Thermosyphon foundation design and performance at Iqaluit ATB and CSB

Ed Hoeve[1], Brent Wall[2] & Justin Panagapko[3]
[1]*HoevEng Consulting Ltd., Yellowknife, Northwest Territories, Canada*
[2]*Achieve Engineering Inc., Winnipeg, Manitoba, Canada*
[3]*Arctic Foundations of Canada Inc., Elie, Manitoba, Canada*

Abstract

The Air Terminal Building and Combined Services Building at Iqaluit Airport are supported on thermosyphon stabilized foundations. The design incorporated the use of a "warm fill" layer above the thermosyphon system to facilitate the installation of below-grade utilities and services. This foundation design concept was an innovative variation and has since become a typical configuration for large-scale flat loop thermosyphon systems. This design concept is described. The design review analyses considered three short-term severe climatic conditions as well as projected climate warming over an assumed 50-year service life. The climate assumptions are reviewed, and the short-term conditions are found to remain conservative, but the climate change assumption may not be. The foundations were constructed in 2014 and 2015. Instrumentation was installed at the time of construction to permit the thermal performance of the foundation to be monitored. Performance monitoring data are reviewed. The available data indicate that thermal performance to-date has exceeded design expectations. The implications of the performance to-date with respect to the climatic assumptions are reviewed. Satisfactory long-term performance is still anticipated.

1 Introduction

The Iqaluit International Airport is key component of Nunavut's transportation infrastructure and Canada's sovereignty in the Arctic. It is a hub for air travel in the eastern territory, and a Forward Operating Location, operated by Defence Canada, is located there. About 10 years ago the Iqaluit International Airport Improvement project was implemented by the Government of Nunavut to improve the airside surfaces and replace two major buildings. The project was procured as a Public-Private Partnership, which was awarded to Arctic Infrastructure Limited Partners.

The new Air Terminal Building (ATB) and Combined Services Building (CSB) were constructed between 2014 and 2017 as part of the airport improvement project. Design of the buildings was coordinated by Stantec Architecture Ltd. Best (2017) provides an overview of the design features of the ATB.

Each building is founded on concrete spread footings and has a concrete slab-on-grade floor. The permafrost under the building is protected with thermosyphons and insulation. The thermosyphon system was delivered as a design-build by Arctic Foundations of Canada Inc. Thermal design of the foundation system was developed by Achieve Engineering Inc. Tetra Tech EBA Inc. was retained to provide geotechnical services to the project, including independent review of the thermosyphon system design.

The objective of this paper is to review the thermal performance of the foundation since construction, specifically with respect to the expectations at the time of design, but also to consider the implications of evolving climate warming projections since design.

2 Design and Construction Summary

Space does not permit a thorough description of the foundation design, nor is that the purpose of this review. However, since the design has not been previously documented in an accessible publication, key elements of the design are summarized in the following sections.

2.1 Site Characterization

The community of Iqaluit is located at the northeast end of Frobisher Bay, on Baffin Island. The airport is situated at the northwest edge of the community. Figure 1 shows the location of the buildings at the airport.

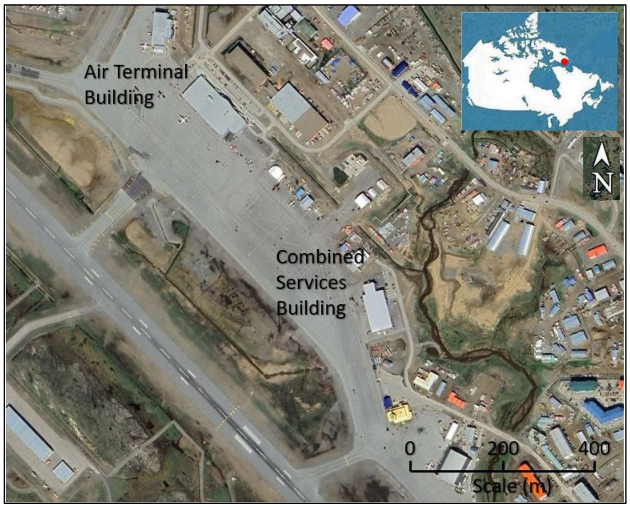

Figure 1. Site location plan.

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Broadly, the town is located in an area composed of predominantly quaternary sand sediments, with some granite bedrock outcrops (St-Onge et. al. 1999). The surficial geology of the area of the airport where the buildings were constructed was mapped in more detail as a glaciomarine delta (Allard et.al. 2012), though a glaciofluvial channel passes along the southeast edge of the ATB. Numerous frost cracks and ice wedges were mapped in the delta unit.

The airport site was generally investigated for the purpose of improvement project procurement (Peto MacCallum 2012a, b). The building areas were specifically investigated to support foundation design (EBA 2013).

The ATB is situated on and adjacent to a pre-existing airport apron. Where fill thickness was discernable, it was interpreted to range from about 1.0 m to 1.2 m in thickness. The CSB site was vacant prior to building construction, and while the surficial soils may have been reworked, fill was not detected. The prevalent native soil is sand. The sand was determined to generally be gravelly near the ground surface and the fines content (silt and clay-sized particles) increased with depth, such that silty sand was logged in about half the holes below about 8 m. Natural moisture contents in the sand were measured to range from 3% to 18%, and average 10% by volume, so were not high. Bedrock was not encountered within the maximum 33 m depth drilled in any of the investigations.

The community is in the continuous permafrost zone, and the ground ice is broadly characterized as low (i.e., less than 10% by volume; Heginbottom et. al. 1995). This generalization was confirmed during the site investigations. Active layer thickness was interpreted to range from about 2.5 m to 3.5 m. Ground ice was generally non-visible, with occasional traces of visible ice, which is consistent with the moisture content data. Mean annual ground temperatures, below a depth of zero annual amplitude, were found to be about -4 °C at the ATB site and -3 °C at the CSB site. The difference in ground temperature was attributed to snow being cleared from the apron area in the winter. Porewater salinity was found to be negligible at the site.

2.2 Annual Air Temperatures

At the time of design, the available Environment Canada climate normals were for the interval 1981–2010. Climate change was considered during design in accordance with the guidance of CSA (2010); specifically, a moderate emissions scenario was assumed (AR4-A1b). The possibility of anomalous years was considered through a probabilistic analysis of annual air temperature data to arrive at a 1:10 warm year and a 1:100 warm year. 2010 was warmer than the 1:100 warm year, so was considered an “extreme” warm year (Tetra Tech EBA 2014). The properties of each of these cases is summarized in Table 1.

Table 1. Summary of climatic conditions considered in thermal review.

Climatic Case	Annual Air Temperature (°C)	Freezing Index (C°-days)	Thawing Index (C°-days)
Mean (1981-2010)	-9.0	3938	673
1 in 10 Warm Year	-7.1	3350	790
1 in 100 Warm Year	-5.4	2850	900
Extreme Warm Year (2010)	-4.3	2437	904
Estimated in 2065 with Projected Climate Change (AR4-A1b)	-6.5	3192	837

Note: table derived from Table 5.3.4-1 (Tetra Tech EBA 2014).

To assess the anticipated thermal performance of the foundation system, the following cases were modeled (Tetra Tech EBA 2014):

- Long-term mean air temperatures (1981 to 2010);
- 10 years of mean air temperatures followed by 5 consecutive 1 in 10 return event warm years;
- 10 years of mean air temperatures followed by 2 consecutive 1 in 10 return event warm years plus one 1 in 100 return event warm year;
- 10 years of mean air temperatures followed by 2 consecutive 1 in 10 return event warm years plus one extreme warm year (2010); and
- 50 years of estimated air temperatures with the projected long-term climate change, assuming AR4-A1b (moderate) emissions scenario (CSA 2010).

Two-dimensional geothermal analyses were carried out using Tetra Tech EBA’s proprietary finite element computer model, GEOTHERM. The model simulates transient heat conditions with change of phase for a variety of boundary conditions, including heat flux, temperature, and ground-air boundaries using an energy balance equation (Tetra Tech EBA 2014). The theoretical formulation of the model is discussed in Hwang (1976).

2.3 Thermosyphon Design Configuration

While the use of adfreeze steel pipe piles for building foundations was considered, the desire for slab-on-grade floors resulted in a horizontal thermosyphon stabilized foundation system being selected. The generalized foundation configuration is summarized in Figure 2.

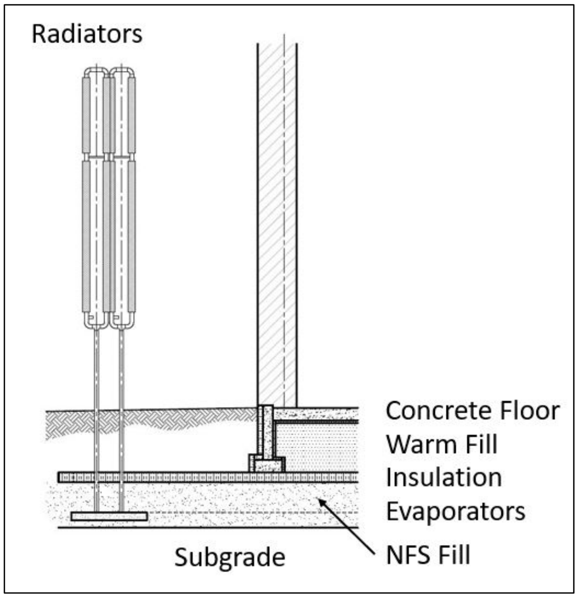

Figure 2. Thermosyphon system section.

The provision of a warm fill layer above the insulation was a relatively new, innovative variation of the foundation system at the time. The warm fill facilitates mechanical installations below the floor without compromising the continuity of the insulation layer. Incorporation of a warm fill layer has become the norm in design of buildings with at-grade floors. Concrete spread and strip footings were cast on the insulation layer. A summary of the design configuration of each building is presented in Table 2.

Table 2. Thermosyphon Stabilized System Configuration.

Item	ATB	CSB
Building Size	8112 m^2	4589 m^2
Assumed Average Floor Temperature	20°C	20°C
Concrete Floor Thickness	125 mm	150 mm
Warm Fill Thickness	875 mm / 2450 mm (airside edge)	850 mm / 2850 mm (airside edge)
Insulation Thickness	200 mm	200 mm
Perimeter Insulation Width	3000 m	3000 mm
Non-Frost-Susceptible Fill Thickness	1000 mm	1000 mm
Radiators	63 – 39 m^2; 4 – 19.5 m^2	34 – 39 m^2
19 mm dia. Evaporator Spacing	1100 mm – 1670 mm	1500 mm
Evaporator Loop Length	85 m – 165 m; avg. 129 m	87 m – 148 m; avg. 126 m

Extensive use was made of 39 m^2 radiators to accommodate the long loop lengths, i.e., more than 100 m, dictated partially by the sizes of the buildings but also by constraints on the permissible locations of radiators. At the time, this was unprecedented in Canada.

There were two deviations from the foregoing generalized profiles:

- The requirement for an elevator in the ATB necessitated the construction of a pit, which deviated from the above generalized configuration. The elevator pit was accommodated by increasing the insulation thickness to 300 mm below and around the base, increasing the non-frost-susceptible fill (NFS) thickness to 1.3 m below, and supplying a dedicated evaporator loop to the bottom of the elevator pit; and
- The floor of the CSB had a sump with an oil interceptor at the transition between the “thin” and “thick” warm fill sections. The sump had a 200 mm thickness of insulation installed on all sides, and the lower level of horizontal insulation below the sump was kept continuous, such that there were two layers of insulation below the sump.

2.4 Construction

The thermosyphons, insulation and footings were constructed in 2014. Figure 3 shows a typical evaporator layout. Thermosyphons were active during the winter of 2014/15.

Figure 3. Evaporator installation at the ATB. Rigid insulation is stockpiled in the background.

Freeze-back of the subgrade was confirmed by March 2015. The balance of fill placement and superstructure erection occurred in the summer of 2015. Temporary construction heat began in the winter of 2015/16. The buildings were turned over for operation in the summer of 2017. Figure 4 shows several radiator banks in front of the completed building.

Figure 4. Front of the ATB showing three radiator banks.

While the possible presence of ice wedges was mapped in the area, none were detected during the site investigation for the project, nor during excavation for foundation construction.

Thermistor cables were installed to permit ground temperatures to be monitored. The thermistor cables, dataloggers and associated telemetry equipment were supplied by BeadedStream of Anchorage, Alaska. The dataloggers became operational in late 2014. The installed instrumentation is summarized as:

- 4 horizontal thermistor cables at the ATB, with a total of 67 sensors, intended to record ground temperatures adjacent to each evaporator loop;
- 4 vertical thermistor cables at the ATB, one inside the building in the area of "thin" warm fill, one in the area of "thick" warm fill, and two about 6 m away from the building, with 12 sensors on each cable, installed to a nominal depth of 12 m;
- 2 horizontal thermistor cables at the CSB, with a total of 34 sensors, intended to record ground temperatures adjacent to each evaporator loop; and
- 4 vertical thermistor cables at the CSB, one inside the building in the area of "thin" warm fill, one at the transition between "thin" and "thick" warm fill, and two about 6 m away from the building, with 12 sensors on each cable, installed to a nominal depth of 12 m.

3 Evaluation of Performance Since Construction

3.1 Review of Annual Air Temperatures

Actual annual air temperature characteristics since 2015 are summarized in Table 3.

Table 3. Summary of Climatic Conditions Since Construction.

Year	Annual Air Temperature (°C)	Seasonal Freezing Index (C°-days)	Thawing Index (C°-days)
2015	-11.1	4309	445
2016	-8.3	3795	705
2017	-7.8	3825	690
2018	-9.4	3648	545
2019	-6.8	3643	787
2020	-7.8	3450	788
2021	-6.1	2996	664
2022	-8.0	3517	807
2015-2022 Average	-8.2	3648	679

Note: seasonal freezing index refers to the freezing index from the fall of the previous year to the spring of the current year.

Comparing the actual annual air temperature conditions in Table 3 with the assumed conditions presented in Table 1, two years were colder than modeled (2015 and 2018), one year was warmer than the 1:10 warm year (2019) and one year was warmer than the projected 2065 mean year (2021, though mainly because of the warm winter; the thawing index was relatively low that year).

The average annual air temperature since construction has been about -8.2 °C. The special cases modeled by Tetra Tech EBA (2014) gave annual averages of -8.4 to -8.5 °C over the 13 to 15-year intervals modeled. Therefore, the average climate since construction compares reasonably with any of the modeled special cases. While one might assume that potential thaw penetration in a particular year would be governed by the thawing index in that year, the heat load from the building is the dominant factor under most of the building and is somewhat independent of the climate.

3.2 Projected Climate

The projected climate change warrants review. The scenario assumed at the time of design is now known to be unconservative Current practice is to assume an AR5-RCP8.5 emissions scenario (CSA 2019). The projections from these scenarios are compared to the 30-year moving average air temperature for Iqaluit in Figure 5. Figure 5 suggests that even the current guidance for climate change may be unconservative.

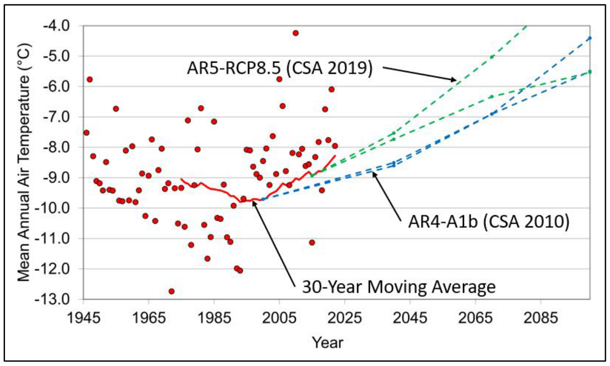

Figure 5. Comparison of climate change projections at Iqaluit with 30-year moving average of mean annual air temperature.

3.3 Review of Selected Ground Temperatures

3.3.1 Ground Temperature Profiles

Ground temperature data have been collected since the end of 2014, though there are some gaps. CSA (2010 and 2019) contains the statement "monitoring is pointless unless the data collected are evaluated". That is the primary motivation for the review described herein.

The ground temperatures recorded along the vertical thermistor cables at each building can be compared to the predictions presented in the review by Tetra Tech EBA (2014). Specifically, the ground temperature along cables V1 in each building (in the area of "thin" warm fill) can be compared to the predictions from the finite element model for Sections 1-1 for each building, and for the climatic case of 10 mean years, followed by two 1:10 warm years, followed by one extreme warm year (2010). The average annual air temperature for this assumed 13-year case would be -8.4°C, which is slightly cooler, but close to the -8.2°C average actually experienced since construction (Table 3). The comparison for each building is shown in Figure 6.

It is evident that the ground below the buildings is significantly colder than was predicted by the modeling during the design review. The design would be expected to have been conservative. The convective heat transfer characteristics of the thermosyphons were based on empirical expressions presented in Haynes and Zarling (1988). One conservative assumption is that wind speed was assumed to be half that reported from the available climate data.

The plots of actual temperature in Figure 6 show that the ground in locally cooler at about evaporator level. This indicates that the evaporators had recently become active, prior to November 15, 2022.

Vertical cables V2 in each building are in or adjacent to areas of "thick" warm fill, and deeper evaporators, so are in less sensitive areas of the buildings and are not specifically reviewed here.

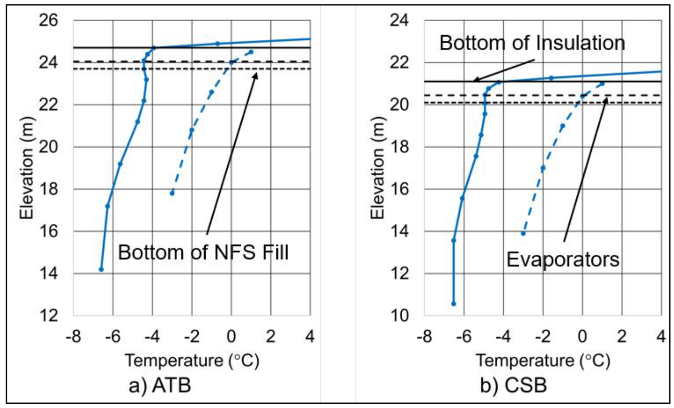

Figure 6. Comparison of measured ground temperature November 15, 2022 (solid line) to predicted (dashed line) after 10 mean, 2 1:10, and 1 extreme year (predicted profiles were extracted from Figures 2 and 6 in Appendix C of Tetra Tech EBA 2014).

3.3.2 Thaw Penetration

A specific design criterion was that thaw should not reach the base of the non-frost-susceptible fill. The ground temperature history within the non-frost-susceptible fill is shown in Figure 7.

The almost isothermal maximum end of the ground temperature envelope for the non-frost-susceptible fill in the ATB (Figure 7a) reflects an anomaly in the data. Apparent warm temperatures were recorded from about October 17 to December 8, 2019, reaching the indicated maximum on November 1, 2019. The ground temperatures of the nearest horizontal sensors (Loops 5 and 6), at evaporator level, were recording about -2.9°C at the same time. The reason for the anomaly is not known.

Removing the apparently anomalous data from the plot results in the dashed red line in Figure 7a, which compares well with what was observed in the horizontal sensors and the similar plot for the CSB (Figure 7b).

The data indicate that thaw did not penetrate below evaporator level since the later stages of building construction. Considering the relatively small temperature gradients through the non-frost-susceptible fill, the interpretation is that there has been no significant thaw below the insulation layer since the buildings have been constructed.

Further insight into the thermal conditions within the non-frost-susceptible layer can be gained by review the temperature records from the horizontal thermistor cables, which were at evaporator level (about 350 mm above the base of the non-frost-susceptible fill). A summary of the data from 2016 to 2022 is presented in Table 4. The data from 2015 are not included because initial freeze-back was still occurring in the first part of the year.

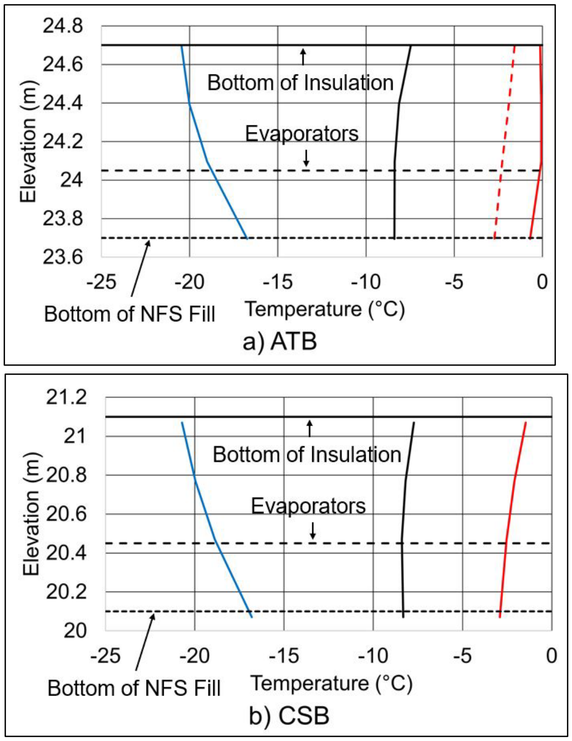

Figure 7. Observed ground temperature profiles through non-frost-susceptible fill layer (blue denotes minimum; black denotes average; red denotes maximum).

Table 4. Summary of Horizontal Thermistor Cable Temperature Readings (2016–2022).

Cable	Maximum (°C)	Minimum (°C)	Average (°C)
ATB H1 (Loops1-2; 64-66)	-1.9	-24.1	-8.9
ATB H2 (Loops 3-19; 54-56)	-2.3	-19.7	-8.6
ATB H3 (Loops 20-53)	-1.2	-20.1	-8.9
ATB H4 (Loops 59-63)[1]	-7.2	-20.8	-12.1
CSB H1 (Loops 1-14)	-2.0	-24.1	-9.1
CSB H2 (Loops 15-28)	-0.8	-16.8	-7.7
Elevator Pit	-2.5	-14.3	-6.5

Note 1: Cable ATB H4 only reflects a portion of 2016 data, as the cable was destroyed at the end of June 2016.

3.3.3 *Climate Change Revisited*

While thermal performance to-date has exceeded expectations, it is prudent to consider the implications of updated guidance with respect to potential climate warming. The modeling has been updated, this time using commercially available software, TEMP-W, considering prevailing ground temperature conditions and climate warming under an AR5-RCP8.5 (high) emissions scenario (CSA 2019). The findings are shown in Figure 8, together with the original predictions to October 15, 2065.

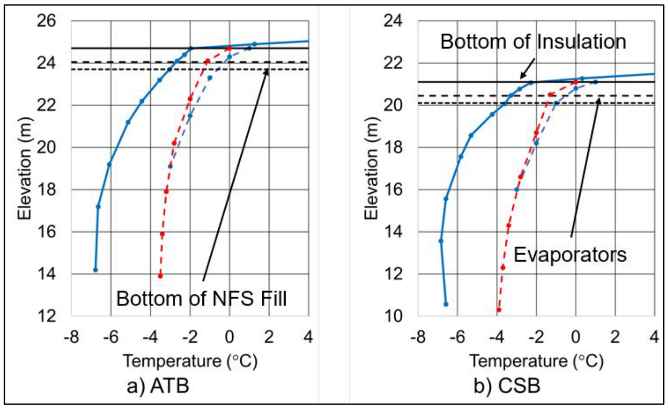

Figure 8. Actual ground temperature profiles October 15, 2022 (solid line) compared with original (dashed blue line) and updated (dashed red line) predictions for October 15, 2065 (original predicted profiles were extracted from Figures 1 and 5 in Appendix C of Tetra Tech EBA 2014).

The updated predictions, based on current guidance, suggest that ground thermal performance of the foundation system should still be satisfactory at the end of the desired service life. However, as current observations suggest that the ambient temperature predictions may be unconservative, the overall system performance should continue to be monitored and evaluated.

There are two deviations from the intended ground temperature monitoring system that should be considered:

- At the CSB, the portions of the horizontal thermistor cable that were intended to monitor the evaporators below the "thick" warm fill were installed at the same, higher elevation as the remainder of the sensors. Consequently, these sensors were installed in warm fill, and do not reflect ground temperatures at the deeper evaporators (Loops 29 to 34); and
- Data from Cables ATB-H4, ATB-V3 and ATB-V4 are not available following June 2016. It is understood that these cables were damaged during construction. Cable ATB-H4 records temperature at evaporator level for Loops 57 to 63. Cables ATB-3 and ATB-4 are outside the building.

As the affected horizontal cables are not able to confirm functionality of their associated evaporator loops, the functionality of those thermosyphons should be regularly checked by recording temperatures at the radiators, early in the freezing season.

4 CONCLUSIONS

Annual air temperatures since construction have averaged within the ranges contemplated at the time of design. However, it is now recognized that climate warming is likely to be greater than assumed at the time of design.

The thermal performance of the thermosyphon system at each building has exceeded design expectations to-date. Specifically, the ground below the buildings has been cooled more than predicted and thaw penetration has not extended significantly below the insulation, which is 1 m above the bottom of the non-frost-susceptible fill layer.

The thermal performance is expected to remain satisfactory under the current understanding of climate warming. However, this should continue to be monitored and evaluated as climate change projections continue to evolve.

The ground temperature data being collected permits most facets of thermosyphon system performance to be evaluated. But there is also merit in regularly monitoring radiator temperatures to gain a more complete understanding of system performance.

5 ACKNOWLEDGEMENTS

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