Development of a Cryogenic Thermal Switch

M. Wang [1,2], L. Yang[1], T. Yan[1], J. Cai [1], and J. Liang [1]

[1]Technical Institute of Physics and Chemistry, CAS
Beijing 100080, China

[2]Graduate University of Chinese Academy of Sciences
Beijing 100039, China

ABSTRACT

The cryogenic thermal switch (CTSW), which is one of the key technologies for thermal integration, is used to couple redundant cryocoolers to cryogenic devices in order to minimize the parasitic heat load from the off-cryocoolers. Based upon comparing the performance of many types of CTSWs for aerospace application, a passively operated CTSW devised by Technical Institute of Physics and Chemistry (TIPC) is presented in this paper.

The CTSW, which works on the principle of differential thermal expansion, has only three parts and weighs about 50 g. The experimental results, obtained from testing, shows that the CTSW has an "on" resistance of about 4.35~5.00 K/W, and an "off" resistance of about 1400 K/W. In addition, an automatic test bench for long duration life time testing has been designed and set up.

INTRODUCTION

With the development of infrared surveillance technology, cryogenic systems on future spacecraft will require a variety of advanced integration components to meet their performance goals, such as long-life, high-reliability, and high-efficiency. There are two key steps to achieve high reliability, one is to use a high performance cryocooler, and the other is to incorporate a redundant cryocooler to protect against individual cryocooler failure. Despite the impressive lifetimes cryocoolers have achieved, the use of one or more cryocoolers for standby is likely to become the norm on future space missions.[1] The parasitic heat leak from the redundant, nonoperating cryocooler increases the cooling requirements of the operating cryocooler. As a result, the inactivate cryocooler needs to be thermally isolated from the cryogenic element, while the active cooler needs to be thermally connected to the system. The capability to thermally isolate can be accomplished by a cryogenic thermal switch (CTSW) as shown in Fig. 1. Because of the reduced parasitic penalty for each nonoperating cooler by CTSWs, the advantage of multiple moderately-priced cryocoolers to satisfy requirements is considerable. The other use of CTSWs is to reduce the initial cool-down time with multiple cryocoolers working in a double harness configuration.

After a brief review of CTSWs for space application over the past 30 years, this paper describes the development status of a passively operated CTE-CTSW. The heat switch was designed and tested to improve performance while providing a highly miniaturized configuration. A life-test

Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr.

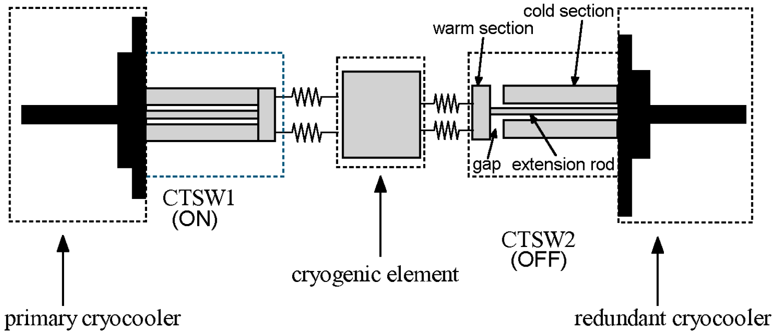

Figure 1. Schematic diagram of the CTSW

bench has been designed and set up, and the life test is in progress to validate the practicality of the design.

EXISTING CTSW

Many diverse CTSW configurations have been explored over the last three decades for applications in the cryogenic systems of spacecraft at temperatures ranging from 300 K to 1 K. Each configuration may be based on a different working principle, but all of them are focused on modulating a thermal break in order to reduce the parasitic heat load from a redundant refrigerator system or the thermal contact between the heat source and the heat sink. There are three generic types that have received widespread attention. The configuration, the principles of operations, and the advantages and disadvantages of each is briefly summarized as follows.

Mechanical CTSW

Mechanical CTSWs control heat flow via the contact of two surfaces with the switching function obtained by the passive control of the mechanical contact between two metallic or nonmetallic components.[2]

One of the mechanical CTSWs is the CTE-based CTSW,[1, 3] which is based on two materials with large differences in the coefficients of thermal expansion. This type of switch does not require external energy to control the switching mechanism. It is passively actuated by the temperature difference across the switch. Although based on the same working principle, the configurations are quite different from each other. B. Marland et al.[3] conducted experimental tests on an Al-Polymer CTSW with only 3 machined parts. The device has demonstrated an "on" resistance of less than 0.49 K/W and an "off" resistance that is greater than 1100 K/W.

The major advantage of this switch concept is the simple design to reduce the cost and weight of the thermal control subsystem within spacecrafts. Another advantage is the capability of repeatable cycles of operation. The disadvantage of this concept is the potential for diffusion bonding, i.e., cold welding of the mating surfaces over long time periods.

Another type of the mechanical CTSW, proposed by Nelson L. Hyman[4], and by Jiangang You et al. [5], is the so called SMA-CTSW. The on/off operation is carried out by a shape memory alloy (SMA) actuating a bolt which shrinks in length according to the temperature change. The switch is an active temperature control device for modulating the flow of thermal energy from a heat source to a heat sink. An "on" resistance of 5 K/W and an "off" resistance of 2456.9 K/W is obtained with this device.[6] The relatively complex configuration is the chief disadvantage with this CTSW concept.

Gas-Gap CTSW

The gas-gap CTSW[6, 7] consists of two cylindrical pieces separated by a small gap, which is filled with a conductive gas. This type of CTSW is actively actuated and requires a system which introduces and extracts the gas. Typically, this is done with a pump or with a gas pressurized reservoir. Its switching action depends on the presence or the absence of gas between two surfaces without any mechanical or electrical actuation.

With this type of CTSW, the major disadvantages are the extremely narrow (0.01~ 0.05 mm nominally) and highly precise flat gap, and the pump for active control.

Heat Pipe CTSW

Heat pipe CTSW [8], also known as the heat pipe thermal diode, uses the difference of thermal conductance between the forward and the reverse mode. In the forward mode, vapor carries the heat load from the evaporator to the condenser. In the reverse mode, the normal condenser zone is hotter than the evaporator zone and the evaporation-condensation process is interrupted. A liquid trap of a non-condensable gas reservoir is used to obtain the diode properties of the heat pipe.

The advantages of using a heat pipe is that it can be used for long distance, is a flexible transport system, and has a very low “on” resistance. The drawbacks of this concept are the low “off” resistance due to the thermal conductivity of the heat pipe tube. Furthermore, CTSW operating on the heat pipe principle have a long response time.

CTSW DESIGN DESCRIPTIONS [3, 9]

The new TIPC CTSW designed, fabricated, tested at temperatures ranging from 80 K to 300 K is based on the differential thermal expansion of dissimilar materials. Figure 1 and Figure 2 show the schematic of the switch with three main parts: cold section, warm section and extension rod. The sections are separated by an extension rod. The rod is made of a nonmetallic material with a high thermal expansion coefficient. The cold section is directly mounted to the heat sink and a narrow, flat metal-metal gap is created between the sections.

As shown in Fig.1, when the cold side of the CTSW1 is cooled with the primary cryocooler operating, the different contraction of the cold section and rod makes the gap between two sections decrease. When the gap is zero, the CTSW1 is coupled to allow heat to be transferred to the heat sink (cryocooler). During the continued cooling of the CTSW1, the thermal contact resistance at the section's interfaces decreases, decreasing the total thermal resistance of the switch. In this situation, the CTSW2 is switched off to minimize the heat load parasites coming from the redundant cryocooler. If the primary cryocooler has failed, the cold section and rod of the CTSW1 will warm up to make the CTSW1 off, thermally isolating the failed cooler from the operating system. After the redundant cooler is turned on, CTSW2 gradually cools down and is turned on at a certain moment.

CTSW PERFORMANCE TESTING

The CTSW testing was conducted in a vacuum chamber with liquid nitrogen as the heat sink. The vacuum chamber was kept at a vacuum of approximately 0.1 Pa with an outside environment temperature of 300 K. The cold side of the CTSW was attached to the liquid nitrogen reservoir. Two

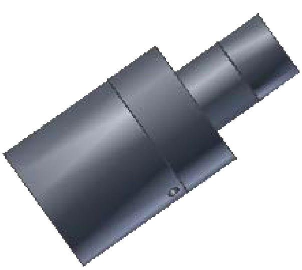

Figure 2. Scheme of the CTSW

heaters placed at the sections of the CTSW were used to provide the heat input for "on" and "off" testing. Two PT-100 thermometers signed Tc and Tw were placed at the cold section and warm section, respectively.

On/Off Switching Time and the Actuation On/Off Temperature

One way to determine the switch "on" and "off" state is through the duration of the temperature change of the warm section. When the gap reaches zero during the cool down, with an inflection occurring on the temperature curve, the temperature rate of change of the warm section will be greater than before. The switch is in the "on" state. On the contrary, the temperature rate of change of the warm section will be lower than the cold section if the switch is "off". Figure 3 shows the test result about "on" and "off" performance. The CTSW is coupled at 25 0K which is called the actuation "on" temperature. The a "on" switching time is about 18 minutes. By applying 3 W power to the heater on the cold section, the CTSW is actuated "off" at about 260 K after 45 minutes.

On and Off Resistance Test

During the first 18 minutes of operation, the CTSW is still open according to the temperature (Tw) measured in the warm section. The temperature drops slowly from ambient. After 18 minutes, the switch closes and the warm section temperature (Tw) decreases rapidly from 250 ^{o}C to reach the temperature of the cold section. In order to calculate the thermal resistance of the switch after stabilization, a power (P2) was applied via an electrical heater to the warm section. The "on" resistance is deduced by the temperature drop measured between the sections. A total resistance of 4.35 K/W was obtained for the model with a 2.25 W heat load when the initial gap is 0.25 mm.

When the CTSW is in the "off" condition, a heat leak exists from the cooler to the instrument via conduction down the central rod, and radiation across the gap between the sections. The heat leak through the CTSW can be calculated from the measured heat load (P1) applied to the cold section and the warm section temperature maintained at 80 K by liquid nitrogen. The results are shown in Table 1.

Thermal Cycling

Figure 4 shows the automatic life testing bench. The CTSW is cooled down by a liquid nitrogen reservoir which simulates the cryocooler. A timer is used to break or make contact automati-

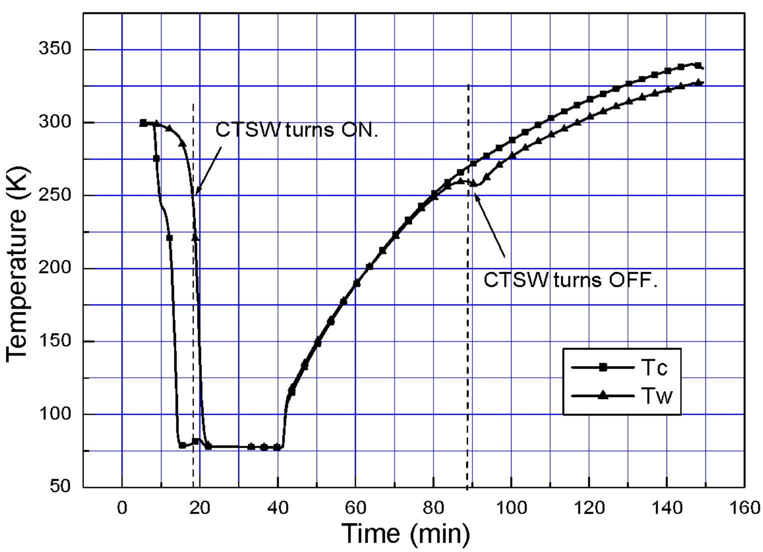

Figure 3. The CTSW ON/OFF thermal tests

Table 1. The Experiment Results of “On”and“Off” Resistance

No.	Cold section T_c (K)	Power Q (W)	Resistance K/W	
			ON Resistance	OFF Resistance
1	77.57	0.01	5	
2	77.67	0.25	4.76	
3	77.93	0.60	4.66	
4	78.50	1.35	4.49	
5	79.18	2.25	4.35	
6	190.05	0.078		1410

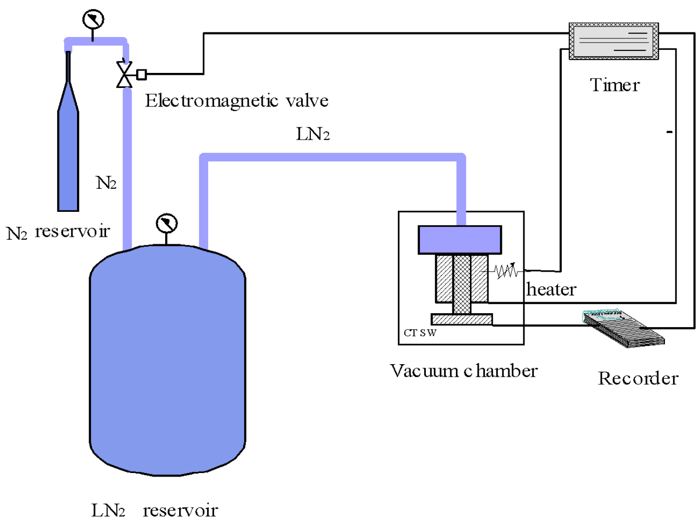

Figure 4. Life Test Bench

cally with the heat sink and the heater to actuate the CTSW. Ten thermal cycles were performed. These tests have not influenced the thermal performances of the CTSW.

CONCLUSIONS

The test results show the TIPC CTSW has an “ON” resistance of about 4.35 ~ 5.00 K/W, and an “OFF” resistance of about 1400 K/W In addition, an automatic test bench for life time testing was designed. The CTSW can be varied in size, number and arrangement to change the ON/OFF performance according to the requirements of thermal conduction. TIPC will continue to advance its integration technologies to reduce parasitic thermal losses and increase reliability.

REFERENCES

1. Van Oost, S., Bekaert, G., Bhatti Sabca, R.S., Scull, S., and Jewell, C., “A Heat Switch for Space Cryocooler Applications,” *Proceedings of the 4th European Symposium on Space Environmental and Control Systems*, Florence, Italy, 21-24 October, 1991 (ESA SP-324.December 1991).

2. Ross, R.G., Jr., “Cryocooler Reliability and Redundancy Considerations for Long-Life Space Missions,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 37–648.

3. Marland, B., and Bugby, D., “Development and Testing of a High Performance Cryogenic Thermal Switch,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), P729–738.

4. Hyman, N. L., “Package-Interface Thermal Switch,” U.S. Patent 5,535,815.

5. You, J., Dong, D., and Wang,W., “Thermal Switches Overview for Space Application,” *Space Cryogenic Technology Forum,* 2004, pp. 111-117.

6. Johnson, D.L., and Wu, J.J., “Feasibility Demonstration of a Thermal Switch for Dual Temperature IR Focal Plane Cooling,” *Cryocoolers 9*, Plenum Press, New York (1997), pp. 795–805.

7. Chang, H.-M., and Kim, H.-J. “Development of a Thermal Switch for Faster Cool-Down by Two-Stage Cryocooler,” *Cryogenics*, Volume 40, Issue: 12 (December 2000), pp. 769-777.

8. Wolf, D.A., “Heat Pipe Thermal Switch,” NASA Case GSC 12,812-1.

9. Milanez, F.H., and Mantelli, M.B.H., "Theoretical and Experimental Studies of a Bi-Metallic CTSW for Space Applications*," International Journal of Heat and Mass Transfer,* Vol. 46, Issue 24 (November 2003), pp.4573-4586.