Flat Loop Thermosyphon Foundations in Warm Permafrost

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EXECUTIVE SUMMARY

Passive cooling by means of pressured heat exchange pipes was developed in Alaska by the U.S. Army Corps of Engineers in 1965 to preserve foundations in ‘warm’ permafrost. It has been widely applied in Alaska, northern Canada and Russia to preserve and cool permafrost. The original simple 20mm vertical pipe with a radiator in the air has evolved into other designs that include: thermopiles, sloped pipe thermosyphons and flat loop evaporator pipe (flat loop) thermosyphons. The flat loop thermosyphon was developed and field tested in Canada in 1994 to allow the construction of buildings directly on the ground, slab-on-grade. Subsequently this design started to be used also for buildings with crawl space.

The thermosyphon is a closed natural two phase convection device that extracts heat from the ground and discharges it into the atmosphere. The gas/fluid medium is carbon dioxide that functions in a closed ‘pipe’, pressure vessel, under a pressure varying from about 300 to 700 psi. The thermosyphon draws out the heat from below the building by a heat exchange mechanism. During the winter the outside air is colder than the ground temperature causing the gas in the pipe above the ground to condense and flow to the base of the pipe. The cold air drops the pressure in the gas and thereby causes the fluid in the foundation to evaporate. Exchange of heat operates throughout the winter as long as the air temperature is colder than the ground. During the summer the accumulated cold is preserved by a zone of insulation located above the horizontal evaporator pipes.

Components of the flat loop thermosyphon are: 1) evaporator pipes within a granular layer, 2) insulation right above gravel layer with the pipes to minimize the warming, and therefore prevent thawing, of the frozen ground, and 3) above ground surface radiators on top of the vertical conductor pipe to increase the efficiency of dissipating the heat. The components of the flat loop thermosyphon foundation are illustrated in a photo of Pangnirtung health centre thermosyphon foundation under construction.

About 85 flat loop thermosyphon foundations have been constructed in the Yukon, Northwest Territories, Nunavut and northern Quebec. Additionally, 75 thermosyphon systems were installed using vertical pipe, sloped pipe and flat loop pipes in dam designs. Only few problems have been reported on all the thermosyphon foundations since they were developed in 1965; with an exception of 6 installations: Yukon (2), NWT (3) and (1) in NU.

A study was proposed by Public Works and Services of the Government of the Northwest Territories to determine the cause(s) of the poorly functioning flat loop thermosyphon foundation projects, and to assess the suitability of this design as a foundation system for a 50 year life span of a building on ‘warm’ permafrost that is subjected to climate warming. If the thermosyphon system can be considered as a viable foundation for the condition mentioned, the study was to provide recommendations to make buildings supported by thermosyphon foundations sufficiently robust to meet the performance and service life requirements. Results of this study and recommendations for better designs and performance are presented herein.

The study was undertaken under the Public Infrastructure Engineering Vulnerability Committee (PIEVC) program managed by the Canadian Council of Professional Engineers. This study was prepared by I. Holubec Consulting Inc.

The study found that poor functioning of the few buildings supported by thermosyphon foundation are related to: a) poor design/construction of the granular pads on which the thermosyphon evaporator pipes are founded, b) inadequate construction details, construction scheduling, and c) inadequate insulation design.

The following are brief case histories of the studied thermosyphon foundation projects:

Female Young Offender Facility, Inuvik, NT 2001.

The facility is located on difficult ground conditions and the construction was rushed because of a late construction start. This led to multiple problems that took effort and time to correct. These problems were:

The pad for the thermosyphon was constructed on difficult and complex ground without improving it. It sloped, was underlain by peat and was located in a wet area.

Construction was delayed and then hurried leading to many problems. Thick, wet and warm fill, providing a large heat source, was placed on frozen ice rich ground that led to deep thawing of the underlying ground. The thawing led to considerable building settlement. It took great effort and time to refreeze this thawed ground using additional radiators and mechanical refrigeration. The thawed ground refroze after about 3 years.

The thermosyphon pipes were designed as flat horizontal loops which is the normal design. During installation provisions had to be made for grey water piping within the thermosyphon granular pad. Numerous vertical bends were introduced into the horizontal evaporator pipe loops that decreased the efficiency of the thermosyphons.

The building is heated with radiant piping in the slab floor. The heating pipes are located near the bottom of the slab and have been operating at higher temperatures for which was not designed. This introduced much greater heat to the foundation than the thermosyphons were designed to remove.

Finally, an additional flaw of the thermosyphon pad design was poor perimeter drainage around the granular pad. Surface water introduced into the gravel pad resulted in frost heave during the winter and thaw settlement the following summer. This resulted in cracking of the interior drywalls and minor electrical and plumbing failures around the building.

The above led to the addition of radiators and installing a refrigeration system to freeze the foundation. It took 3 years to finally freeze the foundation.

Visitor Center, Inuvik, NT

The major problem at this project was that internal concrete piers and perimeter walls were not insulated and this deficiency was magnified by the fact that the organic layer was not removed before constructing the thermosyphon pad. Lack of insulation around the piers and perimeter walls allowed heat to be conducted through the concrete to the foundation. The resulting thaw of the peat caused considerable settlement because of the large compressibility of unfrozen peat.

Inuvik Hospital, NT

A major problem was that the pipe supplier shipped defective pipes that started to leak after the start of operation. As a result, 17 of 64 pipe loops at this project are losing liquid to different degrees and therefore their cooling capacity. The leaking loops are being recharged either annually or biannually. The second problem, that can be readily fixed, is that proper drainage control of surface water was not provided. Outside water has been penetrating into the granular bedding surrounding thermosyphon evaporator pipes where it freezes during the winter. The supply of water to the evaporator pipes has resulted in numerous large ice boils or 'pingos' to develop at the floor of the crawl space.

School, Rankin Inlet, NU

The problem at this project was caused by burying heat supply pipes within the granular pad several years after construction of thermosyphon foundation and improper replacement of the insulation. These pipes provided excess heat to the school from a nearby power generator. The heat was brought by a large diameter insulated pipe that was installed into the crawl space. The heat from the pipe heated the foundation that the thermosyphon could not cope with. An additional problem was a leaking valve below the radiator on vertical conductor pipe that reduced heat extraction.

Yukon case histories

Two case histories from Dawson City and Ross River in the Yukon are of great interest to this study because the present air and permafrost ground temperatures are values that may be reached in many other larger settlements in permafrost in Northwest Territories and Nunavut in some 50 years or so. The mean annual air temperatures in Dawson City of -3.5°C and in Ross River of -2.0°C indicate that permafrost is at a state melting in areas devoid of trees and organics.

Ice rink for Recreation Centre, Dawson City

In Dawson city flat loop thermosyphon cooling was installed under an ice rink and flat loop thermosyphon foundations were used under the change room and washroom addition of the Recreation Centre. The cooling system under the ice rink was decommissioned because a near two year construction interruption had caused the local ground to thaw too deep for it to be refrozen readily. The flat loop thermosyphon system installed below the addition has worked as designed. The successful construction for this part of the building was done in the fall and the thermosyphon evaporator pipes were covered with insulation right after installation. Ground temperature monitoring during the first two years showed the ground below the facility was being maintained frozen. Ground temperature monitoring was discontinued in mid 2002.

Ross River School

Ross River School provides two case histories that extend from 1975 to the present. A school was constructed in 1975 using a pioneer thermosyphon design consisting of single sloping evaporator pipes that were filled with ammonia. These were manufactured by McDonnell Douglas Astronautics who also supplied the thermosyphons for the Alaska oil pipeline. This installation proved to be inadequate in keeping the ground frozen for three reasons: a) the ammonia gas reacted with the pipe material and formed a gas that hindered the cooling by vapour condensation, b) spacing of the pipes was too wide to provide sufficient cooling, and c) plumbing breakage caused water to percolate into the permafrost and thaw it. It was decided to build a new school within the playground of the old school after various efforts to level the settled portions of the school were found to be inadequate. In 1997 it was decided to replace the school.

A study of various foundations designs for the new school determined that an improved horizontal loop evaporator thermosyphon system would be an appropriate foundation design. The flat loop design was found to be about 140% more efficient and is filled with carbon dioxide that has functioned well over long periods. A new school with the improved thermosyphon design was constructed in 1999. However, from 1975 to 2000 the mean annual air temperature had warmed from -6.8°C to -3.1°C and it was about -2.0°C in 2007 (based on trend analyses estimate). At these mean annual air and ground temperatures the permafrost is practically in the melting stage without any artificial cooling.

Differential settlement of the school was being observed within a year of construction. Fortunately, the school base was designed so that any differential settlement could be corrected. The settlement became a problem by 2005 when a maximum settlement of 75mm was observed. Corrective measures were made in 2006 to improve the cooling system and thereby reduce or eliminate the settlement. The corrective measures included the addition of thermosyphon cooling around the outside perimeter of the building, maintaining the air temperature within the crawl space cooler and installing better insulation on the outside crawl space walls. Results of these improvements are not known.

Recent 2006 flat loop evaporator thermosyphon installation

Four flat loop thermosyphon foundations have been installed in 2006 in four communities with permafrost ground temperatures near the ‘warm’ permafrost state, Iqaluit and Pangnirtung, NU, or near or at the zero ground temperature value at Tulita, NT and Kuujjuaq, QC. Initial thermosyphon foundation monitoring shows that they are performing as per design with no problems. Monitoring of these foundations adds considerable insight on the effect of design and construction scheduling into the performance of flat loop thermosyphon foundations.

The case histories of the first six installations with problems do not compromise the thermosyphons foundation design concept but demonstrate that there is a need to improve the design, construction and monitoring.

The flat loop thermosyphon foundation system is one foundation system that should be considered for future buildings in ‘warm’ permafrost with ice rich soils. However, to ensure desired performance of the flat loop thermosyphon foundation for future buildings with a life span of 30 to 50 years in the present warming climate, there is a need to prepare/develop better information and guidelines as given in the report recommendations. The highlights are given below:

CONCLUSIONS

1) Presently there are no guidelines or standards to determine the present design air temperatures and climate warming rate that can be used for designing building foundations and other structures, such as dams, reservoirs and waste storage facilities in permafrost regions. The National Building Code or the Normals provided by Environment Canada are not helpful.
2) There is a lack of ground temperature reference data that can be used to design and track the effect of climate warming on permafrost in nearly every community be it large or small. The available data is not located centrally, usually incomplete and often outdated because climate warming had changed the ground temperatures.
3) Traditional slurry pile foundations are starting or will start experiencing problems in the near future. Ground warming is decreasing the adfreeze strength that is needed to support the building and prevent frost heaving. Hundreds of buildings have reported these problems in Russia and similar problems are documented at Rankin Inlet, NU. This is likely happening at other settlements in warm permafrost.
4) Thermosyphon foundations have operated for some 40 years without any major problem identified during this period. They were developed for warm and constant permafrost temperatures.
5) Better thermal analyses and calibrated against known ground temperature performance are needed to design future thermosyphon foundation that will still function after 50 years with climate warming. The thermal analysis software should be a commercially available software that can be bought and used by others.
6) Problems of the recent flat loop thermosyphon performance are generally the result of a combination of poor foundation design, poor construction procedures and in one case defective pipes supplied by the mill.
7) There is a need for thermosyphon foundation guidelines that address the design, construction and monitoring of: granular pad, surface and ground water control, thermosyphon system, services incorporated into the slab-on-grade foundations, instrumentation and monitoring.
8) The study has identified flat loop thermosyphon foundations at four locations that have one or more unique air and ground temperatures, ground conditions, design or construction. These are a) Aurora College in Inuvik, NT, b) Health Centre in Pangnirtung, NU, Air terminal in Kuujjuaq, QC and Ross River School, YT. These four sites should be considered as baseline sites to continue monitoring of the local permafrost and performance of the flat loop thermosyphon foundations.

RECOMMENDATIONS

1. Design and construction guidelines for thermosyphon foundations

Case histories have identified that the majority of problems have arisen from insufficient design and construction of the gravel pad, location of services, surface water control and insulation. It is recommended that guidelines be prepared for design and construction of the flat loop thermosyphon foundations. The guidelines should be illustrated with alternative design details that could be considered in the design of a thermosyphon foundation. This would provide guidance to designers, architects, geotechnical engineers, contractors and inspectors. It would also provide background information to reviewers and the project owners.

2. Thermosyphon foundation design thermal analysis; calibration and parametric study

Presently several proprietary thermal analyses softwares are being used to design foundations in permafrost. This makes it difficult to assess independently their predictions and analyze the foundation performance. It is recommended that recognized commercially available software be elected and calibrated with existing performance records. This software should be used to conduct parametric thermal analyses flat loop foundation design and conduct an optimization study to identify impact of change of various thermosyphon components to improve their cooling in climate warming scenarios. The results could be used by others to indicate which changes to the flat loop thermosyphon components are most effective to improve the cooling of the thermosyphons at a specific project. Using commercially widely used software will allow others to confirm the design.

3. Baseline documentation of key projects for future monitoring and studies

The study has identified flat loop thermosyphon foundations at four locations that have one or more unique air and ground temperatures, ground conditions, design or construction. These are a) Aurora College in Inuvik, NT, b) Health Centre in Pangnirtung or the RCMP building in Iqaluit, NU, Air terminal in Kuujjuaq, QC and Ross River School, YT. These four sites should be considered as baseline sites to continue monitoring the local permafrost and performance of the flat loop thermosyphon foundations.

It is recommended that the ground conditions, and air temperatures be established and the design and construction details documented in detail for these projects. This should include the installation of one or two reference ground temperature sensors. The reference ground temperatures and all the ground and thermosyphon system temperatures should be monitored by an automatic logger at each site; preferably be connected to a telephone so that they can be downloaded periodically from a remote site. The monitoring of all sites should be conducted for a minimum of three years by one source that will prepare an annual report. The source will also prepare a base line report that will include detailed ground, design, construction and up to the present monitoring result.

4. Establish design air temperature and climate warming criteria

Present Normals and climate warming rates provided by Environment Canada do not provide design air temperature and climate warming criteria that represent current air temperatures and climate warming rates. Environment Canada is aware of this and is correcting this problem. It has suggested that an analysis based on trends of mean annual air temperature from recent records is a reasonably safe approach (given in attachment). Any analysis should be based on data from the period after an air temperature anomaly was observed around mid 1970. It is recommended that Environment Canada be encouraged and funded to update their climate information used in designs of infrastructures in the North.

5. Guidelines for geotechnical engineering investigation and collection of design information.

Many present geotechnical investigations are limited by available drill equipment and the clients desire to keep costs low. Results of this approach are that the depth of permafrost investigated is limited, establishment of frozen ground properties is poor and ground temperature not well defined. This makes the selection of foundation type and their design difficult; requiring frequently additional follow-up investigation. It is recommended that guidelines be developed for geotechnical investigations, sampling and laboratory testing and ground temperature measurements be developed for proposed buildings in permafrost.

6. Guidelines for instrumentation and monitoring of thermosyphon foundations guidelines

Flat loop thermosyphon foundation is a pressure vessel cooling system where adequate foundation cooling is essential to the permanence of the building it supports. The thermosyphon foundation consists of numerous piping loops connected to radiators. The effectiveness is dependent on the winter air temperatures, maintenance of the pressure within the tubes and prevention of any ground or service water ingress. It is recommended that guidelines be prepared that identify the design and location of temperatures sensors in the ground, the evaporator pipes and radiators, and provide guidance to manual or preferably a logger system to monitor the instrumentation. Guidance should be provided on the analyses of the data and provide some historic results for guidance to the reviewer.

7. Thermosyphon pressure vessel guidelines, codes and standards

It is recommended that a highly experience engineering firm specializing in pressure vessels should prepare technical background, design and construction information and provide a construction recommendations report that can be used by thermosyphon foundation designers and constructors. The report should also identify relevant codes and standards related to thermosyphon systems. The piping in the thermosyphons are pressure vessels that fall under several codes and standards. This report would assist to minimize long-term problems with the pressurized thermosyphon system.

FORWORD

I have been following the air and ground temperatures across the Canadian permafrost for several years now because these impact the stability of many of the infrastructures that have been or are being planned to be built on frozen ground. I became concerned with their vulnerability to climate warming as it has become obvious that climate warming is progressing in the North more rapidly than what is being recognized and this will impact the stability of many structures that are built on frozen ground.

The design of dams on permafrost has recognized the potential impact of climate warming on the frozen foundations by incorporating flat loop thermosyphon cooling at the base of the dams and also designing the dams so that they will adequately function even if the foundation happens to thaw in the future. A similar approach may be one of the options for building foundations on frozen ground.

Thermosyphon cooling has been developed in Alaska in the 1960's to support infrastructures in 'warm' permafrost and this has progressed in the development of the flat loop evaporator pipe thermosyphon foundation in Canada in 1994. This design has been widely used in Canada since 1995.

Asset Management Division of Government of Northwest Territories, Department of Public Works and Services became concerned with the viability of thermosyphon foundations because of foundation problems experienced in three out of their four buildings supported by flat loop thermosyphon foundations. As a result they jointly sponsored this study with the Public Infrastructure Engineering Vulnerability Committee (PIEVC). I was delighted to undertake this study because it combined my interests in foundations in permafrost, including thermosyphons, since 1974 and my more recent interest in the impact of climate warming on permafrost and the infrastructures supported on permafrost.

I hope that the observations and conclusions of the performance the twelve case histories presented in this report will be helpful to the readers. However, my greatest hope is that most if not all my recommendations are followed. There is a great need to improve the design, construction and monitoring of the thermosyphon foundations if they are to function through climate warming and the life span of new buildings. I believe this can be done.

Igor Holubec

ACKNOWLEDGE MENTS

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I would like to thank heartily Bill Wyness, who arranged and accompanied me on my visit to Inuvik and facilitated my obtaining any available information I requested. I enjoyed many of our discussions and appreciated his reviews.

This comprehensive study would not have been feasible without the great support given by John Jardine, president, and Bill Watt, project manager, of Arctic Foundations of Canada Inc. They provided all the thermosyphon foundation plans and sections, photographs, ground temperature records and relevant notes and reports. They provided any information requested and were helpful in discussing any points or questions I posed to them. My thanks to them.

I would like to thank many who contributed information to this study, including; Tim Mac Leod, Clerk of the Works, Pangnirtung Health Centre, and Don H. Hayley, principal engineer with EBA Engineering Consultants Ltd.

I would like to express my gratitude to Heather Auld, Associate Director in Atmospheric Science and Technology Directorate, Environment Canada who understood my dilemma with currently available climate information to the engineer designing infrastructures in permafrost in the present climate warming stage. I appreciate her present work with her group to develop guidelines on selecting design air temperatures and providing the engineer with tools to obtain climate warming rate ranges for future design in the North and be allowed to participate in this task.

I would like to thank Joan and Joel Nodelman of Nodelcorp, who are coordinating various PIEVS case studies co-sponsored by Public Infrastructure Engineering Vulnerability Committee. I greatly appreciated their reviews of my document and many discussions on the aims and structure of the PIEVC program.

Finally, I would like to thank my wife Vera, who did a great job in reading and editing my writing and being patient with me. She was a tremendous help.

Igor Holubec

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1.0 INTRODUCTION

Constructing and maintaining buildings in permafrost regions in Canada, Alaska USA and Russia has always been a challenge in local areas with frozen ground with high ice content. The main reason being that the ice within the frozen ground started to melt from the heat of buildings and caused the buildings to settle as the frozen ground thawed. Historic settlement and damage to buildings is illustrated in Photo 1 from Dawson, YT. It was soon realized that heat from the base of the building had to be kept away from the frozen ground and buildings were started to be constructed above ground leaving an air space between the buildings and the frozen ground. This was done by either placing the buildings on natural stones (Photo 2), wooden, or concrete blocks.

Photo 1. Thaw settlement of early buildings, Dawson City, NT

As drilling equipment was introduced the Arctic the air space was provided by placing the buildings on wooden or steel piles. The piles were installed within oversized drill holes, the annulus between the pile and frozen ground was filled with wet sand slurry and allowed to freeze. The capacity of these piles is derived from the adfreeze creep strength between the frozen sand slurry and the pile. These piles are relatively inefficient because of the low adfreeze creep strength between the frozen sand slurry and pile surface. This foundation design works well in 'cold' permafrost regions but starts to fail in marginal or 'warm' permafrost where the ground temperature is at or warmer than -2°C. Steel pipe slurry pipe foundation for Aurora College residence is shown in Photo 3.

Photo 2. Old church in Igloolik, NU

Search for alternative foundation design for structures in 'warm' permafrost led to the development of the thermosyphon system (Heuer et al 1985). A thermosyphon is a passive two phase, liquid-vapour convection heat transfer device.

Photo 3. Slurry pipe pile foundation in Iqaluit, NU

It is a pressure vessel with the lower portion installed in the ground acting as an evaporator and the top portion above ground being a condenser. It was first used for the foundation of communication towers in Alaska in 1960 and proved itself on the Trans Alaska Pipeline System (TAPS) where 120,000 thermosyphons were installed (Heuer TF al 1985). The thermosyphon heat extraction system evolved from the installation of freezing pipes within the piles for the TAPS, to be followed by thermopiles that are pressured steel piles with a radiator below the building base, conventional sloping evaporators (sloped thermosyphon foundation) and finally the flat loop evaporator foundation (flat thermosyphon foundation) that is reviewed in this document. Radiators of a flat loop evaporator thermosyphon foundation at the Inuvik Hospital are shown in Photo 4.

The first prototype of a flat loop thermosyphon foundation was constructed, evaluated and compared to a sloping evaporator sloped thermosyphon foundation near Winnipeg in 1993-1994 (Yarmak & Long 2002). Both units were installed in unfrozen soil with identical condensers. After a winter of operation, it was found that the flat loop thermosyphon foundation froze the ground in an area with warm climate and it froze 1.4 times the volume of the sloped thermosyphon foundation.

Photo 4. Radiators from a flat loop thermosyphon foundation at Inuvik Hospital.

For the selection and design of a flat loop thermosyphon foundation for a building it is important to understand permafrost, its properties and ground temperature regime. This document reviews: the ground temperature regime and how it may change with time due to climate warming; the flat loop thermosyphon foundation design; history and design; performance of existing sloped thermosyphon foundations; risks for the foundation to operate through the life span of building and finally, what design or remediation options are available in case of poor performance or malfunction of the flat loop thermosyphon foundation system. Finally, recommendations are presented for what needs to be done to improve the longetivity of operation of the sloped thermosyphon foundation.

Several of the last tasks of the scope of this work were not fully completed because presently there is a lack of reference work that has been done on these subjects. The subjects of the areas were considered during the review of the case histories and the results expressed in general observations, conclusions and recommendations. The general conclusion of this work is that thermosyphon foundations can be designed to withstand climate warming at most permafrost locations but there is need to increase the robustness of the thermal design and provide guidelines for all aspects of design, construction and monitoring. This is expressed in seven detailed recommendations at the end of the report.

2.0 PERMAFROST

Permafrost is an encompassing term for frozen ground that provides no information on the soil or type, ice content or ground temperature. Permafrost is defined as ground (soil or rock and including ice and organic material) that remains at or below 0°C for at least two consecutive years (Everdingen 2002). This limited definition does not portray the large variety of ground conditions that may exist in the permafrost region. This may vary from competent bedrock to clean gravels, sand and silts with ice lenses or varved clay with ice layers. Even large ice layers of 1m or larger may be present. Problem ground conditions exist when a soil has an excess of ice then what is necessary to fill the soils pores. In this situation the ice starts to control the soil strength and deformations. However, if the ice melts, it weakens the soil greatly and produces thaw settlement. Finally, it has to be noted that strength and deformation of a soil with excess ice is controlled by rate of creep of the ice and this is greatly a function of the ground temperature. A cut through sandy silt deposit during the construction of a cut trench for a dam at Diavik illustrates the numerous small and larger ice lenses that could be present in Permafrost (Photo 5).

Photo 5. Layered sandy silt and ice at Diavik excavation.

An example of difficult ground conditions is shown by a log prepared during excavation of the natural ground at Inuvik during the construction of the granular pad for the thermosyphon foundation at Aurora College in Inuvik in 1992 shown in Figure 1. Photo 5 and Figure 1 illustrate the extra care that needs to be exercised in the design and construction of foundations in ice rich soils.

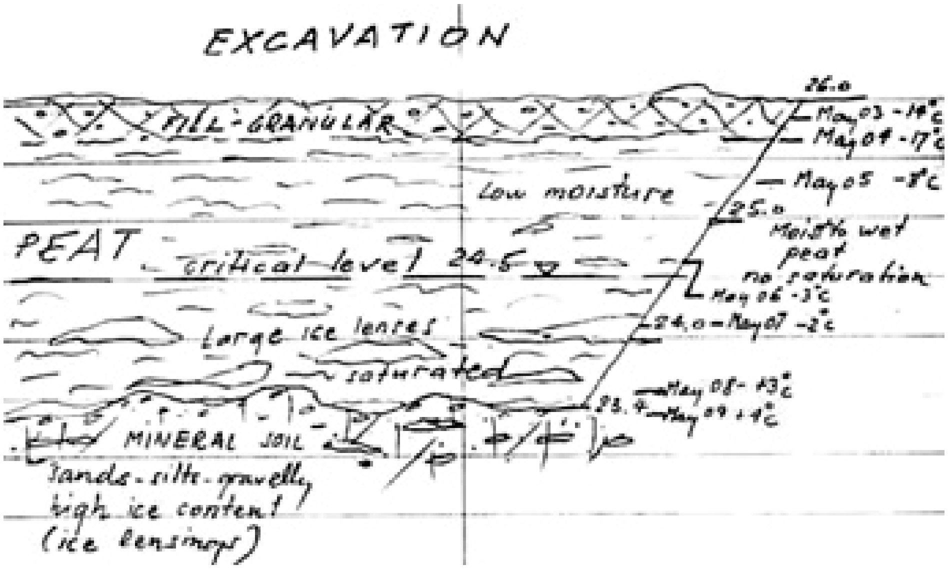
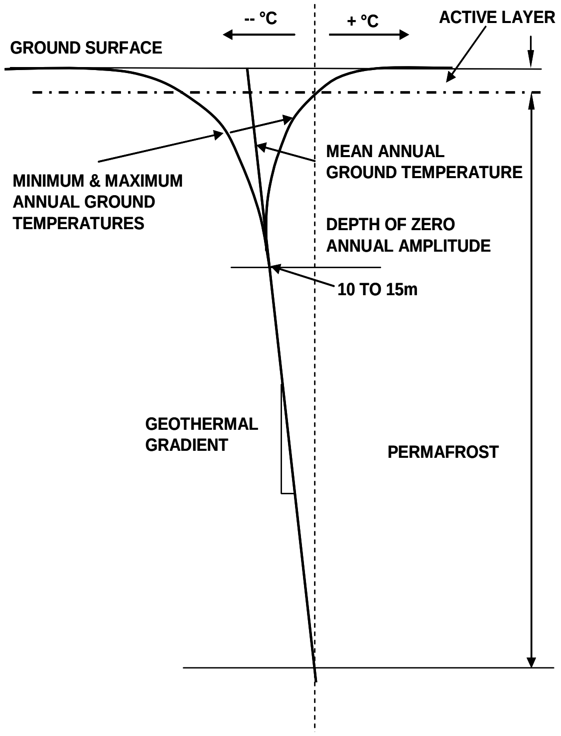


Figure 1. Excavation log at Inuvik Aurora College (Field notes from AFC).

The next parameter that needs to be considered in the design of foundations in permafrost is the ground temperature. Ground temperature is complex because while it is predominantly dependent on the air temperature above the ground, it also depends on vegetation cover, terrain, snow depth during the winter, terrain slope, and mineralogy of the ground and greatly on the water/ice saturation level of the ground. The ground temperature fluctuates with the air temperature in the first 10 to 15m. However, there is a time delay in its response and this lag increases with depth. This ground temperature fluctuation in the upper 10 to 15m through the year as illustrated in Figure 2. Recent ground temperatures measured in Inuvik are shown in Figure 3. Parameters that describe the ground temperature are: depth of the annual thaw (active layer), ground temperature at the depth of zero annual amplitude and the geothermal gradient. Geothermal gradient also varies but has an average value of 1°C/54m (Johnston 1981). This means that the mean annual ground temperature (MAGT) varies only by 0.2 to 0.3°C between the ground surface and the MAGT at depth of zero annual amplitude; therefore, can be assumed to be the same for most of permafrost designs.



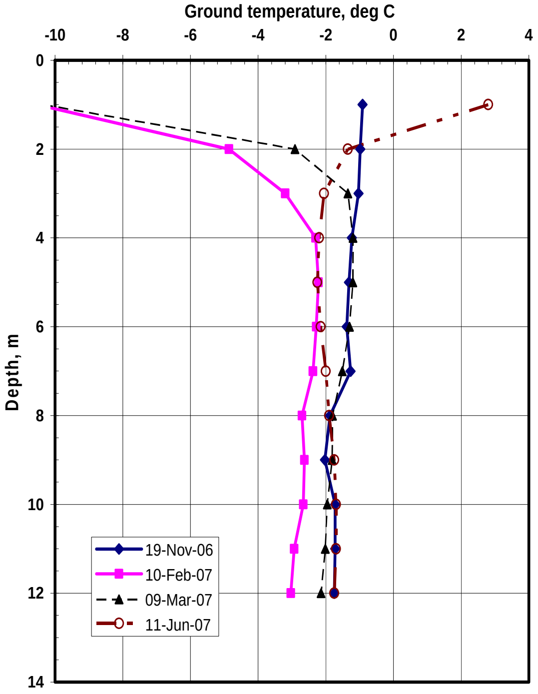


Figure 2. Schematic ground temperature regime in permafrost.

Figure 3. Ground temperatures measured between 2006 & 2007 in Inuvik, NU (AMEC 2007)

The ground temperature at depth of zero annual amplitude is dependent on the mean annual air temperature (MAAT) at the location and various parameters related to ground cover, topography and snow depth. GSC have established that the relationship between the

MAAT and the mean annual ground temperature (MAGT) at the surface is about 4.4°C, the MAGT being 4.4°C warmer than the MAAT (Smith & Burgess 2000). The writer has found this to be relatively true in cleared areas. The MAGT at the surface and at the depth of zero annual amplitude are nearly the same because of the small geothermal gradient. It should be noted that from hereon MAGT is considered to be the near surface ground temperature representing 0 to about 20m depth.

3.0 CLIMATE

Climate warming is widely accepted with the main arguments being how fast it is occurring and how it should be combated. The most recent Intergovernmental Panel on Climate Change (IPCC) made the following statements in its Climate Change 2007; The Physical Science Report (IPCC 2007a):

- Warming of the climate system is unequivocal.
- Average Arctic temperatures increased at almost twice the North American average rate, and
- Temperatures at the top of the permafrost layer have generally increased since the 1980’s in the Arctic by up to 3°C.

The global air temperatures increases since 1975 to 2001 and the future changes predicted by various models are shown in Figure 4. The plot in Figure 4 illustrates two points to be considered by a designer of future foundations in permafrost; a) air temperature started to increase appreciable since about 1985 and b) this rate of temperature increase will likely continue to about 2100.

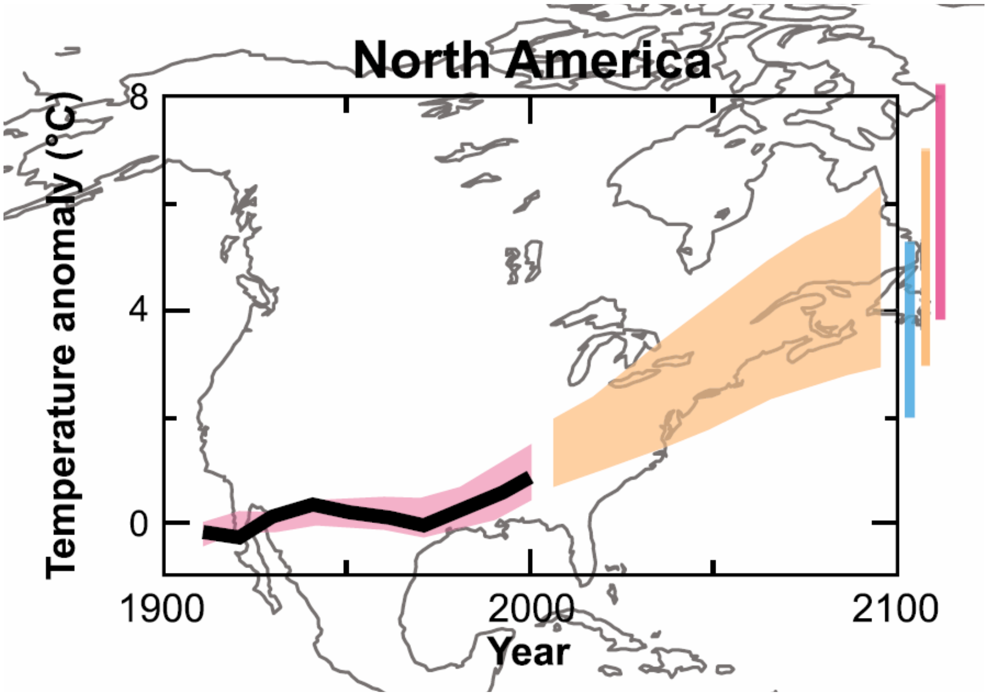


Figure 4.Global air temperature changes (IPCC 2007b)

The mean annual air temperature (MAAT) has been rising considerably across the Canadian Territories and are illustrated by MAAT plots from four climate station records in Northwest Territories in Figure 5. The MAAT varies greatly from year to year therefore it is necessary to look at the MAAT trends over several years. Environment Canada has been publishing climate Normals that provided the average values for a range of years. Initially in printed reports giving the average values from 1951 to 1980 and presently they can be found on the Environment Canada web page from 1971 to 2000. It is suggested that the start of appreciable climate warming is about 1985, and it is necessary to analyze the air temperature trend line. This provides a means to smoothen out the considerable air temperature changes from year to year and also portrays the temperature rise. This has been done with MAAT data from 17 climate stations across the Canadian Territories. The method to represent the MAAT rise, and be able to estimate a ‘mean’ MAAT for a climate station and the climate warming is illustrated in Figure 6 using the Contwoyto/Lupin climate station that is about central to the Canadian permafrost region. The interpretation on Figure 6 shows the MAAT to be -9.3°C in 2006 and the climate warming rate is about 13°C per 100 years. The MAAT values for the quoted locations were obtained from Environment Canada historic data at internet address as given in the Reference section at the end of the report.

Similar plots and analysis were done for 16 other stations across the Canadian permafrost region and are shown in Table 1. In this table the MAGT for 2006 each location was derived by assuming that the MAGT was 4.4°C warmer than the MAAT (Smith & Burgess 2000). Represented MAGT values for the Canadian permafrost regions are illustrated on a map in Figure 7.

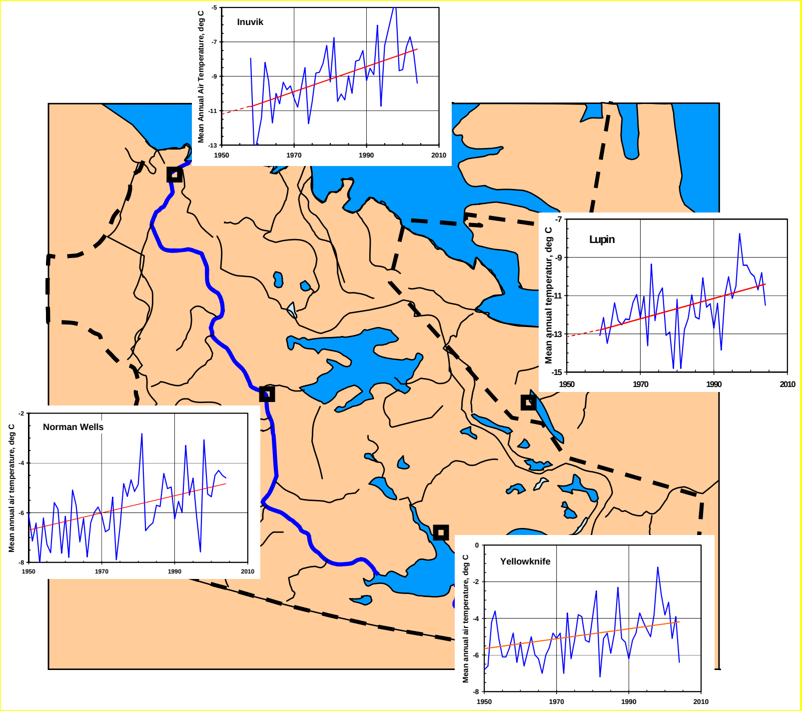


Figure 5. Mean Annual Air Temperature (MAAT) records at four representative NWT locations (from Environment Canada Meteorological station records)

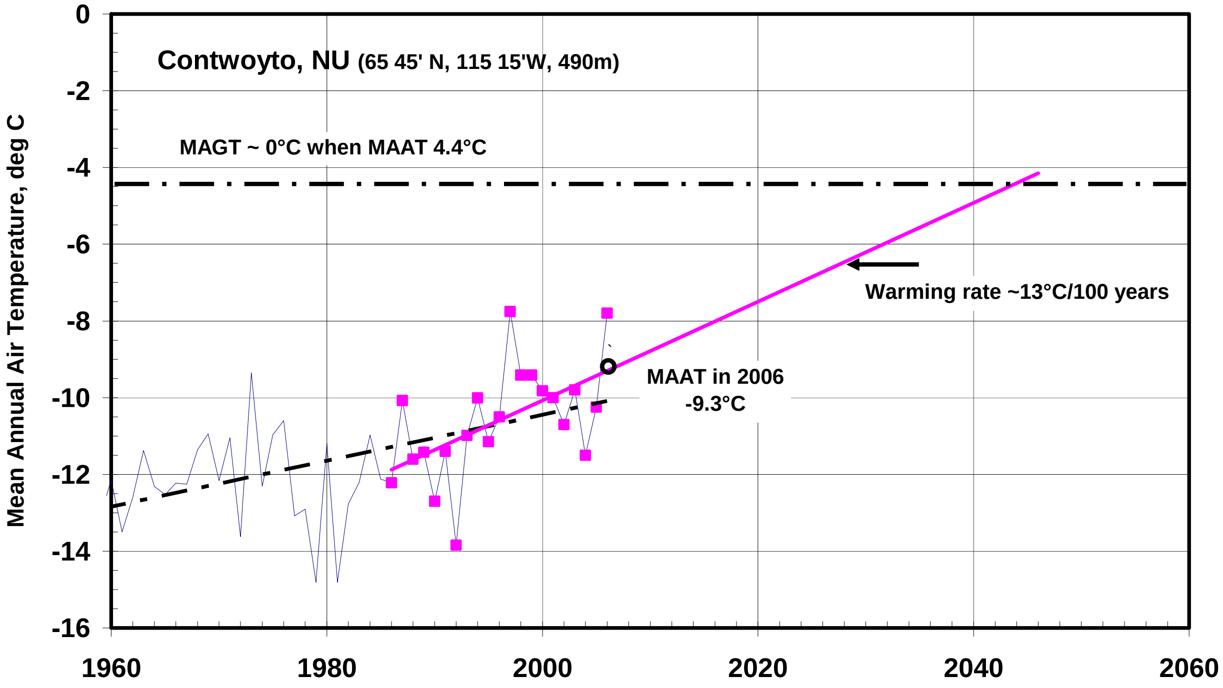


Figure 6. Mean annual air temperatures, and their interpretation, Contwoyto Lake, Nunavut, Canada. (Environment Canada data)

The climate data and estimated ground temperatures obtained by the linear regression was grouped into five zones to interpret the air and ground temperatures across the permafrost region. The Yukon zone is complex because it is within mountains and adjacent to the Pacific Ocean. No further comment is made on this zone. The data in Table 1 suggests the following:

- Western Arctic and the Mackenzie Valley have relatively warm MAAT and MAGT. They warm with the increase of Latitude. Generally the climate warming rate varies between about 6 to 8°C per 100 years; a mean climate warming rate of 7°C per 100 years is about representative of this zone.
- Central Mainland Arctic has a colder MAAT and MAGT range, excluding Churchill, MB, and is experiencing a greater climate warming rate of about 11°C per 100 years.
- Eastern Arctic shows the greatest climate warming rate in the Canadian north; being about 17°C per 100 years.
- Air and ground temperatures in the Arctic Islands are colder and it has moderate climate warming rate of about 9°C per hundred years.

Table 1. MAAT, MAGT and warming rates at selected climatic stations in Canadian permafrost (YT, NT, NU and QC

Location	Elevation m	Latitude	Longitude	2006 MAAT deg C	2006 MAGT deg C	Warming rate since 1985 deg C/100y
Yukon						
Komakuk Beach, YT	7	69°34'N	40°10'W	-10.4	-6.0	3.4
Mayo, YT	504	63°34'N	135°52'W	3.0	'+7.4	7.8
Western Arctic & Mackenzie Valley						
Tuktoyuktuk, NT	5	69°25'N	133°01'W	-9.2	-4.8	5.9
Inuvik, NT	68	68°18'N	133°28'W	-7.2	-2.8	7.4
Norman Wells, NT	73	65°16'N	126°48'W	-4.7	-0.3	6.1
Yellowknife, NT	206	62°27'N	114°26'W	-3.4	'+1.0	8.4
Tulita	101	64°55'N	125°34'W	-3.8	'+0.6	
				Mean value		**7.0**
Central Mainland Arctic						
Coppermine/Kugluktuk, NU	9	67°49'N	115°07'W	-9.4	-5.0	8.4
Contwoyto Lake, NU	490	65°28'N	110°22'W	-9.3	-4.9	12.9
Baker Lake, NU	18	64°18'N	96°14'W	-10.7	-6.3	10.7
Rankin Inlet, Nu	29	62°49'N	92°07'W	-9.3	-4.9	13.0
Churchill, MA	29	58°04'N	94°03'W	-5.5	-1.1	10.2
		Mean values		**-9.7**	**-5.3**	**11.3**
		Note: Churchill temperatures excluded from mean values				
Eastern Arctic						
Pangnirtung, NU	23	67°07'N	65°42'W	-6.7	-2.3	15.9
Iqaluit, NU	34	63°45'N	68°33'W	-7.3	-2.9	17.6
Kuujjuaq, QC	39	58°06'N	68°25'W	-3.5	'+0.9	17.2
				Mean values		**16.9**
Arctic Islands						
Resolute, NU	67	74°43'N	94°59'W	-15.6	-11.2	10.8
Pond Inlet, NU	55	72°40'N	77°58'W	-13.8	-9.4	7.3
Cambridge Bay, NU	25	69°06'N	105°08'W	-13.0	-8.6	9.1
		Mean values		**-14.1**	**-9.7**	**9.1**

Note: MAGT is based on MAAT plus 4.4°C.

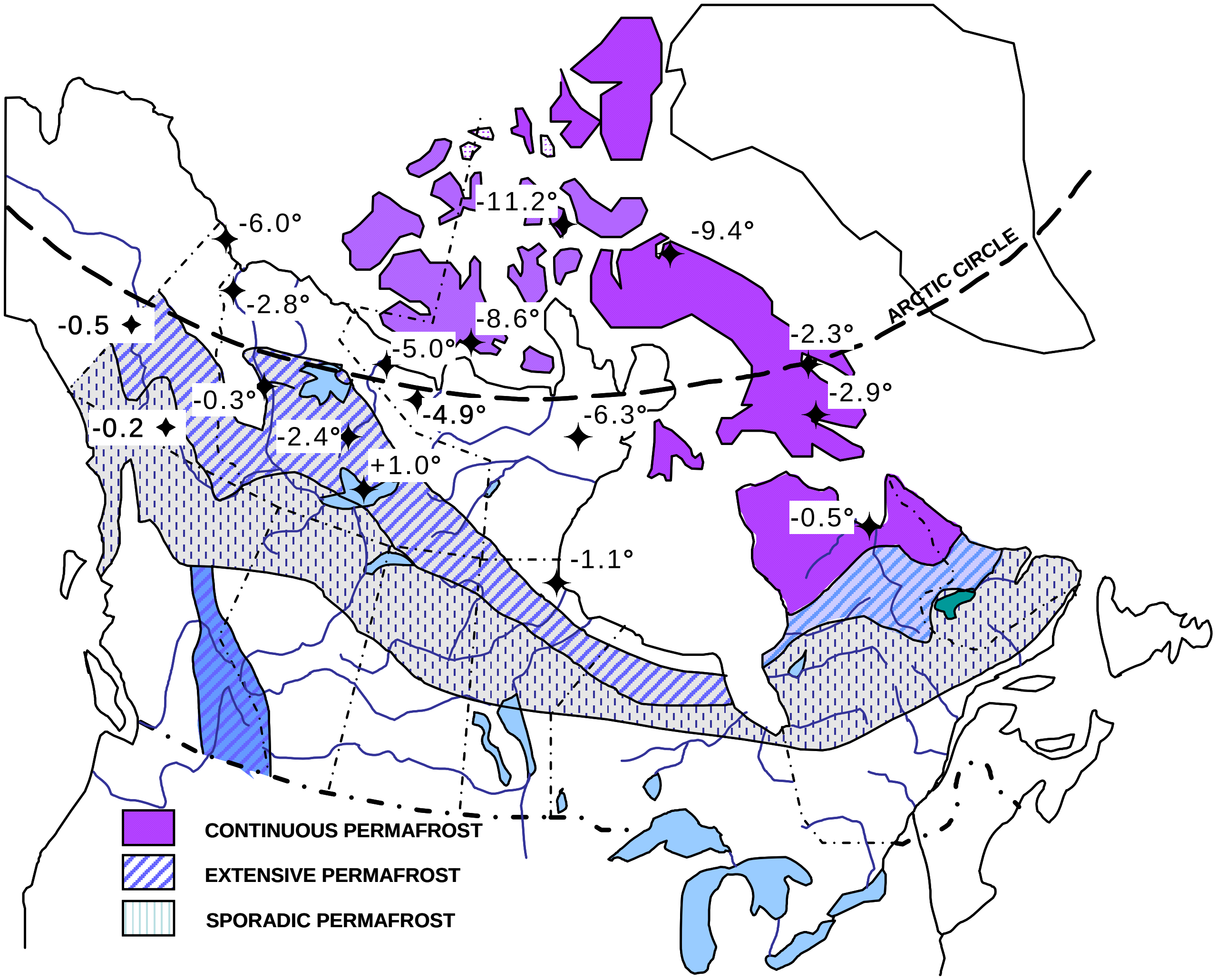


Figure 7.Estimated MAGT in 2006 for selected sites across Canadian Permafrost Regions (Canada Permafrost Map MCR 4177F, 1995)

4.0 IMPLICATION OF CLIMATE WARMING ON PERMAFROST, GROUND TEMPERATURE AND FOUNDATIONS

4.1 Design Ground Temperature

The design ground temperature for traditional slurry piles and the foundation beneath dams on frozen ground is accepted to be -2°C. In case of dams it is taken to be at the base of liner in the key trench. However, for piles, the location of the -2°C is not established. This needs to be noted since the normal length of slurry pile section buried in permafrost is 8 to 10m. Since the MAGT at a depth of zero amplitude is about 10 to 15m below the ground surface, the warmest envelope of the ground temperature cone in Figure 2 will be warmer than the MAGT. This will diverge from the MAGT as it approaches the ground surface.

4.2 Marginal MAGT at major northern settlement

Ground temperatures in all the major Territory settlements are near the maximum ground temperature design value of -2°C for the common slurry pile foundations. MAGT values in 2006 are estimated at: Inuvik, -2.8°C; Iqaluit, -2.9°C, and Rankin Inlet, -4.9°C. The MAGT at Rankin Inlet is about equivalent to -2.9°C because the salinity within the pore ice has depressed the freezing temperature of this 'saline' permafrost by about 2°C.

4.3 Climate warming impact on MAGT

Climate warming rates in most permafrost zones, with the exceptions of the Arctic Islands, will reach the design MAGT, and even 0°C when permafrost will start to thaw, in less than the design life of any new buildings to be built from now on. Reaching 0°C in the design life of a building means that even elevated buildings on gravel pads and insulation will be prone to settle.

4.4 Alternate foundation designs

The design of foundations of buildings in most mainland permafrost region will have to take into consideration that climate warming will raise the MAGT above the design MAGT. The traditional slurry piles will not be able to support the buildings for the normal life span of 50 years. Even small buildings supported above ground on a gravel pad will experience the permafrost below the granular to thaw and result in thaw settlement.

Alternate foundations will have to be considered in these areas. These may be:

Locate the building on bedrock or ice free ground underlain by bedrock.

End bearing piles that extend below the ice rich soil or at least to a soil that has low ice content so that any future settlement can be corrected by adjustments at the pile cap.

Thermosyphon foundations that will keep the ground frozen during the life span of the building. Over the last 50 years several types of thermosyphon foundations have been developed and used in Alaska and Canada. These consist of vertical cooling tubes and piles, sloping cooling tubes and flat looped tubes.

The design, construction and performance of flat loop thermosyphon foundations is presented in the next chapters and the report is completed by providing recommendations for improving the design of the foundations so that they will function for the normal 50 year life span of commercial buildings.

5.0 FLAT LOOP THERMOSYPHON FOUNDATION

5.1 Design Concept and History

The thermosyphon technology is called a “passive technique” because it requires no power to operate and has no moving parts. The thermosyphon is a closed natural two phase convection device that extracts heat from the ground and discharges it into the atmosphere. It is the most effective heat transfer device because for any working fluid, the latent heat of vaporization is much greater than the sensible heat capacity times a typical temperature difference (Yarmak & Long, 2002).

Thermosyphon is a two phase sealed tube containing a suitable fluid; carbon dioxide is used in Canada (Figure 8). When ambient temperature falls below ground temperature, vapour condenses in the radiator section of the tube. Pressure in the tube is reduced and the liquid in the lower section of the pipe starts to boil and evaporates. The cycle of evaporations and condensation extracts the heat from the soil during the winter time when the air temperatures are colder than the ground temperatures. The vapour of carbon dioxide in the sealed tube operates under relatively high pressure from about 200 to 700 psi (Figure 9).

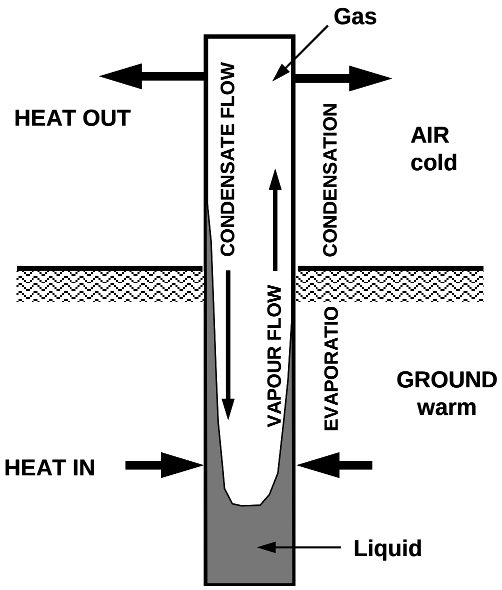
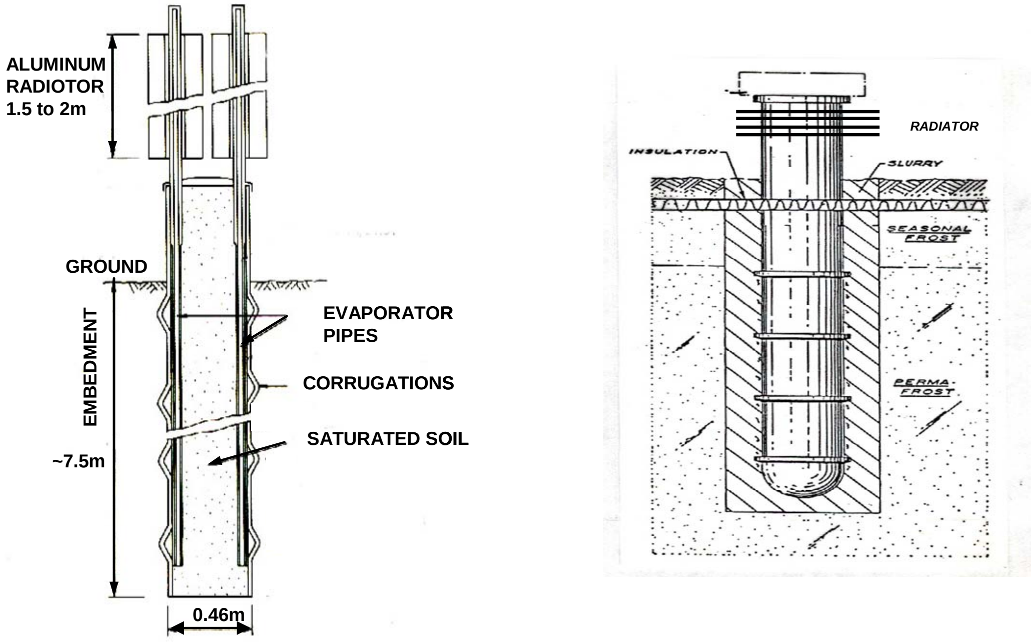


Figure 8. Thermosyphon heat exchange principle.

Thermosyphon cooling was first used in Alaska in 1960 and was clearly demonstrated on the Alaska pipeline where over 120,000 thermosyphons were installed within pipe piles around 1975 (Heuer TF al. 1985). The initial installations were vertical sealed tubes installed into ground with radiators at the surface. The two types of vertical thermosyphon pile designs used in Alaska are illustrated in Figure 9. The thermopile is presently commonly used to support buildings.

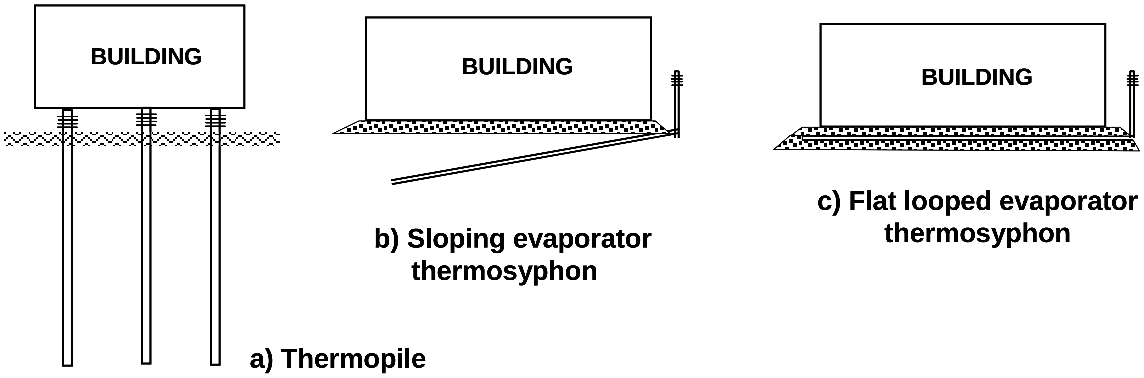


b) Thermopile

a) Vertical thermosyphon tubes (Thermoprobes) within TAPS pile support system

Figure 9. Vertical thermosyphon pile designs

The vertical thermosyphon design has expanded into conventional sloped evaporator thermosyphon (Sloped-TF) in 1978 and then in 1994 the flat loop thermosyphon (Flat -TF) design evolved. The three thermosyphon designs and their uses in building foundations are illustrated in Figure 10.



c) Flat looped evaporator thermosyphon

b) Sloping evaporator thermosyphon

a) Thermopile

Figure 10. Three thermosyphon designs

The uses of thermosyphons can be grouped into four categories as given in Table 2.

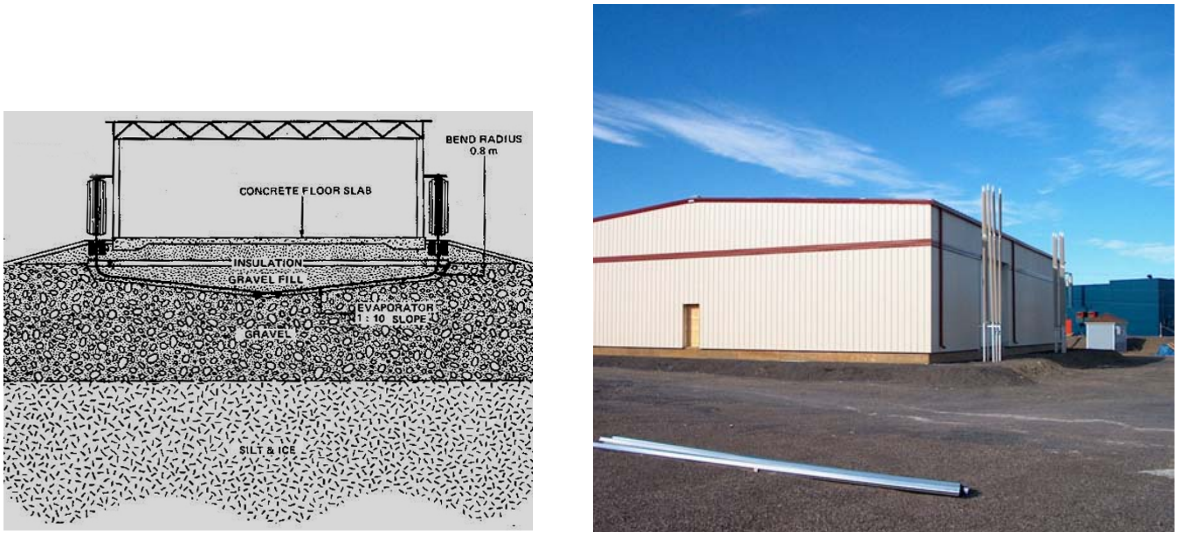
Table 2. Common use and designation of thermosyphon

Designation	Description	Use
Thermoprobe	Thermoprobe	Keeps ground frozen around piles or maintain frozen ground around structures
Thermopile	Thermopile	Supports structures on piles within frozen ground
Sloped-Thermosyphon Foundation	Sloped evaporator pipe under slab-on grade foundations	Keeps ground frozen below slab-on grade foundation.
Flat Loop Thermosyphon Foundation	Flat loop evaporator pipe under slab-on grade foundations	Keeps ground frozen below slab-on grade foundation.

Thermoprobes – This is the first application of thermosyphons and its use illustrated by the TAPS project in Figure 9 (a). They have been used in Canada to maintain frozen ground around transmission towers and along railroad embankments in Manitoba. They do not carry any load (Figure 11, a).

a) Thermoprobes – Joe Lake, MB. Highway stabilization (Courtesy AFC)

b) Thermal Piles – Manitoba DC Line, MB. (Courtesy AFC)



e) Sloped Thermosyphon Foundation at Ross River, YT (Hailey 1982).

d) Flat Loop Thermosyphon Foundation – Airport maintenance garage, Inuvik, NT. (Courtesy AFC)

Figure 11. Photos of types of thermosyphon installed in Canada.

Thermopile – Thermopiles are widely used in Alaska because of available access to large drill equipment that is necessary to drill the holes for the large load carry tubes (piles). There are no thermopile foundations in Canada (Figures 9b & 11b).

Sloped-TF – This concept evolved by the installation of the thermoprobe at slightly sloped grade and covering it with granular cover and insulation with bedding. The building is supported on slab-on grade foundation. It has a single tube evaporation and condensation operation (Figure 11c).

The first building using the Sloped-TF system was the Ross River School in Yukon Territory in 1978 (Hayley 1982). In the early 1980’s the Sloped -TF system was installed routinely to maintain permafrost in the subgrade below heated at-grade structures throughout the Alaskan permafrost region. Hundreds of the Sloped -TF systems are in existence in permafrost across Alaska and Canada. The Sloped -TF units have pipes generally with sufficient large diameter, so that should a breech in the evaporator pipe occur, a new pipe could be inserted and thereby reducing the cost of potential repairs (Yarmak & Long, 2002).

The shortcoming of this thermosyphon foundation is that the evaporator pipes have to be installed on a sloping grade of about 5%. This makes the construction of the base more onerous and a non-uniform thermal regime is produced beneath the slab-on grade.

Flat loop – TF - The Flat Loop-TF design is a relatively recent development (Yarmak & Long 2002). Its performance was tested adjacent to Sloped-TF in Winnipeg during the winter of 1993-1994. After a winter of operation it was found that the Flat Loop-TF froze 1.4 times the volume of soil than the Sloped-TF. It was started to be employed both in Canada and Alaska in 1994 as a result of this performance and easier installation. A Flat Loop-TF installation is shown in Figure 11d and its concept is illustrated on Figure 12.

Two major differences between the Flat Loop-TF and the Sloped-TF are: a) Flat Loop-TF is installed on a level prepared granular base while the Sloped-TF requires a grade and b) the Flat Loop-TF evaporator pipe is normally a 50 mm OD and is a looped configuration while the Sloped evaporator pipe consists of a single 100mm OD pipe.

Since 1994 some 80 Flat Loop-TF systems have been constructed in Canada. Of these, 15 Flat Loop -TF have been placed at the bottom of dams to keep the foundation frozen and 65 Flat Loop-TF under buildings. The Flat Loop has been used in two configurations; either in slab-on-grade where the lower floor or basement is founded on gravel/ insulation/ evaporator pipe system or buildings underlain by a crawl-space that is followed by the gravel/insulation/evaporator pipe system. Majority of the Flat Loop have the building slabs resting directly on the gravel bedding covering the insulation and evaporator pipes. These two Flat Loop thermistor foundations are illustrated in Figure 13.

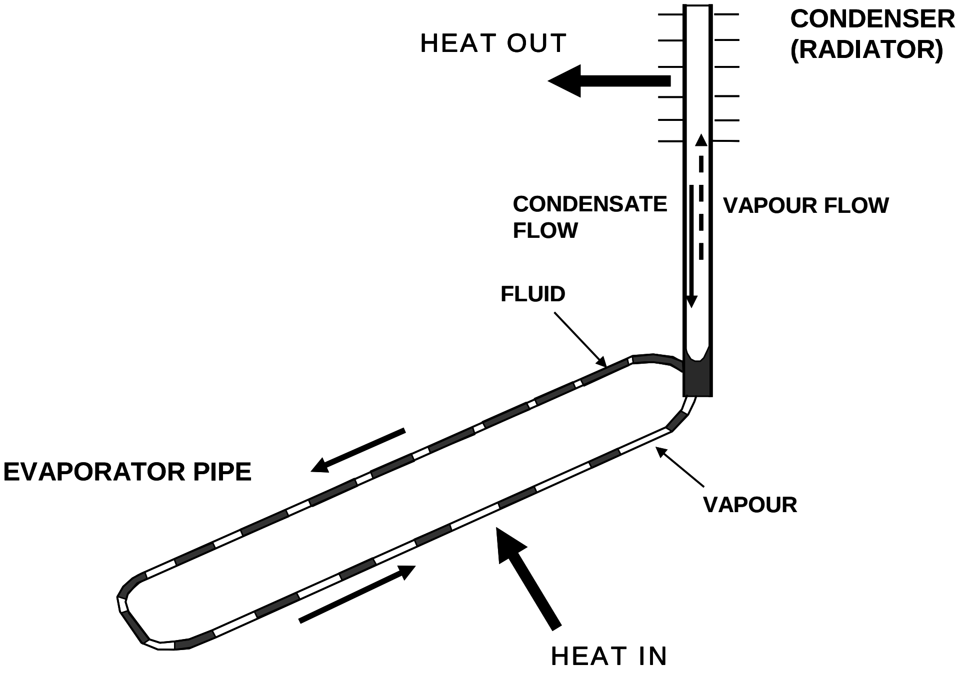


Figure 12. Components of the Flat Loop-TF

The two foundation systems have different requirements for the installation of services, such as: electrical and water and sanitary piping. In the crawl-space designs the services are hung from the floor beams while in the slab-on-grade insulted conduits or corridors are required to carry the services below the floor slab. The slab-on-grade makes repairs or changes to the services difficult. Majority of the flat loop FT have the building slabs directly on the gravel bedding covering the insulation and evaporator pipes

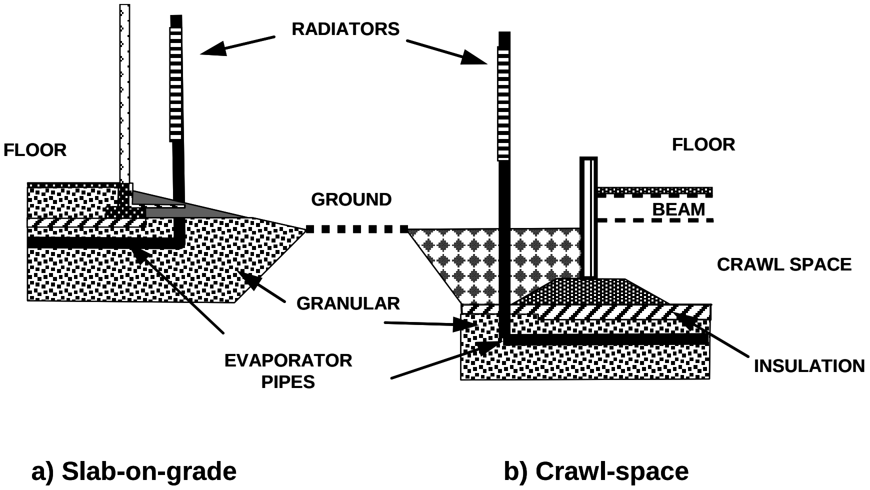


Figure 13. Two flat looped thermosyphon installation types

5.2 Thermosyphon Foundation Installation in Canada

Thermosyphon foundations started to be employed in Canada in 1985 and since that time they were installed at 50 locations in all Territories and two provinces. They have been installed as far south as Thompson, Manitoba (55° 48’N, 97° 22W) to as far north as Alert, NU (82° 31N, 62° 17W). In the south they were installed in embankments to preserve the existing permafrost while in the north to prevent the thaw of foundations below heated buildings with slab grade on foundations. The mean annual air temperature in the south was around -3°C during installation and -18°C in the north.

There have been 127 installations. The distribution by Territory and Province are shown in Table 3.

Table 3. Number of installations across Canada

Region	Number
Nunavut	52
Northwest Territory	41
Manitoba	15
Quebec	10
Yukon	8
Ontario	1
Total	127

Initial thermosyphon installations were vertical probes to stabilize or maintain permafrost in earth slopes or around piles and sloped probes (Sloped TF) under foundations. The development of the flat loop evaporator (Flat Loop TF) thermistor design changed the option of thermosyphon design selection because the Flat Loop TF was easier to install and they were more efficient in the cooling. All new foundations used the Flat Loop TF design since 1994. Since 1994 only one Sloped TF was used to stabilize the permafrost in one building. Vertical probes have continued to be used for some designs, along with hybrid cooling, and vertical piles. The distribution of thermosyphon designs is shown in Table 4.

Table 4. Distribution of thermosyphon designs employed in Canada

Type	Descriptive	Number	Subtotal
Flat	Foundations	69	
	Dams	5	
Subtotal			77
Sloped	Foundations	28	
	Dams	1	
Subtotal			29
Vertical probes & piles	Foundations	15	
	Dams	5	
	Embankments	4	
			24

Table 4 shows that 77 Flat TF have been installed since 1994; of these, 69 were used for building foundations.

The cooling of the Flat-Loop TF was enhanced by the addition of mechanical cooling to enhance the rate of cooling in six installations (hybrid Flat-Loop TF). The hybrid installation involved adding a cooling coil around the vertical evaporator pipe, insulating the coil and connecting the coil to a refrigeration compressor. The mechanical cooling is activated when the air temperature becomes too warm to condense the carbon dioxide in the vertical pipe. The cooling provided by the coil around the vertical pipe condenses the vapour even during the summer and thereby keeps extracting the heat from the foundation. The size of the compressor determines the rate of cooling and therefore heat extraction. Normally the compressors are small and can be mounted on the evaporator pipes. Otherwise it may be a self standing unit installed adjacent to the radiators. An installation of a small compressor is shown in Figure 14.

Figure 14. Hybrid installation at the Young Female Offender Facility in Inuvik. Cooling coils wrapped with insulation are installed below the radiators and the compressor cooling unit is located behind the radiators.

Mechanical (compressor) cooling units have been added to the standard thermosyphon installation to accelerate the freezing of the ground at the Inuvik Hospital in 2001 and at the construction of dikes in Lac de Gras for the Diavik Mine in 2002 and 2006. The reason for installing mechanical cooling units at the hospital was to accelerate the freezing of the granular pad below the evaporator pipes that would allow earlier construction of the footings of the hospital on frozen ground. Mechanical cooling units were installed were installed at the Female Young Offender Facility in Inuvik to supplement the cooling of the thermosyphons during the summer when they did not operate. Supplemental cooling was installed to compensate for the loss of efficiency of the thermosyphon evaporator pipes due to the incorporation of bends in the evaporator piping to accommodate waste water piping services at the Female Young Offender Facility in 2003; and to compensate for the type of installed insulation and to overcome a thaw caused by the incorporation of a heat supply line above the evaporator pipes at Simon Allaituq School in Rankin Inlet in 2007.

5.3 Flat Loop Thermosyphon Foundation Design

The foundation of the flat looped FT system consists of the following basic components: a) 1 to 2m thick compacted gravel pad; b) 150mm bedding below and above the pipes; c) evaporator pipes, d)100 to 200mm rigid insulation, e) vertical radiator f) working fluid and g) charge valve. The design components are illustrated schematically in Figure 15 and in photographs in Figures 16 and 17. Brief comments on the components are given below:

Gravel pad. A 0.7m to 2m non-frost susceptible[1] granular pad is provided for construction purposes, a soil zone with uniform thermal properties and a structural zone that can tolerate a minor annual thaw front advance that is followed by refreezing below the elevation of the evaporator piles during the summer without causing settlement or heave of the slab on-grade.

Bedding. The evaporator pipes should be protected within bedding consisting of sand. Bedding may not be needed below the pipe if the pad granular does not contain cobble sized material and is well compacted to form a smooth pad surface. In this case a 150mm bedding pad on top of the evaporator pipes would be sufficient.

Evaporator pipes. Normally 200mm OD extruded steel pipes Schedule A104. Joints are made using sleeves and elbows that are welded to the pipe. The welds are checked for leaks by introducing helium with 200 psi pressure and running a mass spectrometer helium detection sensor of the pipes.

Working Fluid. _ Selection of fluid is based on the condition that it has an adequate vapour pressure at low operating pressure, low viscosity to enhance flow return, low freezing point and be non-corrosive with respect to the pressure vessel. The fluids that have been used are propane, ammonia and carbon dioxide. Carbon dioxide is the dominant fluid because of its non poisonous nature and being inert.

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[1] Non-frost susceptible soils are used in pavement design to prevent ice lens formation and thereby heaving. There is no accepted standard but it is generally greed that frost heave is negligible if fines content (less than 0.075mm particle size) is less than 12% (Konrad 1999).

The pressure range the carbon dioxide operates in the evaporator/condenser tubing is illustrated by the saturation various pressure versus temperature in Figure 18.

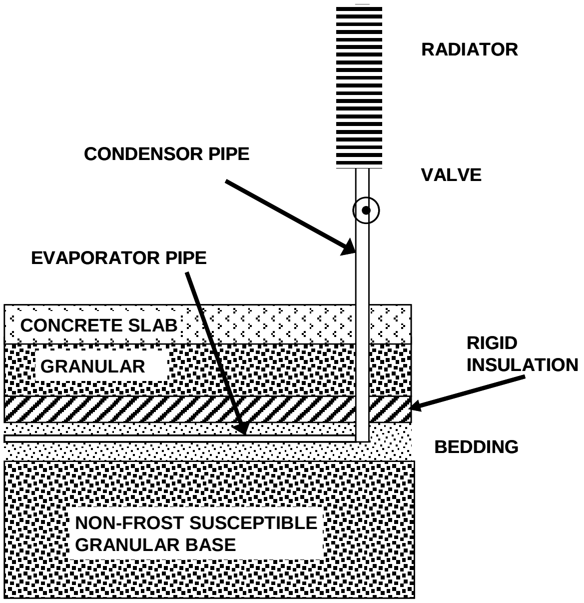


Figure 15.. Schematic of flat loop slab on grade thermosyphon foundation installation,

Figure 16. Flat Loop TF installation in progress at Pangnirtung Health Centre. Photo shows the evaporator pipes along the radiators in place.

Figure 17. Insulation sheets being placed over bedding covering evaporator pipes at Inuvik hospital.

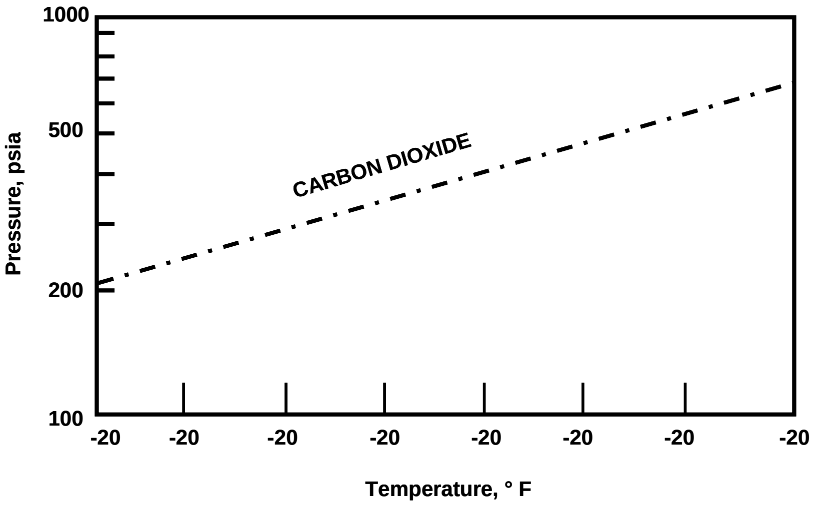


Figure 18. Saturation vapour pressure versus temperature (Heuer et al 1985)

Insulation – Three important properties for the insulation are: good thermal barrier, low moisture absorption rate and rigidity if the building footings to be supported. Two common insulation materials are made from polyurethane and polystyrene. Polyurethane is more pliable but has higher moisture absorption that is detrimental because this lowers with time its insulating capacity. Polystyrene comes in flat sheets and is widely used for road and building insulation projects. Extruded polystyrene is superior to expanded polystyrene because of its high compressive strength. Common thickness of polystyrene used in flat loop thermosyphon foundation has been 150 to 200mm.

Radiators – They consist of 100mm vertical condenser pipes that have steel or aluminum fins attached. Radiator surface treatment of the exposed condenser pipe and fins is important to prevent corrosion and provide maximum heat dissipation. The treatment consists of thorough sand blasting, applying aluminum coating and painting with a white epoxy. The radiators are normally 3 to 5m long.

5.4 Thermal Design Factors

The operation of the Flat-Loop TF is dependent on the extraction of heat from the foundation by means of the radiator cooling and condensing the carbon dioxide vapour in the condenser; thereby reducing the vapour pressure in the system that in turn leads to evaporation of the fluid in the evaporator pipes that extracts heat from the adjacent soil. The insulation above the evaporator pipes slows the heat flow from the building towards the foundation. The thermal properties and thickness of the insulation have to be such that they will minimize the introduction of heat into the cooled foundation to a rate so that the system maintains a frozen foundation through the summer when the thermosyphons do not operate. The key thermal parameters that govern the thermosyphon operation are illustrated schematically in Figure 19 are.

a) Climate – The climate parameters that are needed are the mean annual air temperature, freezing index and wind velocity. It is important that radiators are located on the wind side of the building to take the greatest advantage of the wind.
b) Radiator – Radiator heat dissipation characteristics are determined by the manufacturer and the length of the radiator.
c) Ground – Heat extraction rate from the ground during the winter and the subsequent warming, are a function of the boundary ground temperature and the conductivity of the soil and the granular pad and latent heat in the granular pad.
d) Heat that is introduced to the evaporator pipe is a function of the air temperature above the slab and the conductivity of the concrete slab and insulation.
e) Evaporation and condensation of the fluid are a function of the fluid.

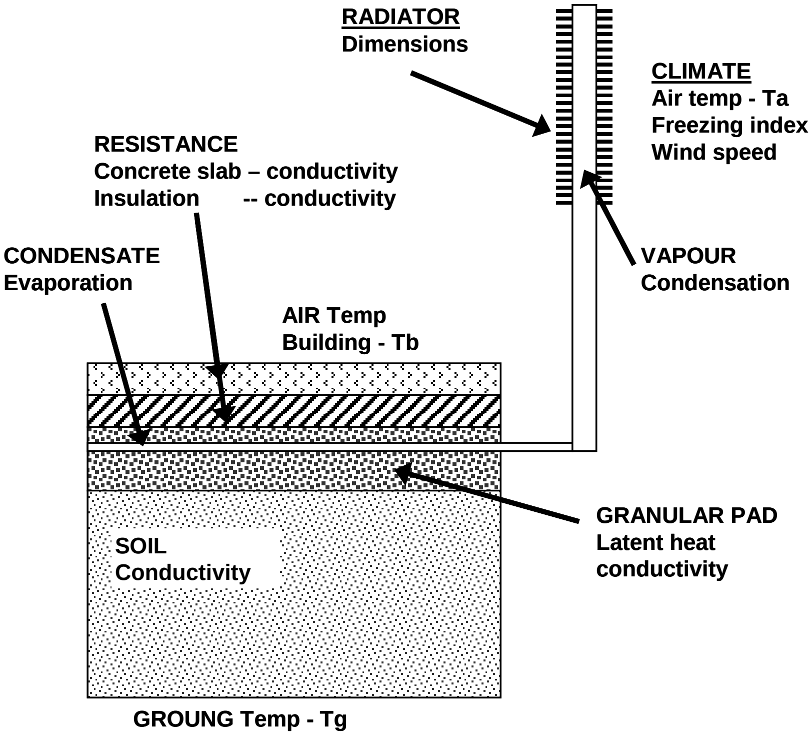


Figure 19. Thermal model of thermosyphon operation

The ability of the Flat Loop TF to maintain the foundation frozen for a given climate is a function predominantly on the length of the radiator, the thickness of the insulation and the spacing of the evaporator pipes. This simplistic statement is based on the assumption that most building space above the slab are at about 20°C and the ground is a sand with moderately ice rich soil.

A thermosyphon foundation design consists of selecting a combination of radiator length, insulation thickness and evaporator spacing to maintain foundation consisting of the gravel pad and the underlying ground frozen for the designated climate. The design is done by the thermosyphon supplier/contractor and geotechnical consultants experienced with permafrost design. It is executed by means of thermal calculation using either proprietary or commercially available thermal analysis software. Presently there is only one supplier/contractor in Canada and one in Alaska who have developed their own thermal analysis method that is based on their experience.

6.0 PERFORMANCE

6.1 General

Satisfactory performance of a thermosyphon foundation system is a function of design, construction and monitoring and maintenance during operation. The design has to consider the air temperature of the space above the thermosyphons and the present and future air temperature during the design span of the building. This was discussed briefly in the earlier chapters. Construction has to consider the provision of good quality with uniform base depth base or foundation on which the evaporator pipes are installed; control of surface water and groundwater occurring during the summer, high quality of evaporator and condenser piping installation and the monitoring and maintenance of the system that is required in a cooling system, even though it is a passive system that has no moving components. The construction and operation are briefly discussed in the next sections.

6.2 Construction

Construction of the Flat Loop TF has to consider the following:

a) Granular pad
b) Surface water and groundwater control necessary during the summer.
c) Welding, leak testing and charging of the operating fluid.
d) Construction scheduling.
e) Design of the services that are installed within the granular zone above evaporator pipes.

Good quality construction and installation is necessary to produce a foundation system that will operate for the life span of the building with minimal or no maintenance or repairs. Presently, guidelines or standards are not available for the design and construction of the Flat Loop TF foundations. Some of the construction issues are identified or given in individual reports or construction drawings. However, there is no document that addresses the combined design and construction requirements. The following are some comments on the five issues identified by the writer.

a) Granular pad, bedding and granular zone

The three components are illustrated in Figure 15. The granular pad serves several purposes. It provides an uniform thermal zone just below the evaporator pipes, a construction pad over thawed soil that develops during construction and allow thaw just below the evaporator pipes to take place within a granular bed should this take place during the summer. The granular material is placed in lifts accompanied with compaction.

Normal practice is to specify non-frost susceptible granular material for the pad. The cost of the granular pad may be high if the specifications call for a 2m thickness. An alternative granular pad design is to limit higher quality of granular material for the zone immediately below the evaporator pipes and using relaxed specifications for the underlying portion of the granular pad.

b) Surface water and groundwater control necessary during the summer.

It is important to prevent surface and groundwater penetrating the granular pad or bedding surrounding the evaporator pipes. Water may seep into the system during the summer or the fall before the ground has completely frozen that will freeze when the thermosyphon starts to cool and freeze the material surrounding the evaporator pipes. Surplus water within the granular pad or bedding may grow ice lenses either around the cold evaporator pipes or within the granular pad if its material is frost susceptible. Ice lensing will in turn produce differential heave of the slab or at the building perimeter or form ice mounds in a crawl space.

c) Welding, leak testing and charging the operating fluid.

To start with, all the thermosyphon products need to be manufactured to ASME Boiler & Pressure Vessel codes and the exposed commons protected against corrosion. The evaporator pipes are high quality extruded steel pipes meeting ASTM A53B specification. The pipes are bent to the designed evaporator configuration and joined by sleeves and elbows that are welded. The welds are tested for leaks by pressurizing each evaporator and condenser pipe loop with helium at 200 psi and going over the welds with detection sensors. This method is used by the space industry. Following this, a vacuum is applied to the loops to remove all moisture and than charged with carbon dioxide fluid at a pressure corresponding to the existing air temperature.

a) Construction scheduling

The construction schedule for the thermosyphon is generally dictated by the time of the year when the layer of the ground that needs to be excavated is thawed, unfrozen granular material for the pad is available and it is planned to start erecting the building. This in turn is governed when the thaw season starts and when material arrives at the site that is controlled by shipping considerations. Normally, ground excavation can be started in May or June, depending on site location. Building materials are either shipped by barge or boat during the summer or brought over ice roads in February or March.

Furthermore, it is desired to construct the thermosyphon foundation in late spring or early fall and then allow the granular pad to completely freeze through one winter before starting to erect the building the following summer or fall after the installation of the thermosyphon foundation. The start of building erection can be expedited by active freezing by incorporating a hybrid thermosyphon cooling or scheduling the superstructure erection to the time the granular pad is completely frozen. Leaving the foundation over one winter or employing hybrid thermosyphon cooling may not be necessary if an advantageous construction schedule is followed.

Excavating and constructing the granular pad is normally done during the year with mean daily air temperatures being above zero degrees Celsius. The length of this period is dependent on the site location. The approximate date when the mean daily air temperature is above zero degrees Celsius in Inuvik is from about the start of May and continues to early November with the warmest mean daily air temperature occurring at about end of July (Figure 20). However, there is a time lag in the response of the ground to the air temperature changes and this is a function of depth. Figure 20 illustrates that at a depth of 3.5m the warmest ground temperature does not occur until early February the following year.

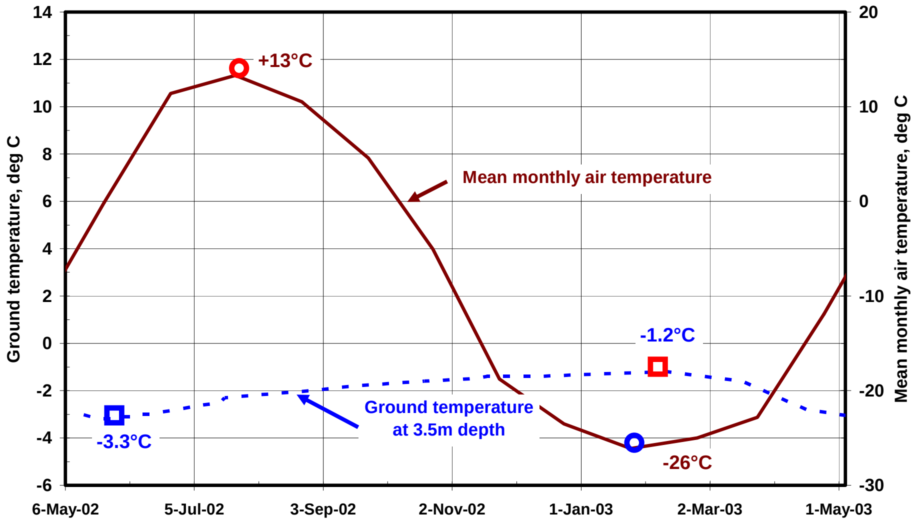


Figure 20. Changes of mean air temperature and ground temperature at 3.5m depth over the year at Inuvik.

The air and ground temperature changes over the year illustrated in Figure 20 indicate that the best time to excavate any poor ground and construct the granular pad are the months of May and June in Inuvik. This way the excavation is performed as soon as thawing occurs and is completed before the warmest air temperatures take place. The installation of the evaporator pipes, bedding and covering with insulation need to follow as soon as possible. The advantage of this scheduling is to take advantage of the coldest temperatures being experienced by the ground at deeper depth and to start to cool the completed granular pad installation.

b) Design of the services that are installed within the granular zone above evaporator pipes.

Design of thermosyphon foundations has to consider how sanitary piping and other services will be incorporated into or below the base of the building base. The location and design of these services needs to be considered because their installation can damage the evaporator pipes, leaks may impact the thermal regime and repair of these or the desire to modify them may be difficult if not properly located.

There is little difficulty in incorporating services in crawl space thermosyphon foundations. As is illustrated in photo in Figure 21, a crawl space design provides greater flexibility for installing sanitary piping and other services and also provides access for repair and modification.

Figure 21. Services hung from floor girders at Inuvik Hospital

The installation of services in a slab-on-grade thermosyphon foundation need to incorporate the services within the granular zone; between the insulation above the evaporator pipes and the slab. Two approaches that have been used are: providing a corridor below the slab, as used at the Kuujjuaq air terminal (Figure 22) or incorporating the sanitary piping within the fill, as used in Inuvik at the FYOF (Figure 23).

Figure 22. Service corridor at Kuujjuaq air terminal.

Figure 23. Buried sanitary lines at Inuvik YFOF

7.0 CASE HISTORIES

7.1 General

The twelve case histories from seven locations are reviewed to establish the adequacy of design, construction and operation of this type of foundation and also to evaluate the longevity of this foundation type to function over the life span of the building they support and their vulnerability to climate change. The locations are: Kuujjuaq, QC; Inuvik, NT, Rankin Inlet, Pangnirtung and Iqaluit, NU and Dawson and Ross River, YT. The factual information from the first 9 case histories is given in Table 5. They are listed in the order of installation. All the projects have flat loop TF foundations with the exception of the first one in Kuujjuaq. This has a sloped TF foundation. It is presented because the thermosyphon foundation was constructed in one of the warmer permafrost areas and has relatively longer ground temperature data showing. References from which the information was obtained are not listed in the text but given for each case history in Section 11.0 References.

The climate and reference ground temperature in Table 5 for the year of installation and 2006, for which whole year's air temperature information is available is based on linear trend lines. This was felt necessary to obtain a better consistency of information since the MAAT and freezing index varies greatly from year to year as illustrated on Figure 24.

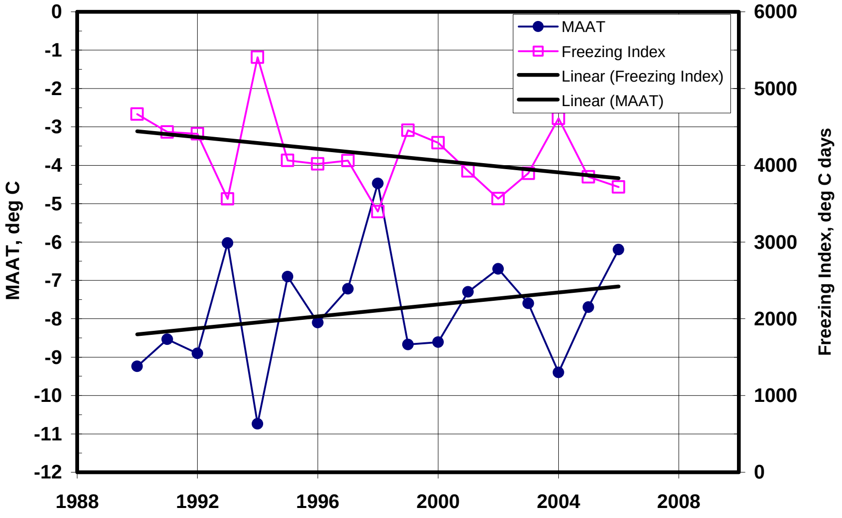


Figure 24. MAAT and freezing index at Inuvik during the period of thermosyphon installation (From EC data)

Information given in Table 5 shows that the thermosyphon cooling results in the ground at and below the evaporator pipes remains consistently frozen throughout the year and the mean annual ground temperature about 5m below the evaporator pipes is about 1 degree colder than the mean annual ground temperature.

Table 5. Summary information on projects discussed.

Name	Service Building	Visitor Centre	Simon Allaituq School	Female Young Offender Facility	Hospital	Aurora College	Pangnirtung Health Centre	RCMP Office	Air Terminal
Settlement	Kuujjuaq	Inuvik	Rankin Inlet	Inuvik	Inuvik	Inuvik	Pangnirtung	Iqaluit	Kuujjuaq
Territory	QC	NT	NU	NT	NT	NT	NU	NU	QC
Year installed	1986	1994	1996	2001	2001	2002	2006	2006	2006
MAAT @ installation	-5.5	-8.2	-10.5	-7.5	-7.5	-7.5	-6.7	-7.3	-3.5
Estimated MAGT	-1.1	-3.8	-6.1	-3.1	-3.1	-3.1	-2.3	-2.9	+0.9
Freezing Index at installation	3200	4380	4800	3950	3780	3730	3400	3550	2570
2006 MAAT	-3.5	-7.2	-9.7	-7.2	-7.2	-7.2			
2006 Estimated MAGT	0.9	-2.8	-5.3	-2.8	-2.8	-2.8			
Freezing Index	2570	4200	4290	4200	4200	4200			
Foundation Design	Slab on grade	Crawl space	Crawl space	Slab on grade	Crawl space	Slab on grade	Slab on grade	Slab on grade	Slab on grade
Insulation thickness ,mm	100	100	100	150	200	100	150	150	150
Foundation excavation					Jun/Jul	May	July/Aug	July	August
Thermosyphon charged					Aug-21	June	24-Aug	19-Oct	End Aug
Max thermistor depth, m					5.0	6.0	4.8	5.8	7.8
Ground temperature at installation					-3	-3	-1.5	-3.3	-0.15
Maximum ground temp after 1 year									
At evaporator pipes	-0.1				-1.0	-0.1	-2.0	-1.5	-0.6
Avg at ~ 5m	-2.5				-4.1	-4.3	-3.0	-6.1	-1.2
Maximum thermistor depth	7.8				5	6	4.8	5.9	7.6
Avg MAGT at max'm depth	-1.0				-4.1	-4.0	-3.0	-5.8	-0.4

Note: Summary information for Dawson City Recreation Centre and Ross River School not included.

7.2 Service Building, Kuujjuaq, QC

The service building was constructed with thermosyphon foundation on fine grained soils estimated to have had a MAGT of -1.1°C in 1986. The design consisted of evaporator pipes at 4m spacing supported on 400mm granular pad and covered with 100mm insulation as illustrated on Figure A1 in the Appendix. Ground temperatures have been recorded for 9 years with the last one being in 1995. Temperature profiles in Figure A1 show the ground temperature at 7.8m being about -1°C in 1995.

7.3 Visitor Centre, Inuvik, NT

7.3.1 Description

The visitor center in Inuvik is one of the first three flat loop TF foundations constructed in Canada in 1994. The visitor centre is a wood frame post and beam building that was constructed on grade beams on compacted gravel. A series of evaporator pipes were installed on top of the grade beams to maintain permafrost below the building. The building started to heave and settle in late 1990 that resulted in several investigations. This case history is based on the initial geotechnical report by HBT AGRA in 1992, several investigation and monitoring reports prepared by Northern Management & Development Ltd. between 1999 and 2001 and letter report prepared by Arctic Foundations (1999). The writer visited the building in September 7, 2007.

The geotechnical report indicated that the proposed building was located in an undisturbed wet area that was covered in the area of the proposed building with about 1m of wet sandy silty gravel that was underlain by 1 to 3m of peat and finally sandy gravel with ice rich clay zones.

The geotechnical consultant recommended that the building should be founded either on adfreeze piles or insulated concrete footings on permafrost. The building was to be elevated with an unobstructed 600mm air space. The peat was not to be disturbed and the area graded to drain off surface water. It appears that the building designers decided to found the building on flat loop FT but incorporating the footing and insulation design given in the geotechnical report. The basics of this design are given in Figure 25.

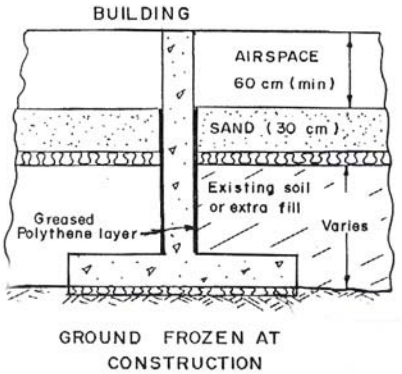


Figure 25. Geotechnical recommendations for Visitor Centre footing.

Arctic Foundation Inc. prepared a thermosyphon design based on the geotechnical information, climate and the building designer's specifications. The cross section of the foundation and layout of the evaporator pipes are shown on Figures A2 and A3 in the appendix. Figure A4 shows the concrete grade beam and the location of the evaporator pipes in a photo.

The key information in these figures is:

- A loop of evaporator pipes located at the edges of each grade beam; resulting in 4 loops connected to four radiators located at the north side of the building.
- Building supported on perimeter concrete wall and eight internal concrete columns supported on grade beams.
- 100mm thick insulation above the grade beams and evaporator pipes. Insulation extends about 1m beyond outside perimeter wall.
- Building foundation constructed on NFS granular pad with base of grade beam about 600mm above natural ground.

7.3.2 Performance

The building floor started to experience non-uniform movements that showed up as cracks in some walls and poorly fitting door frames and considerable settlement under central columns that required periodic shimming. The shimming between the stud-wall and joists at the columns is shown on photo in Figure 4.

Monitoring of the floor movements from summer of 1999 to end of 2000 showed non-uniform movements across the floor. Arctic Foundations Inc. assessment of the operation of the thermosyphon system showed the cooling system was in good order. Arctic Foundation also commented that they did not find any insulation over the interior pony wall. The final monitoring report prepared by Northern Management & Development Ltd. (Feb 1, 2001) summarized the findings as follows:

- Survey results are conflicting because of benchmark problem
- Points in dry areas show little movement.
- Points along perimeter wall near 'run-off' creek showed high movements.

The writer visited the Visitor Centre in September 2007 and observed the central wooden poles supporting the roofs had been shimmed several times at their tops to compensated for settlement, the central area of the building around the columns was depressed and ground surface in the crawl space around the concrete columns supporting the wooden poles was depressed.

7.3.3 Observations

It appears that there are two mechanisms causing movement problems at the Visitor Centre. These are:

a) At the perimeter wall, especially the east and north walls.

The alternating settlement and heave problems are likely due to a combination that the outer perimeter wall is not insulated and the heat conducted through the concrete wall to ground below the pony wall thaws the granular pad during the summer. The wet ground along east and north of the building provide a water supply to the thawed zone below the pony wall during the summer. The activation of the thermosyphons in late fall starts to freeze the ground below pony wall resulting in heave. During the subsequent summer the thawing of this frozen zone below the pony wall causes the pony wall and the above walls to settle. This freeze and thaw cycle likely provide the explanation for the up and down survey records.

b) Central column settlement

The settlement under the central columns was likely caused by the fact that the single loop thermosyphon was not able to freeze and provide sufficient cold storage to prevent the thaw of the ground below the pony wall(s) due to heat conductance through the exposed concrete columns. This may have been exasperated by the fact that the insulation was not found at the studs of the pony wall and furthermore, that the evaporator pipes did not cover the base of one set of central columns (Photo in Figure 4).

7.3.4 Conclusions

Two conclusions can be made from this case history:

1) It is important to insulate outside concrete walls and internal concrete columns so that heat is not conducted into the supporting frozen ground.
2) Water supply should be prevented from reaching the thermosyphon foundation.

7.4 Simon Allaituq School, Rankin Inlet, NU

7.4.1 Description

The Simon Allaituq School (Rankin School) was designed to be supported on thermosyphon foundation with a crawl space. The Rankin School is shown in photo in Figure 7 and a schematic of the thermosyphon foundation design is shown in Figure 8.

Rankin Inlet has colder climate than Inuvik or Iqaluit resulting in colder permafrost. However, this area was inundated by sea water in the past that resulted in the ground being saturated with ice or water with high ice content. This has depressed the freezing/thawing point due to the salinity of the ice/water in the pores and thereby making the susceptibility of the permafrost to melting similar to the other two settlements.

The flat loop ET with crawl space was designed and installed as shown in Figures 9 and 10. The evaporator loops were placed on top of concrete footings, covered with 300mm sand, 100mm rigid polystyrene insulation and this in turn was covered with about 100mm protection sand cover. The floor and walls are supported by large wooden studs and roof trusses are supported on steel section H columns. The crawl space was enclosed and kept above freezing during the winter. Services were hung from the floor joists above the crawl space.

The thermosyphon foundations were installed in 1996 and the school completed in 1997. The air and ground temperatures given in Table 3 are based on the linear trend of the MAAT measured at the Rankin Inlet climate station.

7.4.2 Performance

The thermosyphon foundation appeared to have performed well until about 2005. Around this time suddenly cracks started to appear in drywall and Nunavut Public Works requested Tim Mac Leod to assess the deformations at this building (MacLeod 2007). His observations were that the wall along grid wall heaved and then settled again over the year but that the column along gridline 7, supporting the rood truss, heaved but did not settle back to the original position. He looked for any significant change at the building that happened around this time. He deduced that the most obvious change that happened at this building was a trench excavation and the installation of residual heating lines coming from a recently installed power generation plant. This excavation, and its backfill, allowed surface water to flow into the crawl space that caused additional thaw of the frozen ground below the evaporator pipes. The installation of the heating pipes and the ponded water in the crawl space are shown on photos in Figures 11 and 12. A rod driven into the ground adjacent to the footing along gridline C8 showed the ground to be thawed to about 0.6m below the base of the footing. AFC observed that the insulation over the backfilled trench was poor installed.

Nunavut Public Works also requested Arctic Foundations to evaluate the performance of the thermosyphon system. They observed that one of the valves leaked. This valve was replaced and the loop recharged. Furthermore, the client consented to have a hybrid cooling system added to the passive thermosyphon system to speed up the refreezing to any excess thaw that might have occurred to the combination of additional heat input from the water ingress through the installation of the residual heating lines beneath the building.

7.4.3 Observations

This case history illustrates that any changes made to heat balance in the thermosyphon foundation may cause a failure to the foundation. In this case increased heat was likely produced by creating a drainage path for surface water to enter the granular pad, sand bedding and sand cover. This may have increased the thaw of the frozen ground and also provided an environment for frost jacking of the footings and walls. It is also likely that the residual heat pipes introduced additional heat to the foundation.

The leaking valve points out two things. Leaks may develop in the valves below the radiators. Therefore it is necessary to monitor the efficiency of the thermosyphon system to identify leaks. Once a leak is identified, the valve can be readily replaced and the system recharged with carbon dioxide fluid.

7.4.4 Conclusion

This case history points out three points:

1) Care must be taken if it is planned to introduce any new services into the crawl space of thermosyphon foundation. Two aspects have to be considered; changes should not allow surface water to penetrate into the crawl space and the services should not introduce additional heat.

2) Operation of the thermosyphon needs to be monitored on an annual basis. Over time the most likely leaks that may occur are at the recharge valve. These can be replaced and the thermosyphon system recharged.

7.5 Female Young Offender Facility, Inuvik, NT

7.5.1 Description

The geotechnical and foundation design and construction of the Female Young Offender Facility in Inuvik, NT, started in the summer of 2000 with a geotechnical investigation and foundation recommendations (EBA 2000). The site was covered with trees, shrubs and a hummocky peat surface and the ground sloped northward at about 15%. Ground at the two boreholes was observed to consist of 0.3 to 0.5m of granular fill (placed for drill access); followed by 0.1 to 0.2m peat and than a clayey till. The clayey till had high ice content in the upper 3 to 5m. Ground temperature measured on August 21, 2001 at 9.5m depth was -3.7°C.

Three foundation systems were considered; namely, ‘Greenland Foundation’, adfreeze piles and flat loop slab-on-grade thermosyphon foundation (thermosyphon foundation). Greenland Foundation was advised against because of potential creep in the ice rich soil. Both the thermosyphon foundation and adfreeze piles were recommended as suitable options. The project managers selected the thermosyphon foundation based on cost consideration. The building based on slab-on-grade foundation was to be heated by means of radiant heat provided by tubing installed within the slab. The heating is provided by pumping hot water through the tubing; with the room temperature controlled by room thermostat that controlled the flow of hot water.

The geotechnical engineer (EBA) recommended that earth construction should be done as early in 2001 as practical, thawed engineered fill was available and to set the grade sufficiently high to prevent excavation into the ground. Furthermore, it was recommended that the local clay till could be used for the general fill and that clean granular soils should be used for the structural fill.

Arctic Foundation of Canada Inc (AFC) was selected to design and construct the thermosyphon foundations. The south side of the FYOF, along with the thermosyphon radiators, is shown in a photo in Figure 26. Figure 27 shows the plan and layout of the radiant heating system at the FYOF and Figure 28 shows a section of the foundation with the evaporator pipes, insulation and stratigraphy.

Figure 26. Radiators on the south side of the FYOF, Inuvik, NT

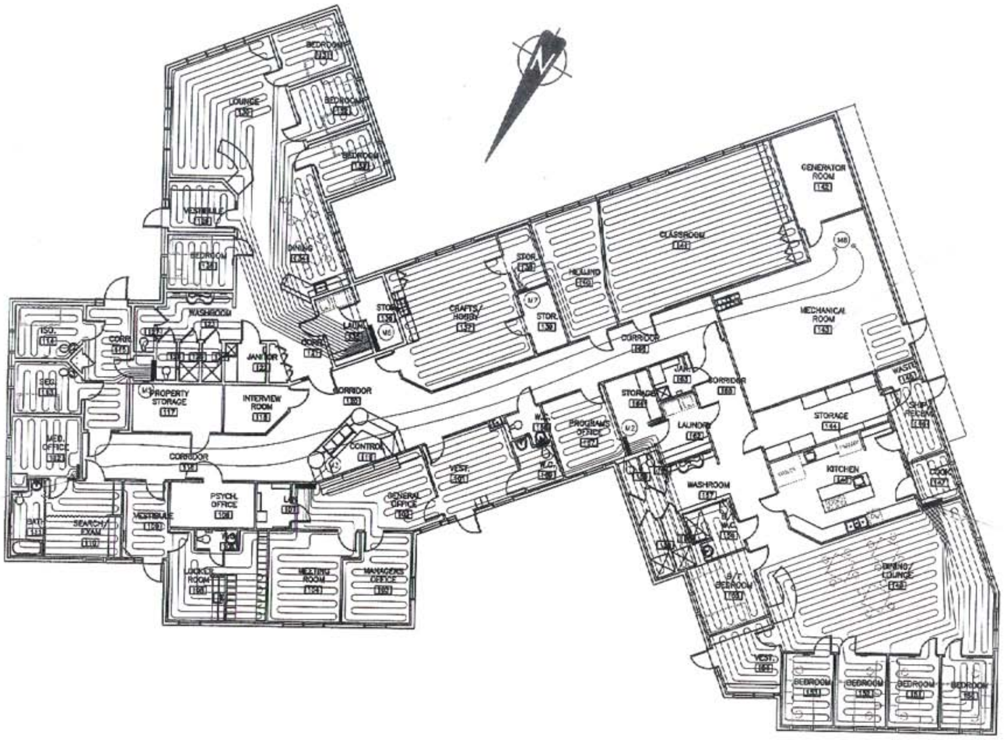


Figure 27. Room and radiant tubing layouts at the FYOF, Inuvik, NT

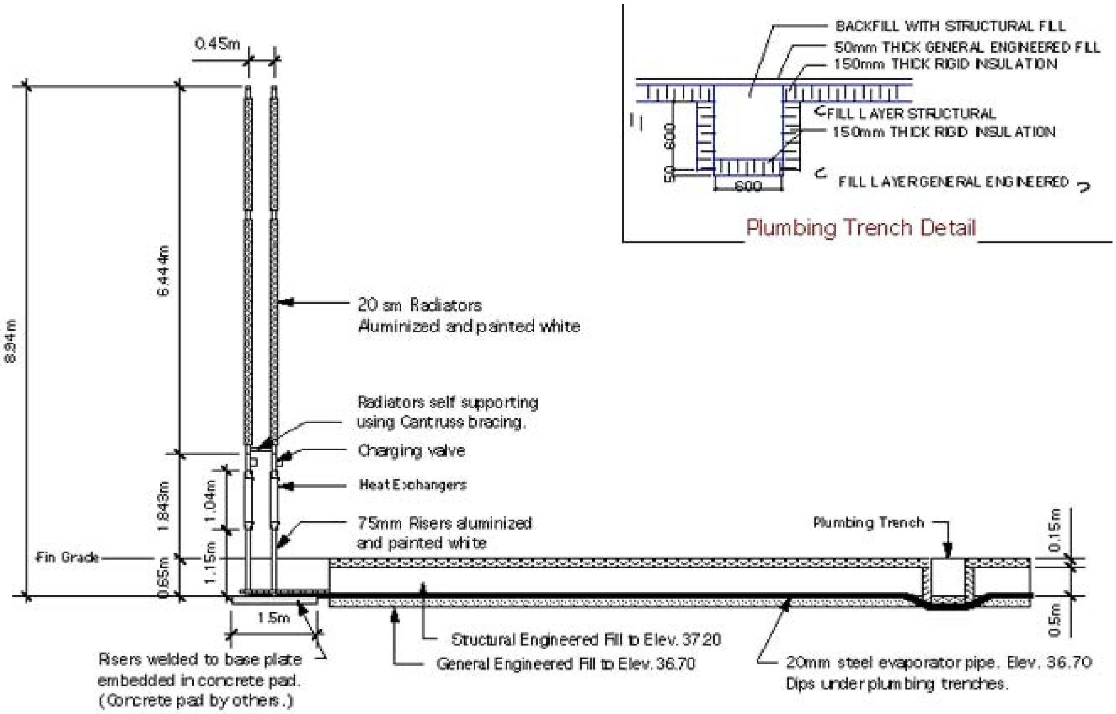


Figure 28. Section showing the evaporator pipe in respect to the slab-on-grade foundation, insulation and the services (plumbing) trench, FYOF, Inuvik, NT

The approximate dates for the conditions and construction at the FYOF that are relevant to the discussion of the performance of the thermosyphon are given in Table 6.

Table 6. Approximate dates for construction activities

Month	Day	Activity
June 2001	12	Peat thawed
	15	Access road constructed
	25	Engineered fill placed
July	14	Evaporation pipes installed
	17	Granular pad placed
	19	Trenches excavated & evaporator pipes damaged
	22	Pipes repaired
	30	Start placing insulation
August	10	Service pipes start being placed
	14	Thermosyphons charged
	24	Chillers start to operate
	24	Start placing concrete slab
October	2	Finished placing concrete slab
	4	Ground completely frozen at T4, southwest corner of building
September 2002	1	3 Radiators added to end of Loops 5 to 7
September 2003	6	2 Radiators added to end of Loops 4 & 8 Installed chillers for above 5 Loops
October 2003	23	Ground completely frozen at T3, west part of building

7.5.2 Performance

a) General

It is understood that there was urgency for completing the construction of the FYOF that resulted in a short time frame for the design review and construction period for this facility. The difficult site condition and the short time frame resulted in numerous factors in delaying the freezing up of the foundations under some sections of the building and thereby producing some of the uneven heave and settlement of the floor. This in turn resulted in wall cracking, door jamming and blockage of the sanitation piping. The likely causes of the performance, as understood by the writer, is described and briefly discussed under the main likely causes of the distress.

b) Foundation for the Flat-Loop TF

The geotechnical recommendations were to leave the peat layer in place and cover it with engineered fill. This resulted in the fill thickness to increase towards the north since the ground sloped down at about 15% towards the north. The ground cover before construction is illustrated in photo in Figure A13. Engineered fill consisting of clay till was started to be placed soon after mid June 2001. At this time the peat was completely thawed as determined by an auger hole on June 12, 2001.

Majority of the engineered fill was placed without engineered control. The poor quality of engineered fill at the excavation at the sump can be observed in a photo in Figure A14. It is likely that the clay till may have been placed at above optimum moisture content since the borrow area would have just recently thawed. It was noted that the engineered fill was placed at air temperatures above plus 10°C.

PWS schematic of the as-built foundation cross section illustrated in Figure A15 shows the as built fill geometry for a section running from the thermistor T3 at the east end of the building to thermistor T4 on the southwest of the building. The sloping and thick, likely wet, clay till at the northeast part had considerable influence for the significant settlement and heave of this part of the building and the slow freezing of the fill and ground. The following observations are relevant to the poor foundation at the FYOF:

1) Delayed start of the fill placement and not covering the fill with insulation until end of July resulted in placing a warm fill on permafrost and being left exposed to the sun and summer temperatures providing extra heat. This resulted in increased thaw into the natural ground. It should also be noted that since the peat was compressed by the weight of the fill, its insulating properties were greatly reduced.
2) The increased thaw depth resulted in the melting of the ice in the ice-rich till that had 30 to 50% ice content. Excess water from the thaw would dissipate slowly because of the low permeability of the till. This would have resulted in settlement over considerable time.
3) The sloping natural ground resulted in uneven depth of fill and thickness of thawed ground that had to be frozen. The east part of the building had about 3m of fill and the thaw into the original ground progressed by more than 1m, creating at least 4m of thawed clay till with a high water content. This would take a considerable amount of time to freeze. The north part of the building is underlain by less than a metre of clay fill and likely only about 2m of thawed ground.

c) Evaporator Pipes.

Normal design and construction practice for the flat loop TF is to have the evaporator pipes located on a horizontal plane and installed on a competent smooth granular bed. Furthermore, it is preferably to install any sanitation services within a granular zone above the insulation and underlying evaporator pipes. To minimize the volume of the material in the granular zone the engineer and Arctic Foundation of Canada Inc.(AFC) decided on a modification to the normal practice by allowing the bottom of the insulated service trench to extend into the engineered fill and route the evaporator pipes by means of a swale below the service trench as shown in AFC section in Figure 28.

After completing the engineered fill, the contractor and engineer requested that the evaporator pipes be located completely within a granular engineered pad and AFC consented when they came to the site to install the evaporator pipes at about mid July. This modification required installing the pipes with four right angle elbows at each trench. This resulted that many of the evaporator loops were directed across one and up to 7 trenches (before extra radiators were installed) with each trench having four right angle elbows. Evaporator pipes being routed past a trench are illustrated in a photo in Figure 29.

Figure 29. Evaporator pipe route across service trench, FYOF.

It would be expected that each right angle elbow would cause some friction loss in the fluid flow and there is an effect of vapour pockets on the flow of the fluid through the vertical pipe depression. This design and construction method resulted in difficulty in providing a good bedding beneath and around the pipes.

A layout of the evaporator pipes and trenches as illustrated in a photo in Figure A16 and a schematic layout in Figure A17. Figure A17 with the layout of the pipes and trenches shows that evaporator loops 4 to 11 crossed trenches. The outside loops 4 and 11 crossed the trenches 2 and 1 time respectively and the largest number of trench crossings, 7 in total, was experienced by loop 7.

Finally, the contractor construction plan consisted of completing the engineered fill, installing the evaporator pipes and then placing the granular fill. After the granular fill was placed, the contractor excavated the service trenches to install the services. This resulted in some of the evaporator pipes being damaged. AFC had to repair the damaged pipes, Subsequently the sanitation pipes were installed within insulated 'troughs' as illustrated in Figure 30.

Figure 30. Sanitation and water lines within a lined service trench, YFOF, Inuvik, NT.

d) Radiant Heating

The FYOF was heated by a radiant system that consists of tubing installed in the concrete slab. Hot water is pumped continuously through each loop and the flow of water within each loop is controlled by a thermostat in each room. The layout of the tubing is illustrated in Figure 27 and a photo of the tubing before being covered in the concrete slab and one group of loops leading to a control room is shown in a photo in Figure 31.

Figure 31. Radiant white tubing before concrete slab was poured. Tubes leading to a temperature control area. FYOF, Inuvik, NT.

In 2003 difficulties were reported with the radiant heating with some areas being cold and others too warm. Radiant heating was set at a warmer temperature to compensate for poor performance of the ventilation system. In a February 2007 a infrared study was made of the temperature at the floor surface. This showed uneven floor temperatures varying from 23 to 27°C. It has to be noted that these temperatures were measured at the concrete slab surface. It is likely that these temperatures were much greater at the bottom of the slab since the radiant tubes were close to the base of the slab.

e) Thermosyphon performance

The thermosyphons were charged on August 14, 2001 but did not start to cool at this time because air temperatures were not sufficiently cold. Chillers were installed below the radiators to speed up the cooling and freezing of the foundation soils. Settling of the floor slab at the eastern part of the building through 2002 indicated that the foundation soil had not completely frozen and three radiators were added at the east end of Loops 5, 6 and 7 in September 2002. Continued settlement in the eastern part of the building resulted in adding radiators at the east end of Loops 4 and 8 and installing chillers at the east end of Loops 4 to 8.

Two of the vertical thermistor cables, T1 and T2, were destroyed during the excavation of the trenches for the sanitation services. As a result only two vertical thermistor cables, T3 below the eastern part of the building and T4 below the southwest part of the building were left to monitor the freezing of the foundation soils. Their approximate locations are shown on Figure A16.

There are three areas of interest in the assessment of the performance of the flat loop ET thermosyphon foundations; namely, the east, northwest and south areas of the building. The east and northwest areas are illustrated with ground temperature recorded at thermister cables T3 and T4.

The east area experienced the greatest structural distress due to settlement and heave of the underlying ground. At T3 location the ground became completely frozen and stayed frozen from about end of October 2003. The movements should have stopped from that date onwards. Inspection in 2006 and 2007 showed some additional damage. It is not known if the damage after end of 2003 was due to a time lag of the deformation or excess local heat produced by the radiant heating system that was not represented by the T3.

The settlement and heave in the east area was likely caused by a combination of three mechanisms; a) warm thick fill placed during the warmest part of the summer; b) inefficient evaporator pipes caused by the numerous vertical bends in the layout, and c) radiant heating system. The thick fill placed in the summer resulted in increased thaw depth into the ice rich till. The melting of the ice resulted in appreciable settlement, and the excess water provided delayed the rate of freeze back and a water supply of water for heave. It is noted that the sanitation pipe was found to slope towards the east which corresponds with increase fill thickness and therefore thaw settlement.

The northwest area had the reverse conditions with respect to the east area and the area as given by T4 measurement became completely frozen on October 4, 2001. This area has the smallest till cover that would warm the natural ice rich soil and the total depth of engineered fill and thawed natural ground to refreeze. At the location of the T4 thermistor cable there was a concentration of evaporator pipes that would extract heat more rapidly and finally, it appears that the T4 was located just beyond the radiant heat piping.

A more representative area of the building with flat loop ET thermosyphon foundation is the south wing area. While there is ground temperature data for this area, the fact that no damage has been reported in this area appears that the thermosyphon foundation is functioning well. This could be attributed to two conditions; the thickness of the engineered fill is small in this area and the evaporator loops effectiveness has not been compromised by vertical bends in the pipe.

f) Outside perimeter fill distress

It is necessary to consider the effect of changing the environment around the site when designing foundations of buildings in near discontinuous permafrost with ice rich soils as is the case at Inuvik where the ground temperatures are in the vicinity of -2.5°C. At this location the tree and peat cover provide considerable insulation to the underlying ground and their removal, or compression, will increase the annual thaw depth considerably. This is illustrated by Figure 32 from a classic paper by Linell (1973).

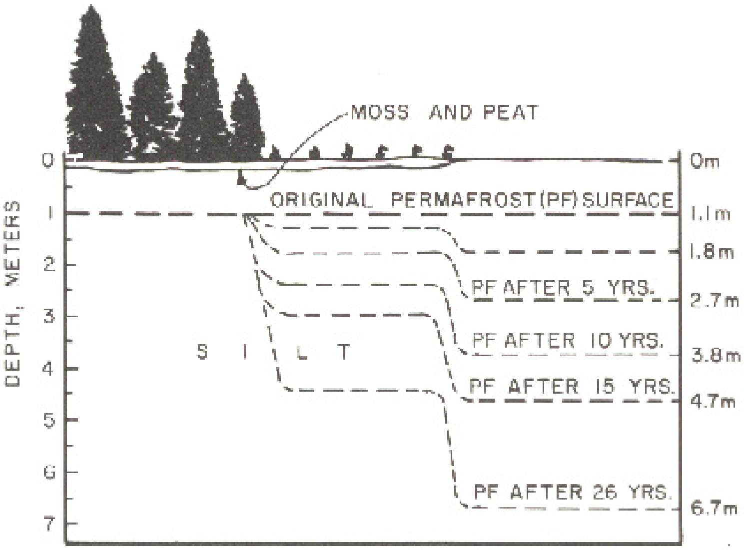


Figure 32. Removal of tree and peat cover resulting in thawing of ground in discontinuous permafrost.

The removal of trees and compression of the peat by fill around the FYOF building has deepened the annual thaw of the ice rich till that resulted in considerable fill settlement and damage to services as illustrated in Figures A20 & A21. The thaw depth around the FYOF building will not be as deep as illustrated in Figure 32, but it has been sufficiently deep to have caused the damage.

Settlement and movement at the southwest wall is demonstrated by the electrical box having been ripped off the wall and its movement down in Figure A20. While initial movement was due to the thaw of the natural ice rich till, movements have likely continued at this location because of surface water availability. This would provide water for frost heave during the fall and the thaw of the ice lenses would produce thaw settlement the following summer.

The settlement and outward movement of the fill at the fence and cracking of the concrete slab is the result of both initial natural and continued ground thaw. This location has a heightened exposure to thaw because the fill is on a slope, is dark in colour and faces south.

7.5.3 Observation

The Inuvik FYOF project represents a multiple design and construction inadequacies that lead to the settlement of various parts of the building, cracking of the floors and walls and blocking of the sanitation pipe by developing a negative slope. The poor performance of the building was due to:

1) Placing thick fill during warmest part of summer. The thick warm fill provided a heat source that took a long-time to freeze.
2) Placing the fill on an ice rich till where ground surface was sloping resulted in uneven depth of thaw into the ice rich soil and uneven settlement.
3) Changing the evaporator pipe configuration first from the original horizontal configuration to slight sloping configuration at the service pipe crossings and then finally accepting near right angle vertical channel configuration. The final changes made during construction resulted in poor cooling performance of the flat loop thermosyphon system. Friction loss and unknown behaviour of the vapour pockets moving through the vertical channel shaped pipe configuration led to considerable efficiency losses.
4) The radiant heating system where tubes with hot water are located near the base of the concrete slab resulted in much greater heat in-put into the underlying evaporator system then realized by the thermosyphon designers.
5) Compression of the peat by the fill resulted in deeper thaw penetration into the ice rich soil around perimeter of the building. The thickest fill placed during the warmest part of year on the north of the building provided a considerable heat source that caused deep thaw of the existing underlying ice rich till and thereby considerable fill settlement. Fill on the south and southwest was thinner, but it obtained extra heating at its slopes due to the southern sun exposure of the sloping surfaces.

7.5.4 Conclusion

The failure of the flat loop FT thermosyphon foundation was caused by a combination of weakness in the design and construction of the facility. This case history demonstrates that the design and construction of thermosyphon in permafrost with ice rich soil is complex and numerous aspects have to be considered.

7.6 Inuvik Hospital

7.6.1 General

It was decided to construct a Regional Health & Social Services Center (hospital) in the eastern part of Inuvik, NT. The site was located east of an existing hospital that consisted of silty sand and gravel fill and natural ground with peat cover. The constructed hospital is shown in Figure 33.

Figure 33. Inuvik hospital, NT.

The native soil stratigraphy consisted of sandy silt with ice lenses. It was decided to excavate to a level to remove the heterogeneous fill and peat and locate the granular pad on the natural ground. The hospital was to be founded on shallow spread footings resting on a thermosyphon granular pad. A crawl space would be provided between the thermosyphon pad and the base of the floor so that services could be hung from the floor beams. The floor of the building was to be level with the surrounding ground level to provide easy access. This resulted in the crawl space being designed below the surrounding ground. The foundation design is illustrated on Figure 34.

The base for the foundations was 1 to 2m into the existing ground to be located on uniform ground conditions. The base of the excavation was covered with compacted structural granular fill, the evaporator piles installed and covered with additional granular fill (Based on design drawings). The structural fill was covered with 50mm leveling sand before 200mm of rigid insulation was placed. The insulation was covered with a liner that in turn was covered with cement board to provide physical protection to the liner. Spread footings were poured on the liner as shown in Figure 34. The space between the insulated wall and natural ground was backfilled with free draining general fill.

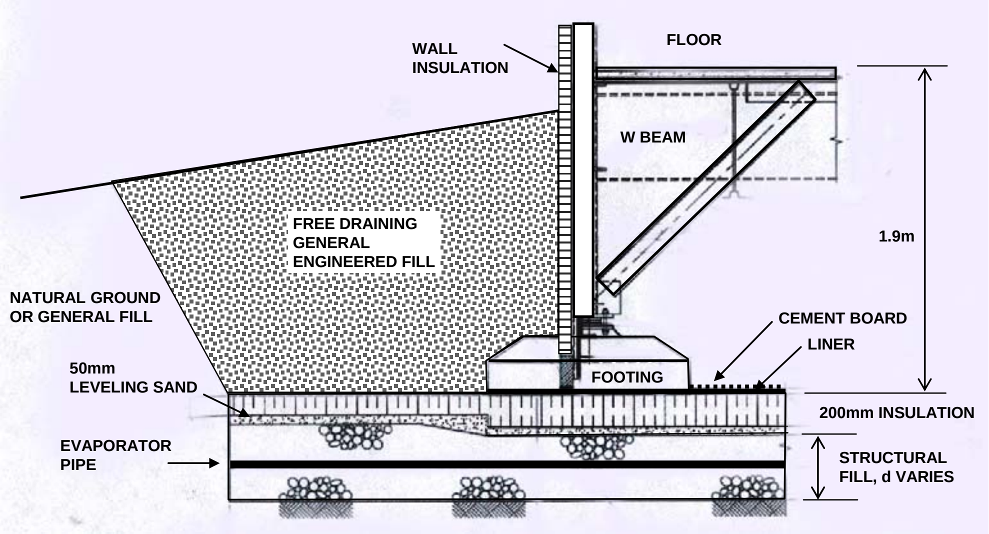


Figure 34. Foundation design at building perimeter for hospital, Inuvik, NT

The Inuvik hospital has a large and complex footprint with a total area of about 6,340m^2. For the installation of the thermosyphon cooling, the hospital was divided into 4 areas with an additional area being the adjacent Satellite Physical Plant. A total of 64 evaporator loops along with their radiators were installed. The geometry of the evaporator pipes and radiators is shown on Figure A22. The construction of thermosyphon foundation along with the footings, steel framing for the crawl space and the radiators with chillers for hybrid cooling are shown in a photo in Figure A23.

7.6.2 Performance

The excavation and the subsequent placing of the granular pad for the evaporator pipes were substantially completed end of July 2001. Installation of evaporator pipes and covering of them with granular layer and insulation was completed on July 19, 2001 in the south part of the Hospital in Area 3 where a vertical thermister cable V-3 was installed. On August 21, 2001 the hybrid cooling system was switched on and switched off on November 15, 2001. These activities are summarized in Table 7. Ground temperature changes measured from 0.5m to 5m below the evaporator pipes during this period are shown in Figure A24.

The impact of the construction schedule and operation of the hybrid cooling are summarized as follows:

- Scheduling the excavation and granular pad placement at the start of the thaw of the ground and covering it with insulation by July 19, 2001 resulted in considerable cooling of the ground. The thaw advance was stopped and the ground 0.5m below the evaporator pipes cooled from 8°C to about 0.5°C by August 21 when the hybrid cooling was started.
- It took the hybrid cooling about 1½ months to completely freeze the ground because of the latent heat of the pore water in the thawed part of the ground. The ground was completely frozen by about mid November.

Table 7. Construction and operation of hybrid thermosyphon system, Inuvik Hospital, NT

Month	Day	Activity
May	Mid	Start excavation
June	End	Place and complete granular pad for evaporator pipes
July	Early	Install evaporator pipes
	21	Pipes covered with granular and insulation in Area 3
August	21	Hybrid cooling started
	26	Ground cooled to 0°C
October	Mid	All of ground below 0°C
November	15	Hybrid system turned off

The ground temperature started to be monitored at three vertical thermistor cables in September 2002 and have been recorded to this date. The ground temperatures and temperatures at the evaporator pipes and radiators are recorded by a data recorder that is down loaded periodically. The fluctuation of the ground temperatures from a depth of 0.15m to 4.15m below the evaporator pipes are shown in Figure A25. The graphs in this figure show that the ground below the evaporator pipes experiences great fluctuations of ground temperature and the magnitude of the fluctuations decreases with depth. A simpler picture of of the ground temperatures beneath the evaporator pipes can be obtained by considering the yearly maximum and minimum ground temperatures that are shown in Figures A26 and A27 respectively. These plots show the following:

- Maximum and minimum ground temperatures have reached steady values after two years of thermosyphon operation.
- Maximum ground temperatures near the evaporator pipes show that the ground is remaining frozen throughout the year with an average ground temperature being about -1°C 0.15m below the evaporator pipe.
- The warmest and coldest ground temperatures 4.15m after two years operation are about -3°C and -7°C respectively.
- It is estimated that the mean annual ground temperature below the thermosyphon foundation is at least about 1°C colder than what is observed in the natural ground.

However, two deficiencies were found in the Flat Loop thermosyphon foundation design: a) fluid leakage in some of the evaporator pipe loops and b) surface water penetration into the floor of the crawl space.

a) Thermosyphon fluid leakage

Poor performance by some of the evaporator pipes was observed in 2004. Detailed evaluation of the thermosyphon system, and excluding likely more problems of leakage at the valves, determined that the leak was the result of manufacturing and inspection at the mill. The installed pipes are ASTM A53B pipes that are produced by rolling flat sheets into a pipe shape and then welding the seams. The leak was observed to occur at some of the poorly welded seams of some pipes. The evaporator pipes and all the field welds were inspected by pressurizing the pipes with a helium pressure to 100 psi and passing a mass spectrometer Helitest unit of the completed pipes. This testing unit can detect very minute leaks and is used by the space industry for checking leakage.

Subsequent evaluation showed that 17 thermosyphon loops experienced leakage varying from very high to high, where the affected loops would have to be recharged annually to low to very low, where the units would have to be recharged every two to three years.

b) Ice mounds forming at the base of the crawl space.

Ice mounds started to be observed several years after start of operation. During the September 7, 2007 inspection of the crawl space more than a dozen mounds were observed. One of the larger mounds is shown in Figure 35.

Figure 35. Ice mound developed at crawl space floor, Inuvik Hospital, NT

These ice mounds developed because the summer surface and ground water was able to seep through the Free Draining General Engineered Fill shown in Figure 34 and penetrated through the insulation joints into the interior where it flowed just beneath the liner into the overall crawl space. Free water was attracted to local areas to grow mounds when the thermosyphon started to freeze again in the fall. Water supply was available due to the following reasons:

- Site visit to the Hospital on September 7 showed that there was hardly any slope or none at all from the wall to drain surface water.
- Design as shown in Figure 34 will not prevent surface and ground water to penetrate the crawl space. The fill should have either have been low permeability

soil or have a 0.60m compacted clay cover that is underlain by the Free Draining General Engineered Fill with a perimeter perforated drain pipe that is heat traced.

7.6.3 Observations

The thermosyphon foundation benefits have been marred by two factors.

1) The mill having shipped a defective pipe to the site. The local imperfections were not evident during pressure with helium and helium detection equipment. It is likely that these leaks developed after the pipe started to be subjected to cold temperature and became stressed due to contraction.

   The evaporator pipe was a seam welded pipe. Since this incidence AFC has started to use seamless pipe with higher quality specifications. The elimination of a welded seam lessens the potential of receiving a problem pipe.

2) Design and construction of a building with a crawl space that is depressed from the surrounding ground has a potential of having surface and ground water seeping into the crawl space.

7.6.4 Recommendations

1) Designer, installer, and the QC staff should ensure that seamless pipes with proper specifications are installed in all thermosyphon installations.
2) The geotechnical and civil engineers who develop the foundation drawings should prepare construction drawings and specifications that prevents surface and ground water penetrating the thermosyphon foundations. Also a functioning perimeter drainage and sump should be provided should water pass through the seepage controls.

7.7 Aurora College, Inuvik

7.7.1 General

The Aurora College flat loop TF foundation design and construction is an example of very high quality. The site is located on higher ground with a slight slope towards the south. The initial ground conditions were very poor with a surface layer of granular fill underlain by more than 2m of peat followed by ice rich silty gravelly sand. The design called for the removal of all peat, excavating into the underlying ice rich silty gravelly sand and replacing it with good quality granular material that was compacted in lifts. A schematic section of the thermosyphon foundation is shown in Figure A28.

The thermosyphon foundation was constructed on a well compacted 1.5m thick granular base. The evaporator pipes were installed within a minus 200mm bedding material and covered with 100mm of rigid insulation. The footings were located within a compacted granular zone that was about 1.6m thick. This zone provided ample depth to incorporate water and sanitation piping that was insulated and heat traced. The ground floor was more than 1m above the surrounding ground surface that the backfill around the perimeter sloped away from the building. The constructed building with the surface grading from the building is illustrated in Figure 36.

Figure 36. Aurora College, Inuvik, NT. Note: Good grade away from building.

The excavation for the foundation started about the first of May in 2002. The base of the excavation was reached on about May the 9th.. The 1.5m of granular fill consisting of minus 200mm was completed on May 24, 2002. After placing a bedding layer, 13 loops of evaporator loops were installed. Four vertical thermistors to a depth of 6m were installed within the footprint of the building. Within the perimeter foundation the individual evaporator pipes were spaced at 0.81m and connected to 15 radiators on the north west corner of the building. Following this the pipes were covered with additional 200mm bedding, 100mm rigid insulation and finally by 300mm minus 20mm granular. This work was completed on June 12, 2002. Hereafter, the prepared thermosyphon foundation was left in place through the 2002/2003 winter before completing the remaining granular base, installing the services and pouring the slab during the summer of 2003.

7.7.2 Performance

Early placement of the fill, installing the thermosyphon system and covering with insulation and granular protective cover prevented the warmest summer temperatures from warming the ground below the installation. During construction it was observed that the thaw advanced about 200mm into the base of the excavation and the thaw advanced through the summer to about 1m below the excavation or 3.6m below the evaporator pipes as shown in Figure A29. The granular foundation below the pipes cooled through the summer and the upper 1.7m froze by October 20, 2002 (see Figure A29). The whole fill below the pipes and the thawed ground in the excavation was frozen by early December 2002. Ground temperature changes below the pipes from one vertical thermister cable T6 are shown in Figure A30. Figure 30A illustrates that there is fluctuation of ground temperatures below the pipes and the amplitude of the fluctuation decreased with increase of depth below the pipes. It shows that the ground temperature at the pipes decreased from about +8°C in July 2002 to

-17°C in early April 2003, then increased to near 0°C July to mid October 2003 and then dropped again to about -17°C. Six metres below the pipes, about 3.4m into the natural ground, it reached a maximum temperature of about -1.5°C. This temperature was the result of the construction and cooled to about -4 in June 2003 and than subsequently warmed to about -2.5°C in December 2003.

Ground temperature monitoring was suspended in April 2004 with the exception of readings taken again on October 1, 2007. Ground temperatures were also taken at a vertical thermistor cable installed outside of the building site that provides reference ground temperatures from an undisturbed ground. The changes of ground temperatures from July 2002 to July 2003 are provided in ground temperature profiles in Figure A31.

The following observations are made from the ground temperature data:

- Ground temperature at 5.5m depth, deepest thermistor sensor, in the undisturbed ground showed an average ground temperature to be -2.4°C. It varied from -1.7°C to -3.8°C.
- Three vertical thermistor cables installed to 6m showed the same ground temperatures.
- The average ground temperatures at 6m cooled from -2.2°C (June 2002 to June 2003) and to -4.0°C (May 2003 to May 2004).
- The ground temperature at 6m appears to have remained steady thereafter as indicated by one set of readings taken in October 2007.
- Average ground temperature at 5.5m was -4.2°C. This is about 1.8°C colder than observed in the natural ground.
- Coldest ground temperature at 5.5m was -7.7°C and the warmest -2.3°C.

7.7.3 Observations

The Aurora College flat loop slab-on-grade thermosyphon foundation installation provides a good example of design and construction for this type of foundation. The presence of thick peat at the site required deep excavation of the existing ground and replacing this material with an appreciable thick granular pad (about 2.6m). This thickness was needed to compensate for the excavated peat and to ensure that the Aurora College floor would be above the surrounding grade. But this great thickness provides extra stability of the foundation should any problems develop with the thermosyphon foundation at or beyond the design life.

The designers of the building provided sufficient thickness of granular material between the thermosyphon insulation and the floor slab to install water and sanitation services below the slab and located the building floor sufficiently high above the surrounding ground to allow good surface water runoff.

The thermosyphons have kept the foundations frozen right up to the bottom of the evaporator pipes with the average ground temperatures 5.5m below the pipes being about -4.2°C. This is 1.8°C colder than the mean annual ground temperature in adjacent ground. The foundations ground temperatures will not respond to climate warming as much as the undisturbed ground because the thermal regime below the thermistor foundations is greatly influenced by the all year round building air temperature.

7.7.4 Conclusion

The Aurora College provides an excellent case history on how to design and construct a high quality flat loop thermosyphon slab-on-grade foundation.

7.8 Three Recent Projects

7.8.1 General

Three buildings with flat loop ET foundations were constructed in 2006 at three different sites. These buildings have a similar thermosyphon foundation design but the differences of construction schedules and location provide interesting case histories in regard to design and performance. The ground temperatures at these three sites were monitored from the time the thermosyphons were installed to the present. The three case histories are: RCMP building in Iqaluit, NU; Health Centre, Pangnirtung, NU and Air Terminal, Kuujjuuaq, QC. Basic information on these case histories are given in Table 5.

7.8.2 RCMP Building

The RCMP Division HQ in Iqaluit, NU was designed with a traditional flat loop thermosyphon foundation. The site was excavated in June 2006, the evaporator pipes were installed, charged, covered with 150mm rigid insulation and a protective granular layer and allowed to cool over the following winter.

The natural ground at Iqaluit consists of silty sands with variable ice content. The mean annual air and ground temperatures at Iqaluit for 2006 were about -7.3 and -2.9°C. The thermosyphon foundation design consists of local excavation to develop an uniform natural ground base and backfilling with compacted engineered fill to thermosyphon foundation base shown in Figure A32. The thermosyphon foundation consisted of 150mm leveling course, 20mm evaporator pipes spaced between 1.4 to 1.6m covered by a 300mm granular bedding layer. The bedding layer was covered with 150mm rigid polystyrene insulation that was covered in turn with a 300mm granular protective layer.

The thermosyphon foundation design was based on a schedule where the thermosyphon foundation was constructed during the summer, the ground below the evaporator pipes was allowed to freeze and develop cold permafrost conditions during the winter and the building constructed the following year.

The construction schedule at the RCMP Building was: excavation and construction of the thermosyphon foundation in June 2006; the evaporator piping completed in early July; the thermosyphons charged in July 19, 2006. The surface granular base and building slab started in the summer of 2007. The foundation completed in the fall of 2006 is shown in Figure 37.

Figure 37. Foundation completed in fall of 2006, RCMP building, Iqaluit, NU

The ground temperature changes below the evaporator pipes. Zero depth being at the evaporator pipes, are shown on Figure 29A. It should be noted that the vertical thermistor cables did not start to be read until October 19, 2006; the time thermosyphons started to cool the ground below the evaporator pipes. Figure A33 in the Appendix shows the following:

- Ground below the evaporator pipes was already relatively cool; the thaw depth at this date was less than 1.5m and ground within the 1.5m depth was at about 0°C in October 19. This means that the moisture within this depth was changing to ice.
- The ground was completely frozen by the end of October.
- Cooling of the ground progressed rapidly with the upper 3m of the ground below the pipes reaching the coldest ground temperatures around March 2007.
- After March the upper ground started to warm, as air temperatures started to be warmer, but the ground at 6m depth continued to cool because of a time lag in ground response that increases with depth.
- On October 8, 2007, the surface started to cool and ground at about 6m being at about -5°C was still likely warming. Further warming would be small because of small ground temperature fluctuation amplitude at this depth.

This case history demonstrates the benefits of early excavation of the ground, and placing the granular fill early in the year before the warmest period of the year that occurs in July and extends to August. It can be concluded that by covering installed evaporator pipes by end of July resulted in:

- Not exposing the base of the excavation to warmest air temperatures.
- Placing granular fill in June minimized the fill from warming during July and then applying the heat to the completed foundation.

- Early completion of the foundation and covering it with insulation caused the deep underlying cold ground to cool the upper ground.

7.8.3 Pangnirtung Health Centre, NU

The Pangnirtung Health Centre flat loop ET thermosyphon foundation design was similar to the RCMP building. It consisted of covering evaporator pipes with 150mm rigid insulation followed with a granular protective layer and leaving the installation for the winter before placing of the construction of the building. The insitu ground on which the thermosyphon foundation was constructed was similar to the ground at the RCMP site in Iqaluit; frozen silty sands.

Two differences in the ground conditions at this site to RCMP building site were that the site was previously a water supply pond that was backfilled with sandy fill and the immediate area was on a fluvial/colluvial sloping ground with considerable surface and ground water flow during the summer. This led to provision of surface and groundwater flow measures on the uphill side of the site. The general section and excavation of the foundation is shown on Figure A34 and the two measures to control the groundwater flow during the summer are shown in Figure A31. Figure A35 shows that a perimeter drain was provided on the uphill side of the building to intercept groundwater and an additional drain was designed below the slab and above the insulation inside of the building perimeter. The thermosyphon foundation consists of 14 evaporator loops with the evaporator pipes being spaced from 1.3 to 1.9m.

The construction schedule was altered because the thermosyphon foundation was not completed the year earlier before the building material arrived at the site and the contractor was mobilized to start construction. The excavation of fill from the infilling of the previous pond and preparation of the granular pad for the evaporator pipes was done in July and first week in August 2006. The evaporator pipes were installed the 2nd week of August, tested and charged mid August 2006.

The desire to not delay construction until the following year, it was decided to allow the construction of the footings for the building to proceed just after the insulation was placed, but have the contractor wait before erecting the building super structure until the ground was completely frozen. The site conditions during placing of the insulation and preparation of the forms for the footings is shown in Figure 39. The pouring of concrete footings started about the first of November.

The progress of the cooling and freezing of the foundation is shown by the ground temperature profiles in Figure A36. These show the following:

- Ground temperature at the evaporator pipes on August 24, 2006 was about -1ºC and the ground was thawed to a depth of 3.2m.
- The thawed ground started to cool from the time the insulation was placed and it reached about 3ºC on September 28.
- The air temperatures remained consistently above the freezing point until about the end of October.
- The thawed ground starting to freeze, as indicated by zero degree Celsius, around November 10 and became completely frozen as indicated by the ground

temperature in all the previously thawed zones started to cool beyond the 0ºC temperature on about December 15, 2006.

- The overall coldest ground temperature profile over the 5m depth was reached in February 2007 but the ground at about 5m did not reach the coldest temperature until about mid June 2007.

Figure 38. Covering of the evaporator pipes with insulation and preparing form work for footings, Pangnirtung Health Centre, NU.

Erection of the superstructure was permissible after November 10, 2006. Elevation measurements of the tops of the completed footings after they were poured on November 10, 2006 showed that the tops of the footing rose uniformly due to the conversion of water to ice within the thawed layer by an average of 10mm.

The interior of the enclosed building started to be heated in mid January 2007 and the heating continued until the summer. Until the end of summer the insulation located just under the floor slab had not been installed and floor slab had not been poured. In spite of the lack of this additional surface insulation protection, the ground temperatures in October were -1ºC at the evaporator pipes and -3ºC at 5m depth. It is assumed that the ground temperatures below the thermosyphon foundations will be colder the following year after the additional insulation and floor slab are installed later in 2007.

Comparing this case history to the Iqaluit installation that had similar ground conditions and air temperatures illustrates the following:

- Excavating the ground and construction of the granular pad and evaporator pipes along with the insulation delayed the complete freezing of the foundation until nearly the end of December. This is about 1 ½ months later than at Iqaluit.
- The freezing of the 3m of thawed ground resulted in minor and uniform heave of about 10mm.

7.8.4 Kuujjuaq Air Terminal

Kuujjuaq Air Terminal varies from the earlier two case histories by the following: a) it was constructed in warmer climate, b) ground consisted of finer grained soils and c) the foundation design. The terminal under construction is shown in Figure 39.

Figure 39. Kuujjuaq Air Terminal under construction, QC.

Climate as given by 2006 data shows the mean annual air temperature to have been -3.5ºC with a freezing index of 2570 degree days. This is considerably warmer than the mean annual air temperature from previous case histories at Inuvik and Iqaluit that had MAAT of -7.2 and -7.3ºC in 2006 and Freezing Indices of 4200 and 3650 degree days in 2006. The MAAT at the Air Terminal means that the ground temperature was at or above 0ºC when construction started.

The ground at the Air Terminal consists of a clay till that would have higher water content and therefore greater latent heat than the silty sand soils at Inuvik and Iqaluit. The clay till with greater latent heat would take longer to pass through the 0 degree point, when the water changes to ice.

Finally, at the Air Terminal raceways for services are located above the thermosyphon foundation insulation and below the floor (Figure A37). The raceways provide ready access to the services for repair and changes. The services at the other case histories with slab-on-grade foundation designs were located within the gravel zone above the insulation. The thermosyphon cooling consists of 20 loops of evaporator pipes with individual pipes spaced at about 1.2m.

Ground temperature profiles in Figure A38 indicate that it took a while for the ground to freeze at Kuujjuaq because of the smaller freezing index, the ground being likely above zero degrees and therefore thawed and or in the process of thawing. However, eventually the ground froze to a depth of about 7m in March 2007. Thereafter the ground kept cooling to reach -0.4ºC at about 8m depth. From an earlier Sloped thermosyphon foundation installation at the airport it appears that the ground temperature may stabilize around -2°C at a depth between 2 and 5m below the evaporator pipes as illustrated on Figure A39.

7.8.5 Observations

The three preceding case histories illustrate different ground freezing performance as a result of either design, construction schedule or climate. They all have flat loop thermosyphons that support the building by means of slab-on-grade design. In all cases the evaporator pipes are covered by 150mm rigid insulation. The three have been constructed in 2006.

The ground temperatures at Iqaluit and Pangnirtung in Nunavut were between -2 and -3°C, that is in similar range as in Inuvik, Northwest Territories, where a number of buildings with thermosyphon foundations were constructed. The site condition at Kuujjuaq, QC is quite different from the other two in Nunavut and the projects in Inuvik. The ground temperature in 2006 was above zero, had warmer climate and the ground had larger water content that required longer to freeze. The thermosyphon foundation froze to the underlying ground. However, the time it took to freeze was a function of the type of ground, local climate and construction schedule. These three parameters need to be considered in the design of the thermosyphon cooling system and construction scheduling.

The construction of the thermosyphon foundation at Iqaluit took place in early summer that in turn preserved the cold regime of the ground. As a result it started to cool earlier and the ground below the thermosyphon was completely frozen by mid October 2006. Leaving the installation exposed to the climate for the first winter added considerably to the cooling of the ground beneath the thermosyphon foundation. (If construction of the building had started in mid October, closed by Christmas and the interior heated in the New Year, the ground would still have been frozen but not at as cold temperature as having the thermosyphon foundation with an insulation cover exposed to the climate through one winter.) At this project the ground temperature below the evaporator pipes varied from about -3°C at the pipes to -5°C at 6m depth in October 2007.

Pangnirtung has similar climate and ground conditions as Iqaluit. The difference between these two case histories is that at the Pangnirtung project; a) thermosyphons were not constructed a year earlier and allowed to develop a good frozen base and b) the site is located on a long slope with considerable surface and ground water flow towards the building. Ditches and rerouting of a stream were constructed to handle the surface water flow and ground water control was incorporated by means of a granular French drain on the upslope of the building and internal drain adjacent to the footing as shown on Figure A39. It was decided to manage the construction schedule in order to construct the building between fall of 2006 and winter and spring of 2007 since the contractor was on site and the building materials were being brought by sea in September 2006. The thermosyphon foundations were completed mid August 2006. It was decided to allow the pouring of the footings in September 2006 but wait for erecting the superstructure until the foundation was completely frozen. This occurred in early December 2006. Monitoring of the top of the footing elevation showed that footings heaved uniformly less than 10mm due to expansion of the soil pores when water changed to ice.

The foundation below the evaporator pipes froze completely by mid December 2006. On October 11, 2007, the ground temperatures at the evaporator pipes was about -2°C and at 5m depth -4°C. In spite of the late start of excavation and installation of the thermosyphon foundation and starting to heat the interior of the building in mid January 2007, the foundation was only about 1°C warmer than the foundation at Iqaluit.

It is interesting to compare the Kuujjuaq air terminal installation with the other two previous ones because of the different design for the services and warmer ground and climate. At Kuujjuaq concrete raceways (corridors) were provided for the services to provide easy access for modifications as needed. The ground at Kuujjuaq was not frozen but had a mean annual ground temperature around 1°C. In spite of much warmer mean annual air temperature, and also freezing index, the ground froze to about -0.4°C over the first year. Based on previous slope thermosyphon foundations installed at Kuujjuaq it is estimated that the final ground temperatures at the air terminal will stabilize between -1 and -2°C.

7.8.6 Conclusions

The above three case histories illustrate different foundation designs and construction schedules and the resulting foundation temperature performance.

7.9 Yukon Installations

7.9.1 General

Yukon’s three thermosyphon foundation installation are of interest because of the warm air and ground temperatures at the two sites, namely, Dawson and Ross River (Figure 40).

Figure 40. Thermosyphon foundation locations in Yukon

The relevance of the projects at Dawson City and Ross River to the other case histories given before is illustrated by the mean annual air temperatures and freezing indices estimated for 2006 by means of trend analysis.

Table 8. Mean annual air temperatures and freezing indices at studied locations

Location	**Mean annual air temperature, Deg C**	**Freezing Index Deg C days**
Inuvik, NT	-7.2	4200
Iqaluit, NT	-7.3	3550
Pangnirtung, NT	-6.7	3400
Kuujjuaq, QC	-3.5	2600
Dawson City, YK	-3.5	3000
Ross River, YK	-2.0	2500

The mean annual air temperatures at Kuujjuaq, Dawson City and Ross River indicate that the sites at these locations have very fragile permafrost conditions that are practically at a level of thawing; especially Ross River. Observations obtained from Ross River are especially telling for Inuvik, Iqaluit and Pangnirtung since the climate at these locations will likely not warm to the Ross River climate in a normal 50 year life span of a new structure.

7.9.2 Dawson City, YK

A new Recreation Centre was constructed in the north portion of town that is located over a alluvial floodplain underlain by intermittent silt and peat overlying coarse-grained alluvium. It lies within a discontinuous permafrost with ground temperatures being 0 to -1°C. Ground temperature measurements measured in 2002 showed the mean annual ground temperature about 3.5m below the ground surface being about -0.3°C. Dawson City has had a lengthy history of building settling due to thawing of the permafrost by the heat of the buildings.

An initial ice rink was constructed in early 1972. The ice rink was developed on top of a 2m gravel bed located within a building. Ice was formed during the winter by opening large doors, flooding the gravel bed and allowing the winter air temperatures to freeze the water.

In late 1990 it was decided to enlarge the ice rink surface and assist in maintaining the permafrost by means of thermosyphons installed below a concrete slab. There was also a plan to incorporate a brine freezing system at a future date above the thermosyphon piping to be able to better control the ice temperature. Finally, the ice rink building was enlarged to provide heated dressing and washroom facilities (building addition).

Thermosyphon system below the ice rink was installed in June 2000 but the evaporator pipes were not covered with insulation. The design was based on the premise that the temperature at the rink surface would be at 0°C. This resulted in the evaporator piping being wider spaced, varying from 1.75m to 1.5m. Finally, during installation the client decided to incorporate an insulated trench adjacent to the ice rink for the future installation of the brine header.

The trench required four bends in the evaporator piping as illustrated in Figure 41. These bends did decrease somewhat the efficiency of the system.

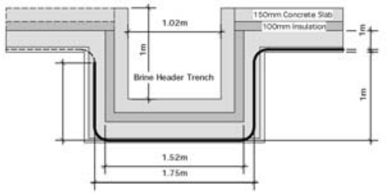


Figure 41. Trench and resulting pipe bends provided for installation of future brine header (Arctic Foundation).

Evaporator piping for the building addition (beneath the heated dressing and washrooms) was installed in October 2000. The spacing of these pipes was narrower to take into account the heated surface assumed to be at 20°C; the pipes were spaced at 0.76m. The insulation was 100mm at both installations. A foundation section at the building addition is shown in Figure 42.

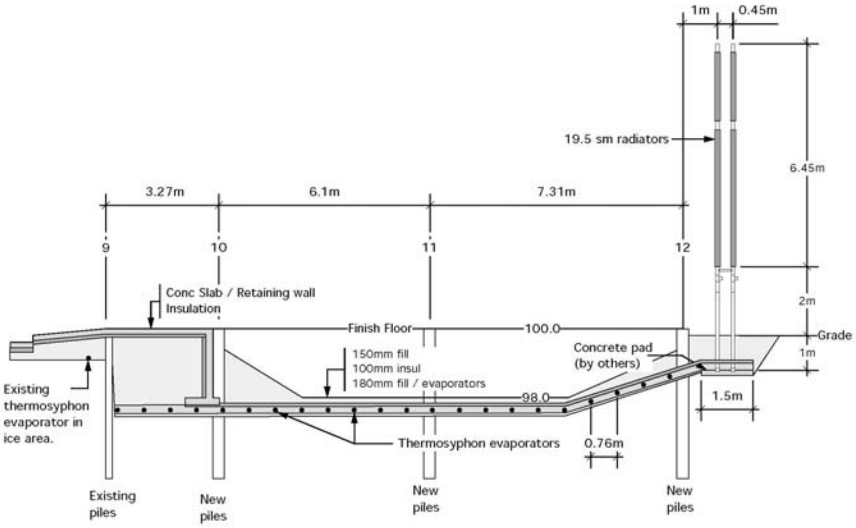
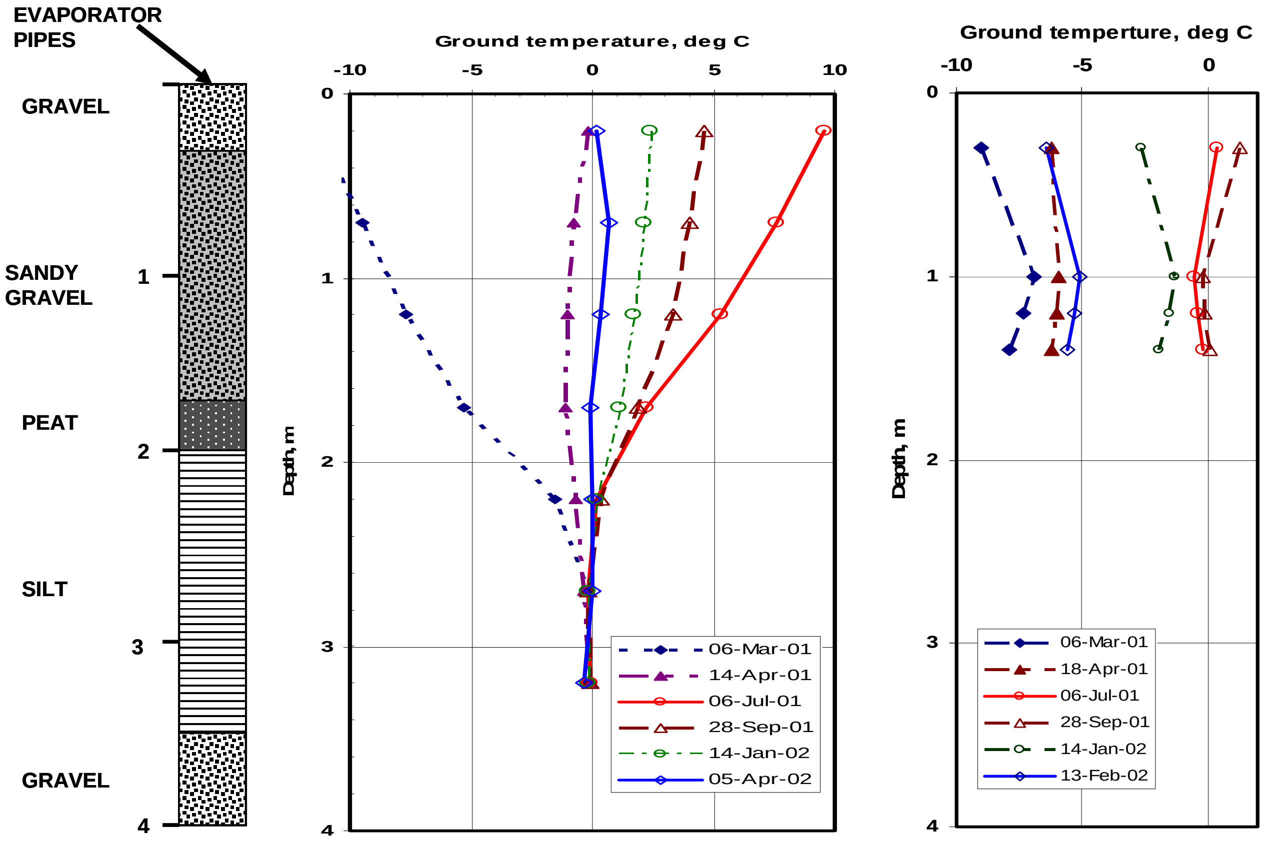


Figure 42. Foundation section at the building addition, Dawson City ice rink (Arctic Foundation).

A dispute between the general contractor and owner resulted in all the work stopping and the building being closed in the fall of 2000. In July 2001 the evaporator pipes were covered with insulation but by this time the ground had thawed to a depth of 2.8m. It was decided not to proceed with the pouring of the concrete slab that year because of anticipation of further thaw and potential damage to a slab poured on a thawing ground. The closed building was heated to 11°C through the winter of 2001/2002 that reduced the efficiency of the thermosyphon system that was designed with surface temperature of 0°C. The owner decided to abandon the thermosyphon system beneath the ice rink.

The thermosyphon system was installed beneath the heated dressing and washrooms in November 2000. The design was based on the heated floor resulting in closer evaporator piping being 0.76m and with 150mm insulation thickness. This thermosyphon kept the foundation below this part of facility frozen as designed. Ground temperature performance at this project is illustrated in Figure 43.



a) Ground temperatures below ice ring

b) Ground temperatures below building addition

Figure 43. Ground temperature profiles at the ice rink and building addition, Dawson City Recreation Centre

During the first winter 2000/2001 ground froze completely to meet the permafrost as illustrated by the March 6, 2001 ground temperature profile in Figure 43. The deeper permafrost was likely at about -0.3°C. The ground thawed below the ice rink (Figure 43, a) to about 2.8m early in July 2001 because insulation was not placed in 2000; nor at the end of 2000/2001 winter. The thawing likely continued to a depth of about 3m and the ground started to freeze again in late fall of 2001. The cooling and freezing was progressed slowly because the building was being heated to 11°C (evaporator spacing was designed for 0°C).

The thermosyphon cooling system below the building addition (Figure 43, b) performed as designed. The ground completely froze during the first winter and maximum thaw during the following end of summer 2001 reached about 1m. The total thaw depth was located within a frost heave free sandy gravel.

The design concept at the ice rink was changed in 2002 and the thermosyphon system terminated. At the same time ground temperatures at the building addition was discontinued.

7.9.3 Ross River, YK

Ross River has two thermosyphon foundation case histories; with the first one built in 1974 and the second 25 years later in 1999. Both of these projects are schools. Ross River is located about 400km southeast of Dawson City with a mean annual air temperature being about 1.5°C warmer than Dawson City. It is located in a glaciated valley that is underlain by about 5m of sand and gravel followed by at least 23m of ice rich silt (Haley 1981). The sand and gravel layer was judged to be thaw stable with a water content of about 5% and less than 10% of silt sized particles. The base of permafrost was measured at 28m. The mean annual air temperature is warming at Ross River from about -6.8°C in 1975 to -3.1°C in 2000 (Figure 44).

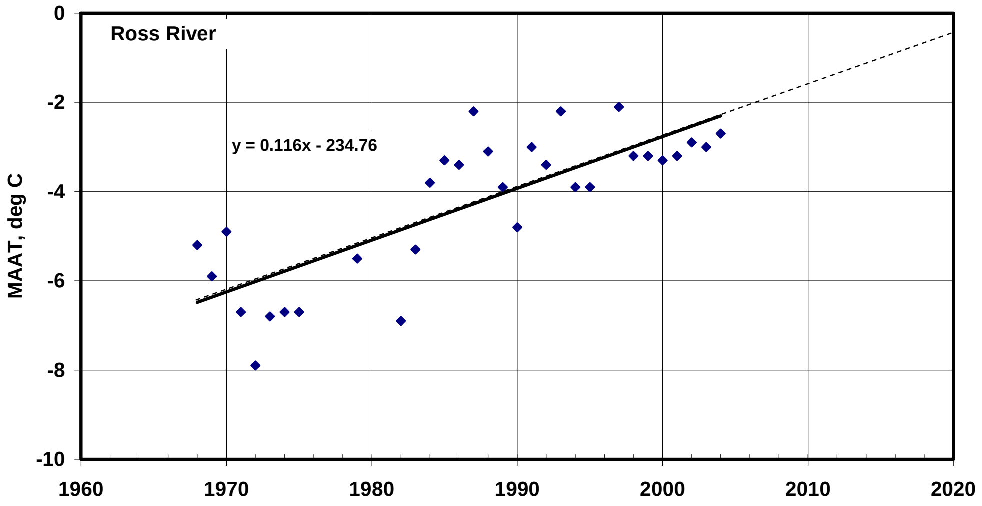


Figure 44. Mean annual air temperatures changes at Ross River, YK (Environment Canada)

While the warming of the mean annual air temperature warms the permafrost and decreases the depth to the base of the permafrost zone, it also decreases the freezing index that determines the amount of cooling the thermosyphon will produce. The historic decrease of the freezing index with time at Ross River is shown in Figure 45.

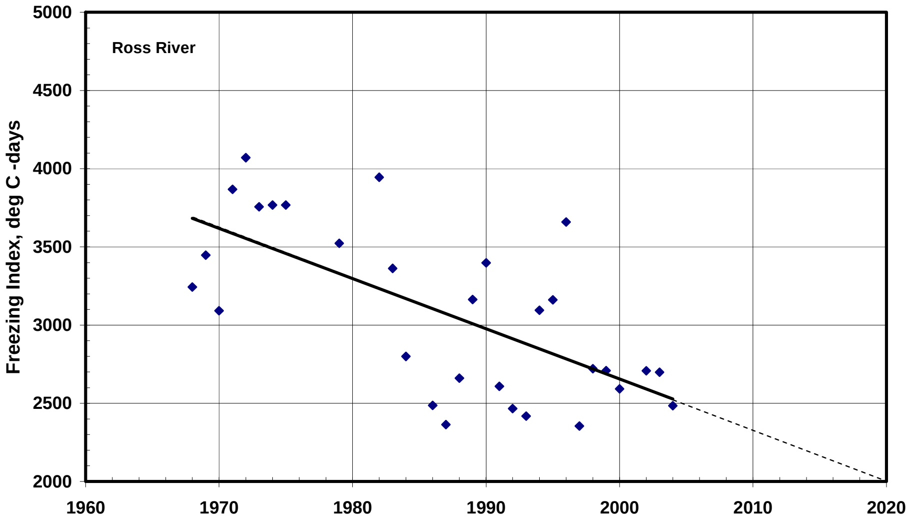


Figure 45. Freezing index change with climate warming at Ross River (Environment Canada)

a) Ross River School 1974

It was decided to construct the school at grade by using slab-on grade foundation and maintaining the permafrost using a new developed Cryo-Anchor heat pipes (sloped pipe evaporator pipes illustrated in Figure 11e) developed by McDonnell Douglas Astronautics Company (Haley 1981). This design uses single 100m diameter sloping pipes below the foundations that are connected to vertical risers with radiators. The pipes at Ross River were installed with a 10% slope with 3m spacing and covered granular bedding followed by 100m of rigid insulation. The system was filled with ammonia gas in 1975. The ground temperature in 1975 was estimated to be about -0.5°C. Thermal analyses showed that the depth of thaw below the designed thermosyphon pipes would be less than 4m and therefore it would maintain within the frost stable sand and gravel.

First two year ground temperature monitoring showed the ice rich silt at 6m depth was maintained at about -0.5°C. However with time the foundation developed uneven settlement of about 60cm. Pressure grouting was employed to correct the settlement but the results were unsatisfactory. In early 1990 it was decided to replace the building. It is believed that the thaw settlement of the building may have had three different causes; namely:

- Plumbing breakage caused water to percolate into the permafrost and thaw it.

- Reaction of the ammonia gas with pipe or pipe compounds may have produced a gas that settled at the top of the radiator pipes and thereby reducing/preventing the ammonia gas condensing at the top of the vertical pipes with the radiators.
- Wide spacing of the evaporator pipes at 3m was inadequate to deal with the air temperature warming (Figure 44).

In 1990 it was decided to replace the building.

b) New school with flat loop thermosyphon cooling.

In 1997 Government of Yukon commissioned a study to evaluate a foundation design for a new school to be located in the playground of the existing school (EBA 1997). Several slab on grade and elevated structural floor designs were considered and new thermosyphon design was selected from maintenance and cost considerations. The thermosyphon design selected is the flat loop evaporator pipe design that was considered to be as improved design from the early single pipe MacDonnell Douglas design using ammonia gas. The flat loop evaporator design has several advantages from the MacDonnell Douglas design:

- Flat loop thermosyphon was observed to be 1.4 times more efficient than the single tube sloped thermosyphon design (Yarmak & Long 2002).
- Flat loop thermosyphon system is charged with carbon dioxide that eliminates the dead zone phenomena at the radiator.
- Flat loop allows the horizontal granular pad as compared to a sloping pad. This allows easier construction and more uniform cooling below the slab.

The foundation design was a flat loop thermosyphon foundation with a crawl space. The main floor of the school was slightly elevated above the surrounding ground and the base of the floor of the crawl space being about 2m below the finished floor (Figure 46). The evaporator pipes were spaced between 0.9m to 1.7m, depending on the length of the evaporator pipe, and were filled with carbon dioxide.

The basement of the new school was excavated and prepared in late spring of 1999 and the flat loop thermosyphon foundation was installed in early July 1999. The as-built elevations of the evaporator pipes and the surrounding ground are not known. Figure 47 provides a photo of the base of the crawl space being constructed in the summer of 1999.

Judging from the information (EBA 1997) that the ground below the play ground was underlain by about 5m of sand and gravel that in turn was underlain by ice rich silt, it appears that the evaporator pipes were installed about 4m above the ice rich silt.

Typical ground temperature profiles measured at one of the vertical thermistor cables in the basement of the school is shown in Figure 47. The measurement showed that the granular material below the evaporator pipes thawed generally each year to a depth of about 3.3m. This meant that the thaw was generally within the thaw stable gravel under the building. However, two of three vertical thermistors showed ground temperatures slightly above 0°C at the 4m depth between about mid November and end of December in 2001 and 2003. This means that the thaw extended to or slightly into the ice rich silt during this period. It needs to be noted that these years were not abnormally warm as indicated by the mean annual air temperature and freezing index in Figures 44 and 45. It should be noted that the three vertical thermistor strings are located in the central portion of the crawl space.

The likely deep advance of the thaw front into the thaw compressible silt became evident by differential settlement during the first year after construction (Blum 2008).

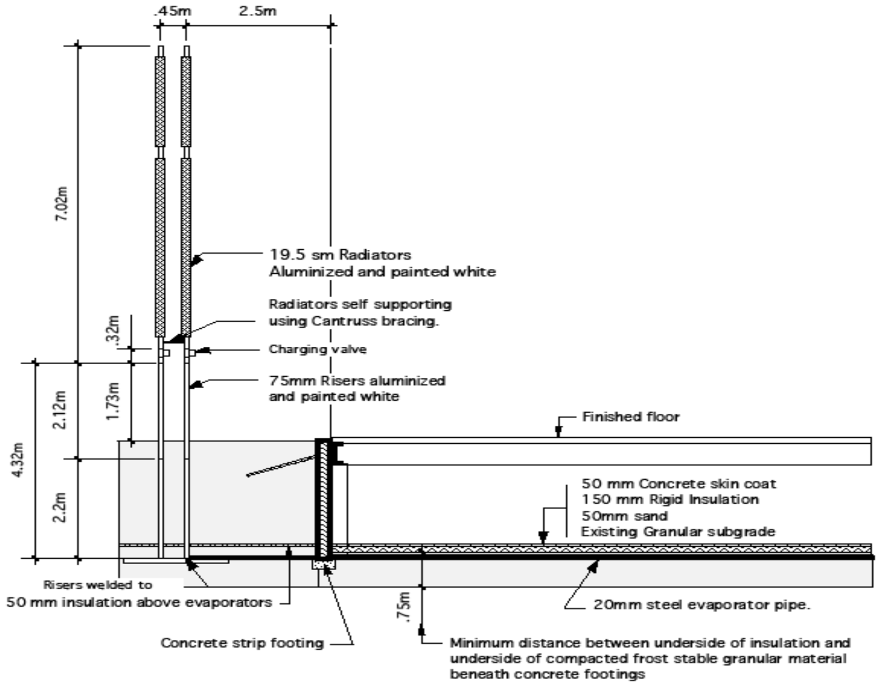


Figure 46. Typical flat loop thermosyphon section, Ross River School (Arctic Foundation 1999)

Figure 47. Covering of evaporator pipes at new Ross River School in progress (Arctic Foundations)

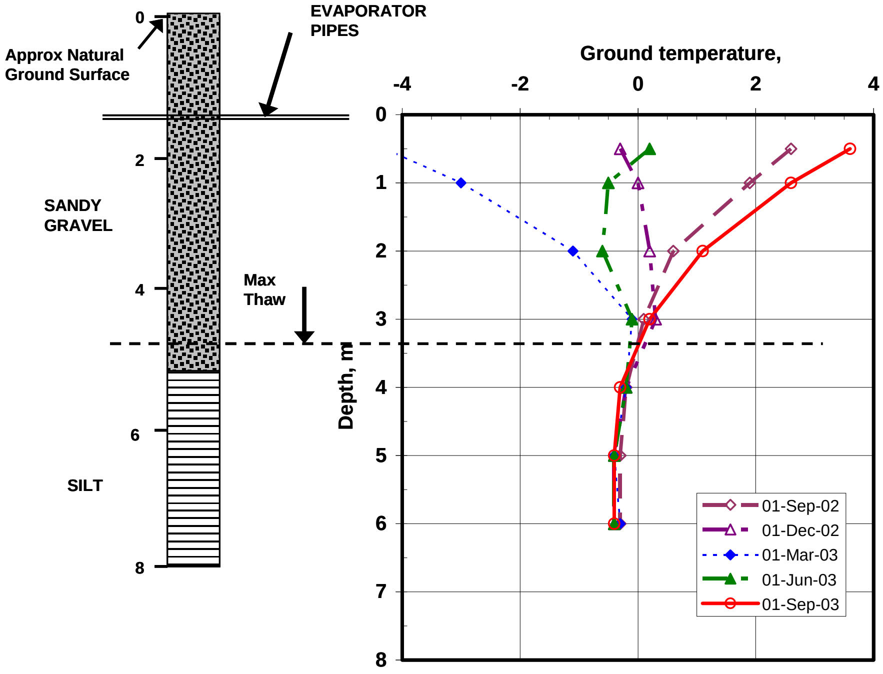


Figure 48. Typical ground temperature profiles below thermosyphon foundation at Ross River School (Arctic Foundation).

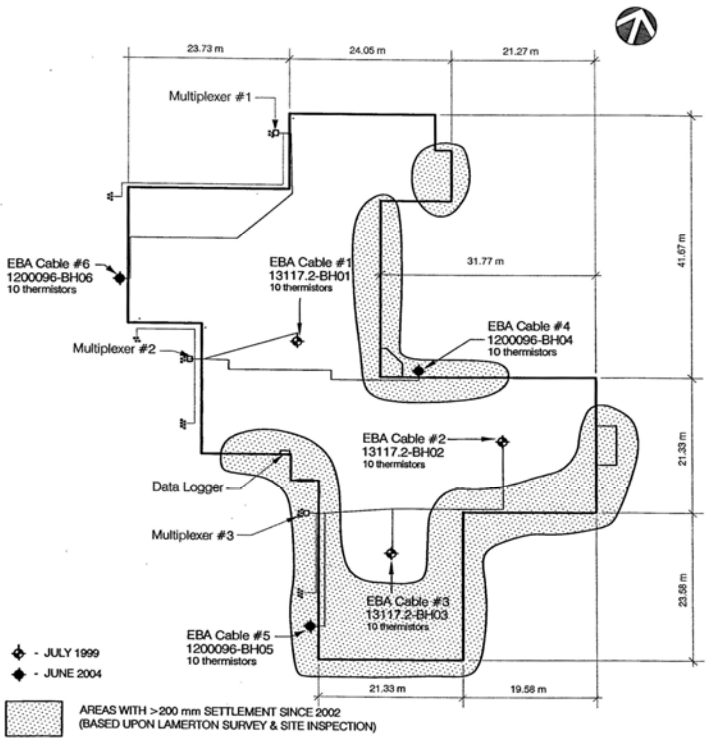


Figure 49. Settlement plan at Ross River School in 2005 (EBA 2005)

With time Differential settlement continued with most of the settlement occurring on the south and east side of the building as shown in Figure 49. The shaded areas indicate settlement greater than 20mm. The greatest differential settlement of 75mm was observed in the SW corner of the building since 2002 (EBA 2005). Three vertical thermistors installed around the perimeter of the building showed that the thaw front in the soil around the perimeter of the building advanced to about 7 to 10m depth below the natural ground surface.

The cause of the settlement was assumed to be caused by roof runoff entering the ground around the perimeter of the building and/or solar radiation. It was also felt that the use of fiberglass insulation on the vertical perimeter walls may have contributed to heat transfer from the building into the outside ground. The inadequate insulation of the fiberglass insulation was due to its becoming saturated.

Based on detailed analyses of performance data and thermal analyses the foundation design engineer EBA (2006) made the following recommendations to reduce/eliminate the ground warming and thereby thaw settlement:

- Add insulation to the interior crawl space walls.
- Lower the crawl space air temperature to no warmer than +16°C through the winter and +20°C during the summer.
- Install additional horizontal thermosyphon loops around the outer perimeter of the building and cover these with 75mm insulation, 2.44m wide.

The perimeter of the building was excavated to the footing level in 2006 to install the perimeter thermosyphons and insulation. A water-proof membrane was added to the outside crawl space walls and on top of the insulation. Finally, insulation was installed on the crawl space walls. It was anticipated that at least 2 years will be required to stabilize the permafrost and building foundation (Blum 2008).

Finally it has to be noted that the building foundation includes means of adjusting the floor level to compensate for differential settlement.

7.9.4 Observations

Dawson City and Ross River are located in a ‘warm’ to ‘very warm’ permafrost that is likely melting in areas with no tree shade and organic cover. Permafrost at mean annual air temperatures of -3.5°C in Dawson City and -2.0°C in Ross River, MAAR in 2006 based on trend analyses plots, is likely going through a thaw period that may take 10 to 15 years due to the latent heat of the ice within the frozen soil. During this thaw period the ground temperatures may be around -0.3 to 0°C, as is being observed at Dawson City and Ross River. It should be noted that the mean annual ground temperature is about 4.4°C warmer than the mean annual air temperature (Smith & Burgess 2000). While this relation has considerable scatter to it, the writer has found that it is reasonably true for sites without trees and normal or less organic cover. This would mean that Dawson City and Ross River are already in a permafrost thaw stage in clear areas.

It is likely that the flat loop thermosyphon foundation in the addition area of the Recreation Centre in Dawson City is keeping the foundation frozen as designed. Unfortunately, the ground temperatures have not been monitored since 2002. The thermosyphon system under the ice rink has not performed as intended because of a shut down of the building construction that prevented insulation to be installed when needed. Thermosyphon cooling below the ice rink was abandoned because of the excessive thaw of the ground during the construction shutdown.

The initial thermosyphon installation at Ross River School in 1975 was a pioneer project that used an early version of thermosyphon design provided by MacDonnell Douglas. The evaporator pipes were single sloping pipes that were installed at a slope of 1 vertical to 10 horizontal. These evaporator pipes are not as efficient as the presently used horizontal looped evaporator pipes and also they were installed at too wide of a spacing at 3m. Finally, in addition, the pipes were filled with ammonia gas that was found to react with the interior of the pipes and create a gas that is trapped at the top of the pipes at the radiator section. The inert gas limits the condensation of the ammonia and thereby the efficiency of the heat exchange. Ammonia gas is not being used anymore in thermosyphons.

The new Ross River School used the improved thermosyphon design that is presently being used. This is a horizontally placed looped evaporator pipe that is connected to a vertical condenser pipe with a radiator at the top. These pipes are filled with carbon dioxide that has been proven to function well over the last 20 years. However, Ross River has seen considerable climate warming from the first thermosyphon installation, being about 1.5°C warmer when the second school was designed and constructed in 1999. The mean annual air temperature being about -3.0°C in 1999 based on a trend analysis of historic data. Ground temperature data measured in 2001 indicate that the permafrost mean annual ground temperature was about -0.3°C. This temperature is representative of a very fragile permafrost that could be going through a melting phase.

The new school started to experience differential movement within a year of construction and continued to the period of available information in 2006. Ground temperatures from the central part of the crawl space within the building show that the annual thaw depth extends generally to 3.5m below the evaporator pipes but has exceeded 4m. Ice rich soil is located about 3.5m below the evaporator pipes. Therefore, any thaw below the 3.5m is prone to thaw the ice rich silt and cause settlement.

Major differential settlement was observed around the perimeter foundation; with a maximum settlement of 75mm on the southwest corner measured in 2005. The likely cause of the greater thaw and settlement around the perimeter was that the thermosyphon pipes did not extend beyond the building perimeter. The warming of the outside perimeter ground resulted in the thaw of the perimeter ground and this was extended to the perimeter footings. The warming of the ground below the perimeter wall footings was exacerbated by using fiberglass insulation on the perimeter walls. This insulation lost most of its insulation properties when it became wet.

The corrective measures made in 2006 should improve the cooling performance of the thermosyphon foundation. The thermosyphon loops installed around the outside perimeter of the building will prevent the warm ground around the building from warming the permafrost below the building and therefore lowering the operating temperature within the crawl space and will reduce the heat input into the foundation.

7.9.5 Conclusions

The performance of the thermosyphon foundations in the Yukon are of great interest to future installation of thermosyphon foundations in the rest of the Canadian permafrost region because they are at site with mean annual air ground temperatures where permafrost starts to thaw. This is confirmed with the very warm ground temperatures measured in Dawson City and Ross River. Most of the larger northern communities in permafrost, with the exception of Yellowknife, have air and ground temperatures that are colder.

It would be worthwhile to monitor the performance of the thermosyphon installation at both Dawson City and Ross River. They are of interest because of the warm air and ground temperatures and the fact that Dawson City air temperatures are about 1.5°C colder than Ross River.

The thermosyphon foundation under the change and washroom addition to the Dawson City Recreation Centre was performing well in 2002 when last ground temperature readings were taken. It is likely that they are still working as per design,

The modification made at the Ross River School should improve the frozen condition under the building. However, the fact that Ross River has already a high mean annual air temperature that is likely to rise due to climate warming, additional effort may be needed to keep the ground below the building frozen. Close monitoring of the ground temperatures will be required to assess how the modifications have helped in keeping the ground frozen and also warn if and when additional modification may be required.

8.0 OBSERVATIONS

8.1 General

Permafrost areas where the majority of Northwest Territories and Nunavut settlements are located are in a perilous state with mean annual ground temperatures in the minus 1 to minus 3 degrees Celsius. These ground temperatures and the present climate warming makes the traditional slurry pile foundation unstable at the present state or in the near future. At around -2°C and warmer the adfreeze capacity of the pile may not be sufficient to prevent heave during the annual freeze back of the active zone and subsequent settlement.

The potential solution for new buildings are: a) move new buildings to areas with thaw stable ground; b) locate the foundation base to lower depths that have normally less damaging ice rich soils and provide means to adjust for settlement or c) use thermosyphon foundation design.

8.2 Thermosyphon Foundations

Thermosyphon foundations were developed in Alaska for structures in marginal permafrost areas. They have been widely used in Alaska and northern Canada since the 1970's with a relatively small number of problems considering the complexity of permafrost and difficult construction in the north. A flat loop thermosyphon foundation was developed and used extensively in Canada since 1994. Current concerns in regard on how climate warming will impact the stability of structures in permafrost and higher performance demanded by larger structures with a design life span of 50 years being designed requires a review of the current design, construction and monitoring standards and practices. Several case histories of buildings with problems and the design and ground temperatures of three most recent constructed buildings in permafrost provide guidance to what needs to be done to design and construct competent thermosyphon foundations that will handle the effect of climate warming for the design life of the building.

8.3 Design

8.3.1 Climate and ground temperatures

The basis for the design of any type of foundation on ice rich soil or any frozen fine grained soil is the knowledge of the mean annual ground temperature and climate warming rate that will warm and may even thaw the ground during the service life of the building.

National Building Code of Canada 1995 provides design temperatures for January and July that have been compiled up to 1993. These temperatures represent the 1% and 2.5% extreme values that are not applicable for design of foundations in permafrost. It refers to Environment Canada for more specific information. Environment Canada provides Climate Normals that are the averages for the period of 1971 to 2000. These are frequently quoted by geotechnical engineers designing foundations in permafrost regions. However, these Normals or averages do not represent the current climate since the climate started to warm appreciable around 1980 and has been warming on a more or less steady rate since that time. The mean annual air temperatures as given by Environmental Canada Normals are about 1.5°C colder than the present mean annual air temperatures at most northern locations.

Mean annual ground temperatures are reflected directly by the mean annual air temperatures. Therefore the 1.5°C colder mean annual air temperatures would indicate colder ground temperatures.

Presently there is no standard for establishing the climate rate for a particular location. Climate warming rates are normally estimated from computer models. Another method proposed by the writer is to estimate the climate warming rate from the linear trend of actual mean annual air temperatures from the last 20 years records. This normal provides slightly high warming rates than the computer models. However, the computer models are continually updated that increases the rates.

Reference ground temperatures for northern settlements are lacking. Scarce and incomplete ground temperatures are located in consultants and some project owner’s files. This data is frequently poor since it may be one or more decades old. Vertical temperature sensors do not extend to a depth where the ground temperatures do not fluctuate over the year or show only a minor fluctuation and finally, the data was not collected to cover the whole year.

8.3.2 Thermal thermosyphon foundation design

Thermosyphon design is based predominantly on the climate of the site and the air temperature of the building above the thermosyphon foundations. Based on this information the combination of insulation thickness above the evaporator pipes, evaporator pipe spacing and radiator size is selected to ensure that the foundation below the building remains frozen. A proprietary design method has been developed by Arctic Foundation of Alaska Inc. that is being used by Arctic Foundation of Canada. This method is based on theoretical work done in the 1960’s by the Corps of Engineers and is being continually updated based on new technology, field tests and experience gained from the performance of existing structures. The design of the flat loop thermosyphon system has been checked and also designed by one permafrost geotechnical consultant using their own proprietary software.

The writer’s opinion is that the present status of the methods of the thermal thermosyphon foundation design is inadequate for the following reasons:

1) The current design methods are proprietary and cannot be applied or used to be checked by others.
2) The current methods have not been calibrated sufficiently against recent ground temperature performance.

8.3.3 Physical thermosyphon foundation design

Some of the poor performance cases have been caused by not having the complete foundation design before construction started and/or reviewed by the appropriate designers. Design of the thermosyphon foundation is complex because some components that would be considered of minor importance in non-permafrost regions could have considerable impact on the performance of the constructed thermosyphon foundations.

The complete design of thermosyphon foundation should include among other details; excavation and backfill plans, surface and ground water control, location and detail design of services below the building slab (for slab-on-grade design), detailed design of all insulation that include the perimeter base and along the perimeter wall, building heating system, thermosyphon piping and evaporator pipes.

During the review of many of the case histories the writer could not find comprehensive plans and section of the thermosyphon foundations designs aside of the layout of the evaporator pipes and radiators.

8.3.4 Construction schedule

A well thought out construction schedule that is in the contract documents is important will assist in obtaining a smooth construction process, minimize construction changes and prevent harmful impacts on the thermosyphon foundation. There is not a single pattern for a construction schedule since it depends on many issues, such as, approvals, material and construction equipment shipping windows, climate controlling material placement, working conditions, etc.

There are three basic construction schedules available from permafrost consideration:

1) Excavate in late spring and complete construction of the thermosyphon foundation, including placement of the insulation before start of summer. Place a protective granular cover over the insulation and allow the cooling of the ground through the following winter. (Aurora College, Inuvik, NT).
2) As in (1) but construct footings and wait for the construction of the superstructure until ground is completely frozen at the end of the year (Health Centre, Pangnirtung, NU).
3) As in (1) but move forward freezing of the foundation and the construction of the building by the use of chillers. (Hospital, Inuvik, NT).
4) Excavate the foundation in spring, allow the underlying ground to thaw and compress, place the granular pad on top and construct the thermistor system in late spring or early summer. Allow the foundation to freeze through the following winter. This schedule would eliminate another 1m or so of the ice rich soil and provided another 1m of uniform foundation pad with little thaw potential.

8.3.5 Monitoring

Designer and contractor Arctic Foundation of Canada installs elaborate vertical and horizontal temperature sensors and sensors on the radiators. These are monitored generally until the ground below the thermosyphon foundation is completely frozen, normally not much longer than one year.

The thermosyphon foundation is a passive cooling system that is similar to a refrigeration system that may lose efficiency with time. Since the efficient operation of this cooling system is important to structural integrity of the building, it is important to monitor the operation of the thermosyphon system for the life of the building.

8.3.6 Life span of thermosyphon foundations

Some thermosyphons have been operating now for some 40 years. Since the first thermosyphons have been installed the design of the system has been improved by the selection of the operating fluid, pipe and valve quality and coatings of the exposed components.

There have been only two major malfunctions of thermosyphon foundations. One was at the Alaska oil pipeline where ammonia was used as the operating fluid. Chemical reaction and condensation impacted the operation of the thermosyphon and had to be replaced with carbon dioxide that has proven to be a trouble free fluid. The other is the Hospital in Inuvik where the mill shipped defectively welded pipe. This latter caused about 17 of the 64 evaporator loops to lose pressure requiring them to be recharged every one to three years. This has resulted in Arctic Foundation using higher quality extruded pipe.

It is likely that with the progressively improved design the recent and future thermosyphons will have a life span equal to the design life of buildings with the proviso that some fluid recharge may be required during this time. The most likely cause of fluid leakage would be the recharge valve. If the recharge valve became a problem, it can be readily replaced since it is located above ground below the radiators.

8.3.7 Impact of climate warming on thermosyphon foundations

It is difficult to assess if all the present thermosyphons foundations will be able to keep the foundation frozen at the end of a 40 to 50 year life span of the buildings due to climate warming. The existing thermosyphon foundations were designed with a good factor of safety and with some climate warming consideration.

It is felt that during the design of these foundations the present knowledge of climate warming may not have been incorporated. However, in the worst case scenario that the present thermosyphon foundation will not be able to provide sufficient cooling to keep the foundation frozen modifications can be made to the existing installation. This could be by installing adding length to the radiators to increase their capacity and by installing chillers that would keep cooling the foundations through part or all of the summer.

The more likely thermosyphon problems could occur at the more southerly permafrost location, such as Tulita, NT and Kuujjuaq, QC and at installations where only 100mm of insulation was used.

9.0 CONCLUSIONS

1) Presently there are no guidelines or standards to determine the present design air temperatures and climate warming rate that can be used for designing building foundations and other structures, such as dams, reservoirs and waste storage facilities in permafrost regions. The National Building Code or the Normals provided by Environment Canada are not helpful.
2) There is a lack of ground temperature reference data that can be used to design and track the effect of climate warming on permafrost in nearly every community be it large or small. The data that is available is located widely, normally not complete and often outdated because climate warming had changed the ground temperatures.
3) Traditional slurry pile foundations are starting or will start experiencing problems in the near future. Ground warming is decreasing the adfreeze strength that is needed to support the building and prevent frost heaving. Hundreds of buildings have reported these problems in Russia and similar problems are documented at Rankin Inlet, NU. This may likely be happening at other settlements in warm permafrost.
4) Thermosyphon foundations have operated for some 40 years without any major problem identified during this period. They were developed for warm and constant permafrost temperatures.
5) Better and calibrated against known ground temperature performance thermal analyses are needed to design future thermosyphon foundation that will still function after 50 years with climate warming. The thermal software should be commercially proven software that can be bought and used by others.
6) Problems of the recent flat loop thermosyphon performance are generally the result of a combination of poor foundation design, construction and in one case defective pipes supplied by the mill.
7) There is a need for thermosyphon foundation guidelines that address the design, construction and monitoring of: granular pad, surface and ground water control, thermosyphon system, services incorporated into the slab-on-grade foundations, instrumentation and monitoring.
8) The study has identified flat loop thermosyphon foundations at four locations that have one or more unique air and ground temperatures, ground conditions, design or construction. These are: a) Aurora College in Inuvik, NT, b) Health Centre in Pangnirtung, NU, Air terminal in Kuujjuaq, QC and Ross River School, YT. These four sites should be considered as baseline sites to continue monitoring the local permafrost and performance of the flat loop thermosyphon foundations.

10.0 RECOMMENDATIONS

10.1 Design and construction guidelines for thermosyphon foundations

Case histories have identified that the majority of problems have arisen from poor design and construction of the gravel pad, location of services, surface water control and insulation. It is recommended that guidelines be prepared for design and construction of the flat loop thermosyphon foundations. It should be illustrated with alternative design details that could be considered in the design of a thermosyphon foundation. This would provide guidance to designers, architects, geotechnical engineers, contractors and inspectors. It would also provide background information to reviewers and project owners.

Recommendations

Design and construction guidelines for thermosyphon foundations should be developed. The guidelines should address: foundation pad design, surface and groundwater control, design and location of services within granular pad in slab-on-grade design, construction materials (related to granular pad and drainage), construction scheduling and control, etc.

10.2 Thermosyphon foundation design thermal analysis; calibration and parametric study

It is felt that presently there are two weaknesses in thermal design of thermosyphons: a) proprietary thermal analyses are being used to design the thermosyphon foundations and there is limited calibration information available to validate the predictions; and b) there is no known published parametric analyses available that can guide the designer or provide information to a reviewer on optimal design of thermosyphon designs. A parametric study would provide information on the best combinations of design measures to combat climate warming (insulation thickness, evaporator pipe spacing, radiator lengths, pad thickness and saturation, etc) and how these affected different existing mean annual ground temperatures.

Recommendations

The following are recommended to address these issues:

a) A recognized commercially available thermal analyses should be identified and calibrated with several representative case histories with available foundation ground temperature records. The results of the calibration and findings from these calibrations should be available to others so that confidence is developed on the thermal design of the foundation for the total life span of the building.

b) A parametric thermal analyses should be conducted for two different permafrost sites to evaluate how thermosyphon components (insulation thickness and width beyond building wall perimeter), spacing of evaporator pipes, length of radiators and saturation of granular pad effect the robustness of the thermosyphon to maintain the ground below the building frozen. The study should also address different climate warming rates and the impact of above normal summers and/or winters.

10.3 Baseline documentation of key projects for future monitoring and studies

The study has identified flat loop thermosyphon foundations at four locations that have one or more unique air and ground temperatures, ground conditions, design or construction. These are: a) Aurora College in Inuvik, NT, b) Health Centre in Pangnirtung the RCMP building in Iqaluit, NU, Air terminal in Kuujjuaq, QC and Ross River School, YT. These four sites should be considered as baseline projects where the past factual information be summarized, thermosyphon design and monitoring documented and performance of the thermosyphon foundation be monitored on regular and systematic manner.

This information is provided in a general manner in this document. It is recommended that this information be provided in greater detail (based on additional historic information) and be presented in a more systematic manner for use for interpretation of future monitoring, development of future design modification, if needed, due to climate warming and the recommended thermal analyses in recommendation 10.3.

Recommendations

The work at these four base line key projects should consist of the following:

1) Summaries of geotechnical conditions from past investigations that will include: immediate topography and hydrology, ground stratigraphies, soil/permafrost properties and ground temperature measurements.

10.4 Establish design air temperature and climate warming criteria

Present Normals and climate warming rates provided by Environment Canada do not provide design air temperature and climate warming criteria that represent current air temperatures and climate warming rates. Presently available mean normal air temperatures (Normals) are averages for the years 1971 to 2000 while current mean annual air temperatures are about 2°C higher than the Normals because of climate warming. Furthermore, the climatologists are observing that published climate warming rates based on climate models are under-predicting air temperatures.

Environment Canada is aware of this and is correcting the problem. It has suggested that an analyses based on trends mean annual air temperature from recent records is a reasonable safe approach (given in attachment). Any analysis should be based on data from the period after an air temperature anomaly was observed around mid 1970.

Recommendations

It is recommended that Environment Canada be encouraged and funded to update their climate information needed for design of infrastructures in the North. In the meantime, guidance should be provided how to estimate:

- Design air temperatures and precipitation for new proposed structures on permafrost and the extremes for these values.
- Climate warming rates calibrated/adjusted to recent observed climate measurements.

10.5 Guidelines for Geotechnical investigation and collection of design information

Many present geotechnical investigations are limited by available drilling equipment and clients desire to keep costs low. It is common that the depth of investigations is limited to 8 to 10m. These depths are not sufficient to decide if there is a suitable founding zone just beneath the investigated depth or what could be additional thaw settlement of the underlying permafrost, if any. Deeper drilling, during the initial investigation, would provide better information in selecting and designing the most appropriate foundation in permafrost subjected to climate warming.

It is also noted that the limited drilling depths result in temperature sensors being installed only to depths where significant annual ground temperature fluctuations are occurring. Frequently, insufficient ground temperature data representing the annual ground temperature fluctuation is collected. Ground temperatures at 15 to 20m depth would provide a good indication of the mean annual ground temperature soon after installation because the ground temperature at this depth experiences only minor annual fluctuations.

Recommendations

a) It is recommended that guidelines be prepared for geotechnical investigations to provide better information for the selection and design of foundation for future buildings in permafrost. The guidelines should incorporate the recommendations given in the Canadian Foundation Engineering Manual but be modified to permafrost and the effect of climate warming. The guidelines should include:

- Information provided by the client (Proposed building type and design, tolerance to settlement, life span etc.)
- Selection of depths
- Drilling methods and frozen ground sampling.
- Ground temperature installation and recording
- Laboratory testing to obtain index and engineering properties.
- Information to be included in the report; local physiography and topography, drainage, climate, factual information obtained from the investigation, design recommendations etc.

b) It is recommended that GNWT establish one central depository for all site investigation reports and ground temperature monitoring that could be accessed by others for future design, and performance and permafrost changes. This could be structured similarly to the system used by the Territories Water Board who place design, as-built, annual inspection and monitoring reports on their web page.

10.6 Guidelines for Instrumentation and monitoring of thermosyphon foundations guidelines

Flat loop thermosyphon foundation is a pressure vessel cooling system where adequate foundation cooling is important to the permanence of the building it supports. The thermosyphon foundation consists of numerous piping loops connected to radiators. The effectiveness is dependent on the winter air temperatures, maintenance of the pressure within the tubes and prevention of any ground or service water ingress.

It is recommended that guidelines be prepared that identify the design and location of temperature sensors in the ground, the evaporator pipes and radiators, and provide guidance to manual or preferably a logger system to monitor the instrumentation. Guidance should be provided on the analyses of the data and provide some historic results for guidance to the reviewer.

Recommendations

It is recommended that guidelines be prepared that addresses: a) design of ground and thermosyphon monitoring system; b) monitoring frequency and reporting and c) evaluation of results. The results of the monitoring should be stored and made available to others as recommended in 10.2

2) Document the design of the flat loop thermosyphon and summarize the structure foundation section. This latter should include the granular base, design of waste water and heating of building, surface and ground water management and construction.
3) Install ground and thermosyphon temperature sensor logger that will be preferably connected to a telephone line so that the results can be downloaded by a remote site.
4) Install one or two reference vertical ground temperature cables adjacent to the building and tie the sensors to the monitoring logger. These multi sensor cables should be installed to a depth of minimum 15m and preferably 20m. This is to monitor the local permafrost changes and use it to evaluate the performance of the thermosyphon foundation.
5) The monitoring of all sites should be conducted for a minimum of three years by one source that will prepare annual reports. These reports will include the mean monthly and annual air temperatures, reference ground temperature changes, snow and surface water changes around the site, thermosyphon operation, ground temperature changes below the thermosyphon foundation and structural changes of the building, if any.

The recommendations can be adopted and financed by the jurisdiction of the four selected projects. However, the summary reports and reporting on the changes at the selected sites should be prepared or managed by one party for consistency and the interpretation of the combined observations.

10.7 Thermosyphon pressure vessel design, codes and standards

It is recommended that an experienced engineering firm specializing in pressure vessel design should prepare technical background, design and construction information and provide construction recommendations report that can be used by thermosyphon foundation designers and constructors. The report should also identify relevant codes and standards related to thermosyphon systems. This report would assist to minimize long-term problems with the pressurized thermosyphon system.

Recommendations

A qualified engineering firm specializing in pressure vessel design should prepare a report on Thermosyphon pressure vessel design, codes and standards.

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Climate Data

Mean annual air temperatures for trend analyses and estimation of the mean annual temperatures were obtained by customized search of Environment Canada climate historic data at the following: *http://climate.weatheroffice.ec.gc.ca/advanced search.*

Arctic Foundations of Canada Ltd.

Arctic Foundation of Canada Ltd. was the contractor on all flat loop evaporator thermosyphon foundations and they generously provided a large quantity of information on all the case histories; with the exception of the first Ross River School that was designed and built by a different contractor in 1975. Arctic Foundation of Canada was very accommodating in providing plans and section of the thermosyphon installations; construction photographs and ground temperatures measured below the foundations. They provided information on the construction schedules and comments on the overall construction and performance.

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APPENDIX A – ADDITIONAL FIGURES AND PHOTOS

Background Information

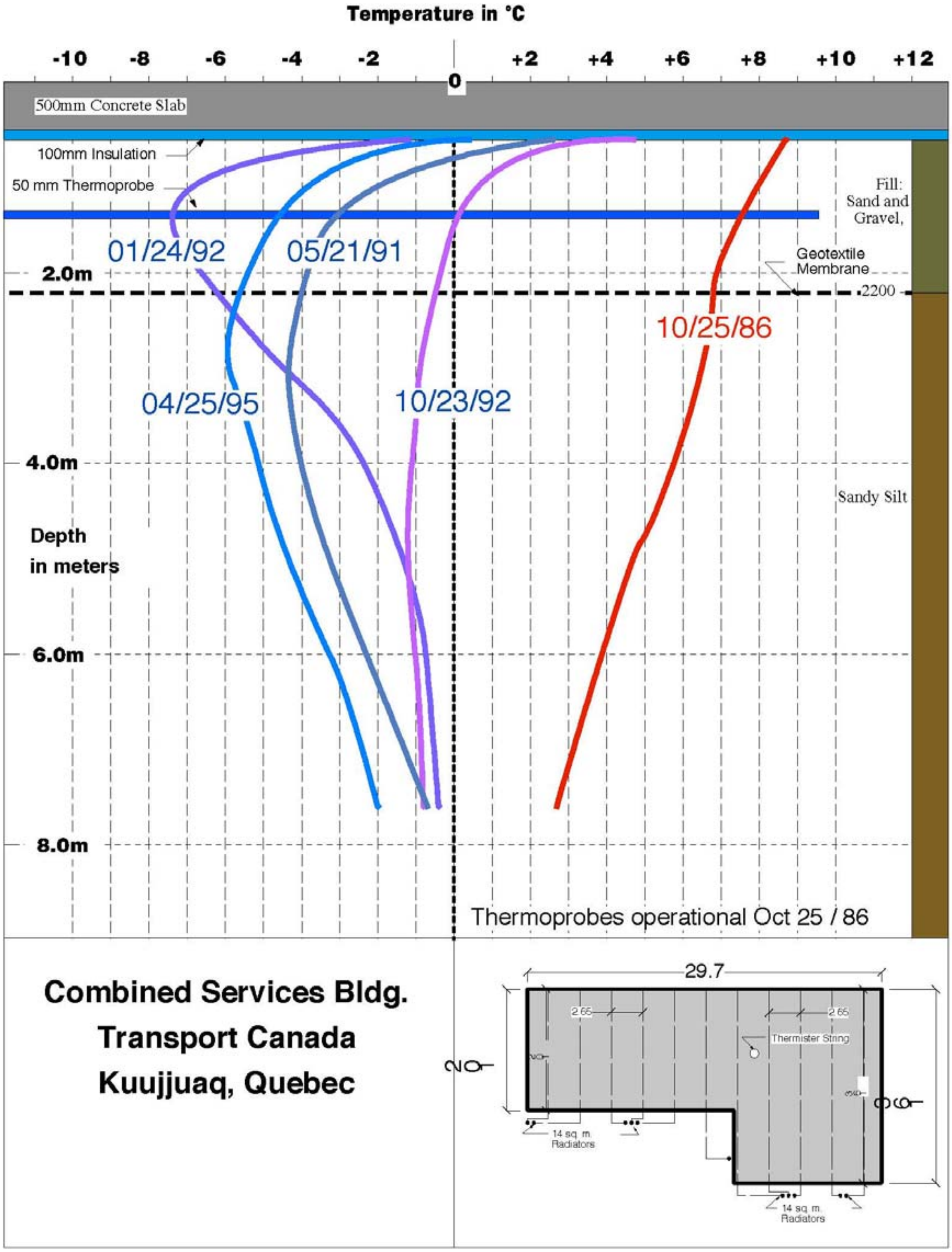

Figure A 1. Thermosyphon layout and ground temperature changes at Combined Services Bldg, Kuujjuaq, QC

Figure A 2. Photo of Visitor Centre in Inuvik, NT

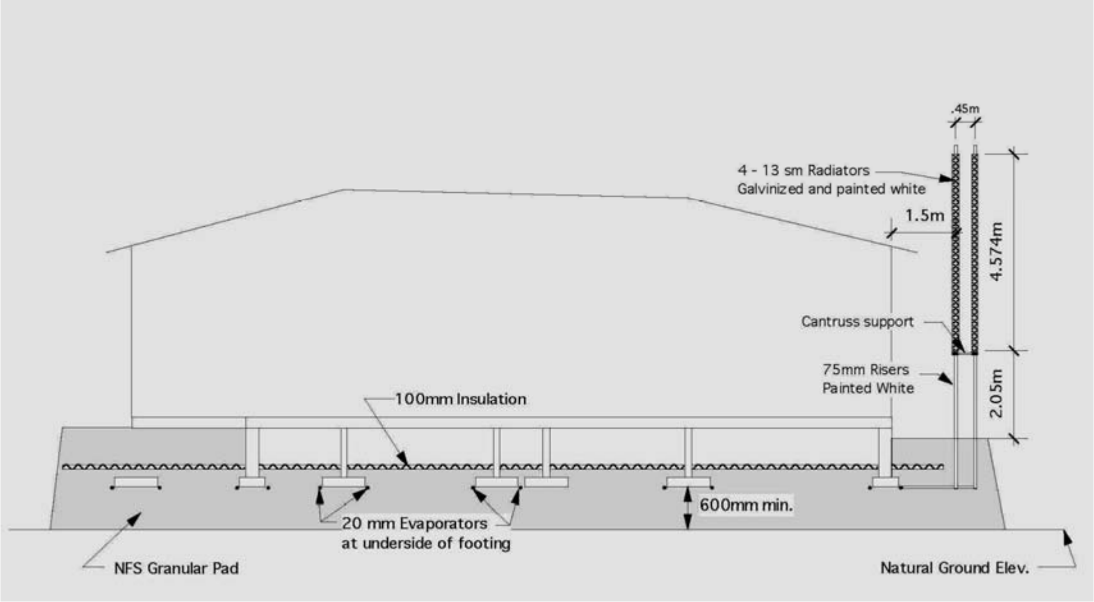

Figure A 3. Cross section of footings, evaporator pipes and insulation at Visitor Centre, Inuvik, NT

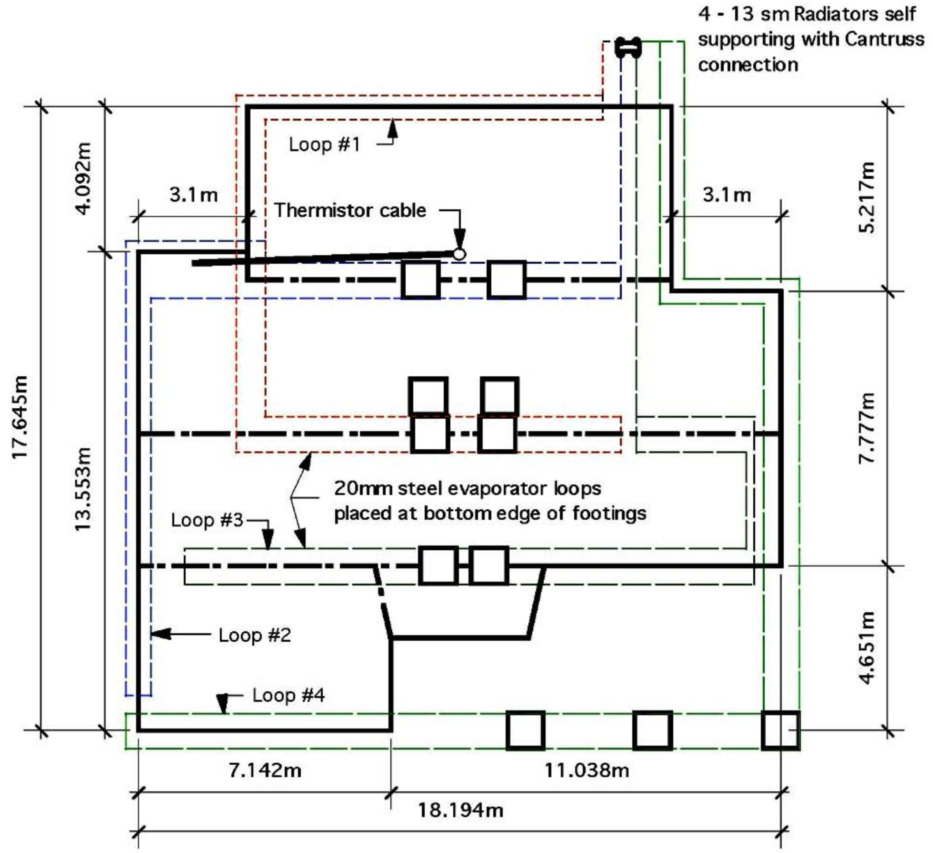

Figure A4. Plan showing footings and evaporator pipes at Visitor Centre, Inuvik, NT

Figure A5. Photo showing grade beams and location of evaporator pipes at Visitor Centre, Inuvik, NT

Figure A6. Photo showing concrete columns and wooden st resting on grade beams at Visitor Centre, Inuvik, NT

Figure A7. Simon Allaituq School, Rankin Inlet, NT

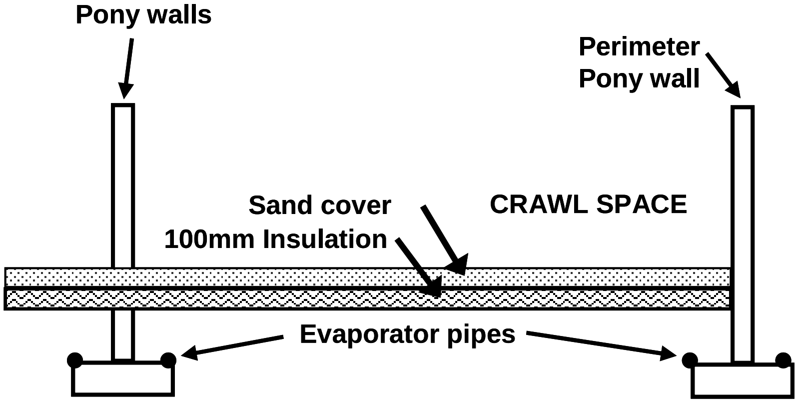

Figure A8. Schematic of Rankin Inlet School thermosyphon foundation design

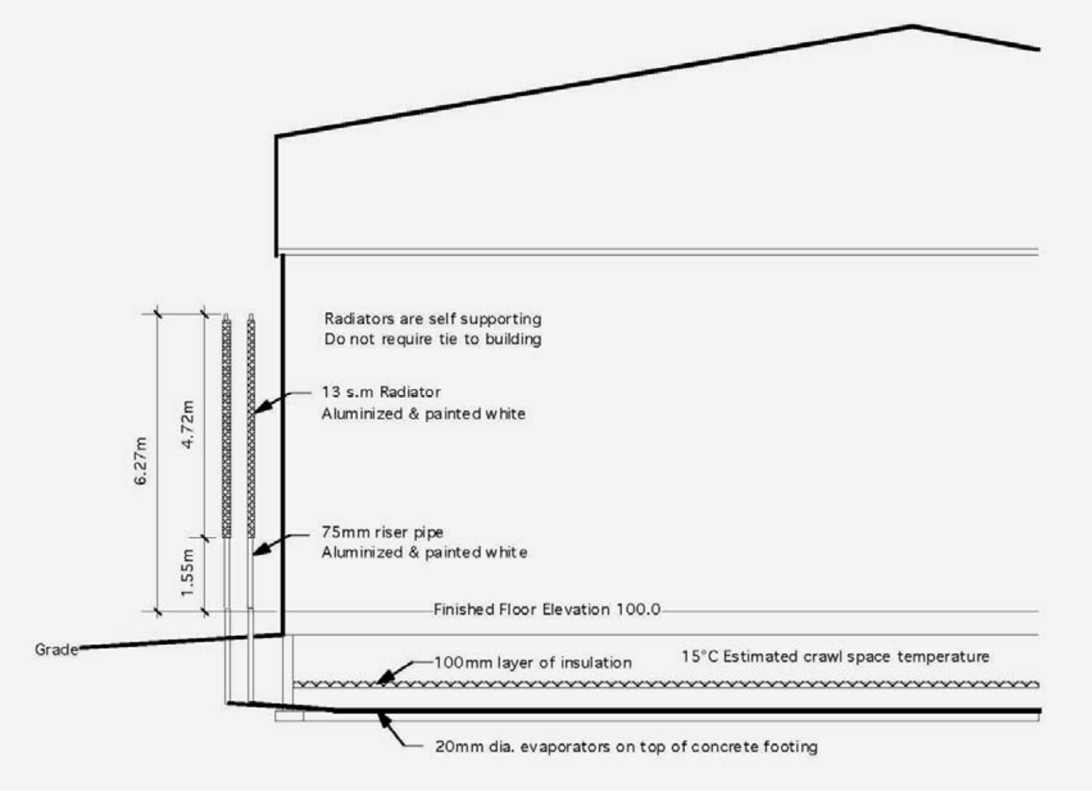

Figure A9. Section showing thermosyphon foundation design, Rankin Inlet School, NU

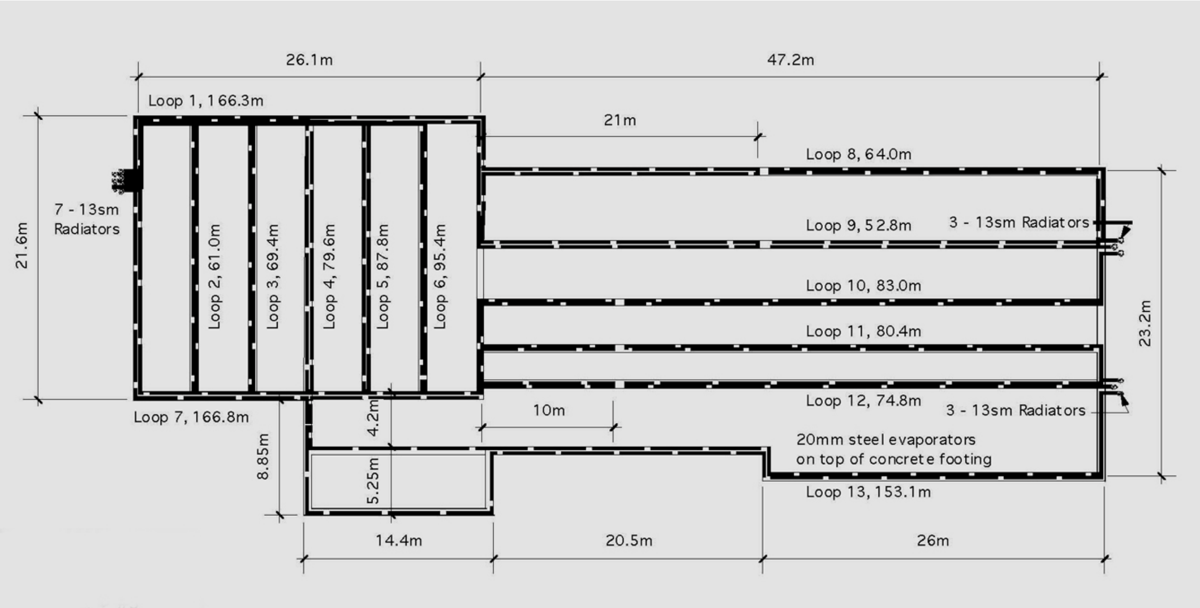

Figure A10. Evaporator pipe and radiator plan, Rankin Inlet School, NU

Figure A11. Installation of heating pipes below Rankin Inlet School from power plant.

Figure A 12. Crawl space at Rankin Inlet School, NU, showing timber columns, ponded water and broken insulation.

Figure A 13. FYOF site with construction access road looking SW

Figure A 14. Excavation through engineered at sump, FYOY

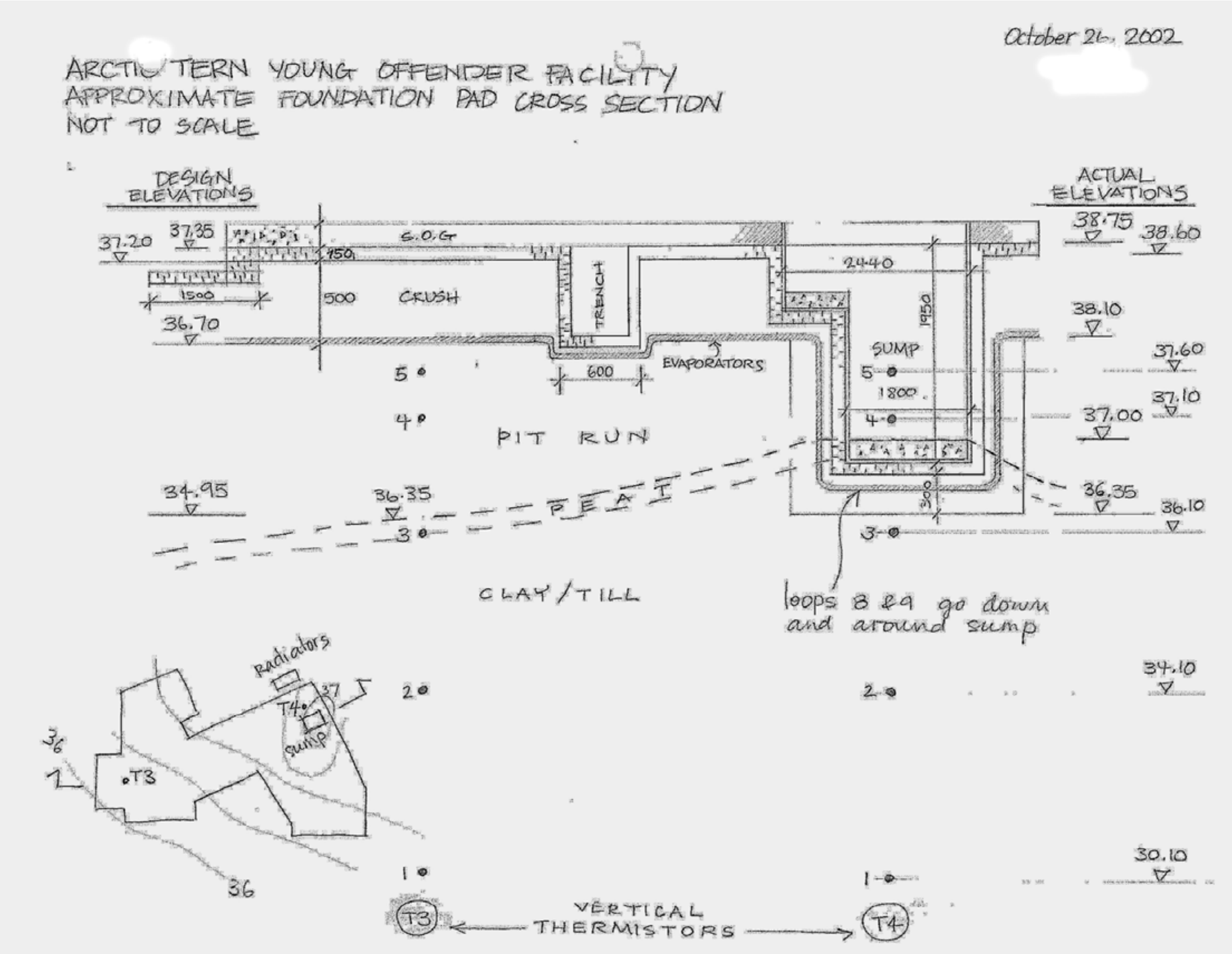

Figure A 15. Schematic of the foundation pad cross section (Public Works & Services files)

Figure A 16. Photo showing layout of evaporator pipes and their crossing trenches, FYOF, Inuvik, NT.

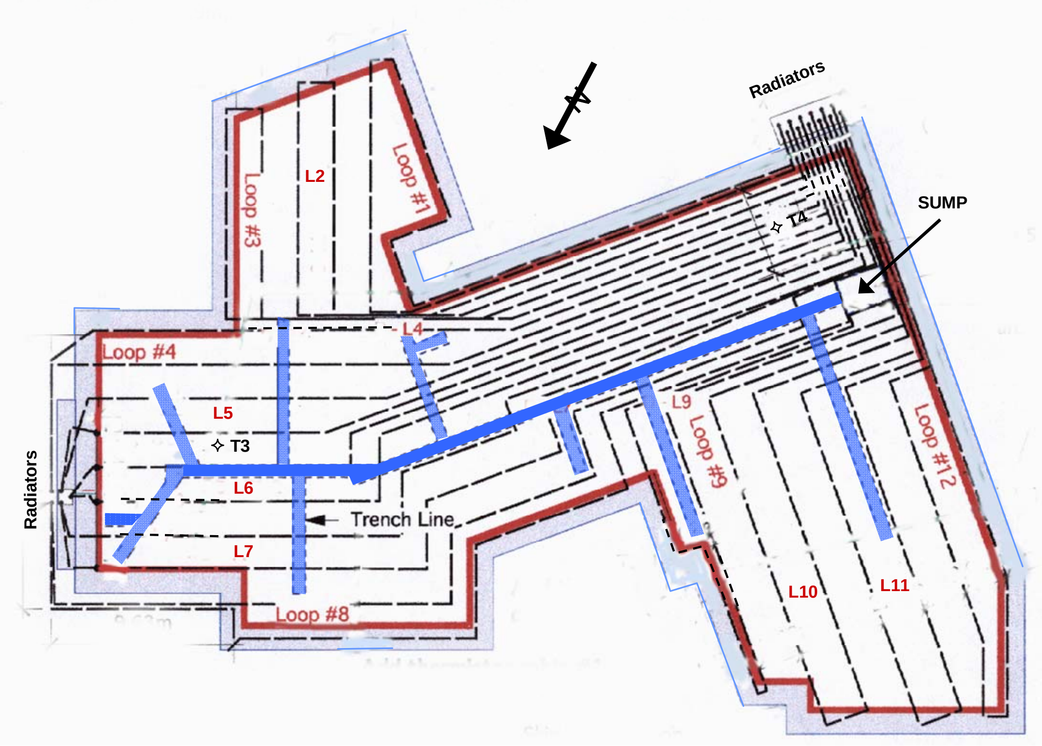

Figure A 17. Plan showing the layout of evaporator piping and trenches, FYOF, Inuvik, NT

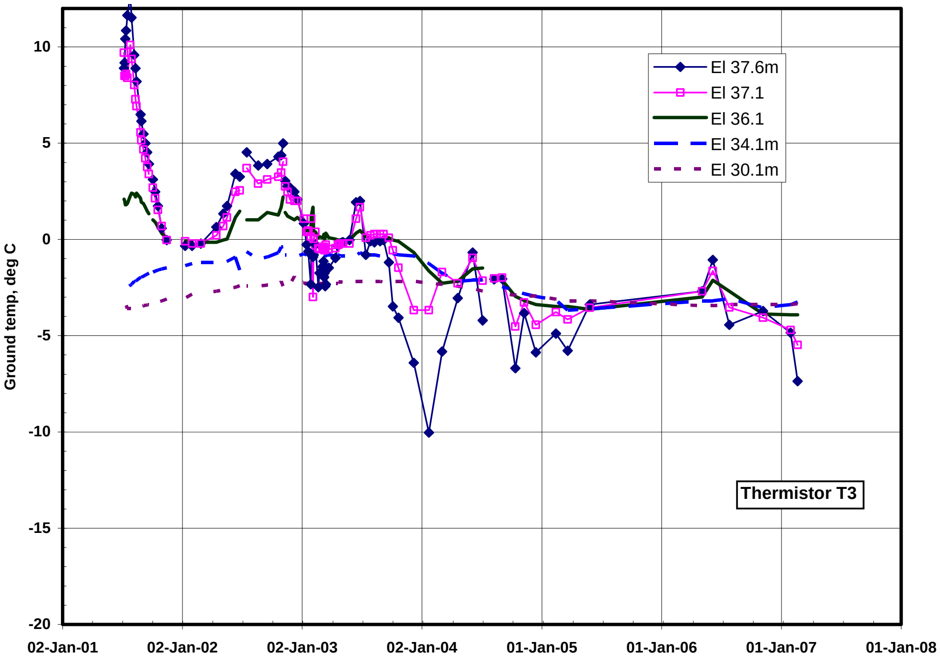

Figure A 18. Ground temperature records at thermistor cable T3, East area of FYOF, Inuvik, NT

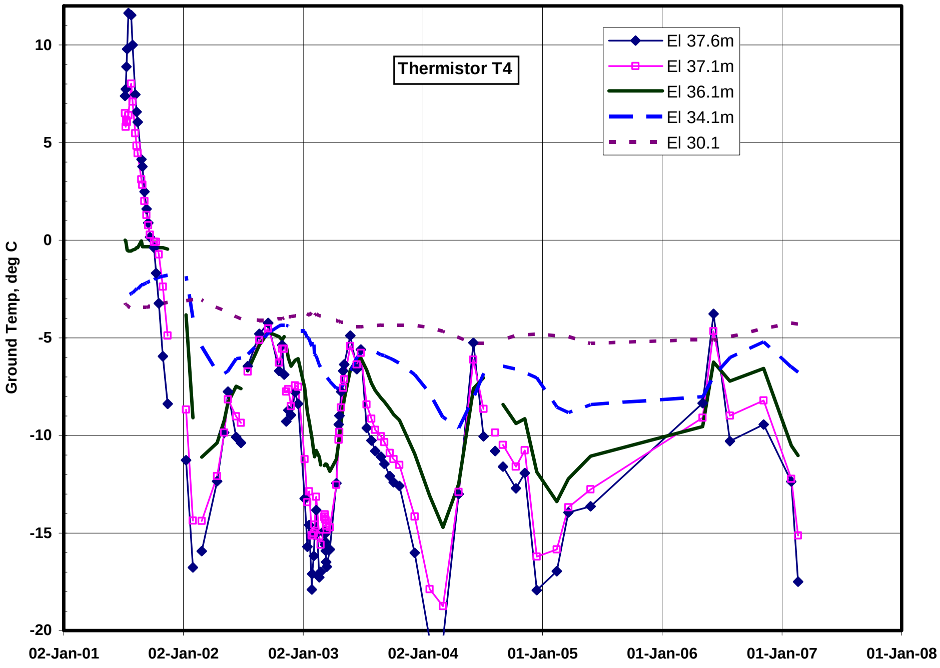

Figure A 19. Ground temperature records at thermistor cable T4, West area of FYOF, Inuvik, NT

Figure A 20. Junction boxes moving down and out due to fill settlement, FYOY, Inuvik, NT

Figure A 21. Fill settlement at exercise yard, FYOF, Inuvik, NT

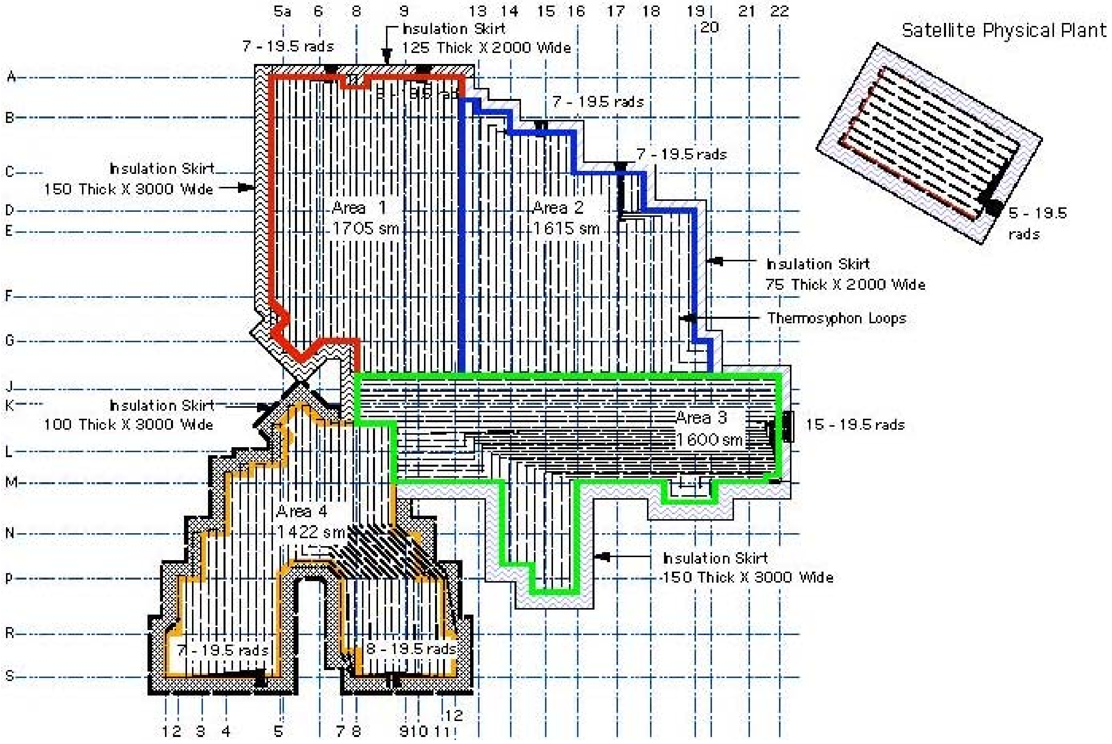

Figure A 22. Layout of evaporator pipes, Inuvik Hospital, NT

Figure A 23. Foundation and radiators with chillers under construction, Inuvik Hospital , NT

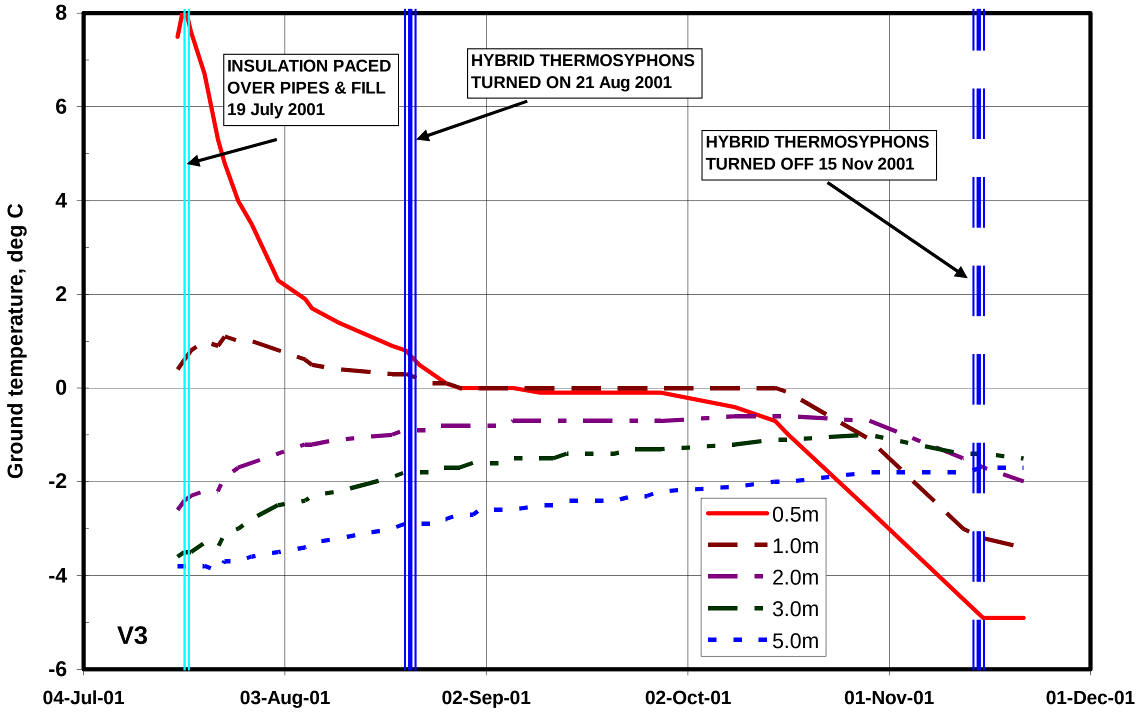

Figure A 24. Ground temperature changes from completion of thermosyphon pad to switching off hybrid cooling in 2001, Inuvik Hospital, NT

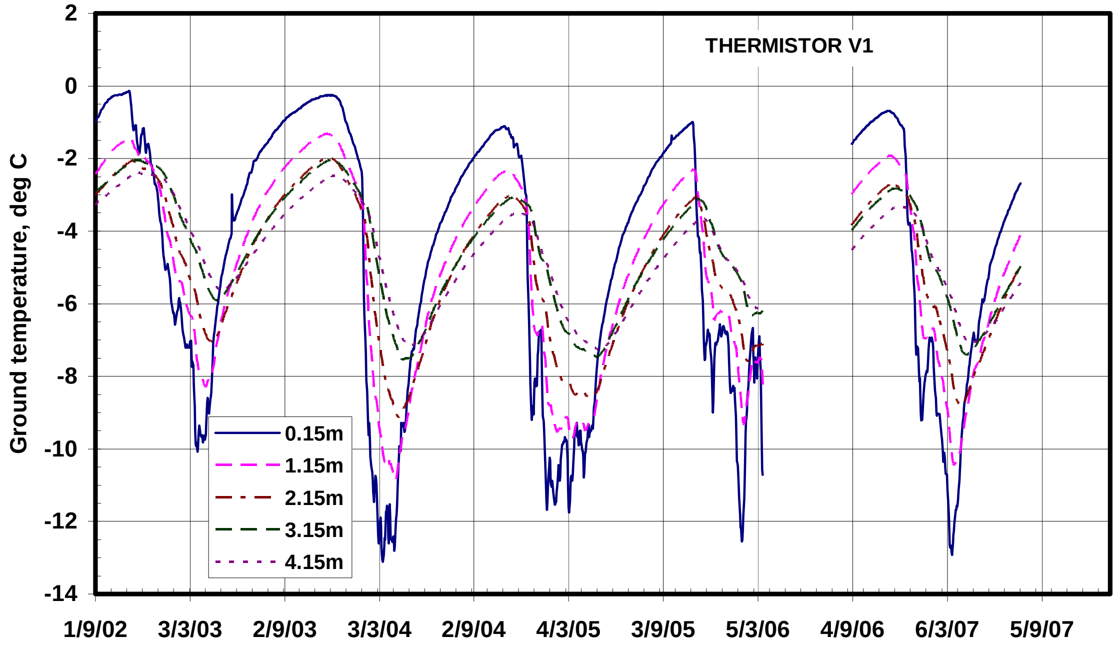

Figure A 25. Ground temperature changes during passive thermosyphon operation from Sept 2002 to Aug 2007, Inuvik Hospital, NT

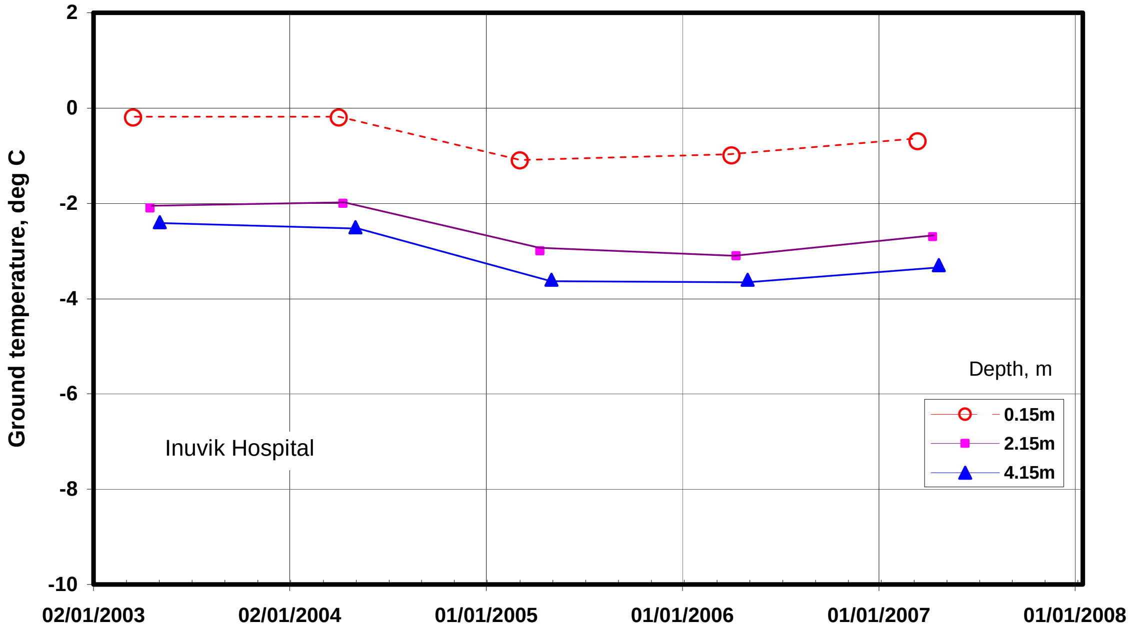

Figure A 26. Maximum ground temperatures recorded from 2003 to 2004, Inuvik Hospital, NT

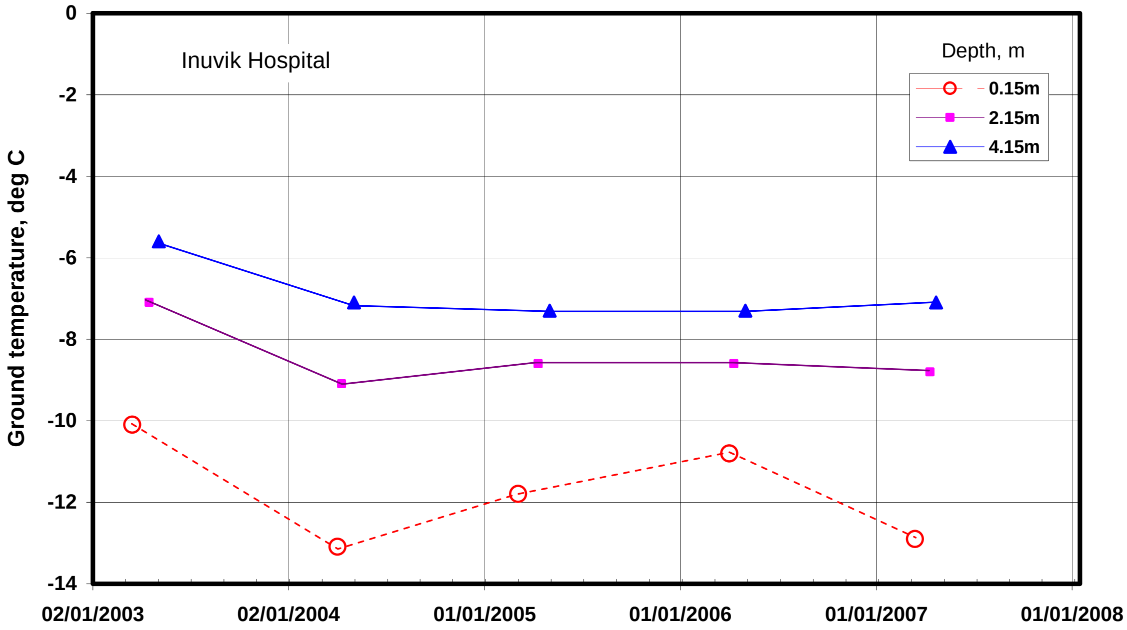

Figure A 27. Minimum ground temperatures recorded from 2003 to 2007, Inuvik Hospital, NT

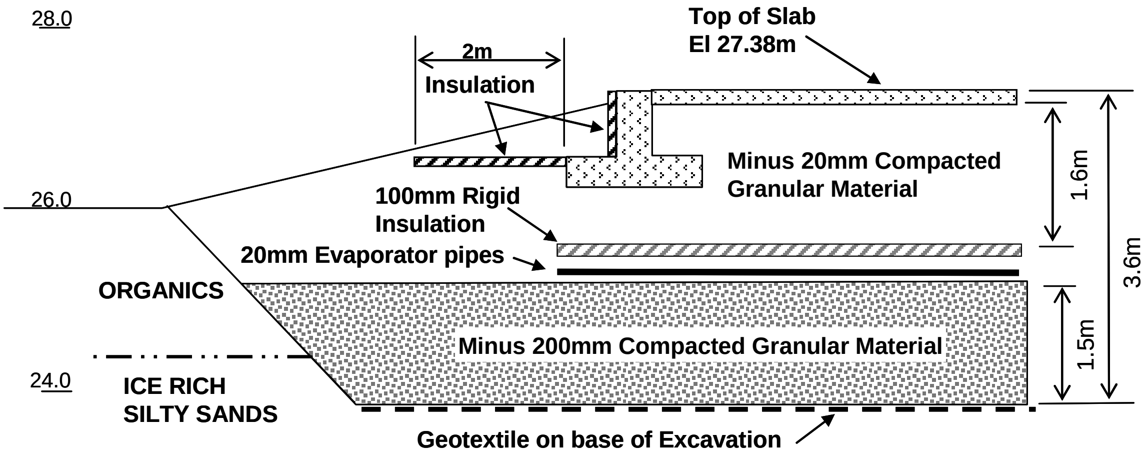

Figure A 28.. Schematic of thermosyphon foundation at Aurora College, Inuvik, NT

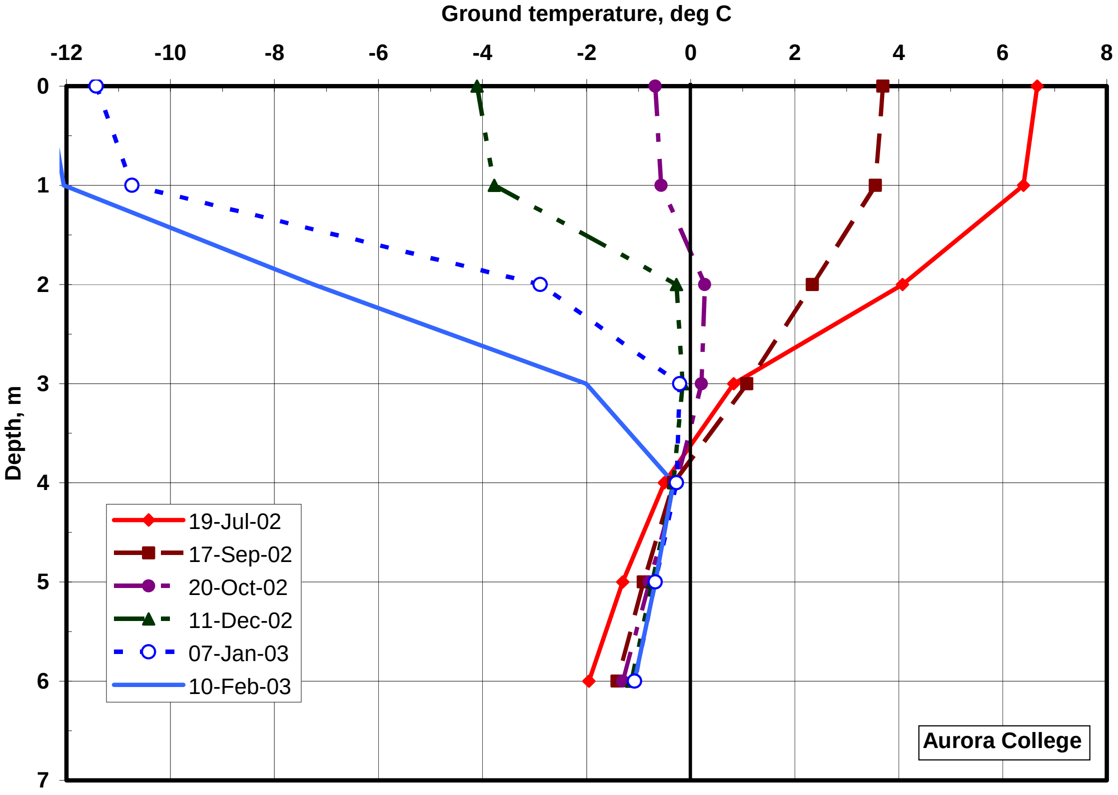

Figure A 29. Ground temperature profiles at thermister cable T5, Aurora College, Inuvik, NT

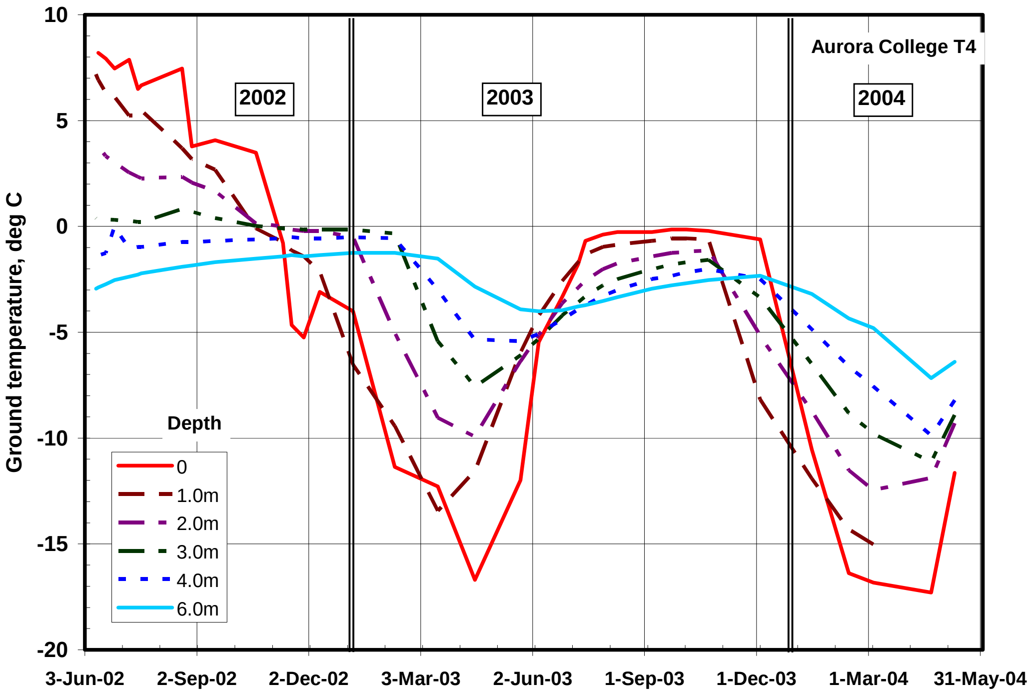

Figure A 30. Foundation temperature changes with time at thermister cable T5, Aurora College, Inuvik, NT (Depth measured from evaporator pipes)

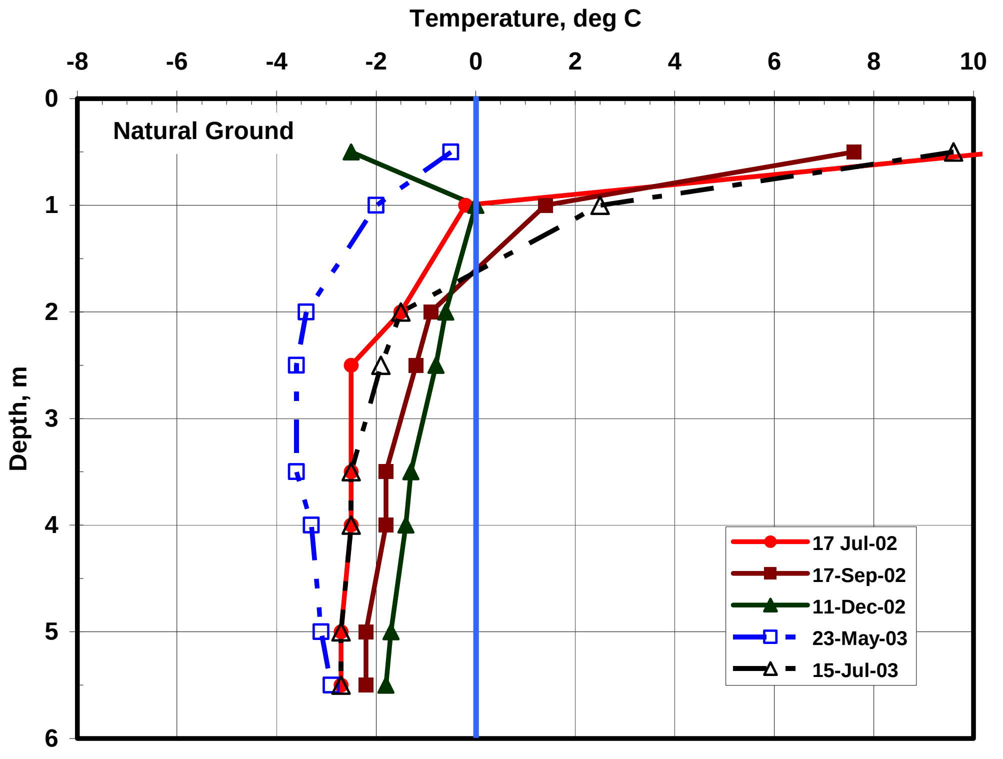

Figure A 31.Temperatures in natural ground, Aurora College, Inuvik, NT

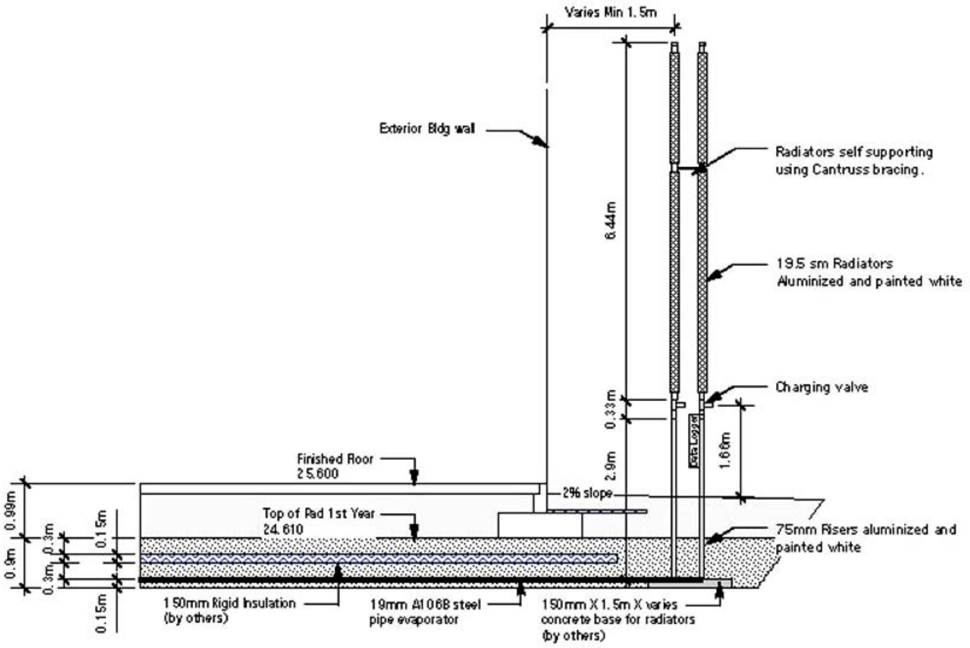

Figure A 32. Thermosyphon detail, RCMP Building, Iqaluit, NT

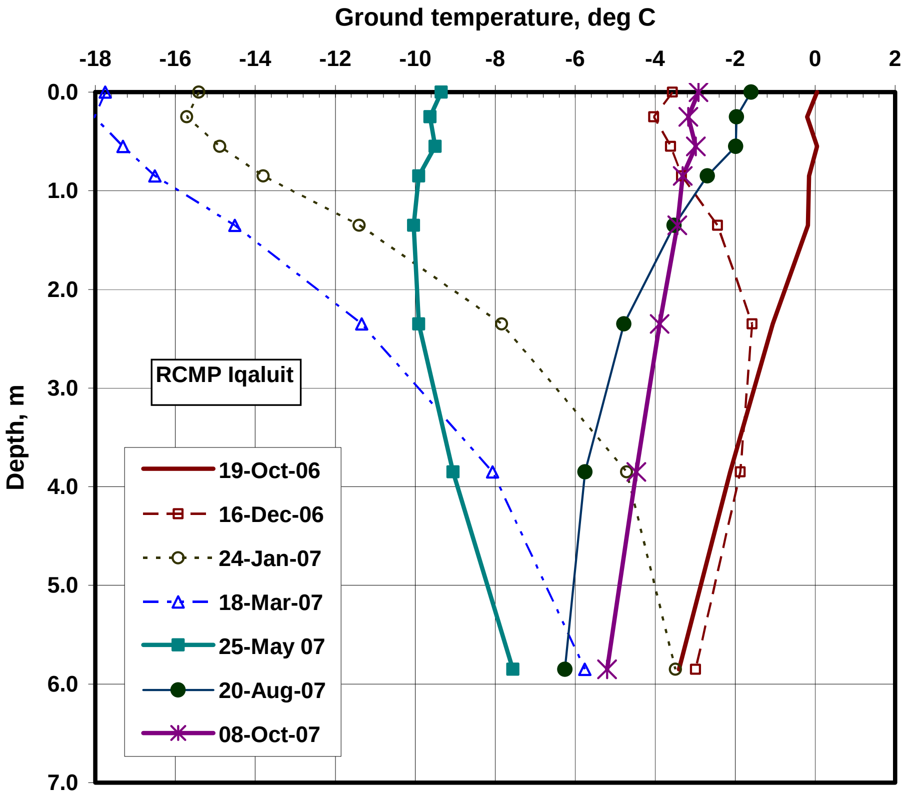

Figure A 33. Ground temperature measurements at RCMP Building, Iqaluit, NU

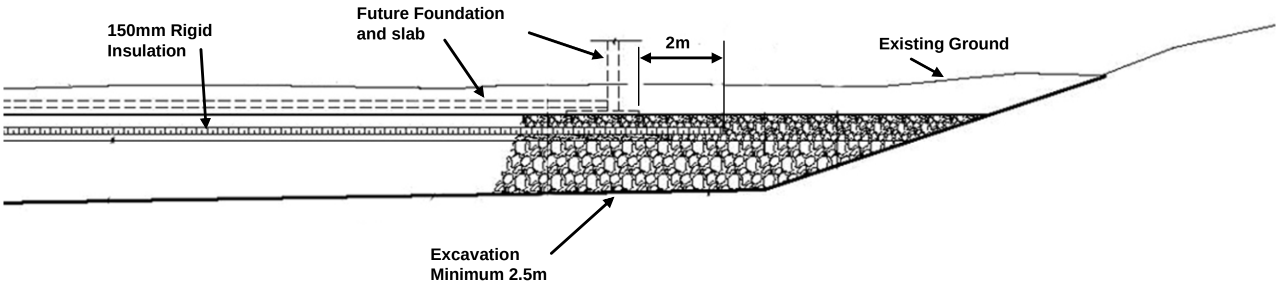

Figure A 34. Excavation and backfill for Health Centre granular foundation, Pangnirtung, NU

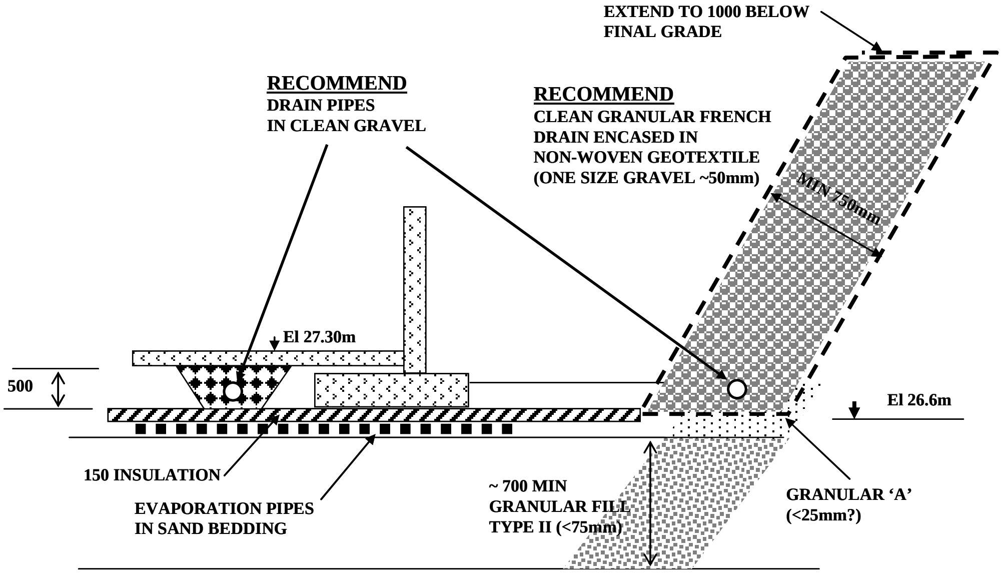

Figure A 35. Detail and drainage control for Health Centre foundation, Pangnirtung, NU

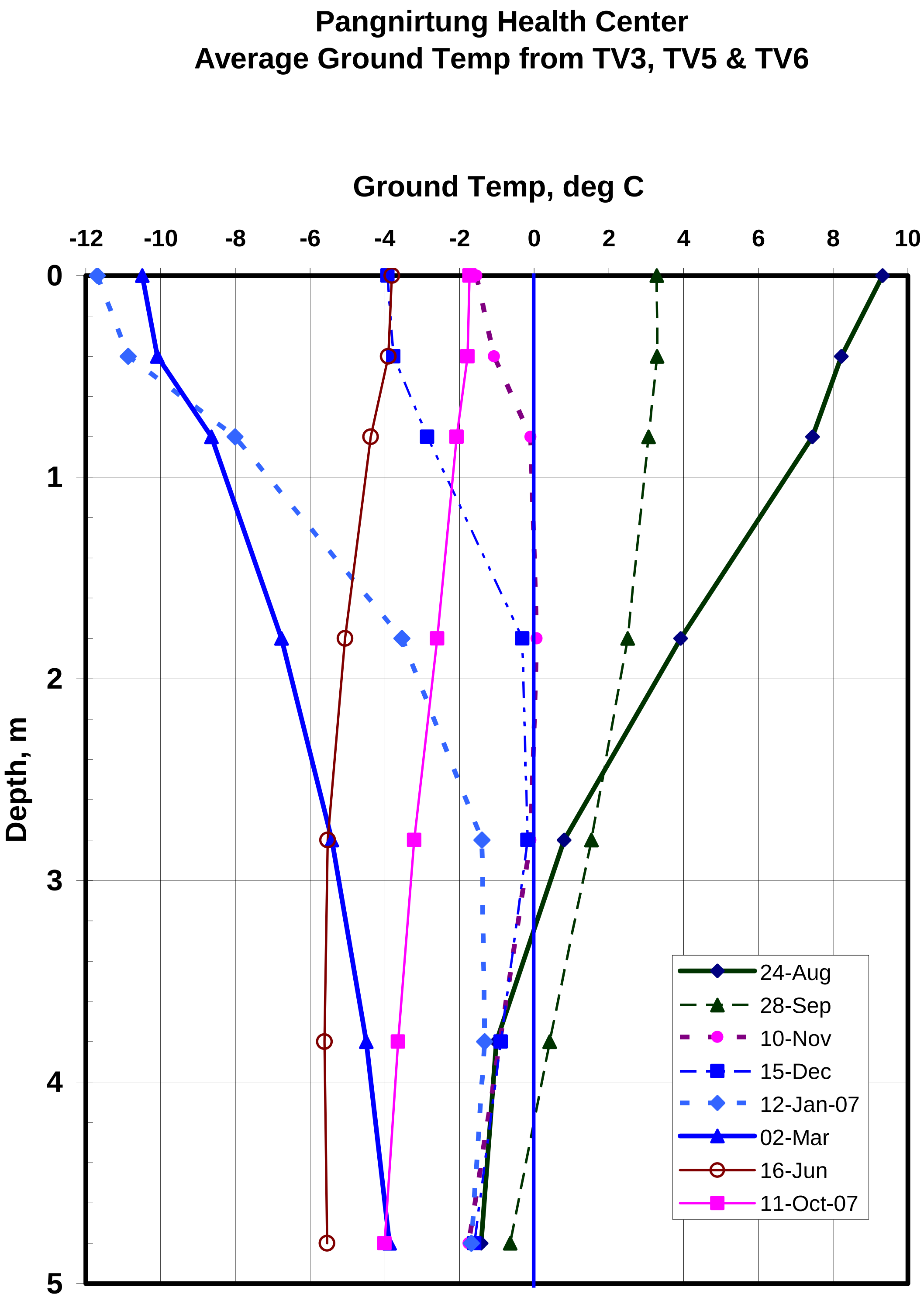

Figure A 36. Ground temperature changes after thermosyphon foundation installation from 2006 to 2007, Health Centre, Pangnirtung, NU (Depth measured from evaporator pipes)

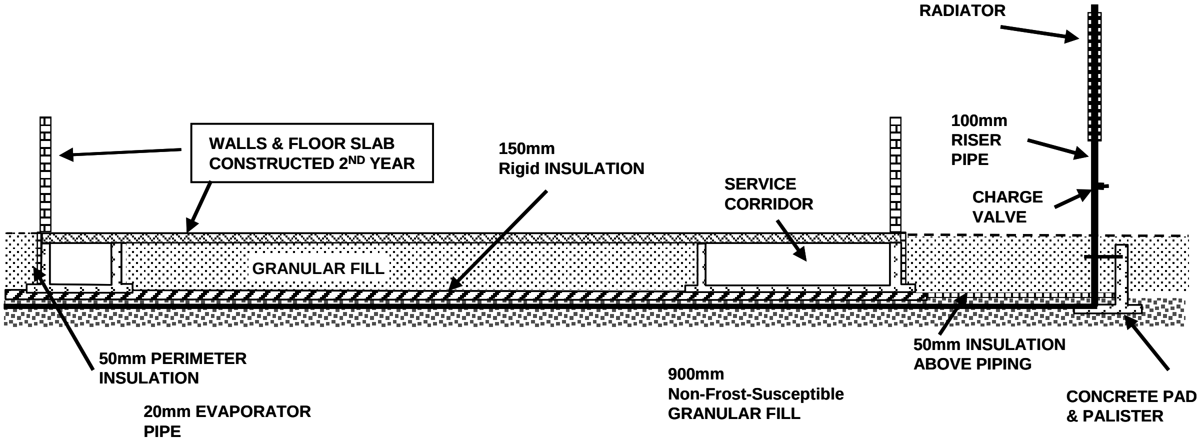

Figure A 37. Foundation design for Kuujjuaq Air Terminal, QC

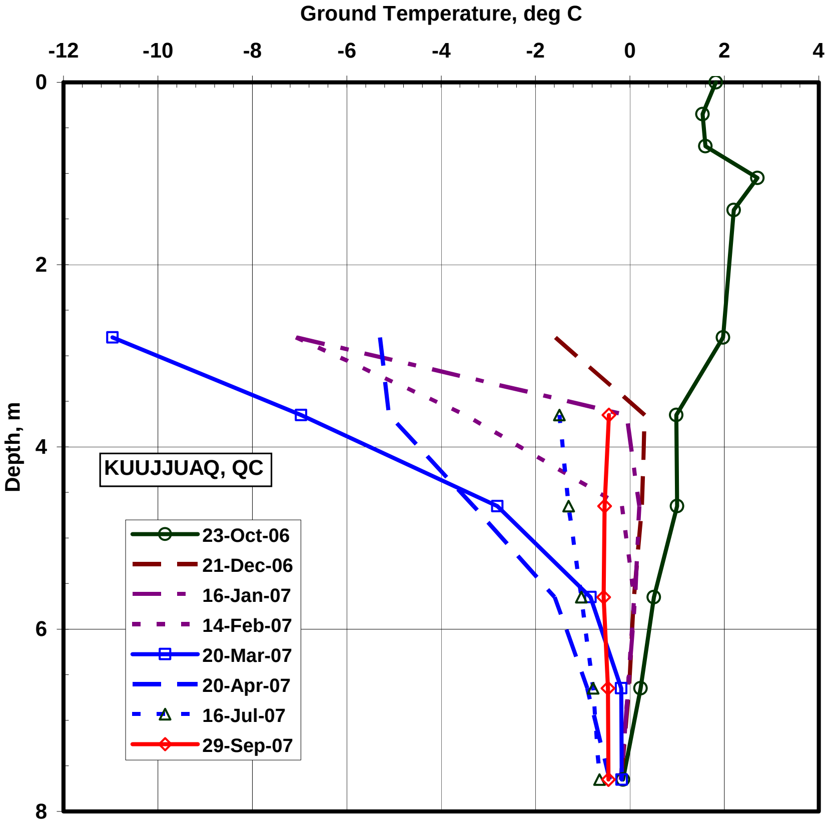

Figure A 38. Ground temperature changes after thermosyphon foundation installation, Kuujjuaq Air Terminal, QC. (Depth measured from evaporator pipes)

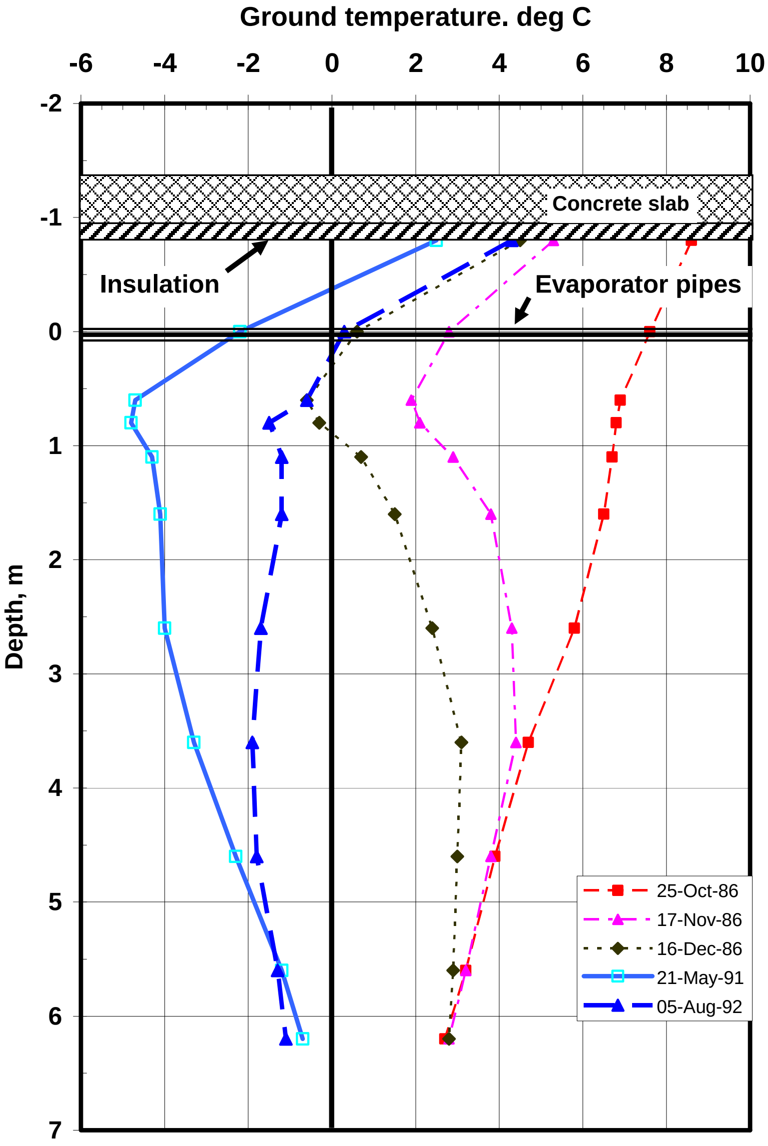

Figure A 39. Ground temperatures at Kuujuaq service building with sloping thermosyphon foundation installed in 1986.