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Review of Thermosyphon Applications

Anna M. Wagner

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Abstract

Thermosyphons have been used for stabilizing permafrost since 1960. The original thermopile was designed as a vertical unit with one end buried in the ground and the other end exposed to the air. More recently, flat, loop, and buried thermosyphons have been developed. Thermosyphons consist of a pipe or series of pipes that are installed with one part below ground (evaporator) and the other exposed to the air (condenser). They are filled with a pressurized fluid that evaporates because of the heat of the soil and rises as a vapor to the condenser. If the air temperature is lower than that of the soil, the vapor will condense on the inside walls of the pipe and release the transported heat from the ground to the air. The condensate then returns to the evaporator by gravity. When the air temperature is higher than that of the soil, the heat transfer ceases and the unit is dormant. Presented here is a general overview of applications of thermosyphons in cold regions.

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Preface

The work was performed by Anna M. Wagner (Biogeochemical Sciences Branch, Dr. Terry Sobecki Chief), US Army Engineer Research and Development Center, Cold Regions and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief, Research and Engineering Division; and Kevin Knuuti was Technical Director for Earth Sciences and Engineering. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert E. Davis.

COL Jeffrey R. Eckstein is the Commander of ERDC, and Dr. Jeffery P. Holland is the Director.

Unit Conversion Factors

Multiply	By	To Obtain
atmosphere (standard)	101.325	kilopascals
bars	100	kilopascals
British thermal units (International Table)	1,055.056	joules
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
Inches	0.0254	meters
miles per hour	0.44704	meters per second

1 Introduction

Permafrost degradation is amplified by the effects of a warming climate. If thermal disturbance of permafrost takes place, the strength of the ground may be greatly reduced, resulting in settlement and stability problems. Insulation, ventilation, or refrigeration systems are often used to locally protect permafrost around foundations. When constructing in permafrost regions, a "passive" or "active" method (Johnston 1981) is typically used to protect permafrost. A passive method maintains the frozen state of the soil. The most widely used passive technique is to incorporate ventilated air spaces beneath elevated buildings (Shur and Goering 2009). This method is recommended for locations with permafrost temperatures below −3°C (Johnston 1981) and provides a measure of thermal stability. Active methods concentrate on removing the thaw-unstable or ice-rich permafrost soils and replacing them with non-frost-susceptible (NFS) materials. Most active methods are installed during construction, when permafrost below structures is thawing or prior to construction when foundation material conditions are modified. Successful construction often pre-thaws foundation soils that may be suitable, such as coarse-grained perennially frozen soils (Shur and Goering 2009). Engineering stability can be provided if the thermal stability of the permafrost can be ensured (Cheng and Li 2003).

Thermosyphons have been used for foundation stabilization in continuous and discontinuous permafrost areas since 1960 (Richardson 1979). As of January 2008, thermosyphons had been used in over 900 installations in AK alone (Figure 1) (Yarmak 2012). The technology of using thermosyphons for construction in cold climates has been developed in parallel in the US, Canada, China, and Russia. The largest thermosyphon installation was along the Trans-Alaska Pipeline (completed in 1977), where about 120,000 units were installed (Heuer 1979). Using thermosyphons in engineering structures in China started in the 1970s (Wu et al. 2010). In Russia, thermosyphons became commonly used for buildings and structures beginning in 1990 (Popov et al. 2010).

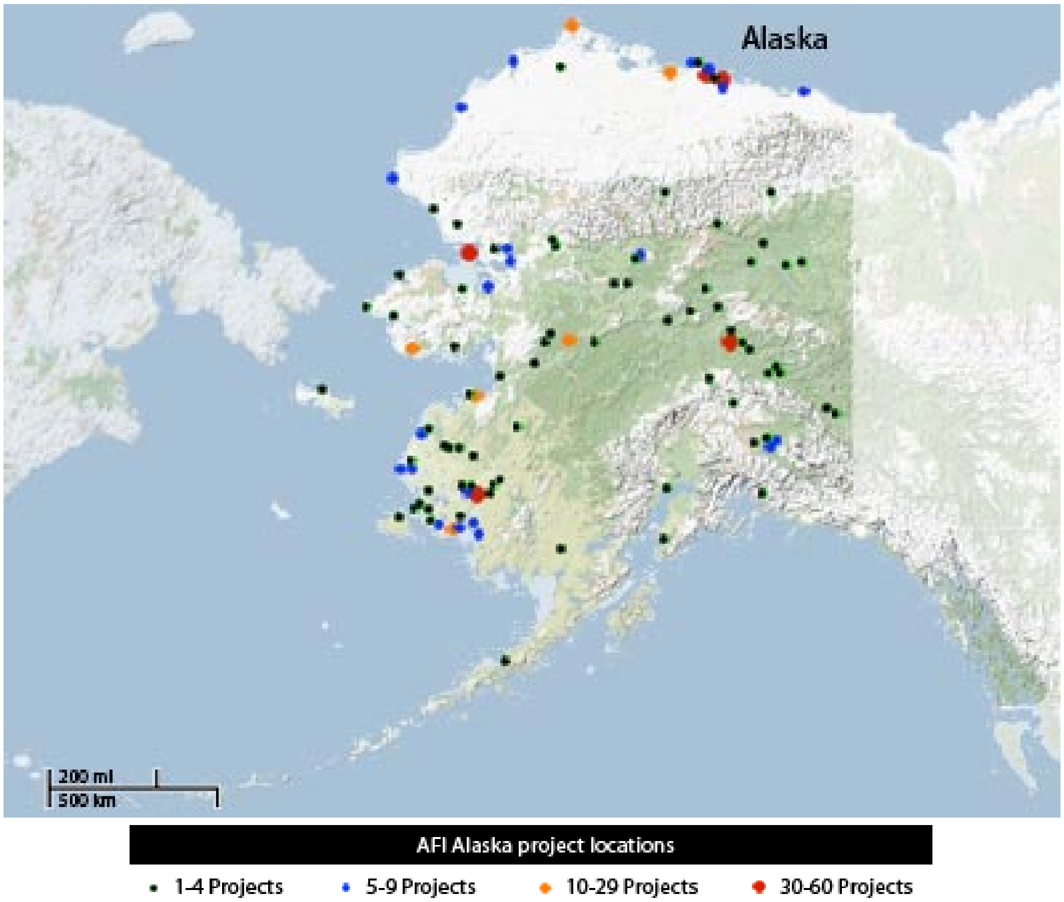


Figure 1. Installations of thermosyphons by Arctic Foundations Inc., AK (as of January 2008).

Zarling and Brayley (1987), Forsstrom et al. (2002), Wen et al. (2005), and Xu and Goering (2008) have investigated the use of thermosyphons in road and rail embankments. Zhang (as cited in Wu et al. (2010)) reported how thermosyphons were installed in 1989 at the culverts of the highway across the Qinghai-Tibetan Plateau. Thermosyphons have also been installed in over 34 km of the railroad embankment of Qinghai-Tibet Railroad (QTR) (Cheng et al. 2009). The Chaidaer-Muli railway was completed in 2009 with about 20,000 thermosyphon units (Zhang et al. 2011a).

Thermosyphons have been used in many technology fields, including, but not limited to, space systems; the automobile industry; the railroad industry; electrical, electronics, and turbine blade cooling; heat exchangers; humidity control; the food industry; solar power systems, and reactors; and the nuclear industries. Thermosyphons have even been considered in more unconventional applications, such as preserving archeological sites in the Arctic or accessing low-temperature waste energy (Goetz 2010, Jeong and Lee 2010). In colder climates thermosyphons are used for preservation of permafrost and de-icing of roadways. More recently, thermosyphons have successfully been used to prevent contaminant migration from tailing dams in Canada and Russia (Edlund et al. 1998, Hayley et al. 2004). This report discusses cold regions applications of thermosyphons.

2 Thermosyphon Technology

Originally, thermosyphons were designed as passive, pressurized, sealed pipes. Later, they were modified to work as an active and hybrid system. The vertical thermosyphon includes one buried end (evaporator) and one end exposed to the air (condenser) (Figure 2). The pipe is charged with a working fluid that convects thermal energy, leading to a one-way transport of ground heat when the temperature is lower at the condenser compared to the evaporator. Thermosyphons operate by vaporization of the working fluid at the lower buried end, the vapor rising through the adiabatic section, and then condensing on the walls of the condenser. Upon condensation, the vapor releases its latent heat to the wall and then to the outer air. Finally, the condensate returns to the evaporator by gravity. The condensation occurs when the air temperature is below the saturation temperature of the gas. Natural convection is created where heat is absorbed from the soil and rejected to the atmosphere. The heat transfer ceases when the air temperature is higher than the soil. Figure 3 shows uninstalled and installed evaporators and condensers.

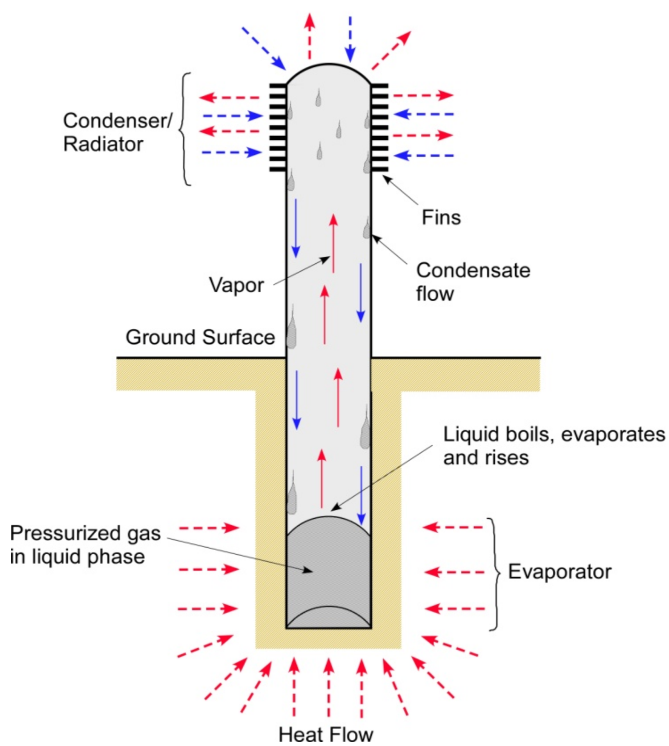


Figure 2. Passive thermosyphon.

Figure 3. Hybrid system: a) Uninstalled evaporators, b) installed evaporator, and c) condenser.

There are three different methods of facilitating the convection cycle of thermosyphons:

1. Passive thermosyphons.
2. Active thermosyphons.
3. Hybrid thermosyphons.

Passive thermosyphons function without external power and only operate when air temperatures are below freezing and lower than the ground temperatures. Active thermosyphons are linked to a heat pump (similar to a refrigerator) and thus can be used in more temperate climates. The passive and the active techniques can be combined into a hybrid system (Figure 4).

The hybrid system functions without power when the temperatures are sufficiently low and once ambient temperatures rise above freezing, the heat pump turns on automatically. This system reduces energy costs compared to conventional freezing techniques that would be running continuously. It is not uncommon to use the hybrid system for installations where faster freezing is needed. Hybrid thermosyphons were tested in the laboratory in the early 1990s (Haynes et al. 1991) but the first commercial installation was in the summer of 1984 at Galena, AK (Yarmak 2012). Dolgikh et al. (as cited in Perlshtein [2008]) state that hybrid thermosyphons are used more and more frequently in Russia.

Figure 4. Hybrid thermosyphons installed in Fairbanks, AK.

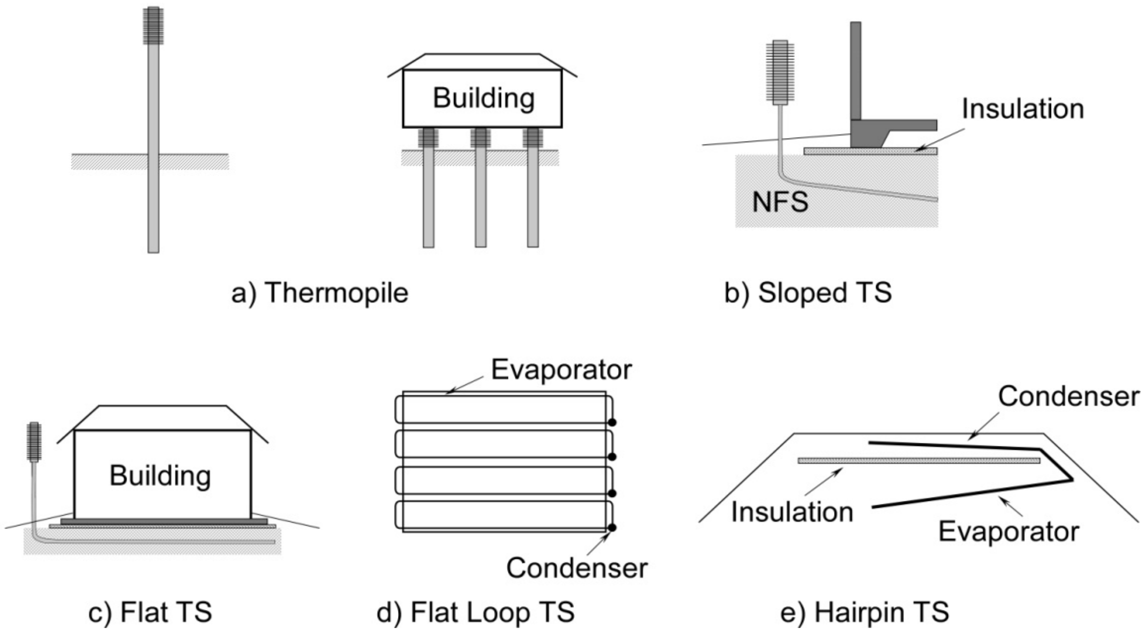


Figure 5. Thermosyphon (TS) designs—modified from Holubec (2008), Xu and Goering (2008), and Yarmak and Long (2002).

Depending on the application, thermosyphons can be installed vertically, on a slope, horizontally, as a flat loop, or completely buried, which also has been called a hairpin thermosyphon (Figure 5).

2.1 Vertical thermosyphons (thermopiles)

Using thermosyphons for maintaining permafrost foundations was first developed by Long in 1960 (Richardson 1979). Initially, it was called "The Long Thermopile" and it was used for foundation support or as an anchor to maintain frozen soil conditions near the pile (Long 1963). Originally, propane was used as the working fluid but carbon dioxide (CO_2) is the preferred working fluid today. A further advancement of the Long thermopile was the ring and helix-type piles (Figure 6) that were developed to support greater loads (Long 1973). The vertical thermosyphon (Long thermopile) has been modified through the years but the basic principal stays the same and the design continues to be used in current installations.

Figure 6. Thermo helix piles loaded for shipment.

Since 1993, Russian scientists have developed small-diameter thermosyphons (Lyazgin et al. 2003). The TMD-5 is manufactured from aluminum alloy and has a diameter of 28 mm. The main advantages of the aluminum alloy are that it has a high thermal conductivity and there is no need for an anticorrosive coating. The improved thermal transport, in combination with internal features of the TMD-5, increases the active running time by 1–1.5 months/year. The evaporator of this unit has an extra plate welded to it for increased conduction and rigidity. The TMD-5 was further modified to develop the Thermo-stabilizer with Improved Productivity (TIP). The cooling capability of the TIP is 1.6 times higher than the TMD-5 (Bayasan et al. 2008). The improved productivity is attributable to the TIP units having a larger heat-exchange surface from secondary fins on the condenser, as well as a second plate welded to the evaporator.

2.2 Sloped thermosyphons

The first sloped thermosyphon (Figure 5b) was installed in 1975 at the Ross River School in Yukon Territory (Hayley 1982). By the beginning of the 1980s, sloping evaporator thermosyphons were installed routinely throughout AK beneath heated at-grade structures (Yarmak and Long 2002). In fact, the great majority of existing passive subgrade thermosyphons are installed with sloping evaporators. Evaporator slopes between 3 to 10% are typically used. There are many advantages with this design. For example, the unit can be fully assembled in the shop (for units shorter than the shipping limits), conventional field methods can be used for field assembly (for longer units), and it can easily be installed by experienced contractors (Yarmak and Long 2002). This unit is less practical at larger buildings where long evaporators are used which, because of its sloped installation, would result in a deep non-frost-susceptible (NFS) fill. Also, where the subgrade is subject to movement, the sloped evaporator may settle or heave.

2.3 Flat thermosyphons

In 1978, the first flat thermosyphons (Figure 5c) in AK were installed in City of Galena's Warm Storage building (Yarmak and Long 2002). The flat thermosyphons were further tested by Denhartog (1988) at a laboratory scale. The grade of the evaporator needs to be absolutely horizontal to ensure a uniform distribution of the liquid phase of the working fluid and, thus, uniform heat extraction. A more recent example of the installation of flat thermosyphons units is the Chena Hot Springs Road project (see Section 4.4.3) constructed in 1998 (Forsstrom et al. 2002).

2.4 Flat loop thermosyphons

The flat loop thermosyphon was first field tested near Winnipeg, Canada, in 1994 (Yarmak and Long 2002). This pilot study showed that 1.4 times more volume of soil froze at the flat loop thermosyphon compared to a sloped evaporator thermosyphon. This system can be used in two configurations: slab grade-on design or a crawl space installation (Holubec et al. 2008). In both installations, the evaporator pipes are placed below gravel (NFS fill) and insulation. Basically, the flat looped system consists of four components as shown in Figure 7 (Holubec 2008; Holubec et al. 2008):

1. 1–2 m compacted gravel.
2. Evaporators (flat).
3. 150 mm bedding (sand layer) below and above the pipes.
4. 100–200 mm rigid insulation.
5. Condensers (vertical).

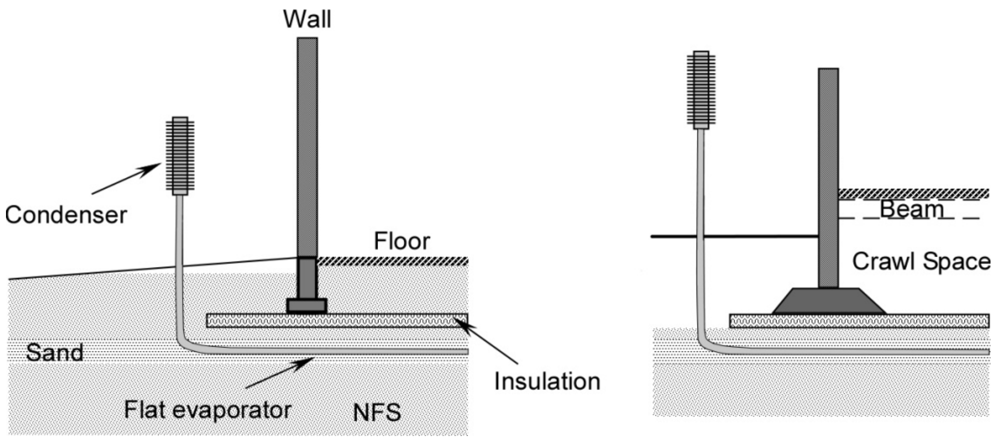


Figure 7. Slab on grade and crawl space flat thermosyphon installation (modified from Holubec (2008).

Evaporator loops can be at least 178 m but 150 m is a more common length (Yarmak and Long 2002; Yarmak and Long 2012). The efficiency of the flat loop thermosyphons can be improved by increasing the condenser surface area, decreasing evaporator spacing, and adding insulation thickness. Some of the advantages with this design is that the NFS fill depth does not need to be increased with an increased building size, the design of the loop is very flexible where horizontal bends can be incorporated to avoid obstructions, and allowance for heave and settlement can be built in (Yarmak and Long 2002). Also, the flat loop evaporator thermosyphon weighs less than similarly sized sloped thermosyphons, thus decreasing the shipping cost to the site. Disadvantages of this system include the small diameter of the tubing, making it easier to damage during excavation. Also, the cost of installation could be higher for the flat loop evaporator because field assembly is almost always required. In Canada (Yukon, Northwest Territories, Nunavut, and northern Quebec), there were about 80 flat loop thermosyphon foundations constructed by 2008. Fifteen of these were installed to keep the foundation frozen at the bottom of dams. A plan view of a flat loop system can be seen in Figure 5d.

2.5 Flexible evaporator thermosyphons

Annealed copper, aluminum extrusions, and coiled steel oilfield tubing have been used for flexible evaporator thermosyphons since the late 1970s (Yarmak and Long 2002). These units can be fully charged with working fluid in the shop prior to shipment to the site, which minimizes field assembly and charging of the units in the field. Proper installation is crucial and they are only flexible for a single field bend.

2.6 Buried and hairpin thermosyphons

Buried and hairpin thermosyphons are entirely buried beneath the ground surface (Figure 5e). The condensers of buried thermosyphons are placed close to the surface and the evaporators are installed deep in the sub-base. The first installation of buried thermosyphons was at the Chena Hot Springs Road project, AK, in 1998 (Forsstrom et al. 2002). The condenser of the hairpin thermosyphon is placed in the fill near the surface, above the insulation (but with a slight upward angle), and the evaporator is bent around the insulation and installed at a downward angle. Hairpin thermosyphons have been successfully used at Thompson Drive in Fairbanks, AK, since 2004 (Xu and Goering 2008). With no above-ground condenser, these completely buried units provide an option for road and runway installations that result in no surface safety hazards. Because the most expensive part of the thermosyphon (the finned heat exchanger) is excluded in this type of unit, the overall cost is less than that of conventional units (Xu and Goering 2008).

3 Heat Transfer of Thermosyphons

3.1 Thermosyphon performance

The heat transfer rate of a thermosyphon is a function of its 1) working fluid, 2) symmetry, 3) construction material, and 4) surrounding environment (Zarling et al. 1990). Different working fluids have different heats of vaporization, vapor and liquid densities, liquid thermal conductivities, specific heats, and viscosities, which all affect the performance of the unit. To ensure turbulent flow within the thermosyphons and to enhance the flow return to the evaporator, the working fluid should have both a high density and low viscosity (Long and Zarling 2004). The freezing point must be compatible with low-temperature operations and the fluid should have a high thermal conductivity. In addition, a sufficiently high vapor pressure at low operating temperatures is needed to transport sufficient mass in the vapor phase for adequate heat transfer. Depending on the application, site conditions, and desired soil temperatures, pressurized working fluids such as CO_2, Freon, butane, propane, or ammonia (NH_3) have been used. Other fluids may be possible. Figure 8 shows examples of saturation vapor pressure for CO_2, NH_3, and propane. The saturation vapor pressure changes with temperature and at 0°C the saturation vapor pressure for CO_2 is quite high at about 3500 kPa. Lastly, the fluid needs to be chemically pure, stable, and compatible with the container material. Currently, CO_2 is the most commonly used working fluid in the US and Canada.

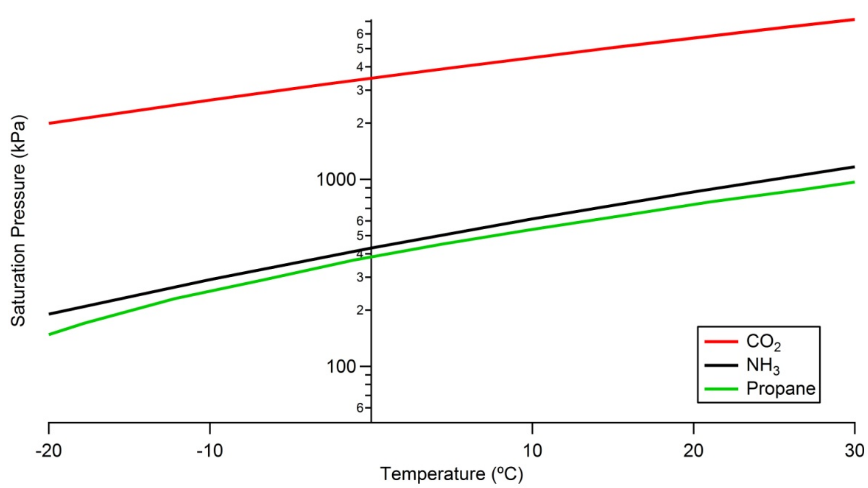


Figure 8. Saturation vapor pressure versus temperature for different working fluids.

The symmetry of the thermosyphon components, such as the length of the evaporator, condenser area (fin size), and the diameter of the pipe, will have an effect on the performance of the unit. The pipe material, fin design and material, and surface treatment of the material will also affect heat transfer. Air temperatures, wind speed, soil properties, and the season of installation will all affect the amount of cooling that can be achieved from the thermosyphon. A negligible amount of heat is transferred through the wall of the steel pipe in the summer.

The heat transfer rate, *q,* of a two-phase thermosyphon is expressed as (Long and Zarling 2004):

$$q = \frac{\Delta T}{R} \tag{1}$$

where

ΔT = difference between soil temperature ambient air temperature
T_s = soil temperature
T_a = ambient air temperature
R = total thermal resistance.

More specifically the total thermal resistance is defined as:

$$R = R_s + R_{we} + R_{ce} + R_e + R_c + R_{cc} + R_{wc} + R_f \tag{2}$$

where

R_s = soil resistance
R_{we} = resistance of the evaporator wall
R_{ce} = resistance of the condensate in evaporator
R_e = resistance of the evaporation
R_c = resistance of the condensation
R_{cc} = resistance of the condensate in condenser
R_{wc} = resistance of the condenser wall
R_f = resistance of the condenser.

The internal resistance to heat flow in a thermosyphon is negligible compared to the resistance between the soil and evaporator and the condenser and ambient air resulting in a heat removal rate (Yarmak and Long 1984). A combination of eq 1 and 2 results in:

$$q = \frac{(T_s - T_a)}{(R_s + R_f)} \tag{3}$$

The convective thermal resistance of the condenser can be expressed as:

$$R_f = \frac{1}{Aeh} \tag{4}$$

where

A = total exposed surface of the condenser
h = heat transfer coefficient that depends on the air velocity and surface characteristics of the condenser
e = fin efficiency which is a function of the fin geometry, fin material, and the heat transfer coefficient.

The radius of freezing from a thermosyphon can be expressed as (Long and Zarling 2004):

$$AFI = (r^2 - r_e^2) L_s \left(\frac{\pi}{C/l_e} - \frac{1}{4k_{sf}} \right) + \frac{L_s}{2k_{sf}} r^2 \ln\left(\frac{r}{r_e}\right) \tag{5}$$

where

AFI = air freezing index
L_s = soil volumetric latent heat, r is the radius of freezing
r_e = radius of the evaporator
C = conductance of the thermosyphon
l_e = length of the evaporator
k_{sf} = frozen soil thermal conductivity.

Empirical equations were determined by Haynes and Zarling (1988) from tests performed on evaporators of different slopes (0 to 12°) charged with CO_2 and NH_3. These expressions are plotted in Figure 9 where it can be seen that the heat transfer conductance increases with air velocity and increasing evaporator slope.

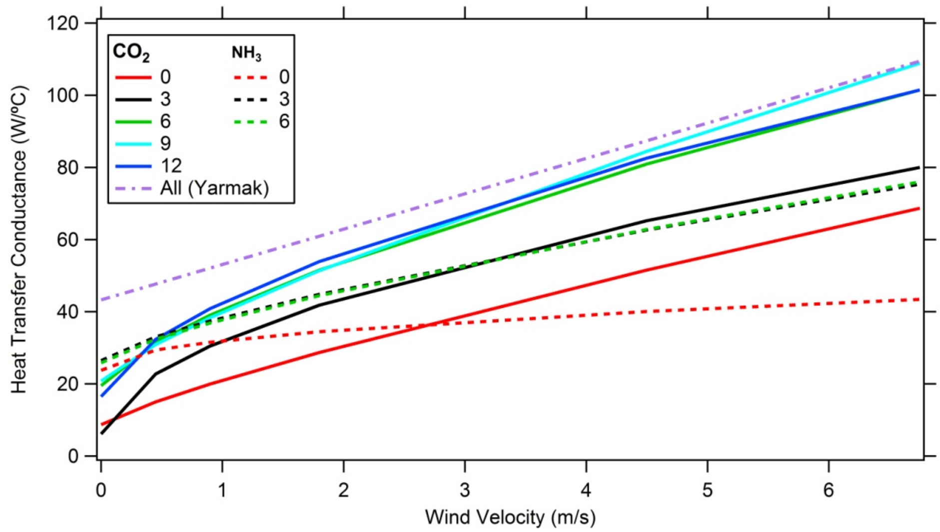


Figure 9. Thermosyphon performance for different evaporator angles (0, 3, 6, 9, and 12°) and working fluids (CO_2, and NH_3). "Yarmak" is for all evaporator angles (eq 6).

The placement of thermosyphons next to a building (Figure 10) also influences the thermosyphon performance. Haynes and Zarling (1988) performed tests using the configurations as illustrated in Figure 10. Results are shown in Figure 11. These tests show that the 45° configuration using CO_2 results in the highest thermosyphon performance.

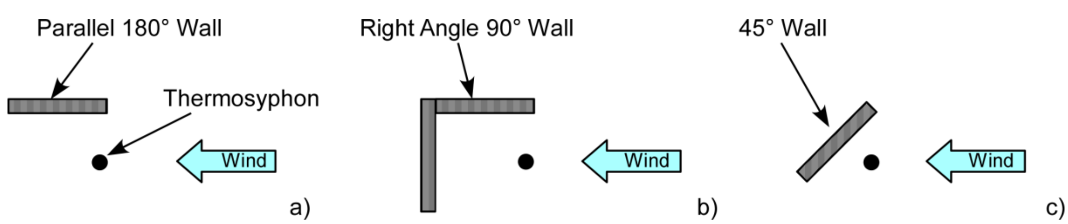


Figure 10. Plan view of wall and thermosyphon configurations as tested by Haynes and Zarling (1988). a) Next to a building, b) inside corner of a building, and c) a 45° wall.

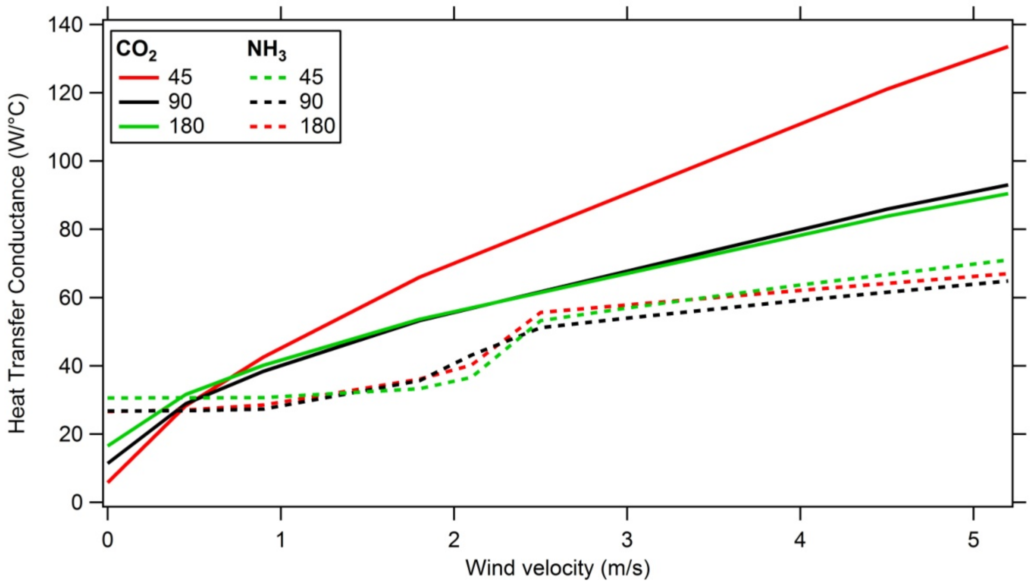


Figure 11. Thermosyphon performance for an evaporator angle of 9° at different wall configurations (180, 90 and 45°), and working fluids (CO_2, and NH_3).

Yarmak (as cited in Haynes and Zarling [1988]) reported that the heat transfer conductance for any evaporator angle can be expressed as

$$C = \frac{Q}{\Delta T} = 8.97 + 34.3B + 9.8V_w \qquad [\text{W/°C}] \tag{6}$$

where B is a radiation factor based on the exposure of the thermosyphon in relation to a building and V_w is the wind speed in m/s. Some of the radiation factors are shown in Figure 10. B = 1 is for a configuration that does not have a wall (an open area), B = 0.75 at an outside corner of a building, B = 0.2 next to a building and B = 0.25 at an inside corner of a building.

The above empirical expressions are for condensers with a 6.5-m² fin area. The condenser conductance C_{rad} for condensers larger than 6.5 m² ($C_{6.5}$) can be expressed as (Jardine et al. 1992)

$$C_{rad} = \frac{C_{6.5} A_{rad}}{A_{6.5}} \tag{7}$$

where A_{rad} is the condenser projected area.

3.2 System monitoring

Major malfunctions of a system can be detected by regular monitoring. There are several ways to verify the operation of thermosyphons: 1) visual observation, 2) infrared thermometry, 3) condenser temperature measurements, 4) evaporator and ground temperature measurements, and 5) internal pressure monitoring (Yarmak and Long 1986; McFadden 1987; Long and Zarling 2004). Because the condenser temperature of an operating unit is usually below the melting point of snow, frost and snow will be absent. There could even be areas free of snow where the thermosyphon tube passes through the surface.

For visual observation to be effective, monitoring should be done when there is a high heat transfer rate. Yarmak and Long (1986), therefore, recommend that visual observations be taken in the first third of the freezing season. When the thermosyphon is operating, the condensing vapor is transferring heat through the extended surface of the fins. The temperature is slightly higher at the base of the fins compared to at the fin tips. This temperature difference can be measured with an infrared camera; however, the temperature difference can be small and difficult to see (nighttime viewing is therefore recommended). Even if no temperature difference can be seen, the unit may still be working properly. Because of how quickly this method can be done, infrared observation is recommended when a large number of thermosyphons need to be monitored.

Measuring the temperature difference between the bottom and top of the condenser unit also gives an indication of whether the system is operating. This temperature difference can also be very small, however, making this method unreliable. Measuring ground temperature at the evaporator compared to the air temperature is the best method to ensure that a thermosyphon is operating. If the thermosyphon is operating, there is a direct response of the temperature at the evaporator when the air temperature is below freezing. To determine if the unit is functioning, the internal pressure of a thermosyphon can be monitored if the unit is manufactured with an access valve (Yarmak and Long 1986). It is recommended that this method be used by the thermosyphon manufacturer or by trained personnel because of the risk of improper closure of the valve when monitoring is completed.

3.3 Performance concerns

Non-condensing gases can collect inside the top of the condenser because of corrosion. This reduces the thermal performance via blockage ("cold-topping") of the working fluid from reaching the entire length of the condenser. This could happen in thermosyphons where a low-pressure gas such as NH_3 is used or where the unit is not properly cleaned before filling. To solve this problem, the non-condensing gases can be bled off through the charging valves at the top end of the thermosyphon (Zarling and Haynes 1991). Hydrogen metal halide can also be introduced into the thermosyphon, which results in absorption of the non-condensable gas. Cold-topping is rarely an issue with CO_2 filled units.

Of 85 flat loop installations in Canada, only six have been reported having issues (Holubec 2008). The reported reasons for failure include: 1) poor design and construction of the NFS within which the thermosyphon evaporator pipes are buried, 2) inadequate construction details, including construction scheduling (such that the system failed due to improper installation), and 3) inadequate insulation design. For example, at Inuvik Hospital, the seam welds of the pre-welded evaporator pipes that were shipped directly from the manufacturer leaked, resulting in a slow loss of refrigerant (Holubec et al. 2008). The firm that designed and installed that thermosyphon system is now only using seamless A106 pipe for evaporators. In addition, at this installation, surface water penetrated the gravel layer above the evaporator and pooled during the summer, creating ice boils between the top of the gravel and the insulation when the thermosyphon started functioning in the fall. Yarmak and Long (2012) indicate that this can be avoided by installing a waterproof membrane on top of the insulation that will restrict surface water infiltration through the joints to the frozen NFS.

Vertical condensers do represent a hazard and they could be hit by snow plows or other vehicles at some locations. If this were to happen, the thermosyphons would still function as long as the bend is minor. They can also be made straight again (Jardine et al. 1992). Long lines of thermosyphons condensers may present themselves as a target. If the unit is punctured by a bullet, the hole can be repaired and the unit recharged. Jardine et al. (1992) state that in 30 years of commercial use, there was only one incident of a bullet strike, and in that instance, the bullet did not penetrate the pipe wall.

4 Diversity of Installations

4.1 Slab-on-grade foundations

Slab-on-grade foundations on permafrost soils require insulation below the floor slab and a heat removal system (such as thermosyphons) below the insulation (Haynes and Zarling 1988). Figure 12 shows a schematic of a slab-on-grade thermosyphon installation. Figure 13 and Figure 14 show finished installations. For a proper design, thawing and freezing should only occur within the NFS. Proper design parameters include the correct insulation and gravel thicknesses, thermosyphon spacing, and vertical placement within the NFS fill. Descriptions of two slab-on-grade thermosyphons systems are provided below.

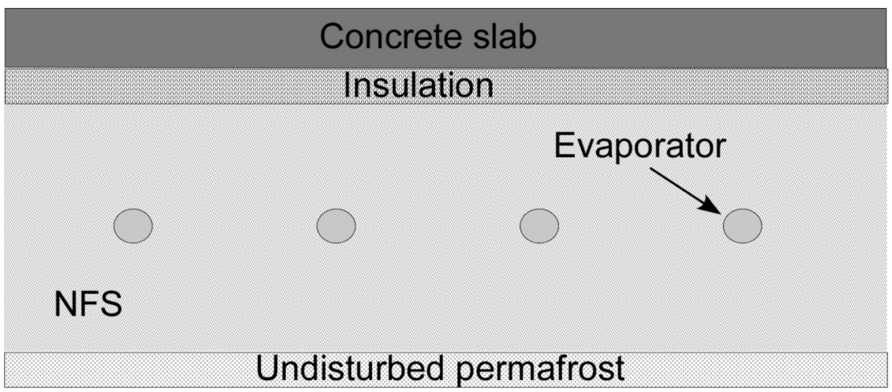


Figure 12. Slab-on-grade thermosyphon installation.

Figure 13. Hangar facility, Deadhorse, AK.

Figure 14. Heavy equipment shop, Chandalar, AK.

4.1.1 Aurora College, Inuvik

In June 2002, 13 flat loop thermosyphons were installed at Aurora College in Inuvik, Canada (Holubec 2008). The thermosyphon foundation including the bedding, insulation, and granular material, was completed in the first year and the slab of the building was poured in the summer of 2003. This allowed the thermosyphons to operate for the entire first winter and thus resulted in freeze-back of the permafrost and granular layer. The extra winter of thermosyphon operation resulted in the measured ground temperatures at a depth of 5.5 m below the slab elevation to be 1.8°C lower than the adjacent ground.

4.1.2 Deadhorse, AK

In 2008, 42 flat loop thermosyphons (Figure 15) were installed beneath a 8700-m^2 heated slab-on-grade building in Deadhorse, AK (Yarmak and Long 2012). A 178-m-long thermosyphon evaporator was instrumented to record its performance. The temperature differential along its length was less than 0.5°C. This installation demonstrates that, for properly designed flat loop thermosyphons, effective subgrade cooling can be provided along evaporators at least 178 m long (Yarmak and Long 2012).

a. Flat loop evaporators.

b. Thermosyphons prior to fin installation.

Figure 15. Installation of a slab-on-grade building in Deadhorse, AK.

4.2 Pile foundations

Thermosyphons are also widely used to ensure the structural integrity of unheated installations such as the foundations of transmission towers or power line tower supports. Thermosyphons can be used as a part of the pile foundations or they can be installed into or around the pile foundation (Wang et al. 2008). The first installation of this type was at the AK Aurora and Glennallen communication sites in 1960 (Richardson 1979; Long and Yarmak 2008). Similar systems have since been installed at several other locations throughout AK (Figure 16), Russia, and China (Kondratiev 2008; Wang et al. 2008). Thermosyphon piles were used to support the antenna arrays at the HAARP site at Gakona, AK, as shown on Figure 17.

a. Deltanet tower, Kwigillingok, AK.

Figure 16. Communication towers.

b. Aurora Tower at Gakona, AK.

Figure 16 (cont'd). Communication towers.

Figure 17. HAARP antenna, Gakona, AK.

4.3 Pipelines

When constructing buried and elevated pipelines in permafrost regions, special designs are needed to prevent permafrost thaw. The permafrost can be protected by either cooling the fluid to be transported inside the pipeline (this is feasible for a gas, not a liquid) or by refrigerating the outside of the pipeline (Reid and Evans 1984). Thermosyphons are designed to ensure that any excess heat transported downward from the pipeline will not cause thawing of the permafrost where supporting piles are embedded. Enough heat must be removed from the soil during the winter to create a reservoir of cold sufficient to absorb the summer heat. Conditions at the site must be such that winter cooling exceeds summer thawing. This is true for all designs using passive thermosyphons.

The Trans-Alaska Pipeline (Figure 18) starts at Prudhoe Bay in the north and ends at Valdez in the south of AK. Originally, all 124,000 units were charged with NH_3 and some of these units have been experiencing blockage. The NH_3 has since been bled off from 14,000 units and recharged with CO_2 to avoid this problem (DNR 2009).

Figure 18. Trans-Alaska pipeline.

4.4 Embankments

Thermosyphons were introduced for railway embankments in 1978 along the Hudson Bay Railway, Canada (Hayley et al. 1983). In 1982, the first runway installation was built at the Bethel, AK, airport (McFadden 1985). Improvements and developments to thermosyphon installations for embankments are a subject of ongoing research. Recently, Lai et al. (2009) combined an L-shaped thermosyphon and insulation into a crushed-rock revetment and carried out a laboratory test on the cooling effect of this new measure. They showed that this combination was able to cool the embankment area. Zhang et al. (2011b) performed a numerical study on the cooling characteristics of thermosyphons installed in embankments. They found that thermosyphons can effectively prevent permafrost degradation beneath embankments and maintain roadway stability.

4.4.1 Bethel Airfield

In 1982, the permafrost degradation of a 61-m portion of the paved Bethel Runway 18-36 was stabilized with 31 thermosyphons (Bradley and Yarmak 1984; Zarling and Haynes 1991). The evaporators were drilled into the embankment at a slope of 15° from the horizontal and the lengths varied from 29 to 59 m. This success was one of the first embankment installations with nearly horizontal thermosyphon units.

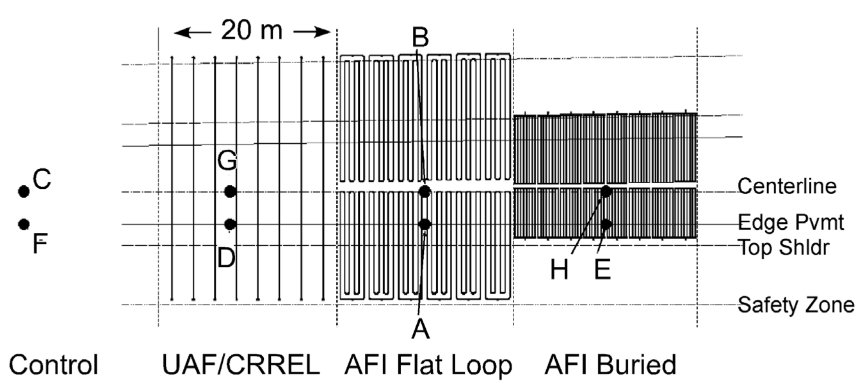
4.4.2 Bethel Highway

In 1989, thermosyphons were installed to treat a 120-m-long highway section underlain by highly unstable permafrost in Bethel, AK (Esch 1996). The site consists of fine aeolian sands to ice-rich organic silts and silty peat soils (Esch 1989). The project included 48 thermosyphons installed perpendicular to the highway on a slope of 1 vertical to 15 horizontal at a longitudinal interval of 3 m. The evaporator units were 7.6-cm-diameter pipes charged with CO_2 to a pressure of approximately 3100 kPa (450 psi). The objective of this project was to freeze the embankment during the winter and prevent thawing of the underlying permafrost soils in the summer.

During the first summer, temperatures did not rise above 2°C, compared to 16°C directly above the insulation layer in the embankment. Four years after the installation, very minimal thawing (less than 0.5°C) was noticed below the insulation layer. This installation showed that thermosyphons in combination with a layer of insulation can be an effective way to thermally stabilize the permafrost (Hulsey 1995). Thermosyphons remove heat from the lower layers of the embankment much more quickly than otherwise possible, eliminating the disadvantage of insulation in the winter.

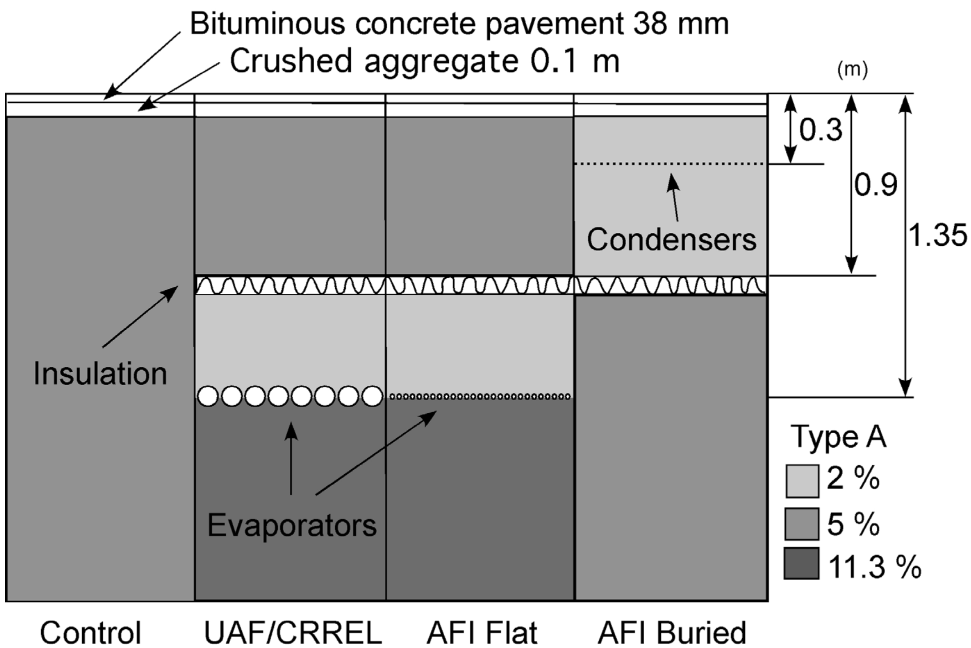
4.4.3 Chena Hot Springs Road

Three types of thermosyphons were installed at a roadway embankment in Fairbanks, AK, in November 1998 to stabilize discontinuous permafrost soils beneath the roadway (Figure 19). Two previously developed thermosyphons operating with level as well as undulating evaporator sections and a totally buried system unobtrusive to traffic and maintenance operations were installed in three different sections. The University of Alaska, Fairbanks, and CRREL (UAF/CRREL) thermosyphons depicted in the figure were standard horizontal evaporator units with vertical condensers. The Arctic Foundations, Inc. (AFI) Flat Loop units were originally laid as horizontal loop evaporators but developed some minor undulations over time. The AFI Flat Loop system included six vertical condenser units. The AFI Buried units were a totally buried system with no vertical condensers, being unobtrusive to traffic and maintenance operations. This study showed that all of the systems work effectively and can be used to prevent thaw settlement problems (Forsstrom et al. 2002). It also showed that permafrost can be enhanced using thermosyphons in discontinuous permafrost locations (Wagner et al. 2010). Thaw depths beneath the roadway decreased from 8.3 to 2 m at all sections (except the control) with permafrost temperatures decreasing up to 3°C.

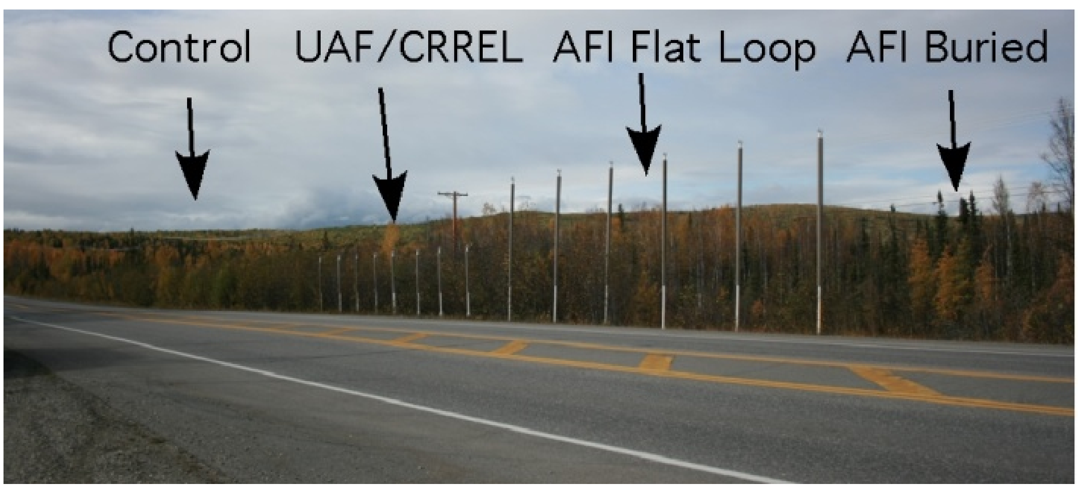


a. Plan view.

Figure 19. Installation at Chena Hot Springs Road, Fairbanks, AK.



b. Cross section of roadway.



c. Picture of final installation.

Figure 19 (cont'd). Installation at Chena Hot Springs Road, Fairbanks, AK.

4.4.4 Qinghai-Tibet Railroad (QTR)

The Qinghai-Tibet Railroad (QTR) crosses 632 km of permafrost terrain. Several different methods have been developed to prevent permafrost degradation beneath the railroad embankment, including adjusting and controlling the amount of solar radiation, thermal convection, and thermal conduction (Ma et al. 2009). Methods such as shading boards, crushed rock embankments, ventilation ducts, thermosyphons, and dry bridges have all been used successfully in the QTR project. Thermosyphons have been installed in over 34 km of the QTR embankment (Cheng et al. 2009). They have been inserted either vertically or at an angle into the shoulders or the foot of side slopes at different lengths (7, 9, and 12 m). Thermosyphons have also been used in combination with insulating layers to stop permafrost from degrading even further.

Lai et al. (2009) concluded that permafrost thaw under the embankment in warm permafrost regions can be prevented using a combination of L-shaped thermosyphons and crushed-rock revetment. Wen et al. (2005) found that using a combination of insulation and thermosyphons was more beneficial than using any of the single method alone on the QTR. Thermosyphons beneath the embankment of the QTR are effectively lowering the ground temperature at Qingshuihe, where the average air temperature is –6.2°C and annual mean ground temperature is –0.9°C (Cheng et al. 2008).

4.4.5 Chaidaer-Muli Railway (CMR)

The Chaidaer-Muli railway is 142 km long and crosses marshy soils and ice-rich warm permafrost in Central Mongolia (Zhang et al. 2011a). The railway was constructed in 2006–2009 and about 20,000 thermosyphon units were installed over approximately one-quarter of its total length. The units were installed vertically and charged with NH_3 The thermosyphons have successfully raised the permafrost table and stabilized the railway bed.

4.5 Artificial frozen barriers

Artificial frozen barriers can be created by thermosyphons and used to redirect contaminant movement and groundwater flow or capture and contain contaminants in the vicinity of a hazardous spill site. In 1996, hybrid thermosyphons were used to contain and immobilize groundwater contaminated with radionuclides at the Oak Ridge National Laboratory, TN (Figure 20) (USDOE 1999). Thermosyphons have also been used to construct containment walls for tailings dams and mining sites in cold regions. This technique has also been used in Canada and Russia (Figure 21 and Figure 22). Wagner and Yarmak (2012) also demonstrated how quickly a frozen barrier can be created by hybrid thermosyphons in Fairbanks, AK. The installation can be seen in Figure 4.

Figure 20. Hybrid thermosyphon system for hazardous waste containment at Oak Ridge National Laboratory, TN.

Figure 21. Thermoprobes at the Long Lake Outlet Dam, Ekati Diamond Mine, Northwest Territory, Canada.

Figure 22. Thermoprobes at the Kubaka Gold Mine, Russia Far East.

4.6 Retrofits

An installation at a tramway on the Alaska Highway in the Yukon Territory is an example where thermosyphons have been used to stabilize previously installed structures that are experiencing settlements (Hayley 1982). Vertical thermosyphons were installed adjacent to the foundation footings and in less than a year the permafrost table had elevated about 2 m into the fill, stabilizing of the tower foundation.

A utility building in Prudhoe Bay, AK, was retrofitted with 22 thermosyphons and extruded polystyrene insulation to stabilize the floor of the building (Zarling and Haynes 1991). This kept the floor from subsiding further. Another building at Deadhorse, AK, was retrofitted with thermosyphons when the ducted air cooling system was deemed to be inadequate (Gill 1984).

A mechanical refrigeration system for maintaining foundation soils in a frozen state that was installed in 1976 at the Senior Cultural Center in Kotzebue, AK, was redesigned in 1986 using thermosyphons (Long and Yarmak 1988). This retrofit resulted in a five-fold higher capacity of withdrawing heat from the underlying soils. Furthermore, the passive thermosyphon system reduced the estimated average operational costs for the Center from about $20,000 (1981 costs) for the mechanical cooling system that was replaced by the thermosyphons to no cost at all.

The performance of current installations can be increased by adding more condenser area (Jardine et al. 1992). This retro-fit does not increase the operating cost. In 1989 additional condensers were added to the Glennallen and Aurora tower facilities (Figure 16) because thaw depths were discovered to be deeper than those in the original design (Long and Yarmak 2008). Unfortunately, this did not solve the problem entirely. At the Glennallen site, settlement was discovered on two tower legs in 2007. During an analysis of the site, Long and Yarmak (2008) found that the thermosyphon cooling capacity was decreased where higher than normal snow depths were encountered. They concluded that knowledge of snow conditions is needed when analyzing the thermal conditions for a structure. Further investigations of the communication tower in 2010 showed that the thermopiles are still operating 50 years later (Drage and Brooks 2012). The tower did not settle because the thermopiles malfunctioned but because of the permafrost degradation created by initial removal of vegetation prior to the tower installation and the rising air temperatures over the last 50 years.

5 Summary and Recommendations

Thermosyphons have been used in construction since the 1960. In AK alone, thermosyphons have been utilized in over 900 installations. Thermosyphons are also heavily used in other cold regions such as Canada, Russia, and China. In the last 50 years the technology has been greatly improved, going from a vertical heat transfer device to a sloped and flat installation and it even now exists as a completely buried design. These developments have resulted in a more efficient and versatile technology that can be used at many different types of installations. Thermosyphons were originally designed to ensure foundation support by maintaining the permafrost in a frozen condition adjacent a pile. Today, they are also used for stabilization of embankments and to create a frozen wall for containment of contaminants.

Owing to a warming climate, it is very likely that buildings or roadways that have been built on what was once cold permafrost will need to be retrofitted with thermosyphons to cool and strengthen the permafrost. It is recommended that further work be done to promote the advancement of the technology so that it can become more efficient and cost effective to be used for new installations and also where the technique can be used to retrofit older installations.

Currently, Arctic Foundations, Inc., in Anchorage, AK, is the only company in the US that manufactures thermosyphons for Arctic use. This company also analyzes and designs the thermosyphon installations.

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14. ABSTRACT

Thermosyphons have been used for stabilizing permafrost since 1960. The original thermopile was designed as a vertical unit with one end buried in the ground and the other end exposed to the air. More recently, flat, loop, and buried thermosyphons have been developed. Thermosyphons consist of a pipe or series of pipes that are installed with one part below ground (evaporator) and the other exposed to the air (condenser). They are filled with a pressurized fluid that evaporates because of the heat of the soil and rises as a vapor to the condenser. If the air temperature is lower than that of the soil, the vapor will condense on the inside walls of the pipe and release the transported heat from the ground to the air. The condensate then returns to the evaporator by gravity. When the air temperature is higher than that of the soil, the heat transfer ceases and the unit is dormant. Presented here is a general overview of applications of thermosyphons in cold regions.

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