# A WIDE TEMPERATURE RANGE, RELIABLE, COMPACT CRYOGENIC THERMAL SWITCH

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## ABSTRACT

Nuclear explosion monitoring systems need an effective cryogenic xenon sampling system to monitor the concentration of the radioactive xenon isotopes in the atmosphere. This sampling system requires a thermal switch that allows a cryocooler to cool the xenon trap during the collection stage, and then thermally disconnect the cryocooler from the trap during the xenon removal stage. To this end, we are developing a compact, reliable thermosyphon that has an adjustable thermal conductance and can operate over a wide temperature range. It has an integrated actuator with no moving parts to thermally disconnect the xenon trap from the cryocooler cold head. This allows the trap to be heated up to a very high temperature (up to 300°C) to effectively remove xenon while the cryocooler still operates at cryogenic temperatures. Our thermosyphon uses a unique working fluid to enable it to operate over a wide temperature range (-50°C to -200°C). The large operating temperature range allows the cryocooler to operate at relatively high temperatures during the early cooldown process to provide a large cooling capacity, and thus speed up the xenon trap cooldown process. The thermosyphon has no moving parts and, therefore, it is very reliable.

## OBJECTIVES

Measuring the concentrations of radioactive xenon isotopes in the atmosphere is a proven technique used for monitoring nuclear explosion testing. A key step in the xenon sampling process is cryogenic xenon collection. A critical need for this collection process is a cryogenic thermal switch that thermally connects the xenon charcoal trap to the cryocooler during the gas collection stage, and then thermally disconnects it from the cryocooler during the gas removal stage. Disconnecting the xenon trap allows it to be heated to a very high temperature (up to 300°C) during desorption without damaging the cryocooler. The high desorption temperature reduces the residual amount of gas in the trap and thus increases the amount of xenon available for downstream processing during each gas collection cycle. In addition, the thermal switch must be able to efficiently conduct heat over a wide temperature range (-50°C to -200°C) so that the cryocooler can also operate at relatively high temperatures (> -50°C) during the early cooldown process of each gas sampling cycle. Operating the cryocooler at higher temperatures will enable it to achieve a much higher cooling power, and therefore speed up the cooldown process of the xenon trap.

There are several existing approaches that can vary the thermal conductance between a cooler and its cooling target. These approaches include (1) mechanical thermal switch, (2) gas gap thermal switch, (3) cryogenic circulator, and (4) conventional thermosyphon and heat pipes (Faghri 1995 and Pioro and Pioro 1997). However, these approaches are either unreliable, bulky, or inefficient, or they do not have the adequate operating temperature range needed for this application. Because of the performance limitations of these current technologies, there is a strong need for a compact, low-cost, reliable cryogenic thermal switch that can operate over a wide temperature range.

### Thermal Switch with a Wide Operating Temperature Range

We plan to develop an advanced thermosyphon using a gas mixture as its working fluid. The thermosyphon relies on condensation and evaporation of its working fluid to efficiently transfer heat. The flow circulation is driven by the density difference between the fluids in the liquid channel and the vapor channel (Figure 1). Our thermosyphon has an integrated bubble valve with no moving parts to actuate (i.e., connect or disconnect) the thermal switch. The bubble valve uses a very small heater to generate a small amount of vapor bubbles to plug the condensate drain line, and thus virtually shut off the fluid circulation and the heat transfer in the thermosyphon. The working mixture has a two-phase region that extends from room temperature to normal liquid nitrogen temperature, allowing the thermosyphon to transfer heat over a wide temperature range. The operating mechanism and unique features are discussed below.

**Operation of a Basic Two-Phase Thermosyphon**. A two-phase thermosyphon is a passive heat transfer device that relies on natural convection to transfer heat from an evaporator to a condenser that is at a higher elevation. When heat is applied to the evaporator section, the working fluid evaporates. The vapor flows upward to the condenser section, where it condenses to liquid. The condensate then drains down to the evaporator in a separate liquid channel, completing the cycle of the working fluid. The convective vapor flow can move upward because the pressure in the evaporator section is higher than in the condenser section due to the hydrostatic head (minus the pressure drop) in the liquid line.

The advantage of a thermosyphon is its very high thermal conductance. Its convective two-phase flow enables it to efficiently absorb heat, transfer it, and dissipate it. Since the heat of evaporation and condensation (latent heat) is very large, a small refrigerant flow in a compact thermosyphon can achieve a very high heat transfer rate. There are no moving parts in a thermosyphon; therefore, it is inherently very reliable.

**Mechanism for Adjusting Thermal Conductance**. The heat transfer rate of a thermosyphon is directly proportional to the two-phase circulation flow rate (thermal conduction through the walls of liquid and vapor channels is negligible if they are made of thin-walled tubes that have relatively low thermal conductivity). Reducing the circulation flow by increasing the pressure drop in the liquid line will reduce the heat transfer rate. This can be simply achieved by placing a bubble valve in the liquid line. The bubble valve can be a small heater attached to the sidewall of the liquid line. When the heater is turned on, a small amount of liquid will be vaporized. This will cause a significant drop in the liquid flow rate and, therefore, the heat transfer rate. The liquid return line near the evaporator has a large flow area so that the parasitic heat conducted from the evaporator will not limit the condensate flow rate during the cooldown process. Using a bubble valve is much more reliable and compact than using a simple solenoid valve to shut off the return liquid flow.

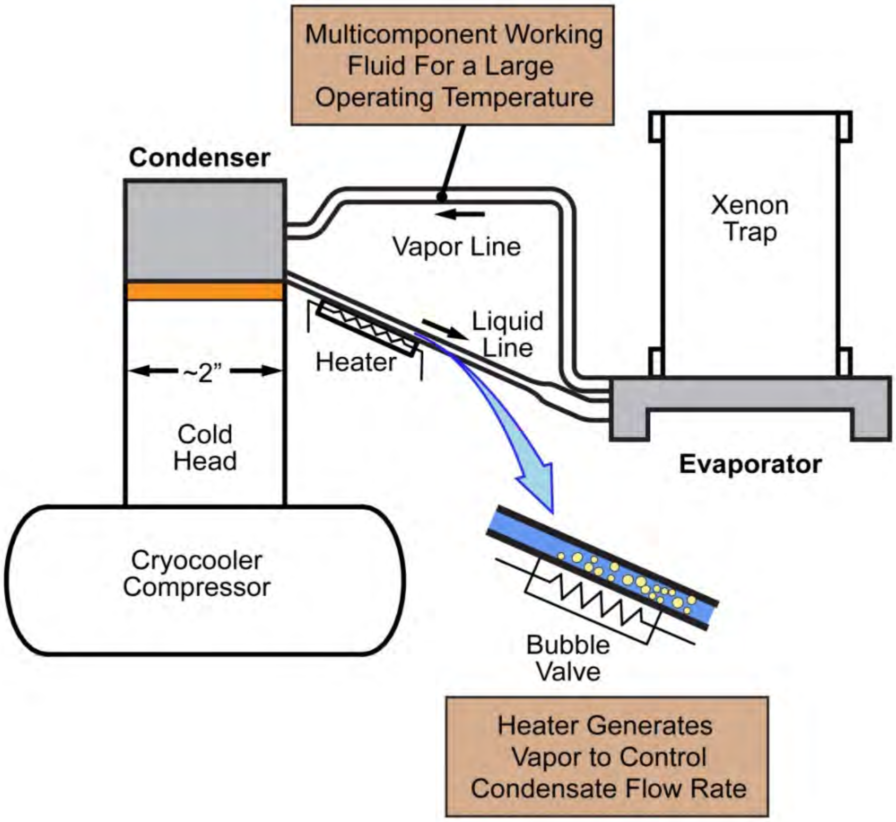


**Figure 1. Schematic of the cryogenic thermal switch based on a unique thermosyphon.**

**Unique Fluid Mixture for a Wide Operating Temperature Range**. One significant downside of a single-component working fluid is that it can operate only over a limited temperature range. To overcome this limitation, we plan to use a multi-component mixture as the working fluid in the thermosyphon. The mixture in general is eutectic; the freezing point of the mixture is lower than the freezing points of the individual components. This allows the working fluid to operate at a temperature near the normal liquid nitrogen temperature (77 K). The heavy components in the mixture have a critical temperature greater than the room temperature. Consequently, the mixture will enable the thermosyphon to operate effectively at temperatures as high as room temperature.

Compared to a single-component fluid, a multi-component fluid in a two-phase thermosyphon has several unique operation issues. These issues stem from fractionation of the mixture during phase change. The composition of the liquid is different from that of the vapor with which it is in thermal equilibrium (i.e., non-azeotropic).

First, fractionation can cause heavier components to gradually accumulate in the evaporator (like a distillation column), resulting in a vapor that is concentrated with lighter components. Consequently, the evaporator temperature (i.e., xenon trap temperature) could be much higher than the condenser temperature (i.e., cryocooler temperature), which is undesirable.

Second, fractionation can cause an adverse temperature glide during phase change, requiring the condenser to operate at a lower temperature and the evaporator at a higher temperature than thermodynamically required (Figure 2). This is because the heavier components in the vapor condense first, leaving a residual vapor near the condensing surface concentrated with lighter components, which require a lower temperature to condense. For a similar reason, fractionation also causes the evaporator to operate at a higher temperature to vaporize the residual heavy components. These effects further increase the temperature difference between the evaporator and the condenser.

Third, fractionation can cause the composition of vapor from the evaporator to be different from the vapor elsewhere in the system, resulting in a much smaller fluid circulation flow rate. For example, during the early cooldown process, the condensate contains very little volatile components (the most volatile constituent). When the condensate is later vaporized, the resulting vapor has a very low concentration of volatile component. However, the bulk vapor in the system still has a very high concentration of the most volatile constituent (which is slightly higher than the initially charged concentration). Consequently, the molecules of heavier components from the evaporator must diffuse through the most volatile constituent and other molecules to reach the condensing surface. This will significantly reduce the condensation flow rate and, therefore, the heat transfer rate. This effect is similar to the noncondensable gas effect in a conventional heat pipe.

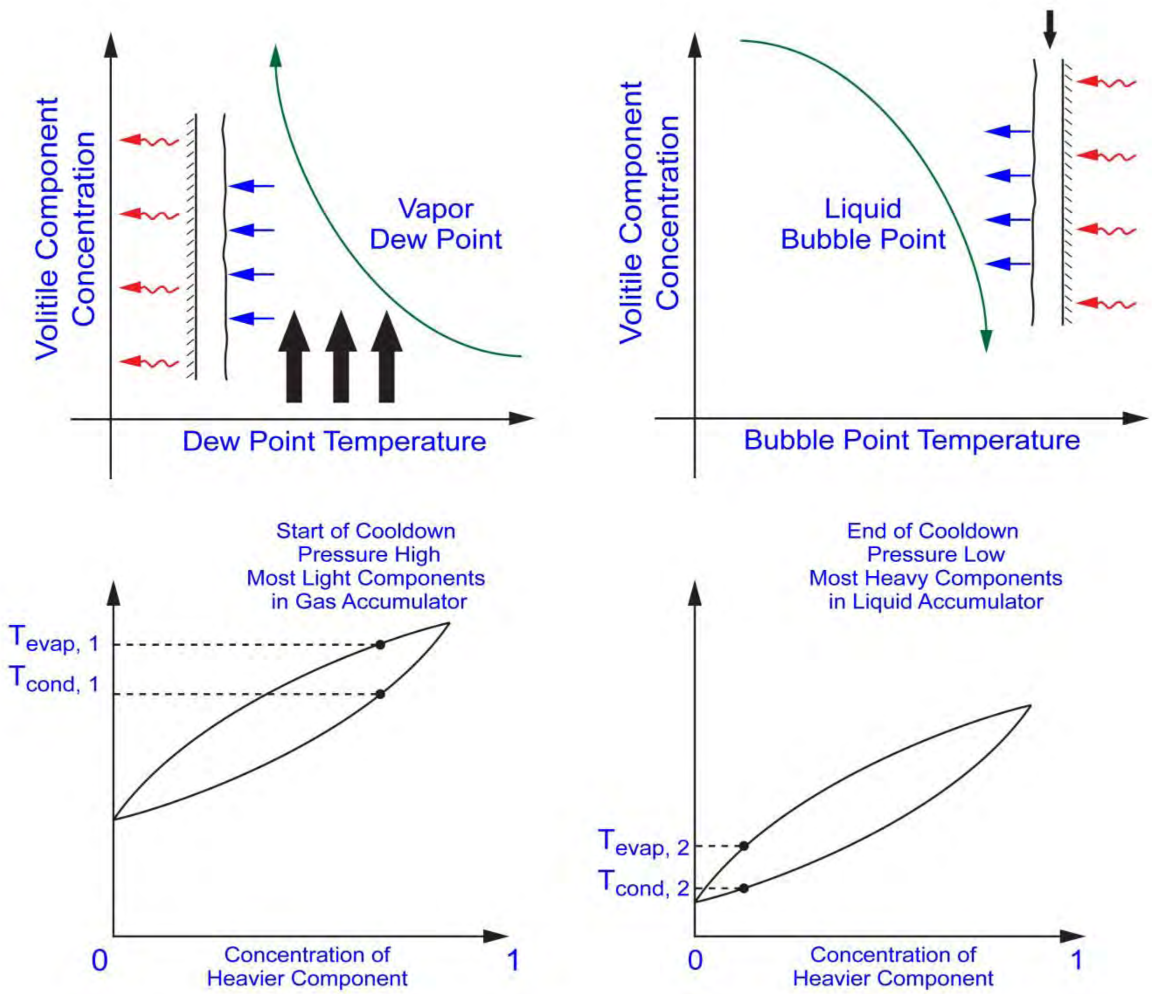


**Figure 2. Temperature and composition of a fluid mixture during evaporation and condensation processes. The characteristics of a binary mixture are used to illustrate the behaviors of a fluid mixture.**

To address these potential issues, our thermosyphon has several unique design features. First, our design will prevent temperature glide during phase change and reduce temperature difference between the evaporator and the condenser. Second, our design will self-adjust the composition of the working fluid in the active regions to eliminate diffusion resistance during steady state operation; this will enable the thermosyphon to achieve a heat transfer rate similar to one using a single-component fluid.

Our thermosyphon's ability to self-adjust its working fluid composition in the active regions will also help to reduce the temperature difference between the evaporator and the condenser. Since the compositions of the condensate and evaporated vapor are the same during steady state operation, the condenser and the evaporator will operate at the dew point and the bubble point of the working fluid, respectively. Their temperature difference will be small when the thermosyphon's temperature is near the upper or lower limit of its operating temperature range (Figure 2). This is because the active working fluid in these cases will mainly consist of one component. At other operating temperatures, the difference between the dew point and the bubble point can be noticeable. However, this temperature drop should be acceptable for this application because it will also slightly reduce the cryocooler cooling capacity during the cooldown process (because the cryocooler needs to operate at a slightly lower temperature).

### Development Approach

The overall objective is to develop a reliable, compact thermal switch to enable effective cryogenic xenon collection in nuclear explosion monitoring systems. In the Phase I program, we plan to prove the feasibility of our approach by conducting the following work:

**Thermosyphon Demonstration**. The goal of this activity is to demonstrate the key performance characteristics of a proof-of-concept thermosyphon using a binary gas mixture. More specifically, we plan to demonstrate (1) thermosyphon thermal switch fabrication using prototypical methods; (2) the efficacy of the heat-actuated valve to create a thermal disconnect between the condenser and evaporator; (3) a large operating temperature range; (4) high thermal conductance between the evaporator and condenser; and (5) performance that agrees well with our design models.

We will assemble a thermosyphon with prototypical features and charge the system with an appropriate amount of working fluid. We will perform a series of tests to measure the performance of the thermosyphon in its “ON” and “OFF” states. With the valve heater off, we will measure the performance of the thermosyphon at different operating temperatures and input powers. After steady state conditions have been reached, we will then activate the valve heater to stop the circulating flow and disconnect the evaporator from the condenser. We will measure the thermal conductance to show the effectiveness of the bubble valve.

**Detailed Thermosyphon Design**. The goal of this activity is to show that a thermosyphon using a gas mixture for a xenon collection system will be compact, efficient, and simple to manufacture. The result will be an optimum working fluid composition, key geometric design parameters, and performance predictions for a full-size prototype.

First, we will optimize the composition of the working fluid mixture to provide adequate heat transfer throughout the target temperature range. We will develop an analysis model to predict thermodynamic states at key locations under different operating conditions. We will calculate the composition of the fluid, as well as the total system pressure, under steady state conditions at several temperatures. We will then predict the dew point and bubble point of the fluid mixture in the active region at each temperature. Based on these calculations, we will determine the temperature difference between the evaporator and condenser at several temperatures. We will optimize the initial charge composition, the initial charge pressure, and the volumes of key regions in the thermosyphon to minimize the temperature difference.

## CONCLUSIONS

The mixture thermosyphon can improve the effectiveness of the xenon sampling system and therefore the efficacy of nuclear explosion detection systems. Its unique working fluid and component design features allow the thermal switch to operate over a wide temperature range. The large heat capacitance associated with a two-phase flow allows a compact thermosyphon to achieve a high heat transfer rate. The entire device has no moving parts and, therefore, it will not have mechanical failures.

## REFERENCES

Faghri, A (1995). *Heat Pipe Science and Technology*, New York: Taylor and Francis.

Pioro, L. S. and I. L. Pioro (1997). *Industrial Two-phase Thermosyphons*, Begell House.