Preservation of permafrost for a fuel storage tank

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The case history is presented of the successful installation of an insulated and ventilated foundation pad for a two million gallon (9100 m^3) fuel storage tank in Inuvik, N.W.T. Because the tank is only heated locally in the winter at the fuel pick-up point near the tank bottom, the tank temperature is relatively low, ranging from 12 to 39°F (-11 to 4°C), with an average of 24°F (-4.4°C).

The foundation design employs no forced-air ventilation system, thus saving the related energy cost for operating such a system. Instead, the winter ventilation is accomplished by a wind draft. During the winter months, the average rate of heat removal through the culverts per unit of tank area is calculated to be about 2.4 Btu/hr·ft² (7.6 W/m²). This rate of heat removal is sufficient to freeze back the foundation pad in the winter and to allow the pad to absorb heat from the tank and the ambient air in the summer. Although the foundation pad undergoes annual freeze–thaw cycles, the lower insulation layer dampens the temperature variation in the subsoil and prevents it from thawing.

Le présent document relate le cas de l'installation d'une dalle de fondation calorifugée et ventilée pour un réservoir de stockage de combustible de 9100 m³ à Inuvik (T.N.-O.). Puisque le réservoir n'est chauffé en hiver qu'au point de prise de combustible, près du fond du réservoir, sa température est relativement basse, variant entre -11 et 4°C, avec une moyenne de -4.4°C.

La ventilation de la fondation n'est pas assurée par un système à air pulsé, ce qui permet d'éviter les coûts inhérents à l'utilisation d'un tel système. La ventilation d'hiver est plutôt assurée par le vent. Pendant l'hiver, les conduits permettent d'enlever la chaleur à un taux moyen d'environ 7.6 W/m² de surface de réservoir. Ce taux d'enlèvement de chaleur est suffisant pour geler la dalle de fondation en hiver et pour lui permettre d'absorber la chaleur du réservoir et de l'air ambiant en été. Bien que la dalle de fondation subisse les cycles annuels de gel et de dégel, la couche inférieure d'isolant amortit les variations de température dans le sous-sol et l'empêche de dégeler.

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Introduction

The integrity of structures in permafrost areas often relies on the continuous preservation of the frozen state of the foundation soils. To maintain the ground in a frozen state, the combined use of insulation and ventilation has been incorporated in the design of pile foundations and ventilated granular pad foundations (Sanger 1969). Case histories of ventilated pad designs were reported by Tobiasson (1973) and Auld *et al.*[1]. The former adopted the "chimney effect" to induce natural convection, while the latter described a case utilizing the forced-air ventilation system.

Both cases were used by Nixon (1978) to illustrate simple design procedures to evaluate required ventilation and pad thickness for ventilated pads supporting heated structures.

In this paper is presented a case history of the foundation design for a two million gallon (9100 m³) fuel storage tank in Inuvik, N.W.T. The tank is 102 ft (31.1 m) in diameter with maximum unit loading of 2400 pounds-force per square foot (115 kPa) which includes the tank, Bunker C fuel oil, and a 12-inch (30.5-cm) thick structural concrete base. The storage tank was constructed in the period between May and August, 1974, and has been operated since then by the Northern Canada Power Commission.

The tank is filled annually in the summer months and emptied gradually over the winter months by pumping the fuel to the diesel-electric generating station at Inuvik. During the winter months, nominal heat is supplied to the fuel pick-up point near the tank bottom to raise the temperature and reduce the viscosity of the fuel locally to facilitate fuel withdrawal. Otherwise, the tank is essentially unheated.

Site Condition

Before construction, the surface of the site sloped from north to south at a gradient of approximately three per cent. Gravel fill had been placed over the site to a depth of 2 to 4 ft (0.6 to 1.2 m), as indicated from the depth of organic material encountered in each of five test hole (Figure 1). Underlying the fill are layers of silt and gravel. The silt varied from low to rich in ice content. In three of the holes (TH-1, TH-3, and TH-4) massive ground ice with soil inclusions was encountered. The ground ice varied from 3 to 10 ft (1 to 3 m) in thickness.

The permafrost condition was variable and was classified by the National Research Council method (Pihlainen and Johnston 1963) as Vx, Vc in the gravel and from Vx, Vc to Vr, Vs in the silt. Typical test-

[1]Auld, R.G., Robbins, R.J., and Sangster, R.H.B. 1974. Foundation Requirements in the Canadian Arctic. Paper presented 24th Can. Chem. Eng. Conf., Ottawa, Ont.

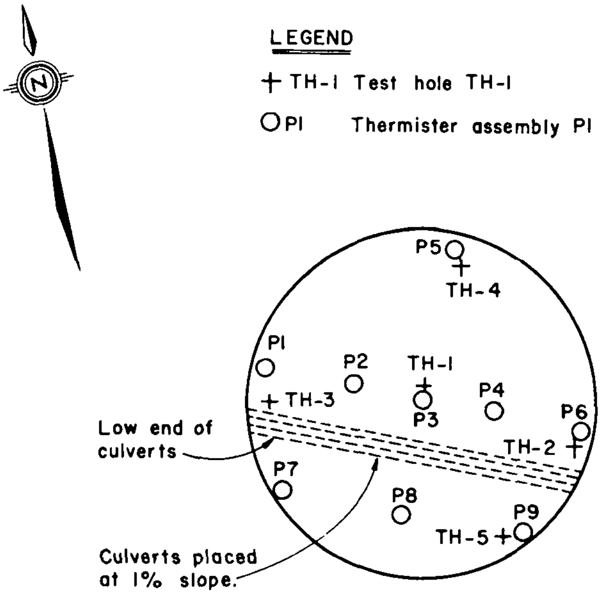


FIGURE 1. Plan view of tank showing locations of test-holes and thermistors.

hole logs for ice-rich soils and for those with low ice content are shown on Figures 2 and 3, respectively.

Design and Construction of Tank Foundation

The presence of massive ground ice in a highly variable natural soil–ice deposit would result in uneven settlement and loss of support of the fuel tank, should thawing of the natural soil below the tank occur. This must be prevented. To meet this requirement, two foundation designs were considered for the fuel tank: first, a pile-supported, ventilated, concrete-pad foundation, and secondly, an insulated and ventilated granular-pad foundation. A cost comparison showed that the cost of the pad foundation was about $85,000 in 1974, which amounted to about a quarter of that of a pile foundation. Hence, the pad foundation was adopted.

An insulated and ventilated pad foundation relies on adequate insulation to prevent the natural soil from thawing during each thawing season. Further it uses the circulation of cold air in each freezing season to freeze back any thawed portion of the granular-pad material. Thus, the proper function of the foundation pad depends on three essential design features:

(i) Insulation for reducing heat flows into the frozen ground;

(ii) Open culverts in the freezing season for circulating cold air and closed culverts in the thawing season for preventing warm air flow through culverts; and

(iii) The water content of the granular pad should be as high as practical for absorbing heat during the thawing season.

The insulated and ventilated granular-pad foundation was constructed during May to July, 1974, and the tank itself was erected in July and August, 1974. Details of the foundation pad are sketched in Figure 4, and the completed storage tank elevated by the foundation pad is shown in Figure 5.

Granular Fill

The area for the granular pad was cleared of snow immediately prior to the placement of the granular fill. Thus, the active layer above the permafrost was in a frozen state at the time the pad was constructed. Prior to construction, a drainage ditch was also excavated around the upslope side of the site to carry drainage from melting snow away from the tank berm. Crushed dolomite of less than 1.5-in (3.8-cm) size from the quarry near the Inuvik Airport was used for granular fill. The crushed dolomite rock was hauled to the site by tandem truck and spread by a D-6 bulldozer in 6-inch (15-cm) layers. The crushed rock was wetted during placement and compacted using a hand-operated Bomag vibratory compactor.

Insulation

Three 4-inch (10.2-cm) thick layers of high-density extruded polystyrene (Styrofoam HI-60) were placed, respectively, on the top and bottom of the granular fill and in the fill between culverts. Each layer consisted of two 2-inch (5.1-cm) thick layers which were staggered to ensure overlapping joints (Figures 6, 7, and 8).

Culverts

Culverts of 16-gauge steel and 2 ft (0.61 m) in diameter were placed at 4-ft (0.61-m) intervals to allow compaction of granular fill between the culverts (Figures 9 and 10). The culverts were oriented in a west-north-west direction (the direction of prevailing winter winds) and were placed at a slope of one per cent with the low end towards the west. The site topography and wind direction records were considered in selecting such an orientation and slope of the culverts in order to optimize the wind draft.

During each freezing season starting in October, the culverts are kept open and maintained clear of snow and any other obstruction to allow free air passage through them. During each thawing season, starting late April or early May, the culverts are sealed with end caps to prevent air passage. Proper operation of culvert openings is important for the successful performance of the tank foundation.

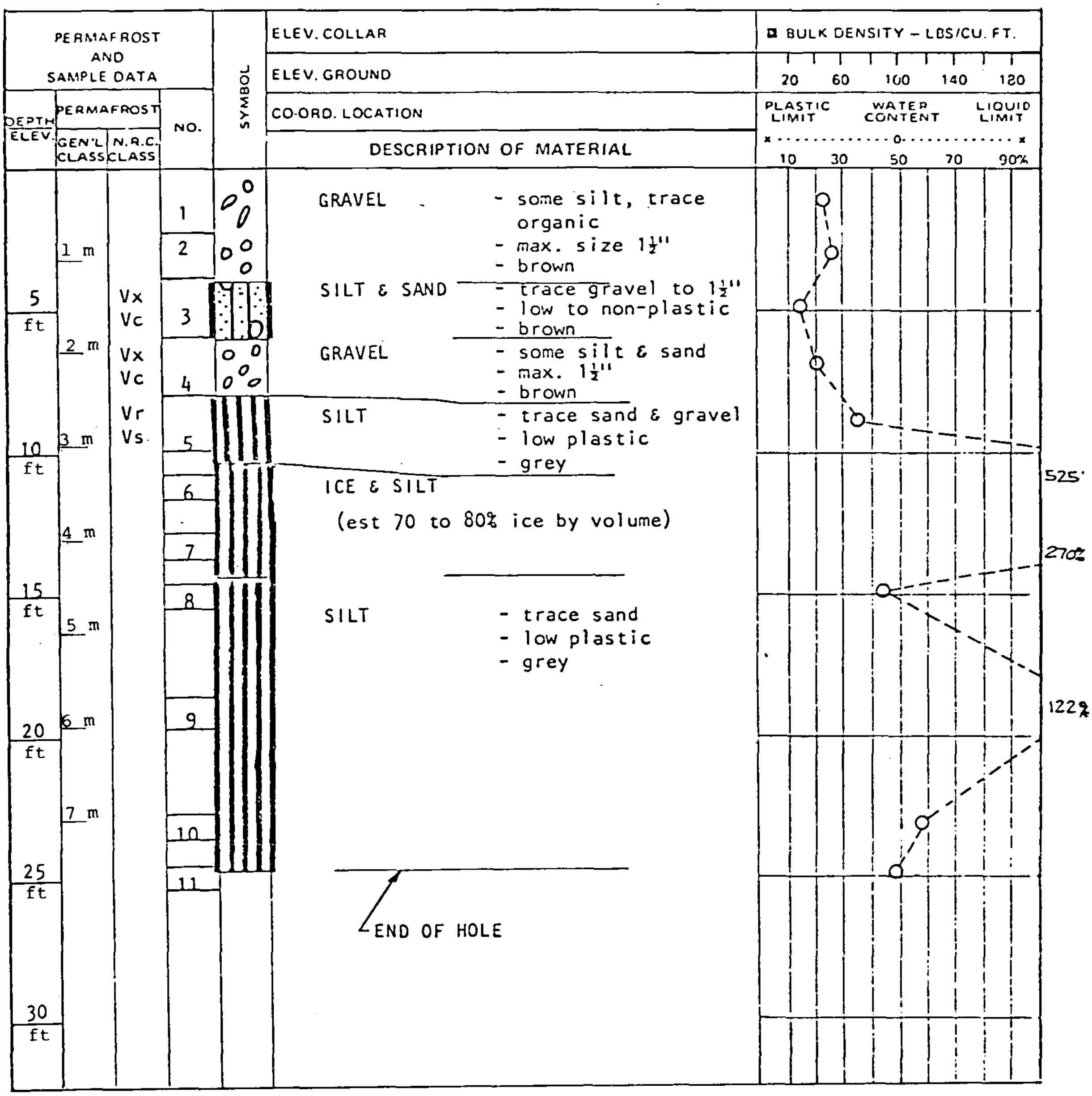


FIGURE 2. Test-hole log for hole TH-1 in an ice-rich area.

Instrumentation

A total of 73 thermistors (Figure 11) were installed within, and beneath, the insulated granular pad to monitor temperatures in the subsoil and the fill pad, in the culverts, and at the tank bottom.

The thermistor leads were carried through the fill in 1.5-inch (3.8-cm) diameter plastic conduits for protection from the crushed rock (Figure 12). All leads were carried to an instrument house constructed outside the pad area for future monitoring. The leads were connected to a splitter box from which individual readings could be obtained with a temperature read-out meter. The thermistors were placed in strategic positions in plan (*see* Figure 1) as well as in profile (Figure 13). In addition, ambient air temperature has also been monitored.

Construction of the fuel storage tank commenced in mid July and was completed on August 24, 1974. Thermistor readings began on July 10, 1974. The tank was partially filled with Bunker C fuel oil for the first time during mid September, 1974. From July, 1974 to December, 1976, periodic thermistor readings

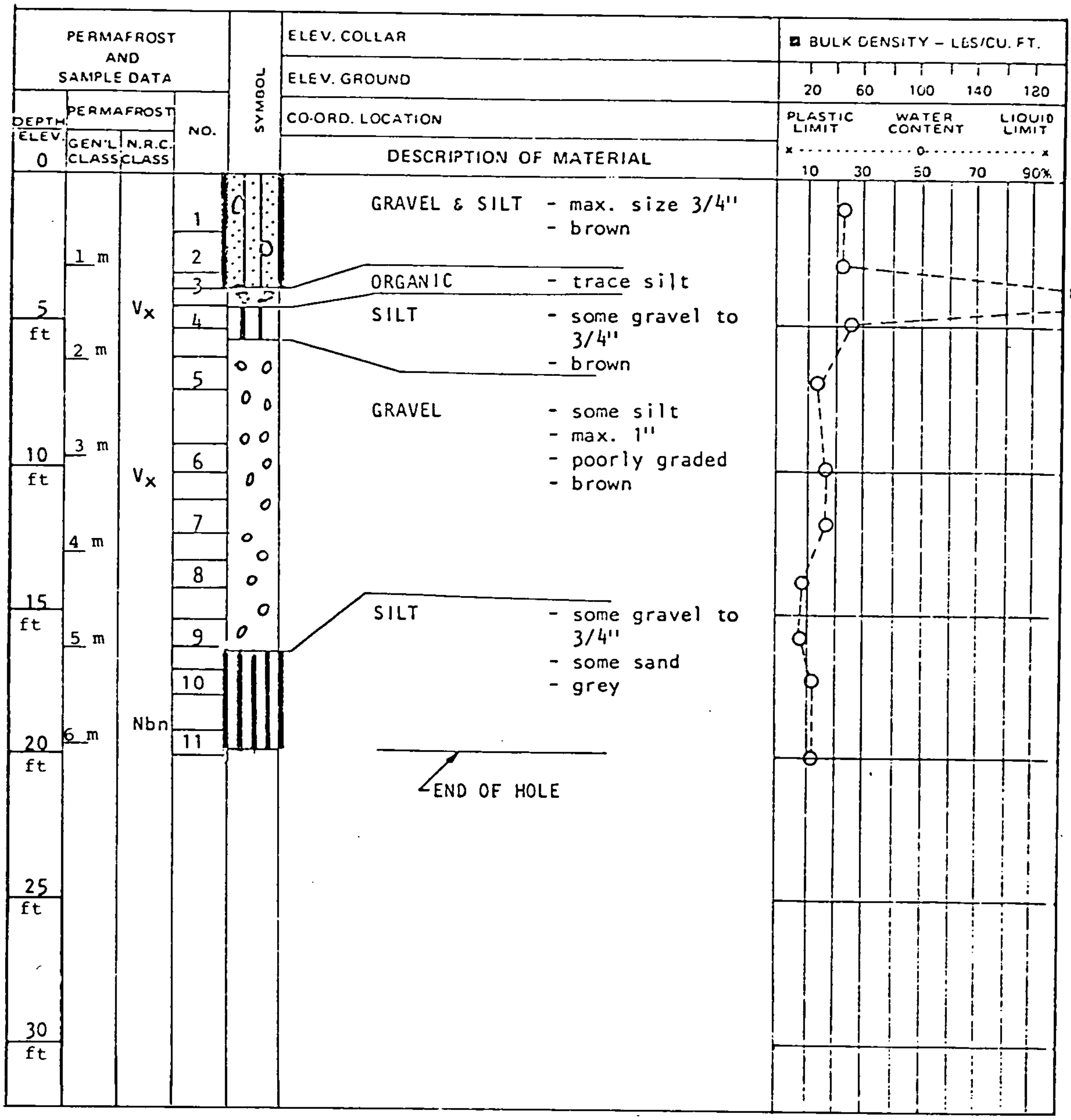


FIGURE 3. Test-hole log for hole TH-5 in an area with low ice content.

were taken by Klohn Leonoff personnel. At the end of 1976, the Northern Canada Power Commission assumed regular monthly monitoring of the temperature readings. The temperature data obtained between 1974 and 1977 confirmed that the natural subsoil remained frozen at all times. Since 1978, only six thermistors located beneath the lower insulation have been monitored in summer months: Thermistors T5 and T8 at thermistor assemblies P1, P3, and P5.

Discussions of Temperature Data

The temperature data available are for the period between July, 1974 and December, 1977. Temperature data recorded in 1977 (Figures 14 to 16) illustrate typical annual temperature variations of the foundation installation.

The three-and-half-year record of the ground temperature measured directly beneath the lower layer of insulation is provided in Figure 17.

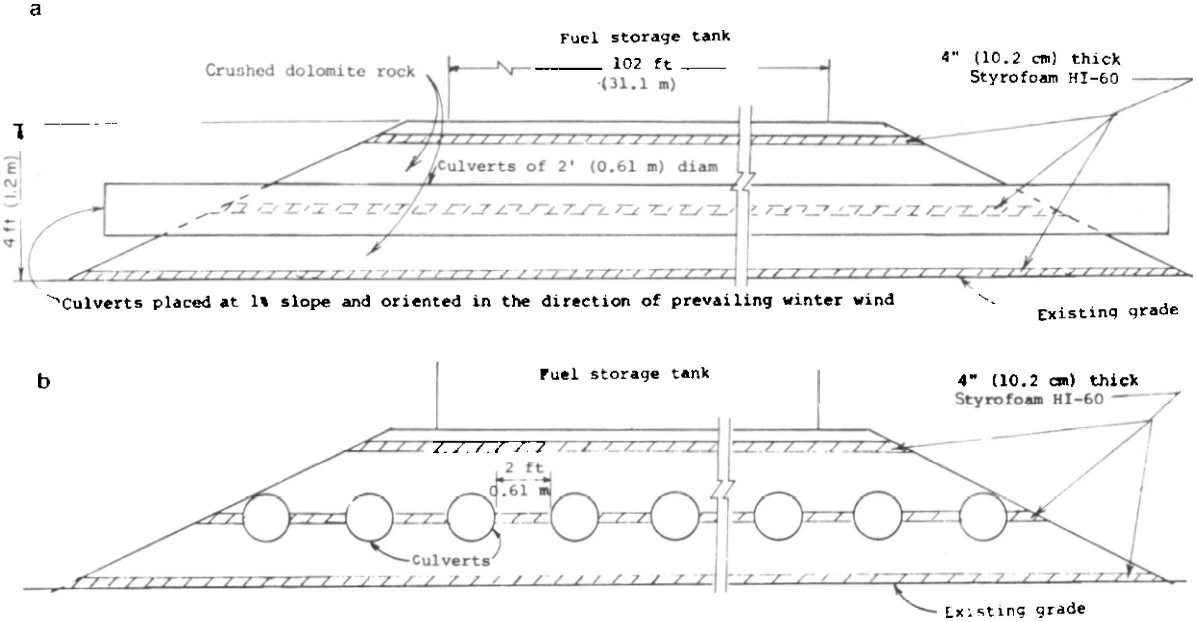


FIGURE 4. Schematic sketch of the insulated and ventilated granular pad foundation: **a** Section parallel to culverts; **b** Section perpendicular to culverts.

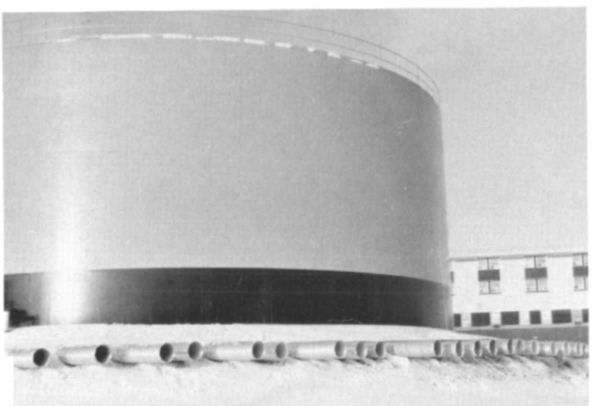


FIGURE 5. Completed fuel storage tank installation on the granular pad.

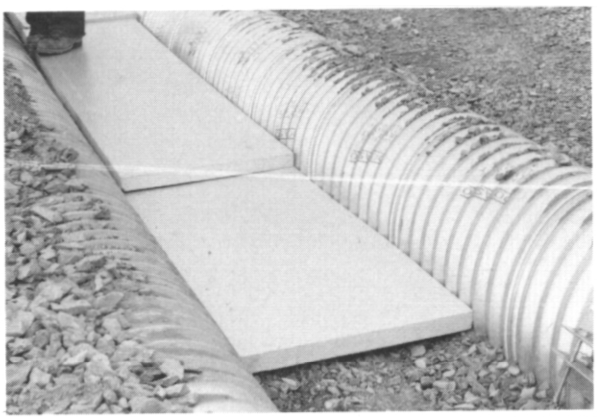


FIGURE 7. Placing the middle insulation layer between culverts.

FIGURE 6. Placing the lower layer of styrofoam HI-60 insulation on the basal levelling course.

FIGURE 8. Placing crushed dolomite on the upper insulation layer.

FIGURE 9. Placing and aligning ventilation culverts in granular pad.

FIGURE 10. Completed installation of ventilation culverts in the granular pad.

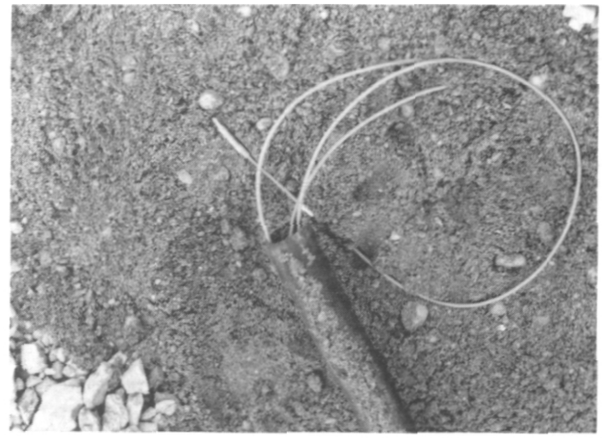


FIGURE 11. Close-up of thermistor.

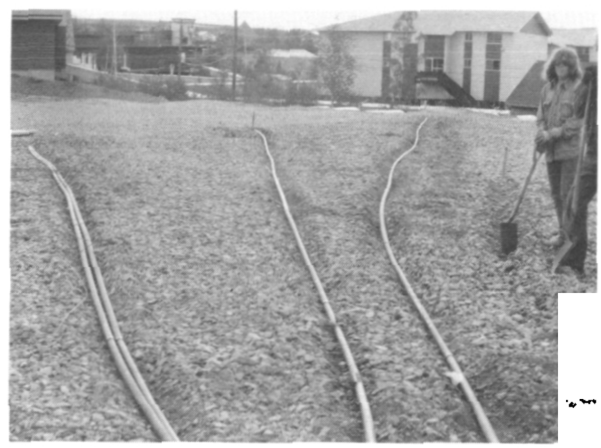


FIGURE 12. Thermistor leads carried through the fill in plastic conduits.

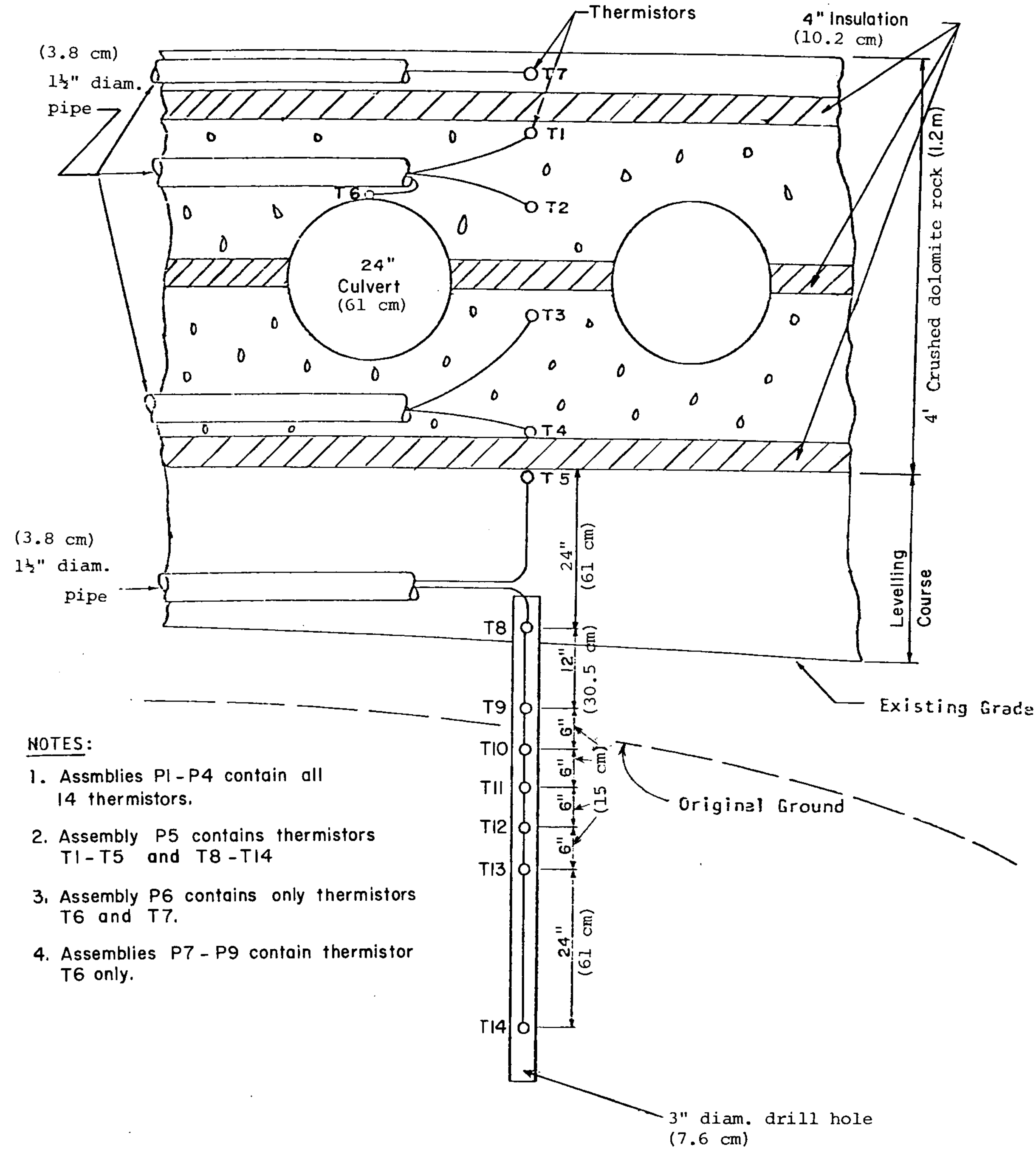
The following discussion relates to first, the monitored temperature variation and, secondly, the removal of heat through culverts in winter.

Monitored Temperature Variation

While the temperature of the tank, as measured near its bottom, reflects the general trend of the ambient air temperature (*see* Figure 14), the tank temperature is influenced by the heat capacity of the stored fuel. Thus, the tank temperature lags behind the air temperature, and the temperature range is smaller for the tank, 12 to 39°F (−11 to 4°C), than for the ambient air, −20 to 53°F (−29 to 12°C). The mean annual air temperature at the site is 15.6°F (−9.1°C). The T7 thermistors (*see* Figure 14**a**) placed near the edge of the tank (assemblies P1 and P6) are more strongly influenced by the outside air temperature than those placed beneath the interior of the tank.

The temperature data recorded along two separate culverts, P1 to P6 (*see* Figure 15**a**), and P7 to P9 (*see* Figure 15**b**), follow closely the variation of air temperature, especially for those thermistors located near the edge of the tank. Because cold air passes through the culverts in the winter and, except for some leakage, warm air is prevented from flowing through the culverts in the summer, the ambient air exerts a stronger influence on the culvert temperature in the winter than in the summer. Besides being affected by the ambient air, the culvert temperature also reflects the warming influence of the foundation pad in the winter and the cooling influence of the pad in the summer.

The temperature variation in the foundation pad (*see* Figure 16**a**), is significantly dampened by the lower insulation layer (*see* Figure 16**b**) and further dampened by the additional depth of native subsoil (*see* Figure 16**c**). The temperature of the foundation



NOTES:

1. Assmblies P1-P4 contain all 14 thermistors.
2. Assembly P5 contains thermistors T1-T5 and T8-T14
3. Assembly P6 contains only thermistors T6 and T7.
4. Assemblies P7-P9 contain thermistor T6 only.

FIGURE 13. Locations of thermistors in profile.

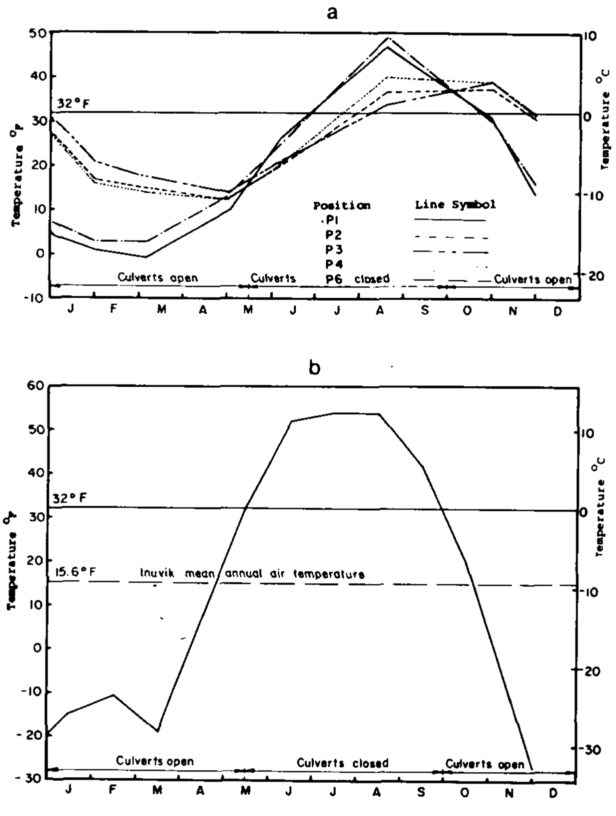


FIGURE 14. Temperatures of **a** fuel storage tank measured at thermistors T7 near bottom of tank, and **b** ambient air (year 1977).

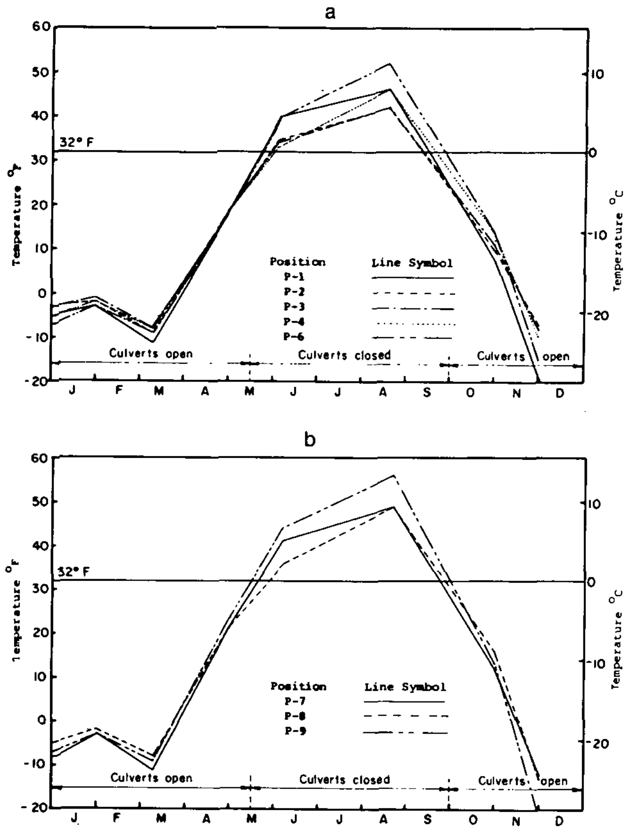


FIGURE 15. Temperature along culverts measured in 1977 at thermistors T6: **a** along diameter of tank, line P1 to P6; and **b** along line half way to edge of tank, line P7 to P9.

pad (*see* Figure 16**a**), is almost the same as that of the culverts in the winter (*see* Figure 15). It shows that the passage of cold air through culverts effectively cools the foundation pad while in the summer, warm air is blocked from flowing through them. Therefore, the temperature of the foundation pad is considerably lower than that of the culverts. Although the foundation pad undergoes annual freeze–thaw cycles, the subsoil has never experienced thawing since the summer of 1974 (*see* Figure 17).

Removal of Heat Through Culverts in Winter

The removal of heat through culverts in the winter can be determined indirectly by calculating the total amount of heat loss from the foundation pad. There are three items of heat loss: (i) Heat flux across the upper insulation layer from the tank; (ii) Heat flux across the lower insulation layer from the subsoil; and (iii) Latent heat of the foundation pad.

For the freezing season between October 1976 and May 1977, the following data were obtained from the temperature record:

Duration of freezing season = 200 days	= 4800 hours
Average temperature difference across the upper insulation layer during freezing season	= 22.8°F (12.7°C)
Average temperature difference across the lower insulation layer during freezing season	= 16.5°F (9.2°C)

The assumed thermal properties of the foundation pad and the Styrofoam together with the average area and volume of the pad are given as:

Latent heat of foundation pad	= 440 Btu/ft^3 (1.64×10^7 J/m^3)
Thermal conductivity of Styrofoam	= 0.017 Btu/hr · ft · °F (0.029 W/m · K)
Average area of foundation pad	= 12,900 ft^2 (1199 m^2)

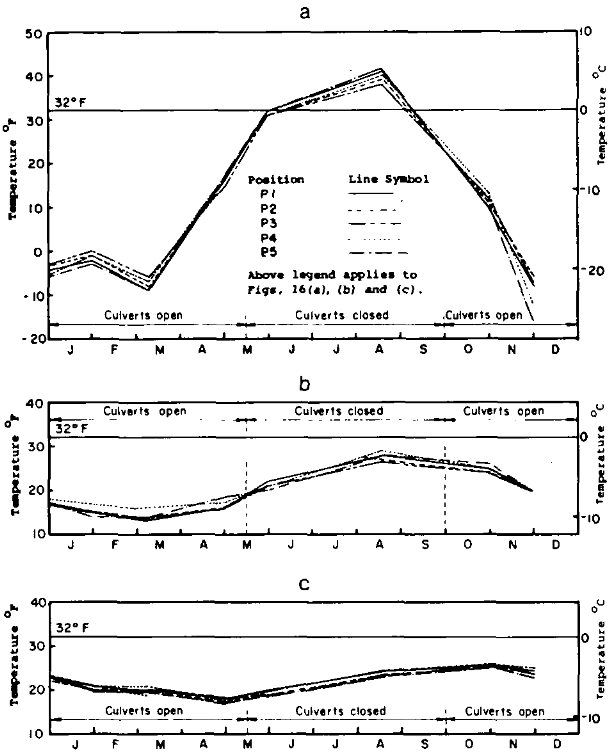


FIGURE 16. Foundation pad and ground temperatures measured in 1977 at: **a** thermistor T4, directly above lower layer of insulation; **b** thermistor T5, directly beneath lower layer of insulation; and **c** thermistor T14, 7 ft (2.1 m) below lower layer of insulation.

Volume of foundation pad	= 51,500 ft^3 (1459 m^3)

Thus, the average rate of heat removal during the freezing season by the culverts per unit of tank area can be computed. Because the foundation pad is colder, heat flows into it from the tank above and the subsoil below. The air passing through the culverts removes all the heat that enters from above and below in addition to the latent heat of the pad. The average rate of heat removal is summed up as follows:

Heat loss from above	= 1.2 Btu/hr · ft^2 (3.8 W/m^2)
Heat loss from below	= 0.8 Btu/hr · ft^2 (2.5 W/m^2)
Latent heat of foundation pad	= 0.4 Btu/hr · ft^2 (1.3 W/m^2)
Total average rate of heat removal	= 2.4 Btu/hr · ft^2 (7.6 W/m^2)

For this tank, which is locally heated in the winter, and has the same thickness of upper and lower insulation layer, the heat flux from the subsoil is three quarters of that from the tank.

The overall cooling effect of this heat removal through culverts on the foundation pad is reflected in the winter temperature at the bottom of the foundation pad (*see* Thermistor T4 in Figure 16**a**). The win-

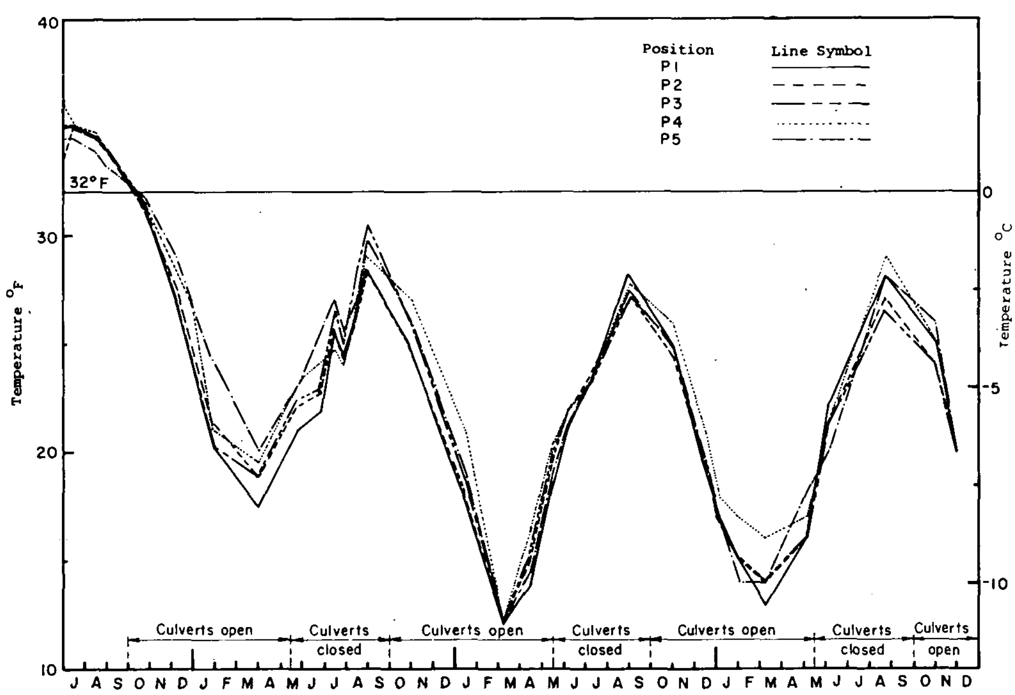


FIGURE 17. Ground temperature measured at thermistors T5, directly beneath lower layer of insulation.

ter temperature at the bottom of the pad is −10°F (−23°C), about 22°F (12°C) lower than that at the tank bottom, 12°F (−11°C).

The function of the insulation layers is to reduce heat input into the ground, especially in the summer. The upper layer of insulation is used to reduce heat input from the tank above into the foundation pad. Likewise, the lower layer of insulation is used to reduce heat input from the foundation pad into the subsoil below. The middle layer of insulation is used to retard the downward heat flow through the foundation pad in the summer. The fact that the culvert temperature is higher than the foundation pad during summer months reduces the effectiveness of this layer of insulation. It is believed, therefore, that this layer of insulation can be eliminated without much influence on the function of the foundation pad.

Conclusion

The integrity of a structure founded on a highly variable soil–ice subsoil depends on the preservation of the frozen state of the foundation soil. A relatively cost-effective design to keep the foundation soil frozen at all times is an insulated and ventilated granular pad foundation.

The temperature data acquired from the instrumentation program provides factual information regarding the performance of various components of the foundation installation including ventilation culverts, insulation, foundation pad, and the subsoil. The insights gained from the performance of the foundation will assist in the design of similar economical foundations for heavy structures in permafrost regions.

Acknowledgements

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