A Critical Review on Mechanical Heat Switches for Space Applications

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Abstract
Thermal switches are typically used to regulate the heat flow between two surfaces. They are broadly categorized as mechanical, gas-gap, superconducting, and magneto-resistive heat switches. Out of these, the mechanical heat switch (MHS) can be used in a wide temperature range of 0.1 K – 400 K. Moreover, the other features of MHS, such as cost-effectiveness, different actuation methods, flexibility in design, and broad applicability, made it a suitable choice over a wide range of cryogenic to room temperature applications. Based on different actuation methods, the MHS can be further subclassified in piezoelectric actuated (PZA), paraffin wax (PFW), differential thermal expansion (DTE), and shape memory alloy (SMA) type of heat switches. This work presents a broad overview of different kinds of mechanical heat switches (MHS) and compares their performances and physical parameters. The switching ratio, mode of actuation, overall size to weight ratio, the initial gap between the two plates, contact forces, and time of actuation are all key elements in the selection and design of thermal switches. Moreover, the present review also discusses the working principle of different MHS, their advantages/disadvantages, and significant design parameters as per their applicability in various engineering and space applications. The study suggests that the DTE type MHS can enforce approximately 30 times extra contact force compared to the rest of the MHS. The higher contact leads to lower thermal contact resistance and a higher switching ratio of DTE compared to other MHS. Moreover, the higher working range (0.1 K – 100 K) made it suitable for space applications.

Keywords: Heat switches; Review; Cryogenics; Space applications; Contact force, Mechanical heat switches.

Nomenclature

HS	Heat Switch
MHS	Mechanical Heat Switch
PZA	Piezo-Electric Actuated
PFW	Paraffin wax
SMA	Shape Memory Alloy
DTE	Differential Thermal Expansion
CTE	Coefficient of Thermal Expansion
MRHS	Magneto-resistive Heat Switch
SCHS	Superconducting Heat Switch
GGHS	Gas-Gap Heat Switch
mK	millikelvin (K)
S	Switching Ratio
K_{on}	Thermal conductivity in ON state (W/mK)
K_{off}	Thermal conductivity in OFF state (W/mK)
T_B	The temperature of the cryocooler cold plate (K)
T_U	The temperature of the upper plate (K)
T_L	The temperature of the lower plate (K)
K_U	The thermal conductivity of upper plate to cryocooler (W/mK)
K_L	Thermal conductivity of lower plate to cryocooler (W/mK)
K_C	Conductance of the upper and lower plate contact (W/mK)
$\dot{\boldsymbol{q}}_U$	Heat flux from upper plate to cryocooler (W/m^2)
$\dot{\boldsymbol{q}}_L$	Heat flux from lower plate to cryocooler (W/m^2)
$\dot{\boldsymbol{q}}$	Heat flux rate (W/m^2)
K_{CP}	Thermal conductance of contact part (W/mK)
Ni	Nickel
Au	Gold
T_{hot}	The temperature of hot surfaces (K)
T_{cold}	The temperature of cold surfaces (K)
V	The voltage of the DC power supply (V)
T	Temperature (K)
K_{Al}	Aluminum alloy cylinder thermal conductance (W/mK)
K_{FP}	Thermal conductance of flexible part (W/mK)
I	DC power supply current intensity (A)
η	Correction factor range from 0.7 – 0.9

1 Introduction

Cryogenic heat switches are the key components of many spaces and cryogenic systems. The flow of heat is controlled by the heat switches between two contact surfaces. Heat switches can give the cold mass with either a high thermal connection or optimum thermal isolation. The majority of thermal switches that function in spacecraft temperature ranges are passively actuated devices that self-regulate their conductance without the assistance of any controller inputs. The heat switches thermally disconnect the two surfaces when no cooling/heating is required and act as thermal resistance. Thus, they reduce heat loads of the cooling/heating systems by disconnecting the components. The heat switches are broadly classified into mechanical, gas-gap, superconducting, and magneto-resistive types. The thermal conductivity of a mechanical heat switch is proportional to contact between two surfaces, whereas the thermal conductivity of a Gas-Gap heat switch is proportional to the presence or absence of gas between two interlocking pieces. In a Superconducting heat switch, phase transition reduces thermal conductivity but, in a Magneto-resistive heat switch, the application of an external magnetic field reduces the electronic contribution to thermal conductivity.

In this paper, we present a broad overview of different types of mechanical heat switches (MHS). The MHS can be subclassified in piezoelectric actuated (PZA) heat switch, paraffin wax (PFW) heat switch, shape memory alloy (SMA) heat switch, and differential thermal expansion (DTE) heat switch. Particularly, this paper discusses the working principle, advantages/disadvantages, and design parameters of MHS as per their applicability in different engineering and space applications. Moreover, comparative studies between the different MHS are performed. The comparison suggests that the Differential Thermal Expansion (DTE) type MHS may impose 30 times higher contact force than other MHS. The higher contact force results in lower thermal contact resistance, and a higher heat switching ratio for DTE. It was also appropriate for space applications due to its larger working range (0.1 K – 100 K).

1.1 Heat Switch

In many engineering and space applications, a heat switch is utilized to make and break the thermal contact. Thermal switches, also known as thermal conductors, are devices that could be good thermal conductors and good thermal insulators as per the demand. When placed in the heat-conduction path between a warm, heat-producing component and a heat sink or radiator, the change in thermal conductance it provides can modify the temperature of a component, and it is represented in Fig. 1. It also acts as a critical thermal contact between the heating element and the cooling system when necessary. The thermal switch acts as an on/off mechanism for heat transfer between the hot and cold reservoirs by changing the thermal conductivity from K_{off} when the switch is open to a larger value K_{on} when the switch is closed [1].

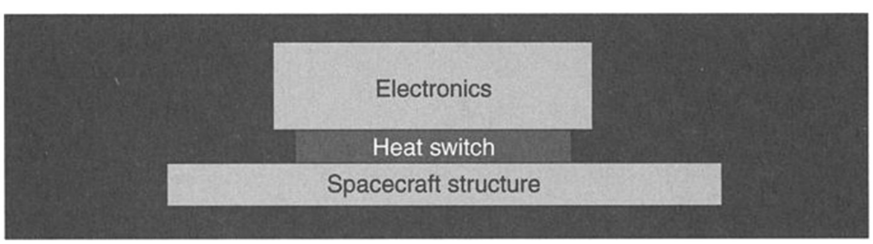


Fig. 1. Heat switch operation between electronics and spacecraft structure [2].

Selection Criteria

The most important considerations in the selection of heat switches are switching ratio, actuation method, size, weight, structural soundness, reliability, and time of actuation are essential for both space and cryogenic applications.

Desired properties

The primary characteristic of heat switches is that heat switches have approximately zero conductivity in the off position, they should have a minimum thermal conductance of 1W/K in its on position and operates at a low voltage. Apart from these, the switching ratio should exceed 100. Extremely small in size (about 5 cm), their operation should be noiseless, with no corrosion, and few moving components and minimal in weight are desired properties of heat switches.

Operating temperature range-based classifications of heat switches

The Heat Switches can be classified in several ways. The key classification is based on the functioning temperature range of mechanical heat switches are cryogenic temperature and normal/ room temperature. The term cryogenics is derived from the Greek words "kryos" (frost) and "genics" (to produce). The term cryogenics means the production and behavior of the material at ultra-low temperatures. In this different material transition from gas to liquid and liquid to solid-state. The temperature range starts from absolute zero (0 K) to 123 K and normal temperature ranges above 123 K.

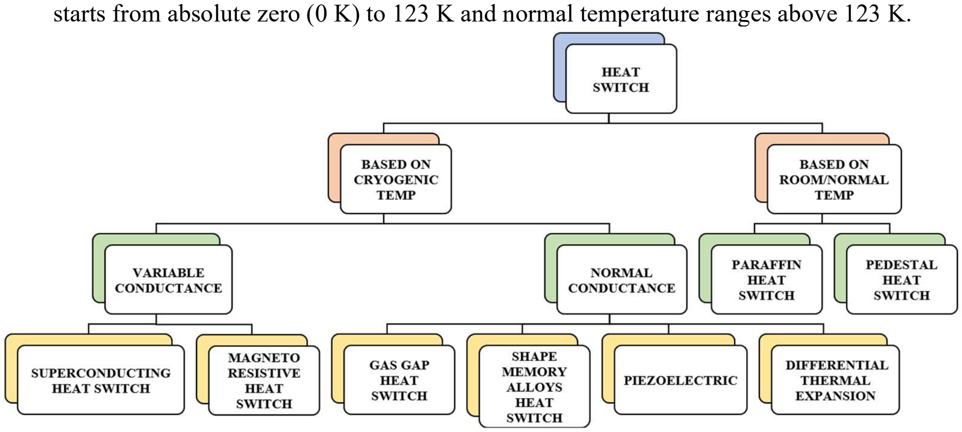


Fig. 2. Classification of heat switches based on operating conditions.

Actuation method-based classification

The heat switches are divided into two categories based on their actuation method are passively actuated and active actuated. Passively actuated devices that self-regulate their conductance instead of reacting to controller inputs. The on/off state of a passive heat switch is determined by temperature. In active actuated the temperature is within a particular range, an active heat switch can be turned on and off by accepting external signal input from a controller. Electrical power is the most typical external input. An external actuation mechanism that can be operated manually or by a motor to enable automatic actuation. Significant forces can be transmitted through a hydraulic operation using gas or liquid helium, which is widely employed to operate valves at low temperatures.

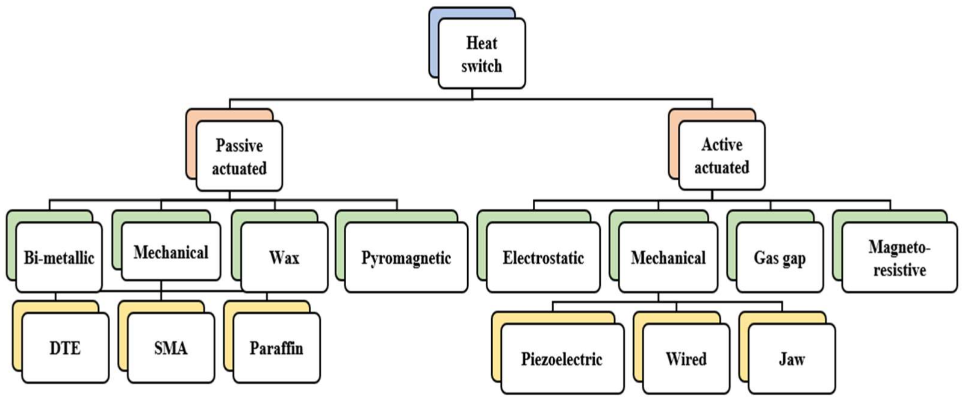


Fig. 3. Classification of heat switches based on actuation methods.

The commonly used heat switches are mechanical heat switches (MHS), magneto-resistive heat switches (MRHS), superconducting heat switches (SCHS), and gas-gap heat switches (GGHS). Among these, the present work focuses on the detailed review of mechanical heat switches (MHS). The MHS has certain advantages over the other heat switches. The MHS has a wide range of applicability in both cryogenic and room temperature applications. The other advantages of MHS are that it is given complete isolation in its off-conductance condition, easy to manufacture, cost-effectiveness, different actuation methods, flexibility in design, and broad applicability. All these features of MHS made it a suitable choice for the wide range of cryogenic to room temperature applications. Previously, these switches are applied in many research and space research mission applications.

2 Mechanical Heat Switches

Mechanical heat switches control heat flow via the contact of two surfaces with the switching function controlled by the passive/active mode of mechanical contact between two metallic or non-metallic surfaces. To establish thermal contact between a sample (in vacuum) and its surroundings, a mechanical heat switch is used (often a liquid helium bath). The cooling power between a cold heat sink and a thermally isolated or semi-isolated stage is controlled by a mechanical heat switch. A moveable contacting surface connects or disconnects two separate phases thermally. In reality, the contact between two highly conductive surfaces requires a great deal of force or pressure and must be broken many times. This can take a lot of force to break the bond. Because of the considerable stresses necessary in creating a detachable contact, a tougher and thus more hefty construction is required than for a Gas-Gap thermal switch or superconducting thermal switch. The main benefit of MHS is that it has zero conductivity in the off position. The mechanical thermal switches in contrast to the gas-gap thermal switch are simple to manufacture and can be turned to actuate/operate at desired temperature range.

2.1 Advantages of Mechanical Heat Switches

The advantages of MHS over other heat switches are that there is negligible conductivity in the off position, it may be applied in cryogenics as well as a room/normal temperature, and they can be shut down at any temperature. Moreover, the MHS is less difficult to manufacture, more versatile, and heat leakage is minimal in the off state. A mechanical thermal switch is a great way to cut down on cool-down time. Most of the MHS are corrosion resistant and have a nearly zero creep susceptibility means solid material can resist the tendency of a material to slowly deform over a long period of stress. Some of the actively controlled MHS comes with both sensor and actuator components, which reduces the overall complexity, and has a high heat transfer ratio between the open and closed states. In addition, the strength-to-weight ratio is ideal for MHS, clean, spark-free, and operates quietly. The ability to work in zero gravity circumstances with modest, controllable accelerations is cheap in MHS, takes up less floor space, and is weightless. Because of its strong contact pressures, great reliability, efficiency, and capacity to perform in repetitive cycles, it has a high heat conductivity in the closed state.

2.2 Limitations/disadvantages of Mechanical Heat Switches

MHS limitations/disadvantages over other heat switches are that MHS has moving parts, so the chances of wear and tear are high, and it requires regular maintenance. Some MHS require a considerable external power supply to deliver the appropriate amount of contact force in their ON position. MHS is large and heavy, in NASA Mars and Moon mission the heat switch requires a vacuum environment [3], and it cannot operate in the milli-K low-temperature region.

2.3 Application of Mechanical Heat Switches in Historic Events

The MHS has previously been widely employed in space and high-end technical applications. Some examples of popular applications are as follows: Thermal switches were invented in the early 1960s for use on the Mariner lunar mission [2]. Thermal switches have long been utilized successfully in single-stage magnetic freezers and have recently been developed for multi-stage demagnetization refrigerators [3]. DTE devices are employed in the James Webb Space Telescope (JWST) [3]. SMA thermal switches based on heat pipes are used in lunar and Mars missions to disperse heat from the cryogenic tank into space during the night cycle and provide insulation during the day cycle [4]. A PZW heat switch was installed at Spirit and Opportunity, a Mars rover in the United States, to control the heat of the battery system [5]. The Propulsive Small Expendable Deployer System uses PFW-based thermal switch technology (ProSEDS) [2]. The Jet Propulsion Laboratory (JPL) Mars `03 Rover uses a thermal switch as standard [2]. The SMA-based retractable construction installed solar panels for NASA's Hubble Space Telescope and opened the solar cell cover glass for NASA's Mars Pathfinder Rover [4]. SMA actuators are used in the gas analyzer (Ptolemy) of the Rosetta spacecraft mission to cut comets of the European Space Agency (ESA) [4].

2.4 Classification of Mechanical Heat Switches

Same as before, the mechanical heat switches can also be broadly classified based on their methods of actuation are passively actuated and actively actuated.

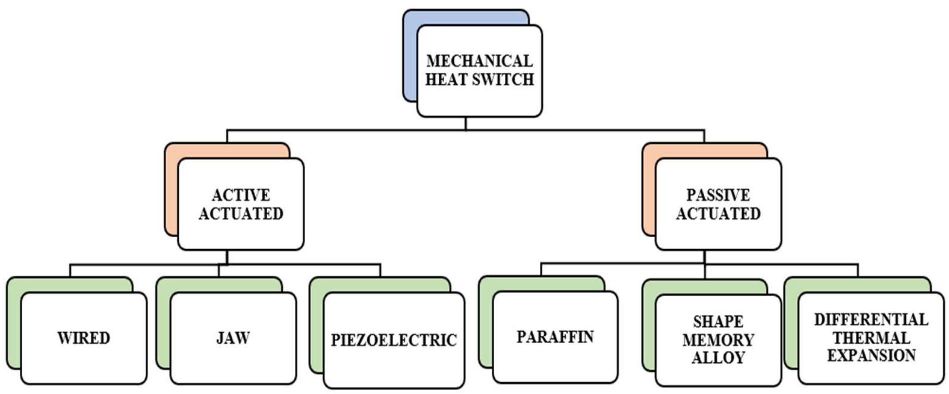


Fig. 4. Classification of mechanical heat switch.

2.5 Performance indices

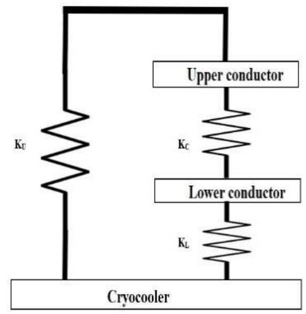
The Switching Ratio

The ratio of heat conduction between ON and OFF is defined as the switching ratio. The switching ratio for any heat switch (the relative ON and OFF conductance) is a commonly used performance parameter. It is a dimensionless quantity.

$$S = \frac{K_{on}}{K_{off}} \tag{1}$$

where, K_{on} is the thermal conductivity of heat switch in ON condition in W/K, and K_{off} is the OFF condition thermal conductivity in W/K.

Table 1, Switching ratio formulation for different types of mechanical heat switches.

The formulation for Switching Ratio (S)			
Type of MHS	***Kon***	***Koff***	**Schematics**
PZA	The joint conductance $(K_C)_{on}$ is calculated when the switch is in the closed state, If $T_U = T_L + \delta T$, $\dot{q}_U = K_U\ (T_U\text{-}T_B) + K_C\ (T_U\text{-}T_L)$ $\dot{q}_L = K_L\ (T_L\text{-}T_B)$ If $T_L = T_U + \delta T$, $\dot{q}_U = K_U\ (T_U\text{-}T_B)$ $\dot{q}_L = K_L\ (T_L\text{-}T_B) + K_C\ (T_L\text{-}T_U)$	When switch is in opened state, $(K_C)_{off} = 0$ If $T_U = T_L$, $\dot{q}_U = K_U\ (T_U\text{-}T_B)$ $\dot{q}_L = K_L\ (T_L\text{-}T_B)$	 **Fig. 5.** PZA thermal conductance and temperature schematic.

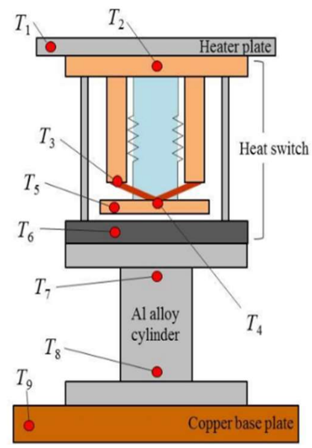
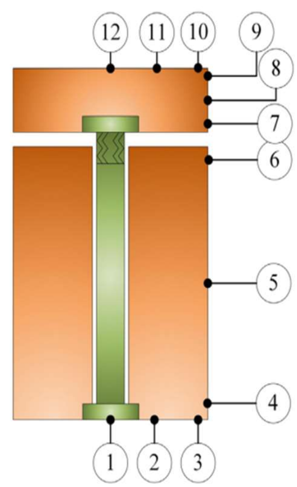
PFW	$K_{on} = \dot{q} / (T_2 - T_6)$	$K_{off} = \dot{q} / (T_2 - T_6)$ Common formulae, $\dot{q} = K_{Al} (T_7 - T_8)$ where, $\dot{q}$ is measured in both on/off states for calculating K_{on} and K_{off} respectively. The thermal conductance of the contact part, $K_{CP} = \dot{q} / (T_5 - T_6)$ The thermal conductance of flexible part, $K_{FP} = \dot{q} / (T_3 - T_4)$	 **Fig. 6.** Paraffin wax heat switch thermocouple distribution [5].
DTE	$K_{on} = \frac{T_{hot} - T_{cold}}{\dot{q}}$	$K_{off} = \frac{T_{hot} - T_{cold}}{\dot{q}}$ Common formulae, $T_{hot} = \frac{T_1+T_2+T_3}{3}$ $T_{cold} = \frac{T_{10}+T_{11}+T_{12}}{3}$ $\dot{q} = \eta * V * I$ where, $\dot{q}$, T_{hot} and T_{cold} measured in both on/off states for calculating K_{on} and K_{off} respectively.	 **Fig. 7.** Thermocouples distribution [6].

Table 2, Switching ratio, thermal conductivity in ON/OFF state for temperature for different types of mechanical heat switches.

Type of Mechanical Heat Switch	Switch ON		Switch OFF		Switching Ratio
	Temp. (K)	K_{on} (W/K)	Temp. (K)	K_{off} (W/K)	
Piezo-electric Heat Switch	200	1.04	10	0.0052	200
Paraffin Wax Heat Switch	335	1.6	321	0.0125	128
Differential Thermal Expansion Heat Switch	100	1.21	0.1	0.003	403.34
Shape Memory Alloy Heat Switch	293	0.5	77	0.0007	715

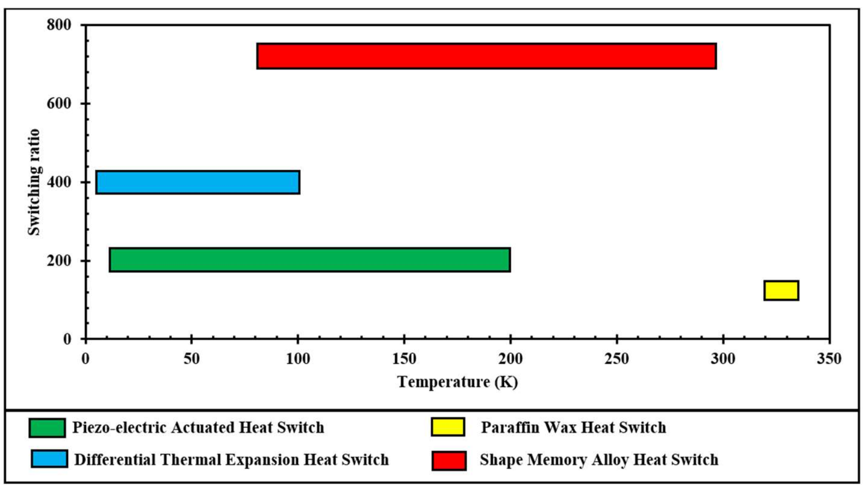


Fig. 8. Comparing the mechanical heat switches variation of switching ratio with the temperature.

Contact Force during the K_{on} condition

The applied force is the force generated by mechanical heat switches to make contact between two metallic or non-metallic surfaces to switch the thermal conductivity in the ON position. In the ON position, it is critical to parameterize total heat dissipation to the surrounding environment. The contact force can be generated using different actuation methods, such as electrical power, hydraulic actuation using gas/liquids, or self-regulate owing to temperature change. From the compression graph shown in Fig. 9., we can say that DTE is having the highest applied force. However, the DTE dissipates a large amount of heat in its active state, whereas SMA heat switches have the lowest heat transfer rate compared to PFW and PZA heat switches.

Contact Pressure during the K_{on} condition

When two metallic or non-metallic surfaces come into contact, mechanical heat switches generate pressure. It is the ultimate pressure generated on the contact surfaces due to applied force. This parameter is used to select contact material, which will thermally connect the two surfaces. The connecting material must have the strength to bare the applied force without failure. The exerted contact pressure in different MHS and corresponding contact forces as shown in Fig. 9.

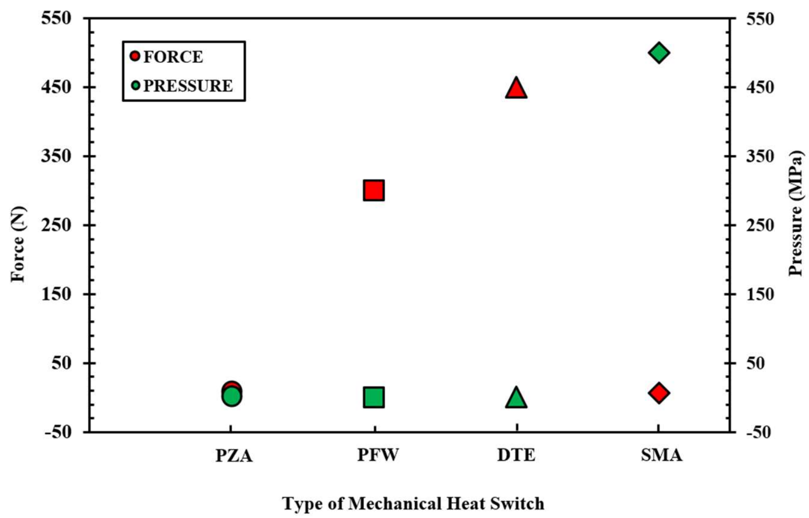


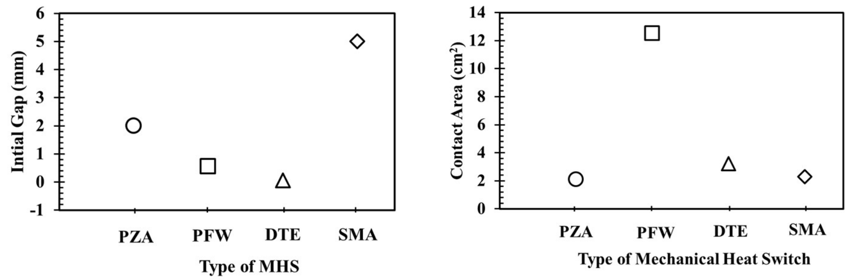
Fig. 9. Force and pressure variation of mechanical heat switches.

Initial Gap

The gap is the maximum required space between the connecting surface and the second surface that need to separate in the K_{off} condition. A prescribed gap is maintained between the surfaces for zero conductance in its off state and to completely isolate the two surfaces. The initial gap is kept based on the experimental results. The initial gap for distinct MHS is shown in Fig.10 (a).

Contact Area

The contact area refers to the surface area of two metallic or non-metallic contact plates/surfaces. From Fourier's basic heat transfer law, it can be understood that the heat transfer coefficient is proportional to the contact area. This suggests that the contact area should be as large as possible for the higher heat transfer in the K_{on} condition. However, the other design parameters come into the picture which decides the actual size of the contact surface. Fig.10. (b) refers to the contact area of different MHS.



(a) (b)

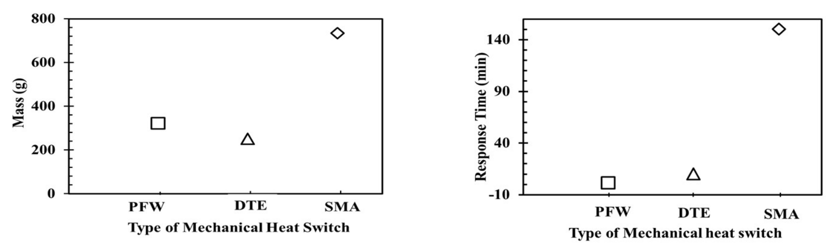
Fig. 10. (a) denotes the initial gap between the contact surfaces for distinct MHS and (b) describes the contact surface area of mating surfaces/plates.

Mass

The utility of MHS in high-grade space applications comes up with a strict requirement of light and compact build. Because of these, the overall volume of the MHS must be kept minimum. The mass of the thermal switch plays an important role in the total weight of the spacecraft. Fig. 11. (a) shows a comparison of different MHS masses.

Time of Actuation

The time of actuation is the duration taken up by the thermal switch to switch between ON and OFF positions. The time of activation is an important factor in the section and design of any heat switches. A good heat switch must immediately respond to the temperature changes and actuate immediately. The comparison of time of actuation for different MHS is shown in Fig. 11. (b). The operating time depends to some extent on various factors such as the material selected, the type of application, and the environmental conditions of the MHS.



(a) (b)

Fig. 11. (a) Represents the overall mass of the different MHS and (b) shows the time required for actuation.

Size

The compactness is a strict criterion for heat switches used in space applications. Therefore, the HS should be as small as possible, and the height must be usually 50mm.

3 Piezo-Electric Actuated Heat Switch

One of the popularly used active actuated MHS is Piezo-electric actuated (PZA) heat switch. It can operate at cryogenic temperatures. Piezoelectric materials are widely used in a variety of electrical and mechanical equipment and devices, such as ultrasonic generators, filters, sensors, and actuators [7]. The thermal conductivity of PZA was measured between 4 K and 10 K, and switching ratios over 100 (on/off conductivity ratios) were measured using a positioner with a maximum force of 8 N is designed and tested by Jahromia [8]. Because of its capacity to function at a wide cryogenic range, the PZA is an appealing alternative technology to a gas-gap heat switch. In addition, PZA is mechanically robust and does not require an airtight seal. In Fig. 12, point 1 is the base support plate, 2 piezo positioners, 3 lower insulators, 4 lower conductors, 5 upper conductors, 6 upper insulators, 7 upper support plates, and 8 structural columns (× 4) [8].

The operation of actuating material is shown in Fig. 13. When you operate the positioner with a positive voltage, the lower plate slides up until the upper plate is mechanically touched. The switch is closed in this configuration, and heat is transferred between the two plates occurs. On applying a negative voltage to the piezoelectric positioner, the positioner will experience a compressible force and which separates the mechanical contact between the plates. In this way, the switching is preformatted in PZA. The piezo material is Attocube ANPz101, the stanchions are high-pressure G10 fiberglass laminate, the top and bottom insulation is Vespel SP1, and the top and bottom plates are ultra-high purity (99.999%) copper [8]. In steady-state operation, when the switch is open, parasitic heat flows from the warm storage to the cold storage through the structural column. To counter this and reduce open thermal conductivity, the column was made of G10 hollow rods and the plate was attached to Vespel SP1 insulation. To optimize high thermal conductivity, the upper and lower plates were manufactured of ultra-high purity (99.999 percent) copper.

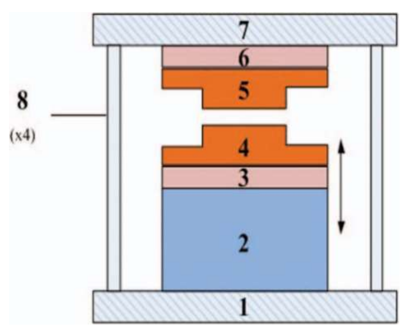


Fig. 12. Structure of PZA [8].

A small thermometer and heater were placed on each plate to individually set the desired temperature of the reservoir and maintain the temperature with the Proportional Integral Derivative (PID) controller [8]. Two-wire resistance measurement was used to check for contact between the plates. No continuity was detected when the switch was open. However, the measurement resistance when the switch was closed was 80, and continuity was confirmed. S~100 at 4 K and S~200 at 10 K are the lowest and highest observed temperatures, respectively [8].

Table 3, Specifications, dimensions, and materials for the Piezo-Electric Actuated Heat Switch.

Parts	Lower and Upper conductor	Lower and Upper insulator	Support columns	Actuating element
Materials	Pure Copper (99.99%)	Vespel SP-1	high-pressure fiberglass laminate G-10	attocube ANPz101
Dimensions	1.45 cm^2 area on each side of the plate	A square block of 7mm thickness	6.3mm outer dia., 4.3mm long, and 3.2mm inner dia.	-

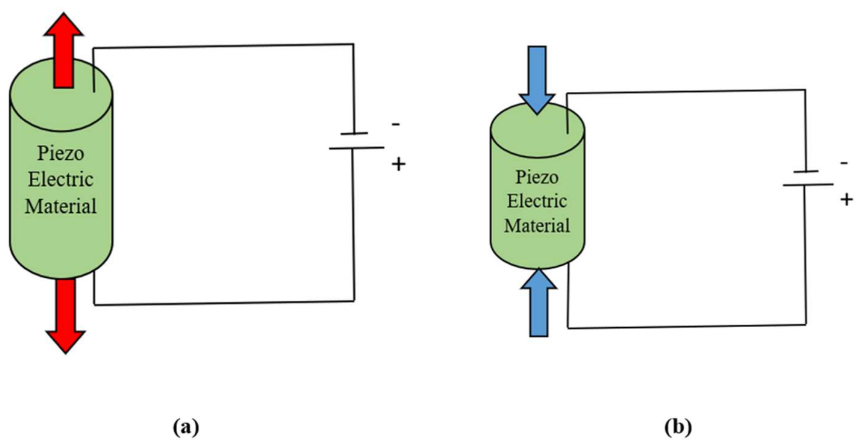


Fig. 13. In (a) Piezo-electric material is energized by the positive voltage and (b) Piezo-electric material is energized by the negative voltage.

4 Paraffin Wax Heat Switch

Another important type of passively actuated MHS is the paraffin wax (PFW) heat switch. It operates in the room/normal temperature range. A paraffin wax HS was developed in 2003 to control the temperature of the Mars rover battery in Fig. 14 [5]. The thermal switch prevents heat from transferring from the rover battery to a radiator. The National Aeronautics and Space Administration (NASA) dispatched two identical rovers to Mars in 2003 as part of the Mars Exploration Rover (MER) mission [5]. The rover's battery temperature is controlled by a paraffin wax-actuated heat switch during the rover's voyage to Mars and on the Martian surface. Starsky's Research Corporation developed these switches a few years ago, based on paraffin wax-operated thermal switches for thermal management [5]. When the paraffin wax is heated and melted, the contact plate is pushed away due to the volume expansion of the paraffin wax, which leads to the contact between the heat source and heat sink plates, thus the heat switch turns into the "on" condition. The phase shift of paraffin wax from solid to liquid demands substantial heat addition. This function adds thermal capacitance to paraffin wax heat switches, enhancing their thermal-control capabilities. The volume expansion mechanism of paraffin wax with temperature change is shown in Fig. 16. At the actuating point, the paraffin wax usually stays in the semi-solid state. The complete phase change from solid to liquid required a large amount of energy input. The quick rise in heat generation when the paraffin wax melts is absorbed first, therefore this energy input is employed to keep the temperature in its current state away from the melting point of paraffin wax. Because the system is over-attenuated, this behavior attenuates the response, allowing the switch to operate in a smooth and controlled manner without the switching periodically when the heat load changes. The contact part of the paraffin wax heat switch consists of a copper contact plate and an Al alloy radiator plate, with the former connected to the paraffin wax actuator via a flexible laminated copper piece. Mirror polishing is used on the surfaces of the contact and radiator plates to improve thermal contact conductivity. When the switch is off, there is a small gap (less than 0.5 mm) between the contact plate and the radiator plate. A paraffin wax-filled piston-cylinder serves as the mechanical component (paraffin wax actuator) which is less than 1g. When the thermal switch is turned off, the mechanical parts are spring-loaded and the piston can be returned to its original position, which is shown in Fig.17. To avoid overloading the contact component in the ON state, the mechanical part additionally features an overload protection spring. The flexible portion morphs in response to the paraffin wax actuator's movement and also serves as a thermal route with strong thermal conductivity. Between the radiator and hot side plates is the support structure. To lower the OFF thermal conductivity, a titanium alloy is used as a support structure.

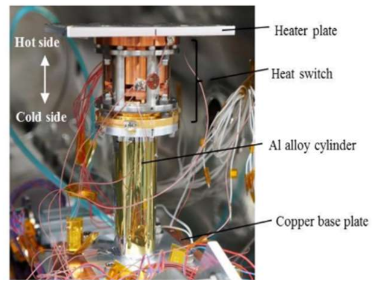


Fig. 14. Paraffin wax heat switch [5].

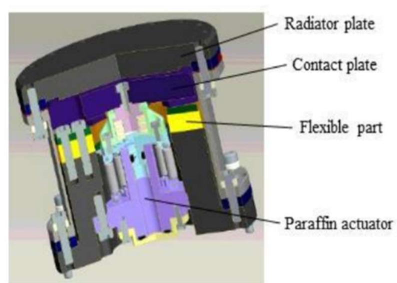


Fig. 15 Cross sectional view of PFW [5].

Table 4, Paraffin wax heat switch components and materials.

Component	**Material**
Contact Part	Copper
Radiator Plate	Aluminum Alloy
Support Structure	Titanium Alloy
Spring	Low Alloy Steel
Actuating Element	Paraffin Wax

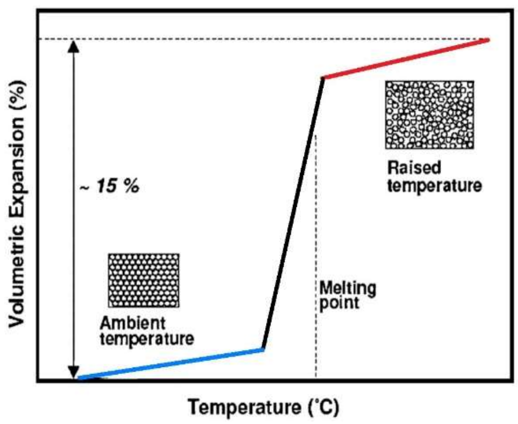


Fig. 16. Variation of Paraffin wax volume with temperature change.

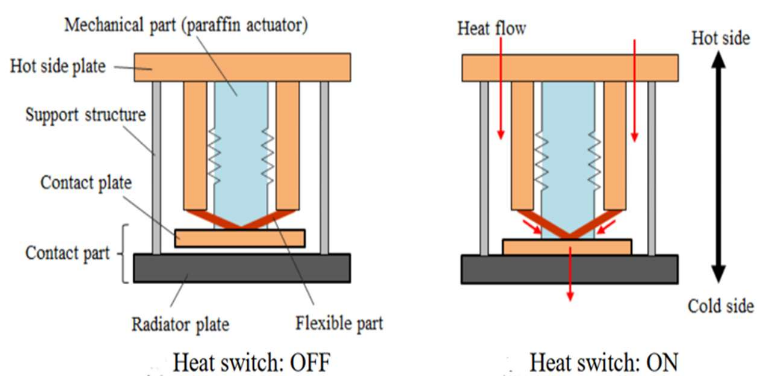


Fig. 17. Schematic of Paraffin wax heat switch [5].

4.1 Enhancement of the Contact Part's Thermal Conductance

Dimensions of the coating

The net contact area must be raised to improve the thermal contact conductance between the contact and radiator plates. There are two factors associated with an increase in net contact area: low contact surface hardness and low surface roughness. The primary coating characteristics are linked to surface hardness and roughness.

Thickness of coating

The surface hardness decreases with increasing coating thickness and thermal contact conductance increases due to increased net contact area when the coating thickness is relatively thin. When the coating thickness exceeds a specific value, thermal contact conductance is thought to diminish due to the effect of the thermal conductivity of the coating material itself. The thermal contact conductance of different metal coatings was measured by Ying et al (Ag, Sn, Cu, Al) [5]. Thermal contact conductance peaks at coating thicknesses of 5-12 m, according to the results.

Coating substance

In our investigation, the baseline is Au coating, and the coating materials are pure gold and hard gold. Hard gold is denser and more resistant to wear.

Nickel base coating

Gold (Au) is frequently coated on nickel base coating. Because of its strong hardness and low thermal conductivity, Ni-base coating is expected to reduce thermal contact conductance. Misra et al. [5] measured the thermal contact conductance of OFHC (Oxygen-free High Thermal Conductivity) copper with a 2 m Ni-base coating and a 0.1-0.5 m Au coating. As a result, the thermal contact conductance of OFHC copper with coatings is lower than that of OFHC copper without coating. Even if Au coating enhances surface roughness, it is assumed that the effect of increased surface hardness owing to Ni-base coating is greater in this scenario. According to the findings, no Ni coating is expected to boost thermal contact conductance, and if Ni is coated, an Au coating greater than 0.5m is required.

Coating technique

The most common coating procedures are electroplating and electroless plating. Electroless plating, which is based on a chemical process, can produce a more uniform coating than electroplating. In this study, the coating process is also addressed as a parameter, and the influence of coating uniformity on thermal contact conductance is investigated.

5 Shape Memory Alloy Heat Switch

Another type of passively actuated MHS is the shape memory alloy (SMA) heat switch. It operates at cryogenic temperatures. Benefan and Notardonato [3] have developed heat pipe-based thermal switches using shape memory alloys for cryogenic applications during expeditions to the Moon and Mars missions are shown in Fig. 18. This switch dissipates heat from the cryogenic tank into space during the night cycle and provides insulation during the day cycle. NASA Kennedy Space Center researchers conducted research to combine innovative SMA material systems with methodologies for managing heat flow in the 4 K to 400 K temperature range. A shape-memory actuated heat switch for small-satellite thermal control has been proposed by the Naval Research Laboratory. SMA is used as actuator elements because they have the unique function of sensing temperature changes and changing their shape to act against external loads (such as preload springs). Shape memory alloys undergo a solid phase shift from a martensite crystal structure to an austenite crystal structure at a given temperature within the temperature range is shown in Fig. 20. By intrinsically sensing a change in temperature and actuating by surviving a form change as a result of a temperature-induced phase transition, a shape memory alloy element can include both sensory and actuation functions. Shape memory alloys are commonly employed to actuate machinery and are fashioned into wire, springs, tubes, or cylinders. SMAs may recover large loads by undergoing a temperature-induced phase transition (e.g., up to 8 percent) [3]. This strain recovery can occur in the presence of enormous forces, leading to their usage as actuators. This phase shift usually occurs in NiTi -SMA between the so-called martensite phase of the monoclinic system and the so-called austenite phase of the cubic system is shown in Fig. 21. When Fe is introduced into the NiTi system, the martensitic transformation occurs at a lower temperature, resulting in the creation of an intermediate R trigonal phase. Typically, there is hysteresis between the forward and reverse transformations. Transformation hysteresis is caused by the dissipation of elastic strain energy, the frictional resistance to interfacial motion, and other dissipation processes. Temperature hysteresis is as low as 1.5 K for the cubic to R-phase transformation, whereas it exceeds 10 K for the cubic to monoclinic martensitic transformation [9]. The low transformation hysteresis helps build actuators that operate over a limited temperature range. Springs have a longer stroke than straight elements such as thin strips and wires, so installing spiral-shaped SMA springs can help compensate for this structural limitation. Another advantage of coil springs is that they have a more uniform stress distribution than a bending mode ribbon, which has a higher stress concentration at the center of the element. Non-uniform stress distribution within the element can shorten fatigue life while improving the hysteresis caused by phase changes.

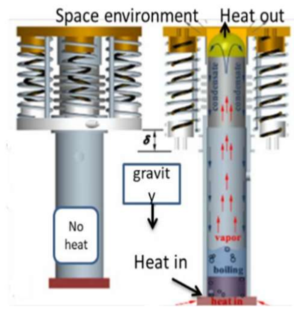


Fig. 18. SMA HS used in Moon and Mars mission [9].

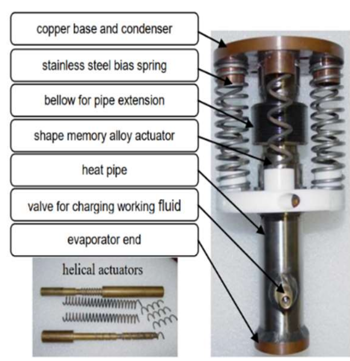


Fig. 19. SMA assembly [9].

Table 5, Shape Memory Alloy heat switch components and materials required.

Component	**Material**
Actuating Element	Nitinol (NiTi)
Stationary and Moving Plates	Oxygen-Free Pure Copper
Support Rods and Bushings	Beryllium Copper (Be-Cu)
Bias Spring	Austenitic stainless steels with a nickel content greater than 7%.
Bias Spring Holders	Brass
Spring Seats	Polytetrafluoroethylene (Teflon)
Grease	Indium Foil and Apiezon® N

5.1 Nitinol (NiTi) Alloy Selection

Nitinol alloy (NiTi) can withstand large elongations (up to 8%), has excellent corrosion resistance, works over a relatively wide temperature range due to significant changes in composition, and is, therefore, a working material for SMA Heat Switch. Selected as. It has mechanical properties, has a high fatigue life of 106 cycles, and has an elongation limit of 1% [10].

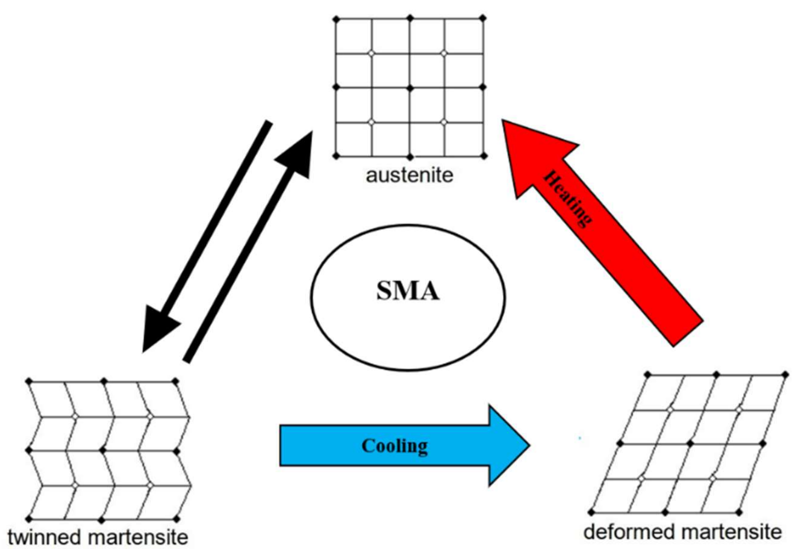


Fig. 20. Lattice Transformation.

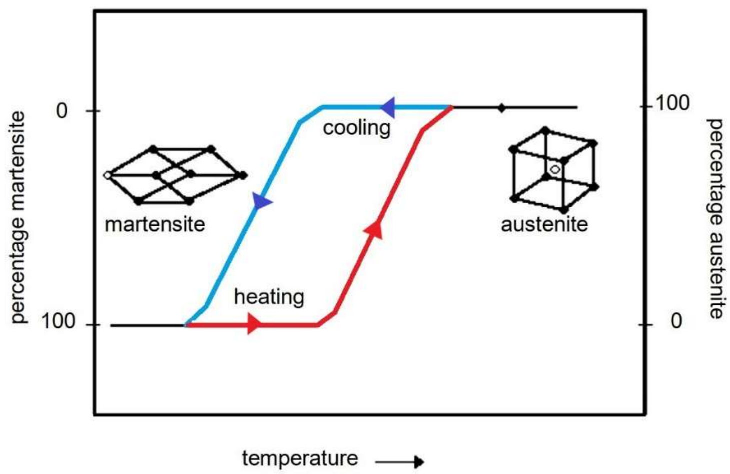


Fig. 21. Shape Transformation.

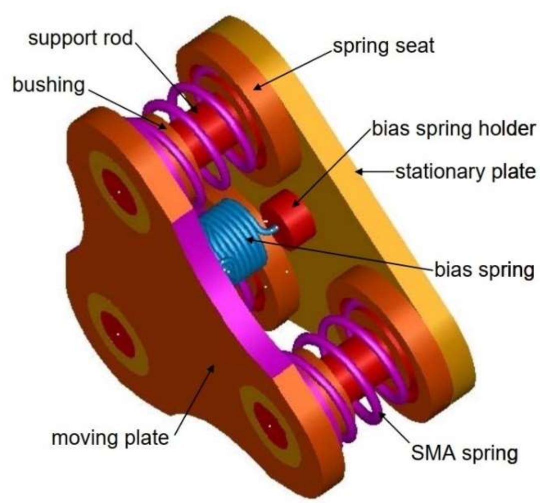


Fig. 22. SMA heat switch [10].

6 Differential Thermal Expansion Heat Switch

A type of passively operated MHS is a thermal switch with different thermal expansion. It operates at extremely low temperatures. Dietrich [3] uses one of the best DTE (Ultra High Molecular Weight Polyethylene) thermoplastics in a single focal plane array detector (FPA) to design two DTE devices for use at a temperature of approximately 100 K and the test was successful is shown in Fig. 23. No power consumption is required for normal operation or switching. This property improves reliability and allows for easier mechanical design. Bugby *et al.* [3] have developed several DTE devices for applications that require temperatures between 30 K and 100 K, such as the James Webb Space Telescope. Thermal switches with different thermal expansions use the difference in the coefficient of thermal expansion (CTE) of two different materials to form or break physical contact at the interface. As a result of a temperature shift, one portion shrinks more than the other.

Fig. 23. DTE heat switch [11].

The Differential thermal expansion heat switch is based on the idea that by adding a heater to the central tube, the switch may be actively turned off, significantly reducing the time it takes to transition from on to off (without the heater, the cryogenic component is warmed to open the gap and turn the switch off). When electricity is supplied to the heating, there is a considerable temperature gradient in the central pipe. When the tube is heated, it expands, creating a gap between the beryllium cylinder and the beryllium endplate. Conduction through this gap is significantly minimized in a vacuum and the switch provides excellent insulation ("off" state).

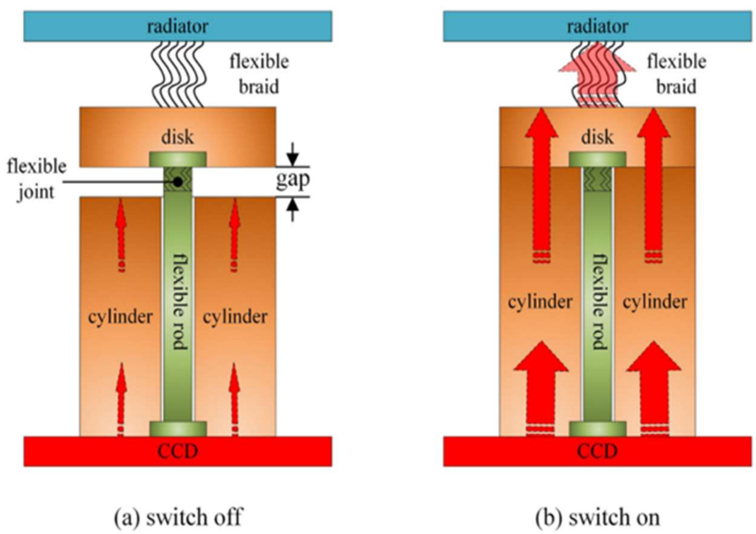


Fig. 24. SMA Heat switches working principle [6].

When the beryllium endplate reaches a certain temperature between the operating temperature of the spacecraft and the cryogenic components, which can be adjusted based on the gap during assembly, the center tube expands sufficiently and switches without additional heating. A cryocooler is used to cool the beryllium endplate as it goes from off to on (heating off). As a result, the center tube is more compressed than the beryllium endplate, the cylinder, cylinder, and endplate come into contact with each other, the gap is closed, and the switch switches to the "on" position (thermally conductive) is shown in Fig. 24. (a). When the small beryllium component is sufficiently cooled, the coefficient of thermal expansion (CTE) of the stainless-steel pipe is higher than that of beryllium, closing the switch gap and turning the DTE "on". By temporarily turning on the small heater on the stainless-steel pipe, the stainless-steel pipe expands enough to fill the gap and the DTE is turned "off" as shown in Fig. 24. (b). When half of the smaller beryllium is fully heated, the heater is no longer needed and the DTE remains "off" i.e., one side is cold and one side is warm. CTSW of two generations was created. The first generation CTSW is constructed of beryllium and stainless steel, whereas the second generation CTSW is constructed of polymer and aluminum [12]. In cryogenic systems, both the Fernando and Marcia and Zhang [12] double direction DTE are used. Two nuts, a flexible threaded rod, and a washer form a thermal switch with a difference in thermal expansion in two directions. The washers are placed in the space between the nuts. Flexible rods are made of materials with a low CTE, and discs are made of materials with a high coefficient of thermal expansion. One nut is attached to the satellite frame and the other nut is attached to the cryogenic sensor.

Flexible rods are made of materials with a low coefficient of thermal expansion, and discs are made of materials with a high coefficient of thermal expansion. One nut is attached to the satellite frame, while the other is secured to the cryogenic sensor. Invar was used to make the flexible rod (4J32). The cylinder and disc are both comprised of aluminum alloy (2A12).

Table 6, Differential Thermal Expansion heat switch components and materials required.

Component	**Material**
Flexible Rod	Invar (4J32), Stainless-Steel
Cylinder and Disc	Beryllium, Aluminum alloy (2A12)

6.1 Critical design features of the DTE

The functions required for DTE design are that the cylindrical beryllium section is very thin (0.07 mm surface value) separated by a precision flat gap, and the thin-walled stainless steel pipe aligns the beryllium parts and is structural. To provide support. There is a large size difference between the two beryllium components, and each beryllium component is individually gold-plated to increase contact conductivity.

6.2 Desired properties for end pieces

The properties required of the end piece are high thermal conductivity, low CTE at very low temperatures, availability, low sensitivity to cold welding, low hardness, and low density.

6.3 Desired tube/rod properties

DTE thermal switch tubes/rods should have low thermal conductivity, high CTE at very low temperatures, high modulus, high yield strength, low density, and are low creep susceptibility.

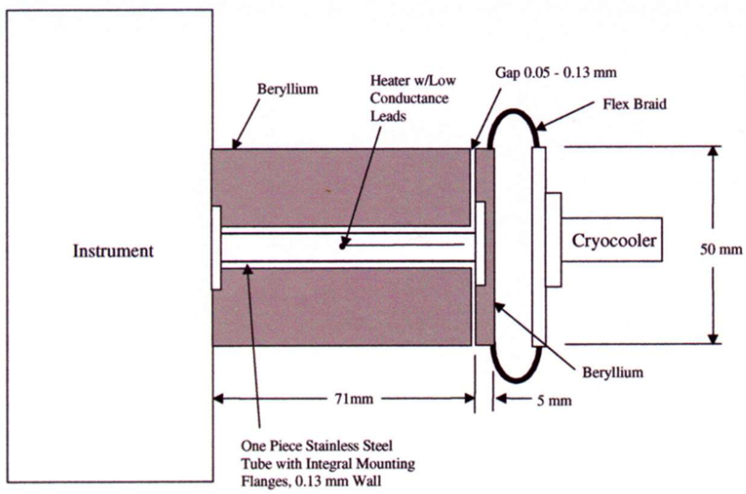


Fig. 25. DTE heat switch with beryllium as cylinder and disc and invar as flexible rod [11].

Table 7, The literature review on contributions over MHS and its types.

Author (Year)	**Type of work**	**Contribution**
R. L. Dolecek *et al.* (1953) [13]	Theoretical	An actively actuated wired mechanical heat switch is described.
J. Ancsin *et al.* (1967) [14]	Theoretical	Describes a dual mechanical thermal switch suitable for calorific value measurement in the 0.2 K to 5 K range.
D. H. Lowndes *et al.* (1969) [10]	Theoretical	An actively actuated jaw mechanical heat switch is described.
B. Marland *et al.* (2000) [11]	Experimental	The development and testing of DTE heat switch.

K. Lankford *et al.* (2002) [2]	Theoretical	A review on the application of heat switches, paraffin wax, pedestal, diaphragm thin plate, SMA, gas-gap, DTE heat switch is provided.
V.B. Krishnan *et al.* (2004) [15]	Experimental	This paper describes the SMA operation between the dewar from liquid methane and liquid oxygen and details the manufacture of SMA with cryogenic conversion temperatures for use in the above switches by arc melting and subsequent material testing.
B. Marland *et al.* (2004) [12]	Experimental	Reliable high-performance CTSW and cryogenic thermal switch test stand details and performance results.
J. L. Lemanski *et al.* (2006) [16]	Experimental	Design and test of low-temperature heat transfer switch with NiTiFe shape memory element for operation
M. Wang *et al.* (2007) [17]	Experimental	DTE on/off resistance is determined as well as switching ratio, an automatic test bench for long-term life testing has been built and installed.
V.B. Krishnan *et al.* (2008) [18]	Theoretical	Design and use of NiTiFe coil springs in low-hysteresis heat transfer switches for advanced spaceport applications in light of NASA's goals for future lunar and Mars missions.
Othmane Benafan *et al.* (2009) [9]	Experimental	Design, manufacture, and test thermal switches made of low-temperature shape memory alloys to meet NASA's thermal management requirements on the lunar surface.
V.B. Krishnan *et al.* (2010) [19]	Experimental	In-situ neutron diffraction was used to study the deformation of the p3-r-phase of NiTiFe during cryogenic compression.
O.Benafan *et al.* (2013) [20]	Experimental	The design, construction, and testing of a thermal switch with SMA elements actuating the open and closed states and a two-phase heat pipe transferring heat.
Makiko Ando *et al.* (2014) [5]	Experimental	The test model for the paraffin wax heat switch was built, and several operations to increase thermal performance, such as au coating on the contact surfaces, were carried out. A breadboard model (BBM) with an improved design was created and tested and its performance was assessed.
Amir E.Jahromi *et al.* (2014) [8]	Experimental	This paper measured and experimented with the thermal conductivity and described the benefits, applications, and performance of PZA.
M.J. Dipirro *et al.* (2014) [21]	Theoretical	All types are heat switches are discussed.

Hilbert van loo *et al.* (2016) [22]	Experimental	Thermal conductivity, mechanical characteristics, and release qualities are all examined for the SMA and the locking of a sensor during a satellite's launch and release once in orbit in this study.
Liang Guo *et al.* (2017) [6]	Experimental	Thermal characterization of a new passively operated DTE thermal switch with automatic adjustment for CCD thermal management of optical remote sensors for space.
Monan Li *et al.* (2017) [23]	Experimental	Mechanical thermal switches are designed and manufactured to reduce the cooling time of conducted cooling cryogenic systems with multiple copper thermal loads.
Q S Shu *et al.* (2017) [3]	Theoretical	A systematic review of the development of innovative cryogenic heat switches is provided.
Michael Pauken *et al.* (2018) [2]	Experimental	In 2003, a waxed thermal switch was created to control the temperature of the Mars Rover battery. The program includes measuring the thermal conductivity of the thermal switch in an 8 Torr CO_2 environment over the predicted operating temperature range of the battery.

7 Conclusion

In this article, we will discuss various mechanical thermal switches (MHS) such as piezoelectric actuated (PZA), paraffin wax (PZW), differential expansion difference (DTE), shape memory alloy (SMA). We also compare their functional principles, strengths and weaknesses, applications, and performance parameters as on/off switching ratio, temperature range, operating method, total size to weight ratio, structural robustness, the initial gap between two plates, contact force, and operating time. Cryogenic thermal switches (CHS) are essential for thermal management applications. The review work highlights that cryogenic thermal switches are essential for an integrated cryogenic bus (ICB) programmed to incorporate new cryogenic technologies into space systems. Moreover in this review, we observe that the DTE type MHS may impose approximately 30 times more contact force than the other MHS. As a result, DTE has a reduced thermal contact resistance and a higher heat switching ratio as compared to other MHS. Further choice, the wider operating temperature range of DTE HS (0.1 K – 100 K) makes it appropriate for space applications.

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