PERFORMANCE OF HEAT PUMP CHILLED FOUNDATIONS

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Abstract

Standard domestic ground coupled heat pump technology has been applied to maintain frozen ground in and beneath insulated slab-on-grade foundations while simultaneously providing substantial heat for the building itself. Thermal and economic performance data are presented for the first year of operation of two 350 m^2 multi-purpose municipal garage buildings located on permafrost in the Yukon. The two cases bracket the range of soil conditions, ground temperatures, operating conditions and logistic problems likely to be encountered in practice. The thermal regime within the foundations was simulated by a numerical model and the results were used to suggest ways of improving the design. The ground coupled heat pump chilled foundation has the advantage, relative to the alternatives, of being less affected by external air temperatures. Initial construction is cheap while net operating costs for electic heat pumps range from negligible to reasonably acceptable. Diesel or natural gas driven heat pumps would further reduce operating costs. The paper also suggests additional possible applications of ground-coupled heat pumps to permafrost engineering.

Résumé

On a utilisé la technologie déjà mûre des thermopompes domestiques dans le contexte des fondations du type dalle-sur-sol pour conserver le pergélisol sous-jaçent dans un état gelé tout en produisant une quantité importante de chaleur pour le chauffage du bâtiment lui-même. On présente des données de performance thermique et économique pour la première année d'opération de deux bâtiments municipaux polyvalents de 350 m^2 situés au Yukon. Les deux cas couvrent la fourchette des conditions de sol, de température et d'opération prévalentes dans le nord canadien. Une simulation numérique du régime thermique des fondations a été effectuée dans le but d'indiquer des améliorations possibles. Un des avantages du système de fondation refoidie par thermopompe est son indépendance par rapport aux conditions environmentales. Les coûts initiaux sont relativement bas et, à terme, les coûts opérationels pour les thermopompes électriques sont soit négligeables, soit, au pire, comparable aux autres systèmes. Des thermopompes à absorption utilisant le mazout ou le gaz naturel comme carburant pourraient s'avérer encore plus économiques. En terminant, on suggère plusieurs autres applications éventuelles des thermopompes aux problèmes de l'ingénierie nordique.

Introduction

For other that small dwellings and similar structures, the most widespread technique for foundation construction in permafrost involves elevating the heated building on piles or posts and pads to permit air to circulate underneath the floor. Piles are relatively expensive to place in permafrost and the approach necessitates a costly structural floor with thick floor insulation. These difficulties can be reduced by using an insulated slab-on-grade foundation, but some means still must be provided to remove the heat which will otherwise ultimately pass through the floor into the ground. Natural and mechanical ventilation or two-phase thermosiphons are currently used for this purpose. These systems depend on natural cooling and may not perform adequately in warm or saline permafrost regions.

Mechanical refrigeration to maintain frozen ground beneath buildings located on permafrost is an old idea which, although ideal in terms of providing complete control over ground temperatures while reducing initial cost by permitting simple slab on grade foundations, has generally been discredited because of high operational costs, technical complexity, and substantial maintenance requirements. At the same time, in temperate regions, relatively simple ground source heat pump technology (Appendix A) has become established as a reliable, efficient means of heating buildings using commercially available equipment requiring minimal maintenance. It is an almost obvious step to realize that the ground source heat pump can be applied to permafrost foundation problems to maintain frozen ground while, at the same time, providing heat for the building itself. This application was in fact suggested at least as early as 1975 by Stenbaek-Nielsen and Sweet but apparently no further work was carried out. More recently, two groups in Canada (National Research Council, Ottawa, and Public Works Canada, Edmonton) and one in Norway (B. Instanes A/S) independently proposed to use ground source heat pumps in this context. In the Norwegian case (O. Gregersen 1987), a 900 m^2 storage building located on ice rich clay at Svea, Svalbaard, the heat pump apparently operates year round to maintain constant ground temperatures. Performance monitoring of the foundation temperatures or the heat pump energetics has not been reported, but the system has been in

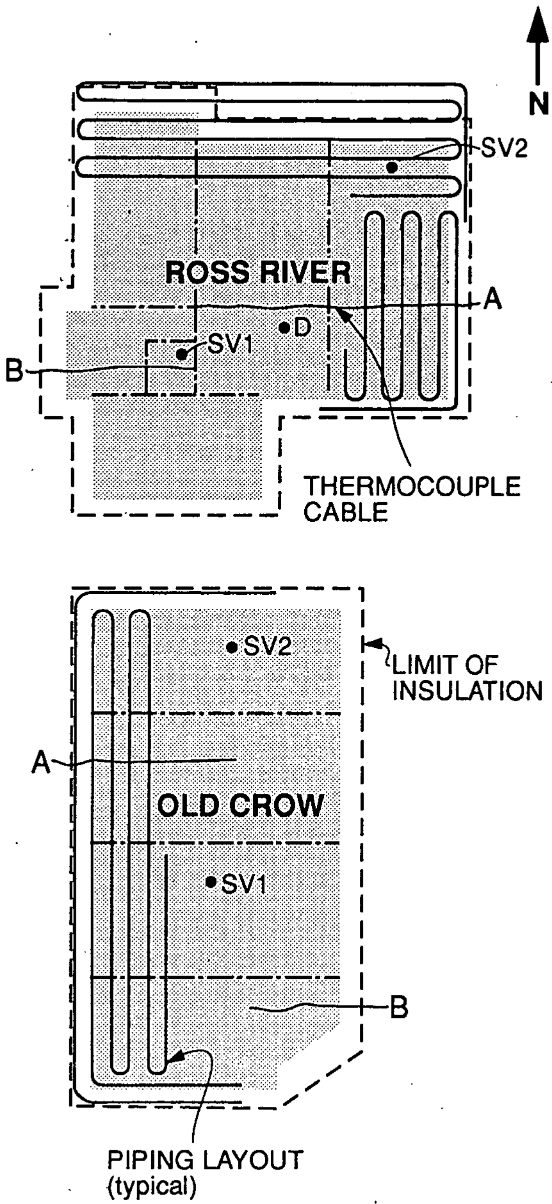

Figure 1. Piping Layout and Instrumentation Location.

successful operation since 1986. Industrial scale (44kW) ground source heat pumps were installed in 1985 by Public Works Canada (W. Sheldon, 1989) to maintain frozen foundations under hangars at Resolute Bay and at Inuvik, NWT. Heat pump performance is monitored manually but ground temperature monitoring is very limited.

Description of two demonstration projects in the Yukon

In a programme jointly sponsored by the Institute for Research in Construction, National Reasearch Council of Canada and the Yukon Government, two multi-function municipal buildings (office and garage for fire, water, and sewer trucks or ambulance) have been constructed in Ross River and Old Crow, Yukon, using the heat pump chilled slab-on grade foundation. This entails the use of a standard vapour compression type domestic water-to-air heat pump in conjunction with a ground heat exchanger made of high density polyethelene (HDPE) pipe of the type widely used in vertical and horizontal ground heat collector loops. Fig.1 illustrates the ground heat exchanger piping layouts while Figs. 2 and 3 show the foundation cross-sections and soil conditions at Ross River and Old Crow respectively.

The foundations, including gravel pad, ground heat exchanger and rigid polystyrene insulation are planned with a view to minimizing costs while enhancing constructibility and reliability. The insulation thickness is designed to accommodate total shutdown of the system for periods of six months to a year. This removes the need for costly back-up units while making it possible to operate the heat pump only during the normal heating season. Complex manifolding as well as internal joints are avoided by arranging the heat exchanger pipe in long serpentines with a minimum of

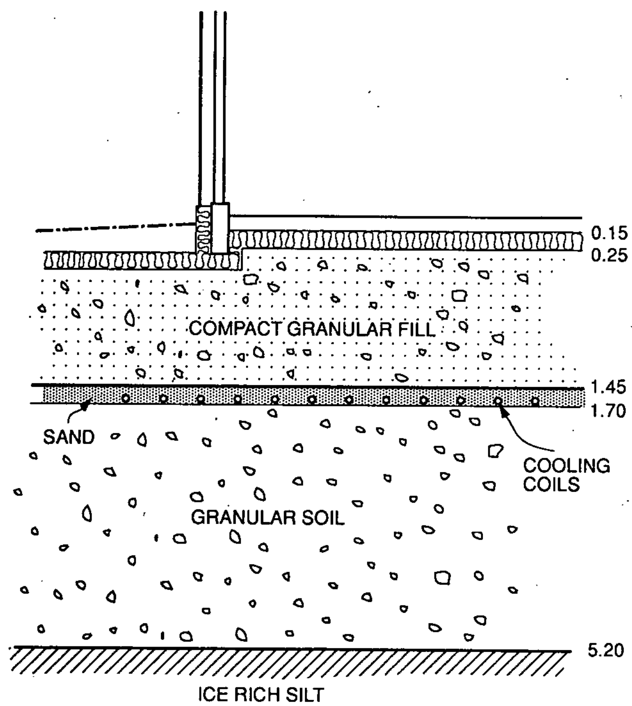

Figure 2. Ross River Foundation - schematic.

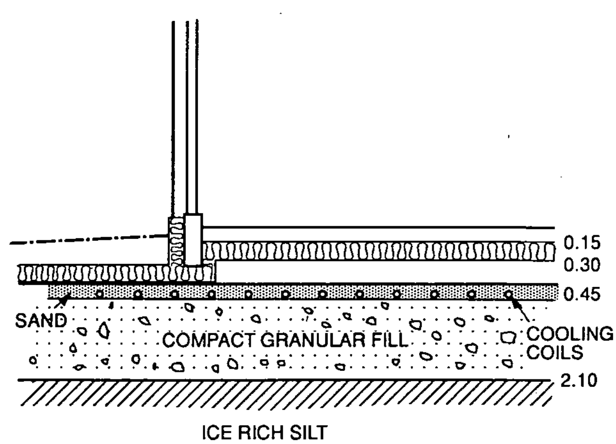

Figure 3. Old Crow Foundation - schematic.

separate parallel loops and headers. To accommodate small movements which might occur during, or prior to initial freezing, the pipe is placed in a bed of compacted sand. All piping is doubled in the unlikely event of a break developing in the ground heat exchanger loops. A methyl hydrate - water mixture is used as the heat transport fluid circulated in the ground loops. This medium is inexpensive, has excellent thermal and flow properties, does not require significant maintenance, and, unlike glycol or ammonia, will not cause permanent thawing if it should leak into ice rich soil.

The output from the heat pump is sufficient to provide approximately 20-50% of the room air heating demand for the buildings. At both locations the heat produced by the heat pump is delivered directly to the room. Because these installations were viewed as experimental no attempt was made to interconnect them to the normal oil heating systems nor modify the design requirements of the latter to account for the additional heat gains. At Ross River the heat pump unit was installed in the fire-truck bay where the output air could be utilized to dry fire hoses. At Old Crow the machine was located in the water-truck bay, this being the zone with the greatest heat demand.

Differences between installations in Ross River and Old Crow

The site at Ross River has a 3 m deep surficial layer of granular material underlain by ice rich silt. Mean annual ground temperatures at the site are greater than -0.5 °C. At the time of initial construction the ground was thawed to a depth of 7.5 m while at the deepest level measured, 11 m, the temperature was -0.3 °C. Since the town, located in the southern Yukon, is served by hydroelectric power, the cost of heat generated by the ground source heat pump is similar to or lower than the cost of heating with fuel oil imported by road from the South. As an operating strategy, allowing summer thaw to penetrate nearly to the top of the silt means large quantities of relatively inexpensive heat is made available the following winter. Old Crow, on the other hand, is the most northerly town in the Yukon. Construction materials and fuel for heating and generating electricity must be brought in over a winter road or transported by air. The natural soil at the site consists of a deep deposit of ice rich silt underlying the thin surface organic soil. Mean annual ground temperatures in the region are in the range -5 to -7 °C but, at the actual building site, substantially higher temperatures are thought to have prevailed recently owing to surface disturbance and to proximity to the river bank. For the Ross River foundation the ground heat exchanger piping was placed at the bottom of the gravel pad. This location maximizes the thermal resistance between the floor surface and the cooling pipes while also providing maximum thermal mass for the ground heat exchanger. The disadvantage is that special care is needed to avoid damage during construction. In the Old Crow foundation the heat exchanger piping was located on the pad surface. This position simplifies construction of both pad and ground heat exchanger while the reduced thermal resistance between the cooling coils and the floor surface is compensated by increasing the insulation .

Analysis

A first estimate of the size of heat pump required to maintain frozen ground beneath a building located on permafrost can be made assuming steady state heat flow. The highest annual average heat flow into the ground will occur inside the building perimeter and it is sufficient to consider one-dimensional heat flow through the floor slab. By way of example, for a 15 cm concrete floor, underlain by expanded polystyrene insulation (thickness 10 cm for Ross River and 15 cm for Old Crow - see below and Appendix B) and 1 m granular fill, if the floor temperature is constant year round at 20 °C whilst the ground temperature at the base of the foundation pad is -3 °C, the heat input to the ground will be at a steady rate of $g = 6.5\ W/m^2$ for Ross River and $4.6\ W/m^2$ for Old Crow. For a pad area of 350 m^2 this amounts to a total heat inflow rate of 2.3 kW for Ross River and 1.6kW for Old Crow. Heat must be extracted at the same rate to maintain the ground temperature constant.

The Coefficient of Performance (COP) of a heat pump system is defined as the ratio of total rate of heat production , G+E, to the electrical power consumed:

$$COP = (G+E)/E \tag{1}$$

where E = electrical power consumed,
and G = ground heat extraction rate.

From manufacturers data, using glycol-water as collector fluid, the COP of typical ground source heat pumps ranges from 2.3 to 2.5 at entering collector fluid temperatures of -10 °C to -5 °C. Assuming a value of COP = 2.40 is representative for a season, the electrical power required is 1.65 kW (1.15 kW), heat extraction from the ground at a rate of 2.3 kW (1.6 kW) and the total rate of heat production is 3.95 kW at Ross River and 2.75 kW at Old Crow, for continuous operation. For an operational mode in which the heat pump functions continuously during only 8 months of the year and is turned off during the remainder, the required heating capacity of the machine becomes 5.9 kW for Ross River and 4.1 kW for Old Crow. These values are well within the capacity range of the smaller size machines normally used for domestic heating in southern conditions.

To gain further insight into the probable long and short term thermal behaviour of the foundations and to verify the adequacy of the insulation thicknesses, a number of computer simulations were made using a one-dimensional finite element model (Goodrich 1989a). This model treats freezing and thawing phenomena using a generalization of Steven's discontinuous element formulation (Steven 1982) and is capable of including layered systems with highly temperature-dependent thermal properties as well as time dependent internal heat sources and boundary conditions. Simulations were carried out using the geometries indicated in Figs. 2 and 3 with the thermal properties given in Table 1.

Starting temperatures for Ross River were based on field measurements (cable D, Fig 1 : see also Fig 10) while those for Old Crow were estimated from a simulation of the pre-construction thermal regime calculated using mean monthly air temperatures and assumed freezing and thawing n-factors

Table I. Properties assumed for thermal simulations.

	density (t/m^3)	moisture (%)	Kfrozen (W/m·K)	Kthawed (W/m·K)
Concrete	2.1	.0	1.50	1.50
Insulation	.034	.0	.035	.035
Sand	1.8	.03	.92	1.41
Granular Fill	2.1	.03	1.69	2.17
Granular Fill	2.1	.05	2.44	2.63
Granular Soil	2.0	.03	1.38	1.88
Silty Soil	1.2	.35	1.75	.96

and soil properties. The calculations assumed constant floor surface temperature of 20°C (see Appendix B) with lower boundary taken to be adiabatic at 15 m. At both locations the heat pumps used were not designed for long periods of operation with evaporator temperatures lower than about -12°C and in practice the heat pumps are shut off whenever the ground heat collector fluid temperature reaches -10°C. This effect was included in the model by setting the heat extraction rate temporarily to zero whenever temperatures at the nearest nodes above and below the heat sink became colder than a given value. In the calculations presented here -8°C was used to ensure conservative estimates.

Five full cycles of annual operation in this mode were simulated for Ross River starting in spring and for Old Crow in mid-summer. The effects of a prolonged shutdown were modelled by carrying the calculations through an additional winter on the assumption that no further heat was extracted. Fig.4 shows the calculated temperature history at the top and bottom of the foundation pad (0.25 m and 1.7 m levels in Fig.2) and at the top of the ice-rich silt (5.2 m) for Ross River while Fig.5 shows the corresponding freezing isotherm. From Fig.4 it can be seen that the top of the pad just barely freezes and only does so after several years operation. At the base of the foundation pad the temperatures descend continuously and uninterruptedly during the winter cooling period. Temperatures do not quite cool to the point where the heat pump begins to cycle on and off. The minimum temperature continues to decrease each year, however, and would eventually reach -8°C. By the fifth summer the base of the pad has nearly ceased to thaw seasonally. As can be seen in Fig.4, and more clearly in Fig.5, slightly more than two years operation are required before the top of the silt is frozen.

Subsequently, summer thaw is contained well within the granular pad and the silt remains frozen uninterruptedly with long term temperatures stabilizing near -2°C. The results subsequent to time 5.5 years, represent, as mentioned above, a heat pump failure occurring at the end of the summer (the worst possible circumstance). Fig.4 indicates that while pad temperatures would rise rapidly to values near 8 to 10°C after a year, some eight to nine months could pass before the silt surface would begin to melt. If absolutely no thawing could be tolerated, cooling would need to re-commence about two months sooner, leaving a still very comfortable repair window of six to seven months.

Fig.6 and 7 present the corresponding simulation for Old Crow. Several important differences arise when compared with the Ross River case. It is immediately apparent that the temperature corresponding to the pad surface, which in this case is also the level of the ground heat collector piping, has a very different behaviour from that at Ross River. After the initial 5 months (prior to startup of the heat pump but subsequent to placing the insulation), the pad surface temperature descends monotonically until, a further 5 months later, the underlying silt has completely refrozen. Temperatures then descend abruptly until the pad surface reaches -8°C, whereupon the heat pump begins to cycle on and off. In the second and subsequent winters the pad surface temperature drops to -8°C within a few weeks of start-up.

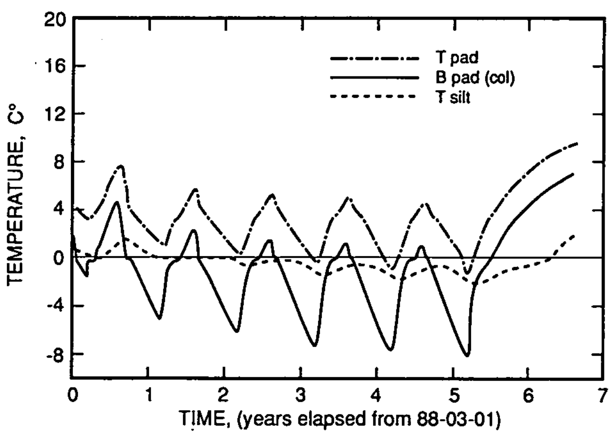

Figure 4. Ross River Calculated Temperatures.

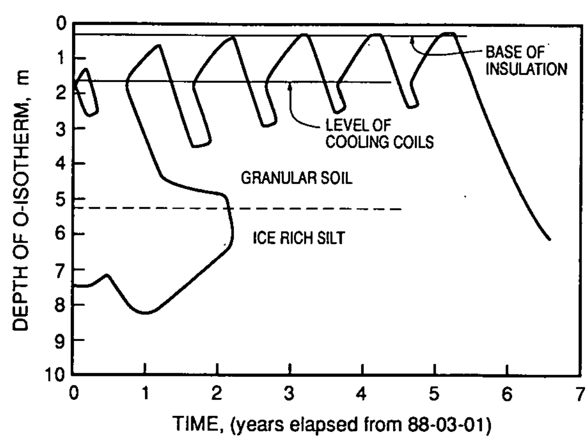

Figure 5. Ross River Calculated 0-Isotherm.

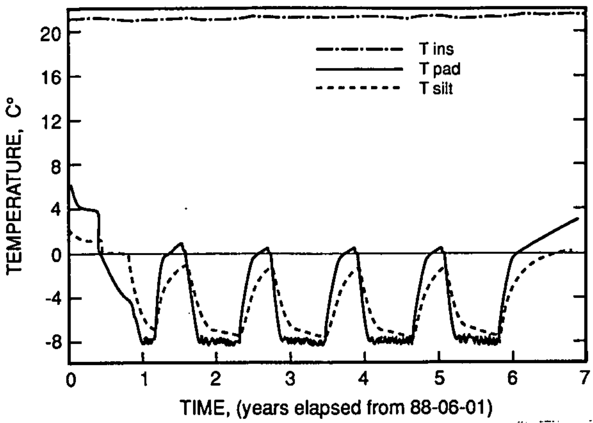

Figure 6. Old Crow Calculated Temperatures.

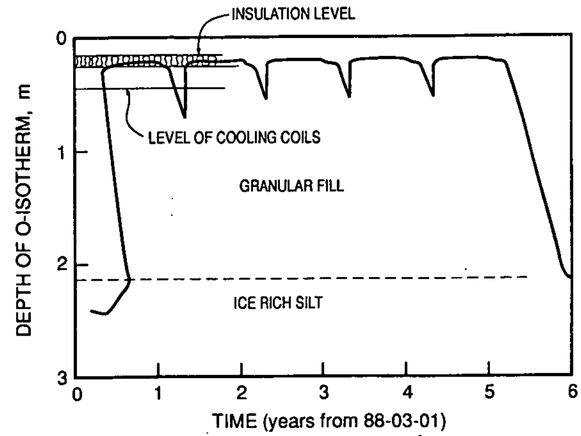

Figure 7. Old Crow Calculated 0-Isotherm.

The silt surface temperatures descend below freezing within 5 months of initial start-up and subsequently oscillate between a minimum -7 to -7.5 °C and a maximum (autumn) of -2 °C. The pad melts briefly during the summers but thaw is confined to the upper 0.5 m at most. As could be expected in view of the location of the ground heat collector, quasi-steady equilibrium conditions obtain after only two cooling cycles. The final year of the simulation again represents a heat pump failure occurring at the end of summer. The calculations indicate that more than six months would be required before the silt surface would begin to melt if the breakdown occurred at the worst possible time. In this case the delay required to refreeze the pad is only about one month, leaving at least five months for repairs if absolutely no thawing of the silt is permitted.

In the Ross River geometry the heat extraction rate is not reduced by the limitation resulting from the operational requirement to maintain collector temperatures above -8 °C. With the Old Crow configuration, however, the heat pump cycles on and off during much of the winter and, as shown in Fig.8, the resulting effective heat extraction rate is significantly decreased.

Calculation of the insulation thickness required to control seasonal thaw under the peripheral areas outside the foundation were based on monthly air temperatures ignoring the additional cooling provided by the heat pump. For Ross River 10 cm was adequate while 15 cm was selected for Old Crow. For ease of construction the peripheral insulation has no sloping or vertical end section. The width (2 m) required to provide complete protection of the footings from horizontal thawing was estimated by calculating the vertical thaw penetration in the absence of insulation. This provides a conservative estimate. The Ross River geometry is relatively uncritical since the silt interface is very deep and it is not essential to totally eliminate seasonal thaw near the foundation.

Design of the ground heat exchanger layout was based on flow and inlet-outlet temperature drop considerations as well as on the need to ensure relatively small temperature differences between two neighbouring pipe segments and the intervening soil. In the two cases discussed this was done using simple steady-state formulas for radial heat flow around buried cylinders (see, for example, Lunardini 1981, p 305). Coil spacing was determined on the assumption that the (steady) horizontal temperature difference between the pipe fluid and the mid plane between neighbouring pipes should not exceed 5 °C. Brine flow rate and loop lengths were determined by requiring a difference between fluid outlet and return temperatures of 0.5 °C while ensuring turbulent flow. Whether these conditions are the most appropriate has yet to be established. At Ross River 1" (25 mm) HDPE pipe was used spaced at $2^1/_2$ feet (75 cm). The heat exchanger was to have consisted of three parallel loops oriented in the same direction. The planned layout was modified radically in the field to accommodate work plans of the contractor. At Old Crow $1^1/_4$" HDPE pipe was used with a spacing of 3 feet (90 cm) split into two parallel loops.

Measurements at Ross River

During construction at Ross River, a thermocouple cable (D in Fig.1, Ross River) was installed directly in a 7 m deep

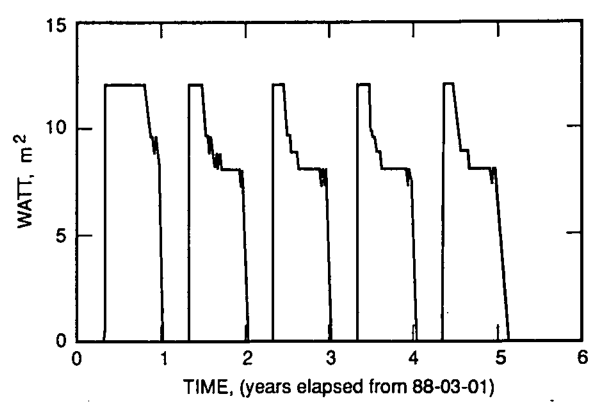

Figure 8. Old Crow Heat Extraction.

uncased borehole made near the centre of the building site to allow monitoring the re-freezing of the silt layer. Two multi-point thermocouple cables (A,B in Fig 1, Ross River) were placed horizontally at the level of the ground heat exchanger piping at locations extending from near the centre-line of the building to positions approximately 1.5 m beyond the foundation limits to monitor temperature differences across the site. Points were alternately located on and mid-way between the cooling pipes. Two vertical cables were also installed, one (SV1) located beneath the mechanical room (highest anticipated surface heat loads) and the other (SV2) in the area of the water-truck bay (lowest surface heat loads). The thermocouple points were potted into horizontal metal tubes affixed to a 5 cm diameter ABS plastic mast inserted into a 15 cm diameter ABS casing penetrating the gravel foundation pad. Additional thermocouple points were located on top and bottom surfaces of the floor insulation and at two levels within the concrete floor slab. Two transient thermal conductivity probes (Goodrich 1986) were also installed, one in the compacted sand layer surrounding the cooling pipes and the other within the granular pad. Two 7 cm diameter flexible metal tubes (BX conduit) were laid in shallow trenches in the natural soil prior to placing the granular fill. Their intended purpose was to permit detailed monitoring of any eventual foundation movements using a hydrostatic levelling device pulled through the tube, as well as to permit additional manual temperature measurements in the peripheral areas.

To evaluate the rate of heat extraction from the ground, electronic paddle-type flowmeters and precision calibrated thermistors were installed in the individual loop circuits. The heat extraction rates are estimated from the flow rate and the difference between inlet and outlet temperature. This method cannot account for possible errors caused by localized heating or cooling of the pipes but is arguably more precise than measurements based on total heat rejected at the condenser. A calibrated recording wattmeter was installed to measure electrical consumption of the heat pump. Additional thermocouples were placed at several locations in the building and provide data on floor surface and room air temperatures. A commercially available electronic data-logger operating under micro-computer control was installed in an instrument cabinet located next to the heat pump. The equipment permits remote interrogation over standard telephone lines with data also recorded locally. Information is recorded on an hourly basis for all channels except deep temperatures, which are recorded daily.

Measurements at Old Crow

The instrumentation at Old Crow is similar to that at Ross River, although equipment limitations precluded installing temperature cables in the natural soil below the gravel foundation pad. One of the vertical cables in the foundation pad (SV1 in Fig 1, Old Crow) was only completed below the insulation and a single BX conduit was installed at the base of the pad, approximately along the building centre-line. The datalogging system as well as the heat pump and associated equipment are the same as that used at Ross River.

Results

Ross River

Construction commenced in October 1987. The building was heated by oil throughout the following winter. In March 1988 the heat pump and monitoring instrumentation were installed but operation of both was intermittent until October 1988. During this period several problems were experienced with the electronic monitoring equipment which led to loss of data. Figs. 9a and 9b show temperatures (daily average) monitored at several levels in the floor and subsurface at the two locations, SV1 and SV2. As can be seen there are substantial differences in the floor slab temperatures during the winter months.

These lead to spatial differences of at least 40% in the heat flows from the room air to the foundation pad (determined from temperature differences across the insulation layer). The minimum temperature at the bottom of the insulation is -5°C at SV1 and -7°C at SV2. At the level of the ground heat collector, temperature differences between the two locations are, nevertheless, negligible, implying that cooling at deeper levels should be uniform. In agreement with the simulated results, the temperature at this level decreased slowly and monotonically during the cooling season (the peak at day 310 was due to erratic operation of the machine caused by improper adjustment at the time of installation). In the spring, however, (elapsed

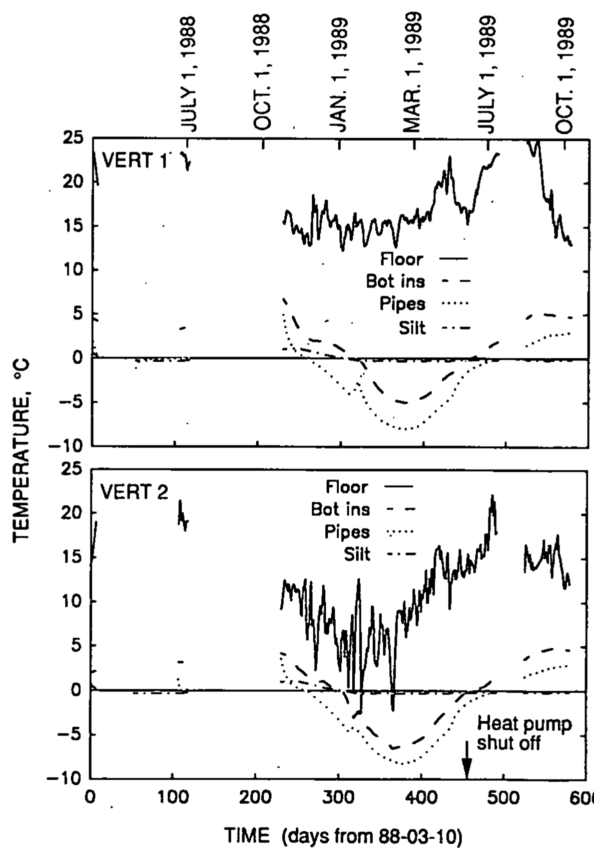

Figure 9. Ross River Shallow Temperatures (SV1 and SV2).

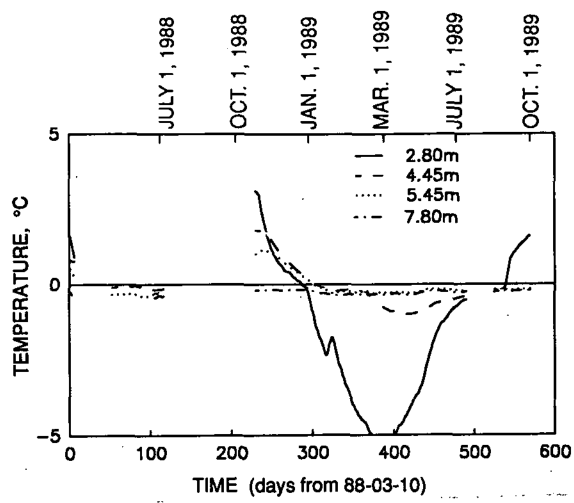

Figure 10. Ross River Deep Temperatures.

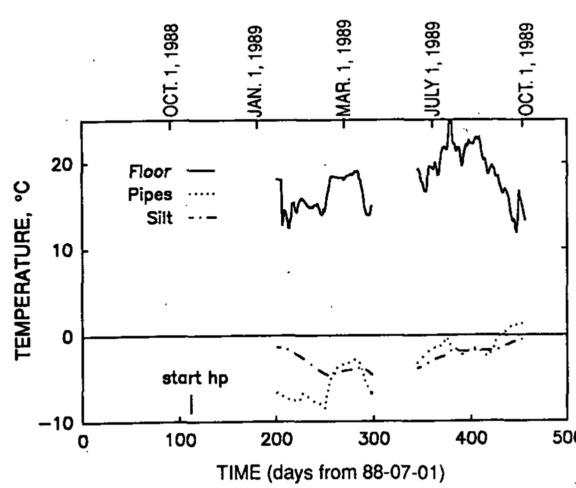

Figure 11. Old Crow Shallow Temperatures (SV1).

days 380 to 430) temperatures at the level of the cooling pipes rose rapidly even though the heat pump was operating fully. This behaviour is interpreted as evidence of inadequate peripheral insulation. Indeed, along the entire northern end of the foundation, the insulation, at the time of writing, is only 5 cm thick and 60 cm wide (instead of 10 cm by 2 m). Since it is unrepresentative of the behaviour that will occur when the missing insulation has been corrected, the data from the horizontal temperature cables is not shown here. It indicates, however, stronger and earlier warming than that observed at the same level inside the building for cables SV1 and SV2. Substantial coupling to the surrounding ground and ultimately exterior air temperatures may significantly affect the efficiency and operating cycle of the heat pump since it must be shut off if fluid temperatures become too cold.

The temperature measured at the top of the silt is also plotted in the figures. The data (unadjusted for channel offset errors) show that the silt had begun to freeze by day 330, about 100 days after start-up, indicating that the simulation calculations are conservative. Fig.10 shows temperatures measured at several depths in the soil below the foundation pad (cable D in Fig 1).

The soil was originally thawed to depths exceeding 7 m. It can be seen that, in spite of the problem noted with the peripheral insulation, under the building itself the soil which was refrozen during the winter did not completely thaw again during the following summer and, in the long term, the permafrost should be easily maintained. Annual average temperatures at the base of the foundation pad (cables SV1 and SV2, Fig 1) are in the range -1.7 °C to -2.7 °C after only the first winter.

Old crow

Construction commenced in September 1987 but was delayed until the following summer. The heat pump was put into operation in October 1988 when the building was only partially completed because of concerns about the extent of the thawed zone. Permanent installation was completed and the electronic monitoring equipment installed in January 1989. External perimeter insulation was absent during the entire winter and was only partially completed by September 1989. Fig.11 shows daily mean floor slab temperatures measured at two locations chosen to be representative of the extremes (water truck bay and ambulance bay).

The sudden rise in floor temperatures around day 250 corresponds to the time when the heat pump compressor was shut down for a period of nearly five weeks because return fluid temperatures had reached -10 °C, the rapid cooling being attributable to incomplete perimeter insulation. Soil temperatures at the level of the cooling pipes measured at a point well within the building are indicated on the figure and, as can be seen, descended to approximately -8 °C (measured next to the pipe). The silt surface was refrozen and had cooled to around -1 °C by the time data logging commenced and approximately -5 °C by day 250. In spite of the shortened operating season, cooling was sufficient to ensure that the silt remained frozen throughout the summer. The annual average temperature at the top of the foundation pad was less than -3 °C. Fig.11 indicates a correlation between floor temperatures and pipe temperatures (see especially day 250 to 300). This suggests that thicker floor insulation might have been preferable. Data from the horizontal cables have not been included. Their significance is limited because the peripheral insulation has not yet been completed along both west or north sides of the building.

At both sites level surveys have been carried out periodically. At the time of construction at Old Crow thawing had penetrated the gravel pad for some 30 cm into the ice rich silt. In addition, drainage was very poor. In these conditions frost heaving during refreezing was anticipated. In fact less than 2 cm of heave actually occurred and values measured at different locations on the floor were identical to within a few millimeters. Floor movements at Ross River have been totally negligible.

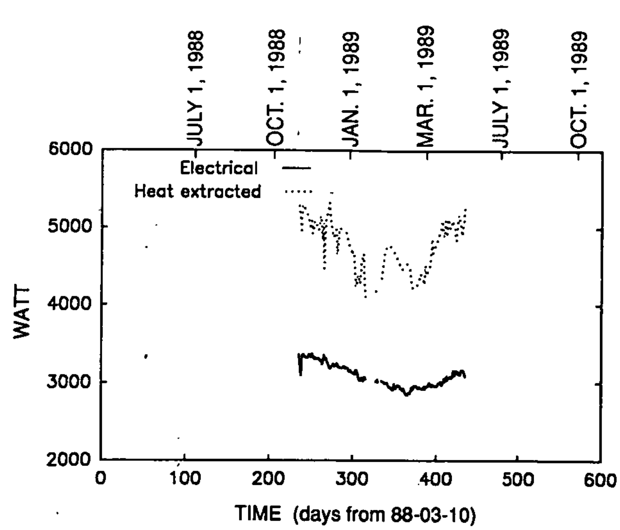

Figure 12. Ross River Energy Performance.

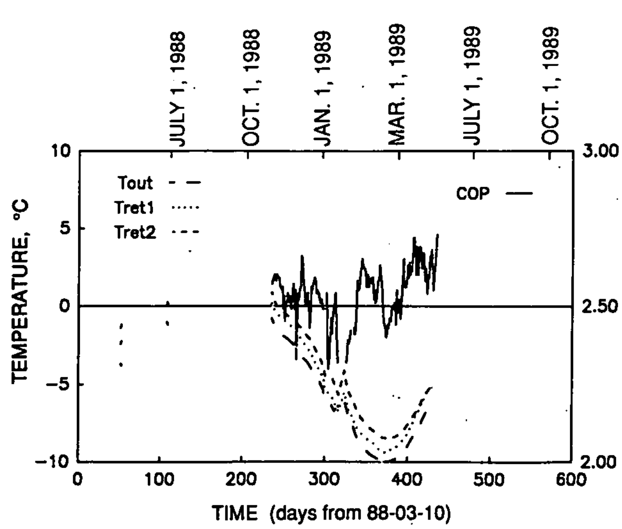

Figure 13. Ross River Fluid Temperatures and COP.

ENERGY AND COST CONSIDERATIONS

Fig.12 compares the rate of electrical consumption and total heat extracted from the ground (estimated from the collector fluid flow rates and inlet-outlet temperature differences) at Ross River during the first full cooling season. Fig.13 shows the corresponding Coefficient of Performance and plots the collector fluid temperatures on the same axes.

Following the machine adjustments made at day 320 the COP increased substantially, notwithstanding the low fluid temperatures. Based on data after day 320 it is concluded that a value 2.5 to 2.6 may be appropriate for estimating operational costs. Comparable COP data for the Old Crow site are, unfortunately, not available at the time of writing, but values are expected to be similar or slightly lower. Table II presents estimates of cost of operation for both locations based on data for 1988-89.

At Ross River the operational costs are almost entirely offset by the savings in heating oil. At Old Crow the estimated net operating costs, $4000/yr, are significant but alternative power sources and optimal operational strategies could radically alter the picture.

The machines are expected to have a useful life at least as great as that of household refrigerators and require minimal routine maintenance. Initial costs including equipment, materials, transportation and installation are approximately $20k. This is believed to be substantially less than for thermosiphons or mechanical ventilation systems of similar cooling capacity. Table III presents a comparison of costs for various types of foundations at both locations.

Recommendations for future work

The present study demonstrates the effectiveness of ground source heat pump technology to maintain frozen conditions beneath buildings located on permafrost. Further analytical work is underway to optimize the design, particularly as regards the heat exchanger geometry and the floor and peripheral insulation, as well as to select the best operating strategy. Although the existing systems using inexpensive polyethylene pipe placed on a wire mesh are reasonably easy and rapid to place, the ground heat exchanger could be improved by increasing the thermal contact with the soil and/or by replacing the polyethylene pipe with a purpose-designed heat exchanger mat which could be simply unrolled on the pad surface. Practical means

Table II. Operational costs of heat pump chilled foundation.

			Ross River		Old Crow	
COP	Elect (kW)	Fuel Equiv (l/day)	Elect$ ($/day)	Fuel Value$ ($/day)	Elect$ ($/day)	Fuel Value ($/day)
2.4	2.9	22.1	10.30	9.05	37.80	20.95
2.5	3.0	23.8	10.66	9.75	39.09	22.56
2.6	3.1	25.6	11.01	10.48	40.40	24.26
2.7	3.2	27.4	11.37	11.21	41.70	25.96
Estimated Annual Cost (net)				$220		$4020

based on: COP = Total Heat Output/Electical Energy Consumed=2.5, furnace efficiency = 65 %, energy content of fuel = 34MJ/l, electricity @ 14.8 c/Kw.hr, fuel @ 38 c/l for Ross River, electricity @ 54.3 c/Kw.hr, fuel @ 88 c/l for Old Crow, heating season = 8 months at both locations

Table III. Cost comparison of foundations.

For buildings of this type it may also prove interesting to use the output heat for hydronic heating of localized areas of the floor slab. This has the additional advantage of better efficiency.

	Ross River	Old Crow
Piles and structural concrete floor	$300,000	$500,000
Ventilated pad	—	$370,000
Slab on grade alone (not viable)	$90,000	$270,000
Thermosiphon chilled slab on grade	$150,000	$370,000
Heat pump chilled slab on grade	$105,000	$290,000
+ 20 year operation costs	$110,000	$370,000

to increase the latent heat in the soil surrounding the heat exchanger would yield both thermal and energy benefits. Additional heat exchanger geometries to accomplish this are being considered. For off-grid locations, heat pumps that use hydrocarbon fuels directly could substantially reduce operating costs relative to electrically operated machines. The applicability of co-generation units, internal combustion direct-coupled heat pumps and absorption heat pumps should be investigated.

Many additional permafrost related applications may be practical whenever the heat produced can be used to offset operating costs. Foundations which have settled could be retrofitted by lifting the existing floor structure and installing heat exchanger piping of the type discussed above, or by using double walled collector pipe passing beneath the foundation from outside the building perimeter. For pile foundations in warm or saline permafrost or unfrozen soft soils the bearing capacity could potentially be improved by freezing the surrounding ground. For cases where thermosiphons have failed to provide adequate chilling, their effective season could be substantially lengthened by installing heat exchangers below the radiators and using the heat pump to provide cooling during the normal "off" season. In place of above ground utilidors, sewer and water lines could be buried in ice-rich permafrost if they were "traced" with heat exchanger pipes used to keep the ground frozen. The heat extracted could be used both in the surrounding buildings, and to ensure against freezing the lines. It may be practical to maintain frozen ground in streets and similar linear structures by a combination of insulation and heat exchanger pipes. The ground coupled heat pump could potentially maintain frozen ground beneath sewage lagoons located on permafrost while providing the heat needed for effective bacterial action in the lagoon. A paper presenting a quantitative analysis of a few of the possibilities envisaged is in preparation (Goodrich 1989b).

Conclusion

Standard electric ground source heat pump technology can be used in conjunction with slab on grade construction to provide an easily constructed permafrost foundation system for buildings with large floor loads. As expected from the numerical modelling results, both designs are proving successful in maintaining adequate long term temperatures under the floor of the buildings. Evaluation of the performance of the peripheral zones is hampered by the incomplete insulation. This circumstance also affects both thermal and energy performance of the entire systems and final evaluation can not be made until the insulation is completed. Installed cost of the equipment is approximately $20k for either site. At Ross River net operating costs are negligible but at Old Crow may be substantial.

Although locating the heat exchanger coils on top of the foundation pad simplifies construction, better thermal performance results if the heat exchanger is placed below the pad. Steady state calculations are useful for preliminary sizing of the heat pump and floor insulation but optimal design of both the floor and the peripheral insulation requires consideration of the transient case and further work is planned. Optimal operational strategies may also be possible. The benefits accruing from improved heat exchangers and artificially modified soil thermal properties should be investigated. Many other applications of ground source heat pump technology to permafrost engineering problems appear justified. Further analysis will be carried out to explore some of these.

Appendix a

A heat pump is a mechanical device that removes heat from one region (the cold evaporator) and redistributes it to another (the warm condenser region). These devices are in essence similar to a refrigerator except that what matters is the heat produced at the condenser rather than the cooling produced at the evaporator end. The device is normally used to extract heat from the outside air or from the ground for domestic heating purposes. Interest in heat pumps is motivated by their excellent energy efficiency. For cold regions the best efficiency is obtained if the heat is extracted from the (relatively) warm ground rather than from the cold air. Their are now used widely for residential and hot water heating in northern Europe and are gaining in popularity in southern Canada. Standard equipment is available off-the-shelf from several manufacturers. Furthermore, by comparison with normal oil or gas furnaces, the amount of heat produced per litre of fuel is more than double. Diesel or natural gas combustion engines can be coupled directly to vapour compression heat pumps and reliability of small scale co-generation units is now approaching practical levels. Absorption cycle heat pumps can be designed for a wide range of fuels and should be more reliable, at the cost of somewhat lower efficiency. At present only industrial scale absorption heat pumps are available commercially although kerosene fired and propane refrigerators have been manufactured for many years.

Appendix b

At Ross River the insulation thickness was predetermined by the designer of the building.

Part of the purpose of the work reported in this study is to determine appropriate design parameters and criteria as well as to establish advantageous geometries for both insulation and ground heat exchanger, and to explore optimal operating strategies. The criteria used for the present designs represent "reasonable" values but are arbitrary. A number of detailed analytical studies are planned to complement the field measurements reported here. The results of these investigations will be reported separately.

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