Heat switch technology for cryogenic thermal management

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Abstract. Systematic review is given of development of novel heat switches at cryogenic temperatures that alternatively provide high thermal connection or ideal thermal isolation to the cold mass. These cryogenic heat switches are widely applied in a variety of unique superconducting systems and critical space applications. The following types of heat switch devices are discussed: 1) magnetic levitation suspension, 2) shape memory alloys, 3) differential thermal expansion, 4) helium or hydrogen gap-gap, 5) superconducting, 6) piezoelectric, 7) cryogenic diode, 8) magneto-resistive, and 9) mechanical demountable connections. Advantages and limitations of different cryogenic heat switches are examined along with the outlook for future thermal management solutions in materials and cryogenic designs.

1. Introduction

Thermal management applications in the field of cryogenic engineering and related sciences are crucial. Often required is the heat switch, a novel device with an externally controlled variable heat conduction, working in a prescribed temperature range from about 50 mK to near 400 K. Heat switches can alternatively provide high thermal connection or ideal thermal isolation to the cold mass. Heat switches are used to minimize heat loads on the cooling system by disconnecting components when cooling is not required, or disconnecting redundant refrigerators that are turned off or failed. Heat switches also provide the vital thermal connection between objects and the cooling system as needed.

Various cryogenic detectors in space are normally cooled by a running cryocooler with a second redundant cryocooler as back-up. Such configurations rely on one heat switch to provide high thermally conductive connection to the running cryocooler and another heat switch to thermally isolate the redundant cryocooler [1,2]. Multi-stage adiabatic demagnetization refrigerators (ADR) are currently being developed for future x-ray, infrared, and sub-millimeter astronomy missions. Heat switches have long been successfully used in single stage magnetic refrigerators as well as developed for multi-stage demagnetization refrigerators [3,4,5]. For many scientific research efforts in the fields of condensed matter physics, optical/laser, and radio frequency experiments, novel heat switches were developed to thermally connect and/or isolate the objects to the LHe bath or cryogen-free cooling stage [6]. Heat switches have also been implemented in many other applications such as superconducting levitation.

For the basis of defining the heat switch ratio, a simplified example cryogenic heat switch (CHS) is shown in figure 1. With the switch closed, heat flows from the cooled object to the cryocooler at temperature T_c. For simplicity, the transition process is ignored so that the ΔT (or D) is constant and D is assumed much smaller than T_c. When the switch is opened, a degree of isolation between the cooled object and the redundant cooler is provided. The heat flow rate between the object and the two coolers is represented in equation (1).

$$\dot{Q}1 = \int_{Tc}^{Tc+D} K(1)dT \quad \text{and} \quad \dot{Q}2 = \int_{Tc+D}^{Th} K(0)dT \tag{1}$$

In practice, other parasitic heat flows into the coolers. Equation (1) assumes that the additional loads are either small or can be included in the thermal conductance (K). Common definitions of the heat switch ratio are given in equation (2). One option (left) is the thermal conductance ratio based on the physical properties of the switch and not on the application details. This approach allows evaluation of a potential switch prior to the development of the detailed design. The second option (right) is the ratio of heat flows representing the usage configuration of the switch including various parasitic losses.

$$R_k = K(1) / K(0) \quad \text{or} \quad R_h = \dot{Q}_1 / \dot{Q}_2 \tag{2}$$

There exist various kinds of heat switches for different cryogenic applications, each with its own advantages and limitations. One kind can work well in a particular application, but may underperform or even fail in another situation. The heat switch ratio is a non-dimensional parameter used to compare the performance of heat switches and strongly depends on the properties of materials of construction. The material properties depend on temperature. Therefore, the design of a given switch is highly limited to and dependent upon the temperature extremes of the application. The geometric configuration, weight limitation, and capacity of the available electrical power in the applications will also constrain the design. Numerous cryogenic heat switches (CHS) have been developed based on the above discussion, technical methods, and customers' varied requirements. These are briefly reviewed and discussed as follows.

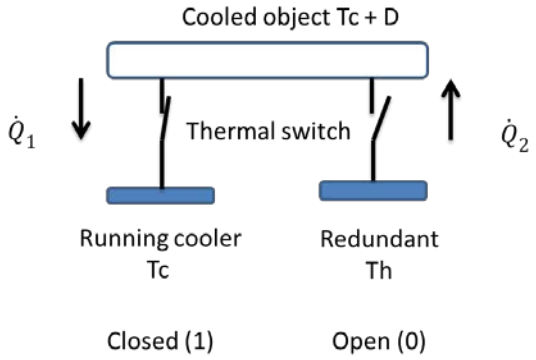

Figure 1. Simplified cryogenic heat switch (CHS) arrangement: instrument being cooled and redundant cryocooler off.

2. Cryogenic Thermal Diode Switch (CTDS)

The thermal diode described here is a device which causes heat to flow preferentially in one direction, like a heat-pump. It usually works with a type of heat pipe that will only allow heat to flow from the evaporator to the condenser. To provide the function of the heat switching, the heat pipe was modified by using small diameter stainless steel tubing to connect it to a liquid trap (LT) cooled by a small secondary cooler which is thermally isolated from the primary cooler. During normal operation, a small heater keeps the LT filled only with vapor. To effectively turn off the heat pipe, the primary cooler is heated, and the the small heater is ramped down, then the LT captures the working fluid.

Paulsen [7], Cepeda-Rizo [8], and Bugby [9] have developed several CTDS. The latter two devices employ a methane heat pipe with a liquid trap for on-off actuation. It allows heat to flow in only one direction (forward mode) to thermally manage two CCD cameras on the NASA/JPL SIM Lite telescope as shown in figure 2. The LT is positioned on the condenser end and it has its own cooling source. During normal operation, the small LT heater keeps the LT warm enough so that it is filled only with vapor while the heat pipe is on. To turn off the heat pipe, the LT heater is turned off and all working fluid migrates to the LT. With the heat pipe in the off condition, only a small amount of heater power is required on the evaporator end to achieve a significant temperature rise for decontamination. The heat pipe can be turned back on by simply re-powering the LT heater. At a hot-side temperature of 150 K the heat load is 6–12 W. The cold-side cryo-radiator is at 140 K with a transport length of 1.4 m. Periodically, the hot-side is heated to 293 K with minimal heater power for decontamination. The CTDS can also work for the cryocooler redundancy application. A suitable working gas should be chosen for each particular application depending on the operational temperature extremes.

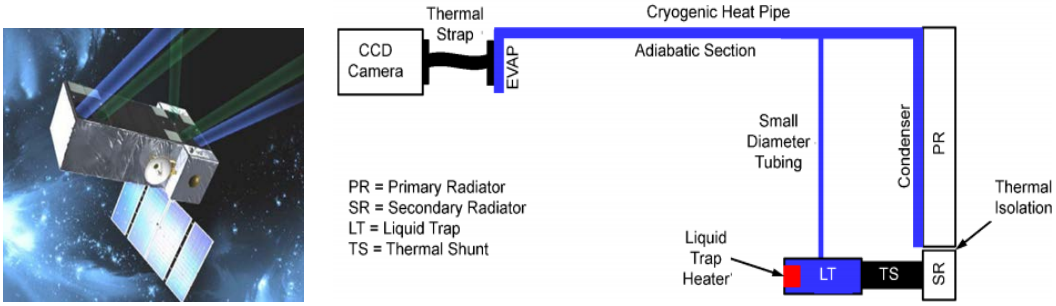

Figure 2. Camera aboard the SIM Lite observatory (left); concept of cryogenic heat switching using a heat pipe (right) [8-9].

3. Superconducting Heat Switch (SHS)

In pure metal the thermal conduction in the normal state is dominated by the electronic conduction term, and the lattice conduction term (phonon conductivity) can be neglected. As the metal becomes superconductive (table 1) its thermal conductance Ks falls below the value of the normal phase Kn. This decrease in thermal conductance is caused by the gradual disappearance from the thermal distribution of the free electrons. Therefore, the ratio the electronic thermal conductivity in the normal state to the phonon thermal conductivity in the superconducting state can be larger than 10^5.

Table 1. Several superconductors in CHS with perpendicular H assumed [5].

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

Based on the thermal properties of superconductors, various types of the SHS have been proposed, tested and implemented at very low temperatures [10-13]. For example, Krusius [10] developed a SHS with zinc foil for large heat flow below 50 mK. Zinc was chosen because of its advantages of mechanical performance, ease of soldering to copper base, and good thermal cycling.

To obtain higher total thermal conductance, a large cross sectional area of the switch is required. To avoid magnetic flux trapping, the switch is divided into smaller elements whose cross section to length is sufficiently small. The switch is thus composed of many parallel foils or wires. Krusius used nine 0.17-mm-thick zinc foils, which were indium soldered to copper end posts. The switch is operated by a small superconducting magnet with 65 mA to close the switch between a He^3–He^4 dilution refrigerator and an adiabatic demagnetization refrigerator (ADR) in the precooling process.

More challenges in recent high-resolution detectors for both space astronomy and some laboratory uses are requirements for targets cooled to extremely low temperature (below 50 mK) with much smaller heat loads (10 μW). These systems employ the use of mechanical coolers (instead of a dilution refrigerator) at higher precooling base temperatures (4–10 K). Shirron, Canavan, and Dipirro [11,13] have successfully designed and developed the multi-stage (3 and 4 stages) ADR system that can provide continuous cooling as summarized in figure 3.

Success of the continuous ADR also depends on having suitable heat switches. In the continuous stage, the switch must efficiently transfer heat at temperature difference of only 5–10 mK. The superconducting switch has the much higher on/off conductance ratio (from 10^5 at 50mK to about 10^3 for a magneto-resistive (MR) switch) and was chosen for Stage 1. The metal In (99.99 +%) with OFHC copper end pieces was used while Sn and Al was a design alternative. The superconducting heat switch has an on/off ratio of 2,000 at 50 mK with an on-stage conductance of 8 mW/K.

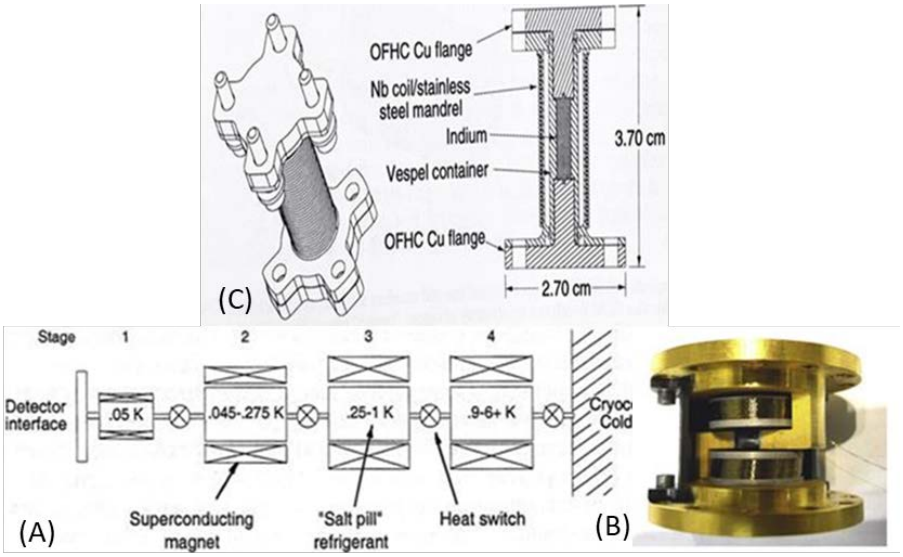

Figure 3. The 4-stage continuous ADR [13] (A); a photo of the SHS used in a continuous ADR [5] (B); the SHS in [11] (C).

4. Magneto-resistive Heat Switch (MHS)

At low temperature, electron thermal conductivity is a linear function of temperature, while phonon thermal conductivity drops off as the cube of the absolute temperature. Electronic heat conduction in compensated elemental metals (Ga, Cd, Be, Zn, Mo, and W) at low temperature can be suppressed so thoroughly by a several Tesla magnetic field that the heat is effectively carried only by phonons. In 1-mm diameter single crystal samples, the ratio of zero field to high-field thermal conductivity can exceed 10,000. Duval [14], Tai [15], Canavan [5,16] and others, used this phenomenon to build solid-state cryogenic heat switch (CHS) with no moving parts and no enclosed fluid.

In a standard ADR the magneto-resistive (MR) heat switch would require a rather large magnet to put it into the off-state at the proper time. Because mass is such an important criterion for a spaceflight instrument, the MR switch at a severe disadvantage relative to alternatives. Canavan et al. minimized the mass and complexity of the controlling magnet for use in the continuous ADR. Tungsten is a good candidate because of its low Tc (15 mK) and reasonably high Debye temperature (310 K). The design element is shown in figure 4. Starting with the largest diameter tungsten single crystal available, a wire EDM process is used to cut a disk 20 mm in diameter by 5.1 mm thick. The cylinder (z) axis is aligned with the 001 direction. Two slots are then cut in the horizontal (xy) plane and nine in the xz plane as shown in figure 4.

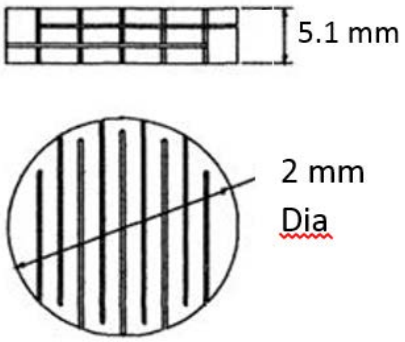

Figure 4. Design element with shape cut from a tungsten single crystal by wire EDM [5];

5. CHS Using Differential Thermal Expansion (DTE)

Many CHS have been developed based on differential thermal expansion (DTE) coefficients for space and ground applications [17-20]. Dietrich successfully designed and tested two DTE devices for application around 100 K using one of the highest DTE thermoplastic (ultra-high molecular weight

polyethylene) of a single focal plane array detector (FPA). Electrical power is not required during normal operation nor for switching. This feature enhances reliability and allows for a simple mechanical design.

The switch also needs to serve as a support for the FPA. The contact areas that are connected to the cold head and FPA must not move upon switching. The switch should present an 'on' conductance of >1 W/K at an operating temperature between 80–100 K, and an 'off conductance of <1 mW/K. With thermoplastics having a relatively high DTE compared to metals but a low thermal conductivity, designs can use a thermoplastic as the switching element for bringing two metals into contact.

The sectional drawing and a 3D-model of the single, cylindrical switch design are shown in figure 5. The part connected to the heat load (detector side) consists of an inner shaft made of a solid copper cylinder (10 mm diameter) with a flange on one end. The part connected to the cold head (PE-side) consists of a copper flange with four integrated copper jaws that are separated from the inner cylinder by the gap. The two copper parts are held together by four thin stainless steel tubes (2 mm diameter by 150 µm wall thickness) which determine the thermal off-state resistance. The contact pressure of the jaws to the shaft at 100 K was estimated to be 1.4 MPa, while the maximum tensile stress in the UHMW-PE was estimated to be 5 MPa.

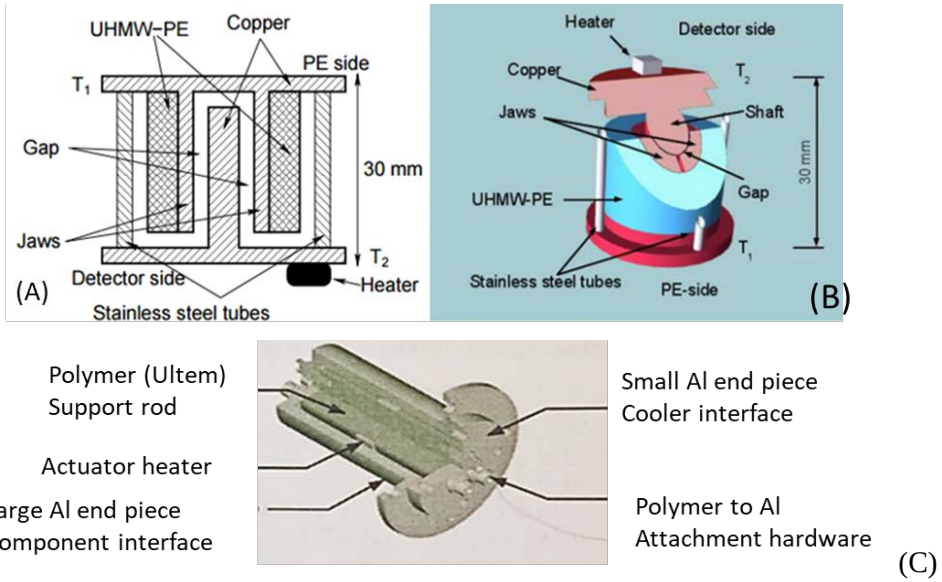

Figure 5. Design of DTE CTS [17] (a, b); photo of another DTE design [18] (c).

Bugby et al. developed several DTE devices for applications around 30–100 K such as the James Webb Space Telescope (JWST) [18]. High-purity Al end pieces and an Ultem support rod were chosen as key materials to build the CHS in figure 5c, which reaches an 'on' conductance of 2–3.6 W/K (from 35–90 K) and an 'off' thermal resistance (the inverse of the thermal conductance) of 1100–2300 K/W (300–230 K warm end). Thompson et al. reported a Quad-Redundant Heat Switch (QRTS) for the JWST.

6. CHS Using Piezo-electric Actuator (PZA)

A novel mechanical cryogenic heat switch actuated by a piezoelectric positioner, the PZA has been designed and tested at 4-10 K by Jahromia [21]. Thermal conductance of the PZA was measured between 4 K and 10 K, and on/off conductance ratios greater than 100 were achieved with the positioner applying its maximum force of 8 N. Cryogenic electromechanical behaviour of multilayer piezo-actuators has been studied by Shindo [22]. The PZA is an attractive alternative technology to a gas-gap heat switch, since this device has an essentially unlimited range of cryogenic operating temperatures, is mechanically robust, and is also free from hermetic sealing requirements. The principle of the PZA is quite simple as shown in figure 6. When the positioner is energized, the lower plate moves upwards until mechanical contact is established with the upper plate. After the desired heat transfer is complete, energizing the positioner with negative voltage moves it downwards until the switch opens. Further improvement is depicted in figure 6 (right) where the contact surfaces were plated with ~ 1 µm of Au.

The plating prevents tarnishing of the copper and also acts as a "cushion" to the switch surfaces, further enhancing the effective contact area. The PZA conductance is 2.8 mW/K at 4 K.

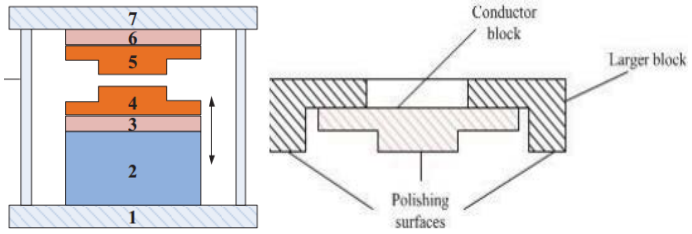

Figure 6. Schematic of the PZA design: support plates (1, 7), piezoelectric positioner (2), insulator (3, 6), conductors (4, 5), G10 structure columns (8) (left); improvement of mating surfaces (right) [21].

7. CHS Using Shape Memory Alloy (SMA)

Shape memory alloys (SMAs) can recover large strains (e.g., up to 8%) by undergoing a temperature-induced phase transformation. This strain recovery can occur against large forces, resulting in their use as actuators. Although research into potential CHS applications of low temperature SMA materials has been explored, the science and understanding of phenomena in the cryogenic realm is still in its infancy.

Research work to combine novel SMA material systems with approaches for the management of heat flow in the range of 4 K to 400 K was conducted by researchers from NASA Kennedy Space Center [23-26]. Alloys providing two-way actuation at cryogenic temperatures are the chief target. Swanger et al. reports a novel mechanical training apparatus for the controlled movement of rectangular strips, with S-bend configurations, at temperatures as low as 30 K. The custom holding fixture included temperature sensors and a low heat-leak linear actuator with a magnetic coupling. Operations included both training cycles and verification of shape memory movement showing that SMAs can recover large strains (e.g., up to 8%) by undergoing a temperature-induced phase transformation. This strain recovery can occur against large forces, resulting in their use cut-away of the Apparatus for Low-Temperature Training of Materials (ALTM) system shown in figure 7.

Benefan and Notardonato [24] developed a shape memory alloy activated heat pipe-based thermal switch for cryogenic use in future Moon and Mars missions to reject heat from a cryogen tank into space during the night cycle while providing thermal isolation during the day cycle. A design of the thermal conduction switch is based on a biased, two-way SMA actuator and utilizes a commercially available NiTi alloy to demonstrate the feasibility of this concept [25], as shown in figure 7c. A custom Ni-Ti-Fe based SMA with a reversible transformation was used as the sensing and actuating elements while thermomechanical actuation was accomplished through an antagonistic spring system. The system thermal performance using a variable length, closed two-phase heat pipe gave heat transfer rates of 13 W using pentane and 10 W using R-134a as working fluids.

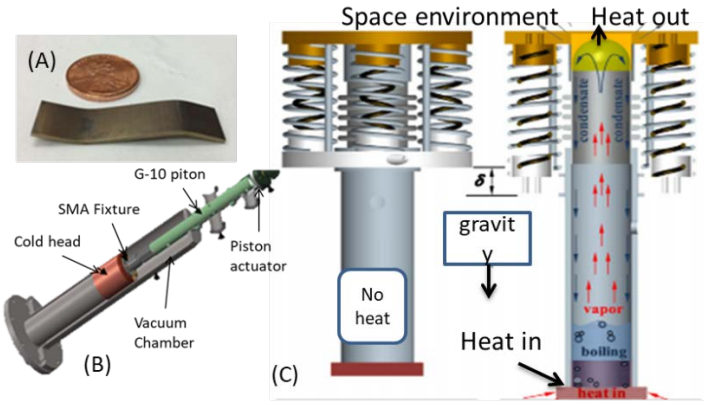

Figure 7. Typical S-shaped SMA specimen (a); cutaway of ALTM hardware configuration (b) [23]; design of a SMA CHS working between on/off states in Moon and Mars environments (c) [24].

8. CHS Using Bimetal & HTS

An energy efficient cryogenic transfer line with magnetic suspension operated by a bimetal CHS has been prototyped and cryogenically tested by Shu et al. [27-29]. A prototype transfer line exhibited cryogen saving potential of 30-35% in the suspension state as compared to its normal support state. Key

technologies developed include novel magnetic levitation using multiple-pole high temperature superconductor (HTS) with rare earth permanent-magnet (PM) elements and the smart cryogenic actuator as the warm support structure. These technologies have applications for extremely low heat leak cryogenic storage tanks, transfer lines, superconducting magnetic bearings, and smart heat switches.

Three performance indices are emphasized and studied in all MagLev configurations: (i) sagging distance, (ii) final levitation gap, and (iii) levitation forces. Shown in figure 8a is a concept using four poles to form the support system. Variations from this concept are also adaptable to transfer line support design depending on the pipeline orientation and fabrication requirements. The YBCO HTS can be curved tiles or rectangular blocks. With one pole, at a displacement of 2-3 mm, a levitation force of 20-40 N was easily achieved. A warm support structure is required in such a MagLev transfer line to keep the inner line supported at the warm condition when the HTS levitation units are deactivated. Shown in figure 8b, the passive actuator does not require power supply, control electronics, and is able to move its working arm over a 6 mm distance and carry up to 60 N per support. The design of a 6-m cryogen transfer line is shown in figure 8c.

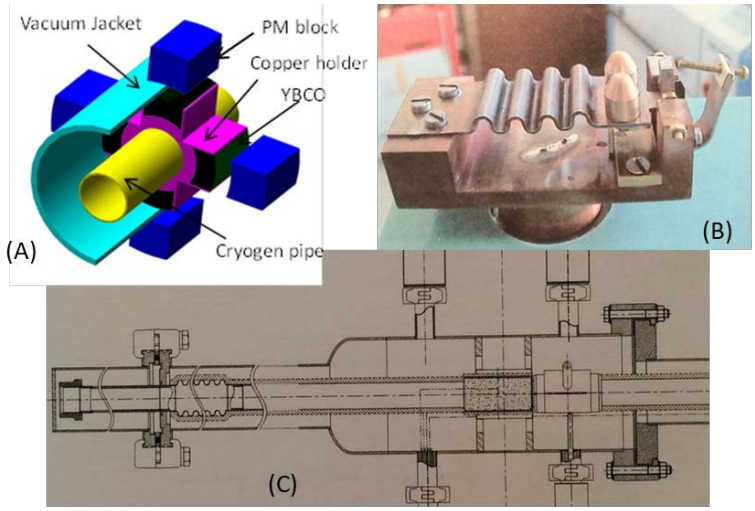

Figure 8. Multiple-pole magnetic levitation [27] (a); bimetal thermal actuator cooled by LN2 [28] (b); and design for a 6-m cryogen transfer-line with bimetal CTS-HTS magnet levitation [29] (c).

9. Gap Heat Switch (GGHS)

The GGHS device has been widely and effectively implemented for thermal management over large temperature ranges. These devices rely upon adding or removing gas from the interior of the hermetical switch body to thermally link or unlink portions of the switch. The gas characteristics and adsorption properties must be taken into account to determine a functioning temperature range. For instance, below about 0.2 K GGHS are not usable since the saturated vapor pressure of even He^3 is too low to provide much conduction [5]. Inside the hermetically sealed shell are two conductive fins (or other shapes) that are attached respectively to one cold end or the warm end, and separated by narrow gaps. If gas is removed from the switch interior by cold getter, the switch is 'off'. The heat leak from one end of the switch to the other is dictated by the conductance of the shell. When gas is refilled in by heating getter, the switch is 'on' and heat flows through the gas between the fins. In the 'on' state the switch must have a large surface area and a small gap between the warm and cold surfaces.

9.1 GGHS using H2 and Ne as heat exchange gases

The CHS were developed by Vanapalli [30], Catarino [31] as shown in figure 9. For neon, the minimum temperature to actuate the switch ranges from 17 K to 40 K; for hydrogen the range is from 9.5 K up to 55 K. The measured values for the thermal 'on' conductance are 74 mW/K at 20 K for neon and 110 mW/K at 11 K for hydrogen. For neon, an 'on/off' conductance ratio of about 220 is obtained at 20 K, and for hydrogen, a ratio near 440 was measured at 11 K.

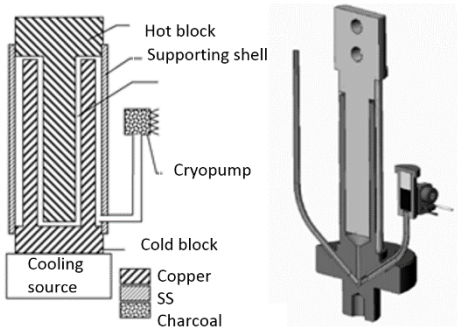

Figure 9. Schematic and sectional drawing of the GGHS prototype [31].

9.2 GGHS using He^4 and He^3

One of distinctive applications for helium devices is in magneto-instruments (optical or electrical) with variable temperature sample cooled by cryogen-free cryocooler or by a liquid helium bath. Reported by Berryhill [32], the GGHS allows the sample temperature to be varied from 4 K to 300 K while maintaining the magnet at 4.2 K. Kimball and Shirron presented GGHS with low activation power and quick-switching time for other low-temperature applications [33,34]. The GGHS with Soft X-ray Spectrometer instrument on the Japanese Astro-H mission [33] requires less than 0.5 mW of power to operate, has on/off transition times of <1 minute, and achieves a conductance of >50 mW/K at 1 K with a heat leak of <0.5 µW from 1 K to very low temperature. Details of the switch design are shown in figure 10. Inside the shell are tapered fins connected to either end of the GGHS shell, but separate from one another by a 0.36 mm gap. The getter material at the top of the switch is bituminous charcoal.

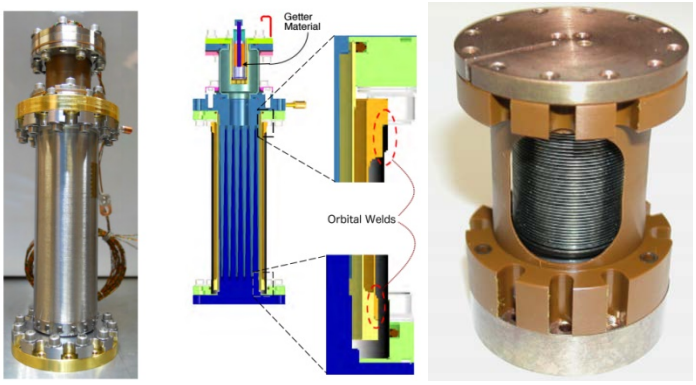

Figure 10. Switch ready for integratioN [33] (left); cut-away view of GGTS with enlarged view of the orbital-welded joints that allow the reentrant titanium shell [33] (middle); bellows-sealed GGTS with external Vespel support and 38-mm outer flanges [5] (right).

Dipirro [5,13] and Hepburn [35] respectively introduced their works about the portable, cryogen-free ultra-low temperature cooling system using a continuous ADR. The system can continuously cool to 50 mK with a cooling power about 20 µW at 100 mK. The GGHS with He^3 shown in figure 10c is a crucial device to manage the heat flow in the system. GGHS shells have been made from polymers (for instance, Vespel™) or composites which are lined or overlapped with a low conductance metal foil and bonded in place with epoxy. The foil liner must be defect-free: pin holes would provide a disastrously large leak path. Meeting a design life of 5 years and losing no more than 25% of the charge requires a leak/permeation rate of $<5 \times 10^{-9}$ standard cm^3/s. A comparable switch of Vespel without foil was over three orders of magnitude worse than required. The He^4 can form a superfluid film trapped between the foil and the polymer shell. Substituting He^3 was successful in solving this problem on the XRS project. As an alternative to polymers and composites, all-metal shells of titanium alloy Ti 15-3-3-3 are used for gas containment. To speed the pumping and reduce the heat from getter, a heat sink is added midway down the pumping line. The amount of gas and getter material in a GGHS is balanced to allow a turn 'on' temperature 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.

9.3 Passively operated GGHS

These can be passively turned off without the need for a separate, thermally activated getter have been developed. Vanapalli [36] reported a passive GGHS around 250–310 K while Dipirro [37-39] published

several passive GGHS near 0.2–13 K. Performance of GGHS at <13 K relies on the strong temperature dependence of the vapor pressure of He^4 adsorbed onto neon or copper substances, respectively, when the coverage is less than one monolayer. Difference in binding energies of He^4 to the neon or copper give rise to different temperatures where the switches transition between on/off. For passive operation the switch must operate in the molecular limit so that a change in vapor pressure has an appreciable effect on conductance. Equally important, the vapor pressure must be a very strong function of temperature near the desired on/off point. Where the switch links the refrigeration stage to a fixed heat sink, rapid turn off is critical for minimizing the parasitic heat flow that will occur when the stage cools below the sink temperature.

The properties of He^3 are almost ideal for a passive switch operation at very low temperature. Its saturated vapor pressure (SVP) varies as an exponential of one over temperature. Over the range from 0.15 K to 0.20 K the SVP changes over 1000, providing the means for a very high switch ratio. Dipirro also employed He^3 condensed as a thin film on alternating plates of copper. The switch is thermally conductive above about 0.2 K and is insulating on either end of the switch cooled below 0.15 K. The 'on' conductance is 7 mW/K at 0.22 K.

10. Conclusion

Cryogenic heat switches (CHS) are crucial for thermal management in many applications. Various CHS have been developed with different principles and methodology for particular applications for operating at temperatures from tens of mK up to about 400K. An idealized performance chart of the range of different CHS technologies, based on the heat flow ratio of equation (2), is given in figure 11.

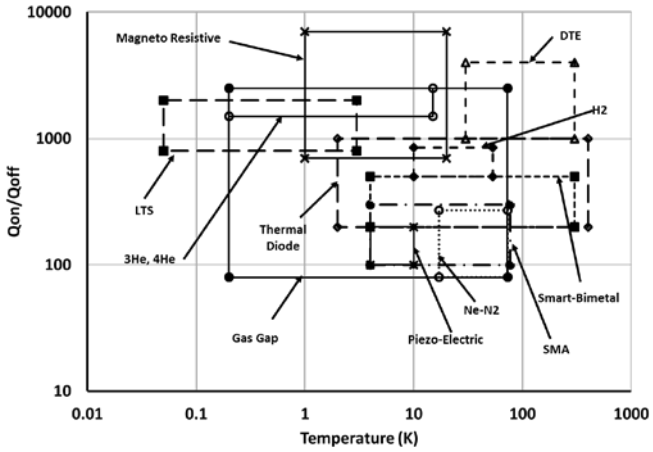

Figure 11. Idealized and simplified performance chart of cryogenic heat switches.

Some of CHS have been successfully implemented in space and universal explorations as well as for researches at laboratories. However, some of CHS technologies are still in an infant stage. Many designs and highly unique and specialized to a given case, but other opportunities exist for more generalized approaches for solving common problems across industry segments. Detailed and precise information must refer to each section of the paper. Combining materials, design, fabrication, and experimental researches, there are many challenges yet waiting for us to face and to resolve in the management of heat at cryogenic temperatures.

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