of heat applied to the copper pin that pierces the charcoal getter. The heat switch begins to thermally connect the two stages when the getter temperature rises about $\sim$ 6.5 K and is fully on at 8 K. The time from applying heat to the getter and the switch beginning to transmit heat is less than $\sim$ 1 minute and the switch is fully on in less than 3.0 minutes.

During the recycle of stage 1 to stage 2 one end of the switch is held at 0.8 K while the other is at 0.72 K.

The measured thermal conductivity at these temperatures is 16 mW/K. This is less than anticipated and adds roughly 50% to the estimated recycle time of the stage. Estimates of the conductivity show it should be closer to 50 mW/K. It should be noted that the measurement of the ΔT across the switch includes two bolted joints. There may be a temperature gradient in those joints that is not included in the calculation of the conductivity and therefore the switch itself may be performing closer to the expected value than the numbers show. A more careful examination of the joints between the thermal straps and the switch is necessary before any conclusion can be made.

CONCLUSION

The heat switches briefly described here are the baseline design for the 3-stage ADR built specifically for the Soft X-ray Spectrometer that will be part of the Astro-H satellite. Currently there are four heat switches, two composite-shell bodies and two titanium-shell bodies, integrated with the engineering model ADR. At the time of this writing the 3-stage ADR is mated with the engineering model detector assembly and is close to cooling to operating temperature to begin testing for the first time as a single unit.

REFERENCES

1. Canavan, E., Tuttle, J., Shirron, P., and DiPirro, M., "Performance of the XRS ADR Heat Switch," Kluwer Academic, 2000, vol. 45a of *Advances in cryogenic engineering*, URL `http://books.google.com/books?id=UmchZzeRfCMC`.