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FROST HEAVE CONTROL OF A CHILLED GAS PIPELINE

by Otto J. Svec

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SOMMAIRE

L'auteur examine la possibilité d'avoir recours à des câbles chauffants pour réduire le soulèvement, sous l'effet du gel, d'un gazoduc refroidi souterrain. A l'aide de méthodes expérimentales et numériques, il détermine l'influence de deux sources de chaleur placées sous une dalle isolante. Deux conditions pédologiques extrêmes sont représentées par un sable saturé et par un limon du Niagara très gélif. Les modèles de laboratoire et mathématiques s'accordent bien en ce qui concerne la prévision de la taille et de la forme de la bulle due au gel, suivant les variations de chaleur provenant des câbles. Des expériences menées sur un limon du Niagara montrent que ce système se prête bien à la réduction du soulèvement d'un pipeline sous l'effet du gel.

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FROST HEAVE CONTROL OF A CHILLED GAS PIPELINE

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ABSTRACT

This paper concerns the investigation of a possibility of controlling frost heave of a buried, chilled gas pipeline by heating cables. Experimental and numerical approaches were used to determine the influence of two heat sources placed underneath slab insulation. Saturated sand and highly frost-susceptible Niagara silt were chosen to represent two soil condition extremes regarding frost heave. Laboratory and mathematical models showed good agreement in predicting the size and shape of the frost bulb with variation of heat output from the cables. Experiments on Niagara silt demonstrated the engineering practicability of this system to control frost heaving of a pipeline.

INTRODUCTION

A number of proposals have been made in recent years for the construction of large pipelines in Alaska and northern Canada to carry Arctic natural gas. These pipelines would cross zones of continuous and discontinuous permafrost. One of the methods suggested was that pressurized gas in buried pipelines in these zones should be transported in a chilled state (below 0°C). This would prevent thawing of ice-rich frozen soil, but on the other hand, chilling of the gas would cause freezing of previously unfrozen soil in discontinuous permafrost zones. As the minimum lifetime of a pipeline is 30 years, a "bulb" of permanently frozen soil would grow around the pipe attaining, ultimately, a diameter up to 10 m.

Along the proposed pipeline routes much of the soil is frost-susceptible and the growth of the frozen bulb in these soils could be accompanied by the transport of large amounts of moisture due to induced thermodynamic potentials. This movement of moisture toward the freezing front could result in ice lensing and lead to large upward movements of the pipelines, particularly in discontinuous and shallow permafrost regions.

THE FROST HEAVE PROBLEM

The problem of frost heaving in soils has been studied since the first works by Taber (1929, 1930) and Beskow (1947). Early experiments demonstrated that frost heave is not only caused by freezing in situ pore water, but also by freezing migratory water. The water flow is induced by suction pressures developed within the "freezing fringe" – the partly frozen zone behind the freezing front.

Ice nucleates in water-filled pores and the boundary layers of adsorbed water on the hydrophilic surface of soil particles remain unfrozen. The presence of significant amounts of such unfrozen adsorbed water in frozen soil has been demonstrated by many authors, such as Anderson et al. (1973), Dirksen and Miller (1966), and Hoekstra (1966). The migration of the unfrozen water has also been routinely measured. In addition, an attempt has been made to measure the negative water head potential or suction developed in the vicinity of the frost line (Beskow 1947, Ruckli 1950, Penner 1958, 1967, Williams 1967). This task is extremely difficult, and the results obtained have not been consistent. It appears that, apart from soil type, the suction pressure is dependent on rate of heat extraction and overburden pressure.

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In spite of the long and concentrated research efforts in the development of frost heave theories, a complete solution to engineering problems involving frost action does not exist. Designers are thus handicapped when faced with the difficult problem of predicting and controlling the frost heave of a pipeline within safe limits.

The critical aspect of frost action on a buried, chilled pipeline is mainly one of differential upward movements causing pipe distortion and breakage. The question is whether differential heaving can be controlled and limited to avoid disastrous rupture of and costly interruptions in pipeline operations. These concerns are real, particularly in times of energy shortages and instability in the world's oil production, when reliable, safe and continuous operation of energy supply is extremely important. Apart from this, if one of the proposed Arctic gas pipeline projects is realized, it will represent the most costly construction enterprise ever undertaken by private industry.

This paper is concerned with the problem of retarding frost heaving of a pipeline by the combined use of thermal insulation and added heat sources. The heat sources considered here are heat-tracing cables buried beneath the insulation. The purpose of a combination of insulation and heat is twofold: to slow and eventually stop frost penetration below the pipe, and to change the direction of the heat flow. The first purpose is obvious, but the latter is also thought to be beneficial. As the direction of ice lensing is always perpendicular to the heat flow, the vertical frost heave can be redirected towards horizontal movements only. Thus the heat extraction resulting from the chilled mode of operation is altered in such a way that the freezing of the soil water and ice lensing will be harmless.

The studies described in this paper regarding the control of frost heave of chilled gas pipelines have been performed by both experimental and mathematical modelling. The computer program is based on a finite-difference representation of both the heat and mass transfer in moist soils, but in this paper only the heat flow aspect is utilized.

LABORATORY MODEL OF A PIPELINE

Many laboratory experiments have been carried out on a pipeline model to obtain quantitative information on the effects of pipe temperature, insulation, heat output from cables and soil types on the temperature distribution in the surrounding soil, the frost bulb size variation and the heave of the pipe. The results of three such experiments have been compared with solutions from a numerical finite-difference model.

The test apparatus consisted of a Plexiglass box 20.3 X 40.6 X 30.4 cm in size (Fig. 1). The brass pipe (5.08 cm O.D.) was mounted on two inner separate sliding walls to allow the pipe to heave. Friction was reduced by using two O-rings on each wall which, together with the use of a lubricant,

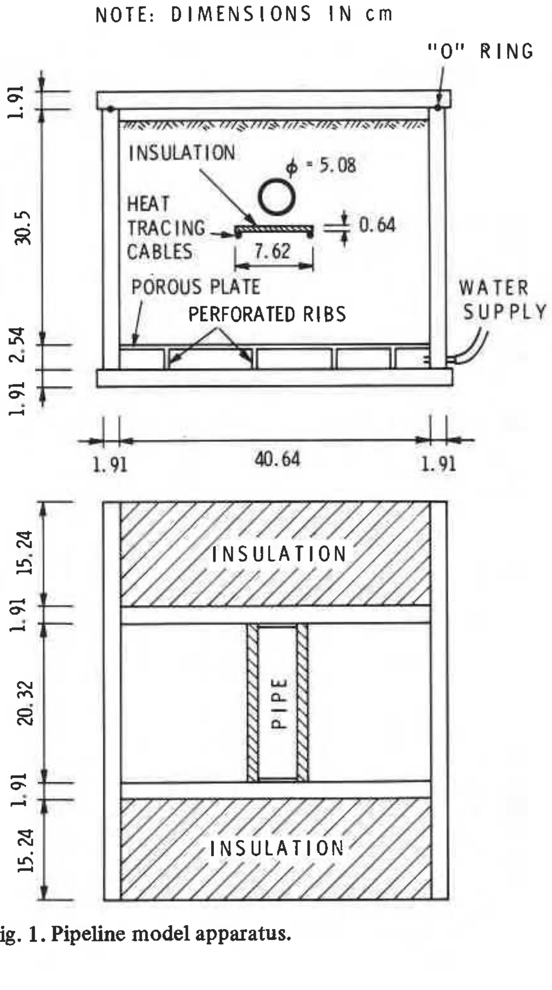

Fig. 1. Pipeline model apparatus.

prevented any water from moving between the sliding and outside walls. The bottom of the box contained a water reservoir; water transfer was achieved through a porous plate. The front and the back of the box were insulated with styrofoam (15.2 cm) to cause two-dimensional heat flow. The inside of the pipe was divided by a membrane into two chambers to provide for the return flow of the circulating fluid. The inlet and the outlet tube were connected to the back of the chamber. This set-up assured circulation of cooling fluid along the entire pipe length at a uniform temperature. A slab of insulation and two heat-tracing cables were placed under the pipe (Fig. 1).

Temperatures in the cell were measured with 56 thermocouples. Four special probes holding these thermocouples were fabricated from thin hardwood rods of rectangular cross-section. Heat conduction along the thermocouple wires was reduced by winding wires a few times around the probe close to the thermocouple tip. Temperatures were measured with a Joseph Kay data logger. Heaving of the pipe was measured with two dial gauges.

All the tests were conducted in a controlled temperature chamber kept at 1.15 ± 0.03 °C. Results of the three tests carried out to date are reported in this paper. Test conditions were as follows:

(1) Pipe temperature = –5°C; soil – saturated sand; cables – variable heat output – $0 \sim 136$ cal h^{-1} cm^{-1}.

(2) Pipe temperature = –3°C; soil – saturated sand; cables – variable heat output – $0 \sim 136$ cal h^{-1} cm^{-1}.

(3) Pipe temperature = –3°C; soil – Niagara silt; cables – variable heat output – $0 \sim 22$ cal h^{-1} cm^{-1}.

NUMERICAL MODEL

There can be a strong coupling between the processes of moisture and heat transfer in soils during freezing. This is particularly true for frost-susceptible soils such as clays and silts. Coarse-grained soils, e.g. sands and gravels, do not experience significant suction potentials induced by freezing (Kaplar 1974). The problem of freezing of saturated sand can therefore be formulated on the heat flow basis only. The computer program based on the mathematical model developed in this paper includes both the heat and moisture flows. However, mainly due to a lack of knowledge of the applicable hydraulic properties and suction potentials of highly frost-susceptible Niagara silt used in the third experiment, the numerical results are based on heat flow only. A simultaneous one-dimensional experiment and numerical study is now under way in which attempts are being made to find proper definition and evaluation of suction potentials initiated and sustained during the freezing process. This work will be reported in a future paper (Svec 1981).

A two-dimensional heat transfer equation for soil–water systems undergoing a phase change and in the absence of a vapour transfer can be written as follows:

$$c_a \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) - c_w \left[\frac{\partial(v_x T)}{\partial x} + \frac{\partial(v_y T)}{\partial y}\right], \qquad (1)$$

where λ = thermal conductivity (W m^{-1} °C^{-1}); c_w = volumetric heat capacity of water (MJ m^{-3} °C^{-1}); c_a = apparent volumetric heat capacity (MJ m^{-3} °C^{-1}); v = water velocity (m h^{-1}); T = temperature (°C); and t = time (h). Furthermore

$$c_a = c_m - L \frac{\Delta\Theta}{\Delta T}, \qquad (2)$$

where

$$c_m = \sum_{i=1}^{n} c_i X_i . \qquad (3)$$

Here c_m = volumetric heat capacity of soil–water–ice mixture (MJ m^{-3} °C^{-1}); c_i = volumetric heat capacity of ith element of the mixture (MJ m^{-3} °C^{-1}); x_i = a volume fraction of the ith material in the mixture (m^3 m^{-3}); and L = latent heat of the bulk water/ice phase change.

At the temperature, T, below freezing the unfrozen water content, Θ, can be approximated (Wheeler 1973) by:

$$\Theta = \gamma\Theta_{ef}\left(\frac{\alpha}{\alpha + T_f - T}\right)^4 + \delta . \qquad (4)$$

The notation used in Eqn. 4 is shown in Fig. 2. Equation (4) represents one of the coupling mechanisms between heat and moisture flows (Svec 1981).

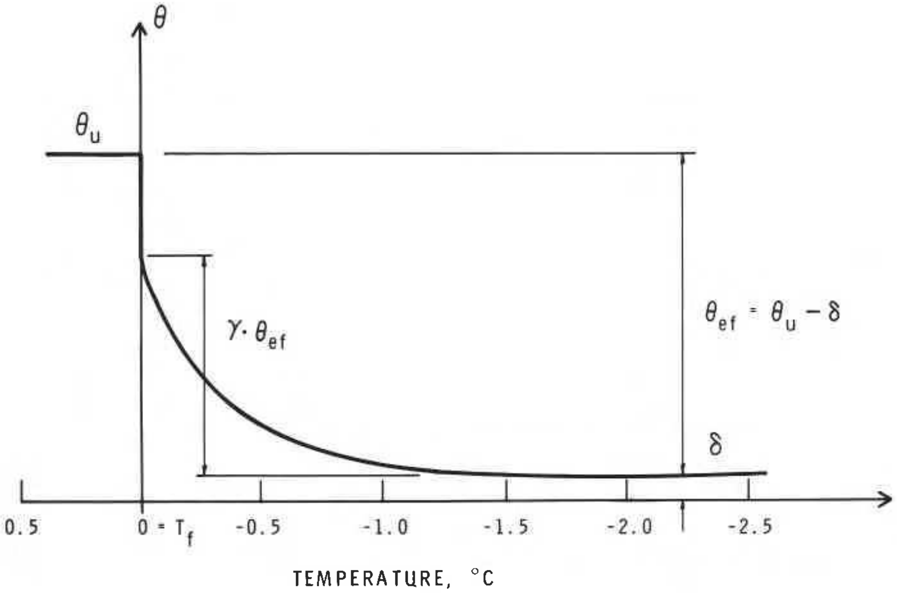

Fig. 2. Unfrozen water content.

The thermal conductivity, λ, is calculated according to Kersten's (1949) equation. At a boundary of two different materials (+, –), for example, soil layers, the following geometric approximation is used:

$$\lambda = \frac{2\lambda^+\lambda^-}{(\lambda^+ + \lambda^-)} \ . \tag{5}$$

During the phase transition, λ is calculated on the basis of water and ice fractions. At 14% water content, the following thermal properties were used for sand: $\lambda_u = 2.9$ W m^{-1} °C^{-1}; $C_u = 0.21$ MJ m^{-3} °C^{-1}; $\lambda_f = 3.75$ W m^{-1} °C^{-1}; $C_f = 0.17$ MJ m^{-3} °C^{-1} (where u and f denote the unfrozen and frozen states, respectively).

A computer program based on the finite difference scheme has been written in FORTRAN language. No details will be given here as they are to be published (Svec 1981). A few features, however, should be mentioned. The values of the heat capacity, thermal conductivity and unfrozen water content for a given grid point at a given time are expressed by explicit linearization from their values at the preceding time step. The freezing fringe is tracked down behind the moving 0 °C isotherm. An overall heat balance is computed at every time step. As a result the total heat crossing all the external as well as internal boundaries (including internal heat sinks and sources) are known for every step. An iterative solution of an implicit approximation of the partial differential equations, by Stone (1968), together with a built-in acceleration technique, has been used. A satisfactory convergency has been achieved by a time step cutting scheme based on the convergency rate during the iteration as well as on the overall heat balance. All the stationary and moving boundary conditions are defined in a time-dependent and spacewise general way with the moving freezing front. The inside heat sources or sinks (as, for example, heating cables or pipe respectively) were treated by using internal boundary conditions.

RESULTS

In the first test, the pipe was embedded in saturated sand and positioned 1.27 cm above a single slab of styrofoam insulation 0.64 cm thick. Two heating cables were placed under it (Fig. 1). The pipe temperature was kept constant at –5°C during the entire test. The variation of voltage in the heating cables and temperature at surrounding points (3 and 4), are shown in Fig. 3.

The 0°C isotherms indicate the change in the direction of heat extraction, from vertical to almost horizontal, due to the insulation. This change is obvious after 9 h (Fig. 5), when sand is freezing due to horizontal heat extraction around the insulation. It should be noted that even when the frost had penetrated well below the insulation a region immediately under the insulation remained unfrozen.

At 24 h, after the entire frost bulb was formed with no unfrozen cavities, 1 V was applied to the cables giving a heating output of 5.56 cal h^{-1} cm^{-1}. This initial heat, together with an even further increase (1.5 V, 12.52 cal h^{-1} cm^{-1}), did not produce a significant change in the position of the frost line. Only when the voltage had been increased to 3 V (50.1 cal h^{-1} cm^{-1}) at 49 h did the region immediately around the cables start to warm up. This increase caused thawing of a rather local zone which quickly stabilized. An increase in the voltage to 5 V and consequently the heat output from cables to 136.3 cal h^{-1} cm^{-1} was sufficient to thaw a relatively large area underneath the insulation. Figure 6 shows the progress of the thawing as well as the deformation effect on the lower frost line. As the heat source is sufficiently large, the lower frost line will eventually join the thawed cavity under the insulation.

The computer program already mentioned was used to simulate this test. As, at that stage, we were dealing with saturated Ottawa sand, material that is not frost-susceptible (i.e. not capable of developing an appreciable suction potential and supporting the ensuing water migration), the system of equations has been limited to the heat transfer only. The circular shape of the pipe was approximated by a square

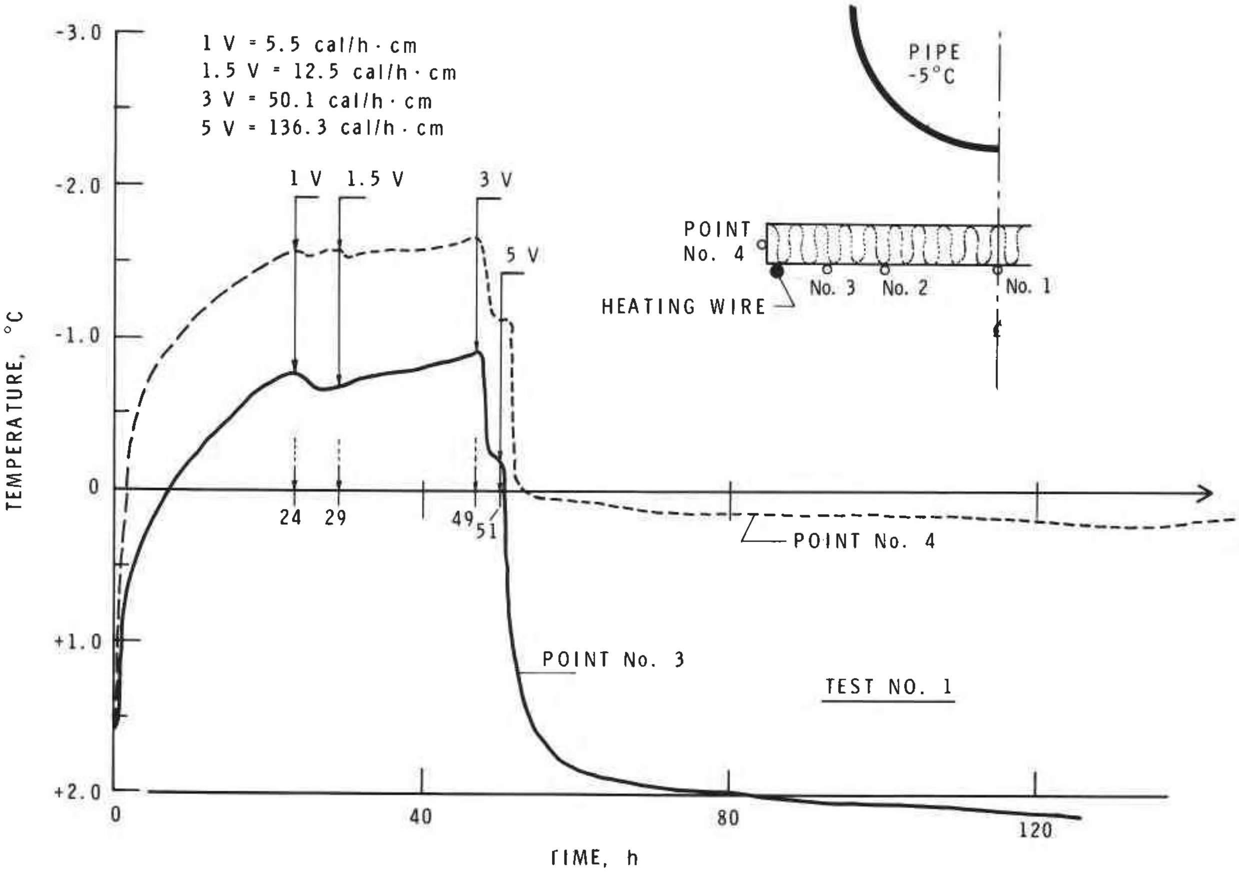

Fig. 3. Heating regime during test No. 1 (saturated sand).

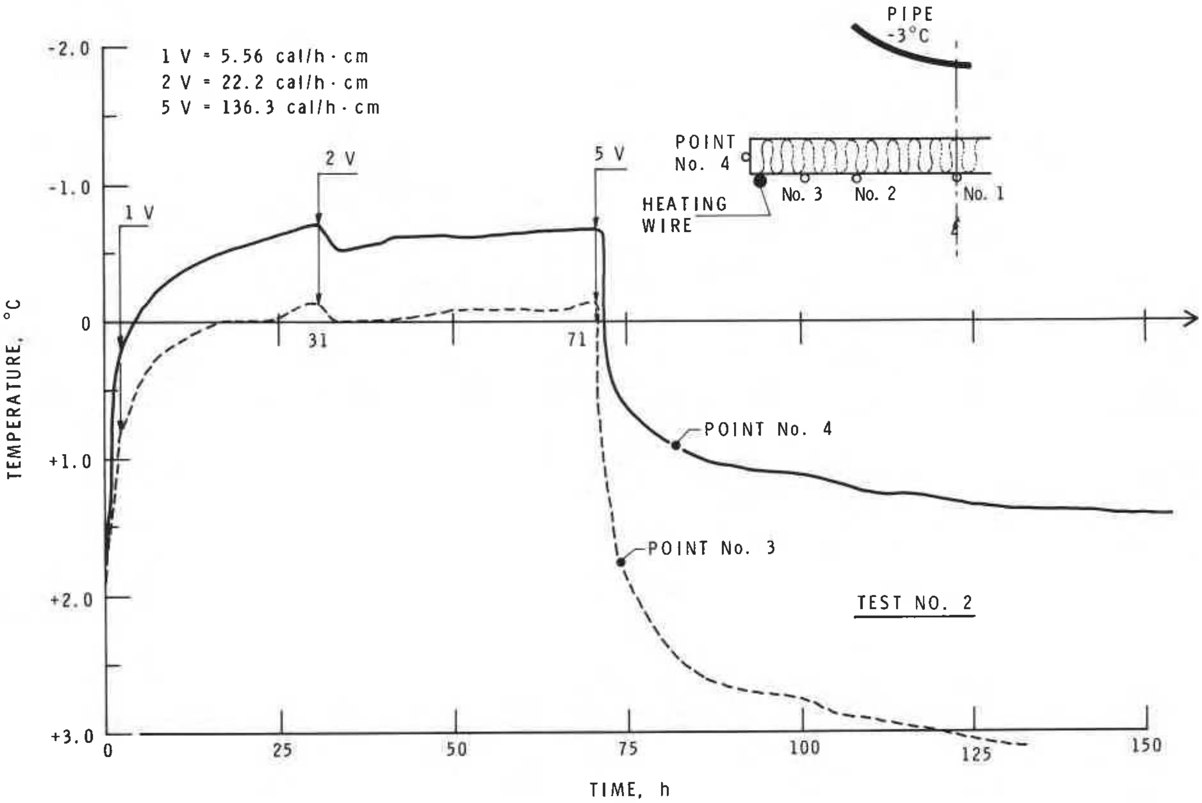

Fig. 4. Heating regime during test No. 2 (saturated sand).

of the same surface area. As is shown in Figs. 5 and 8, the shape of the pipe affects the frost penetration patterns during initial stages only. Later this effect vanished and the results were well in line with the experiment.

Test No. 2 was performed in the same manner as No. 1, and also used Ottawa sand, but the pipe temperature was held at –3°C. Figure 4 gives the history of applied voltage and the heat output from the cables. It also shows the temperature changes with time for the two selected points. Similar to test No. 1, it was observed that the heat generated by 2 V (or 22.2 cal h^{-1} cm^{-1}) was sufficient to stop any further cooling of surrounding soil. Increasing the voltage to 5 V (or output of 136.3 cal h^{-1} cm^{-1}) caused the entire area beneath the insulation to melt (Fig. 7). Experimental and numerical results obtained by using only the heat transfer equation are seen in Fig. 8. This comparison is based on observation of movement of the 0°C isotherm during freezing and thawing. As in test No. 1, the experimental results compare favourably with the simulation.

Test No. 3 represents a major departure from the two previous tests since a highly frost-susceptible soil was used (Niagara silt). It was prepared in a saturated state by mixing the dry silt with water (21% by weight).

Figure 9 is a record of the heat output from the cables during this test. The two upper curves show the temperature change in points Nos. 3 and 4 due to a change in voltage applied to the cables. The lower curve represents the total frost heave of the pipe. Before any voltage was applied a heave rate of 0.028 mm h^{-1} was measured. The heave rate was decreased to 0.015 mm h^{-1} at 1 V (or 5.56 cal h^{-1} cm^{-1}), and at 2 V (or 22.2 cal h^{-1} cm^{-1}) the heave stopped. Lowering the voltage from 2 to 1.5 V (or 12.52 cal h^{-1} cm^{-1}) caused frost heave to recur at

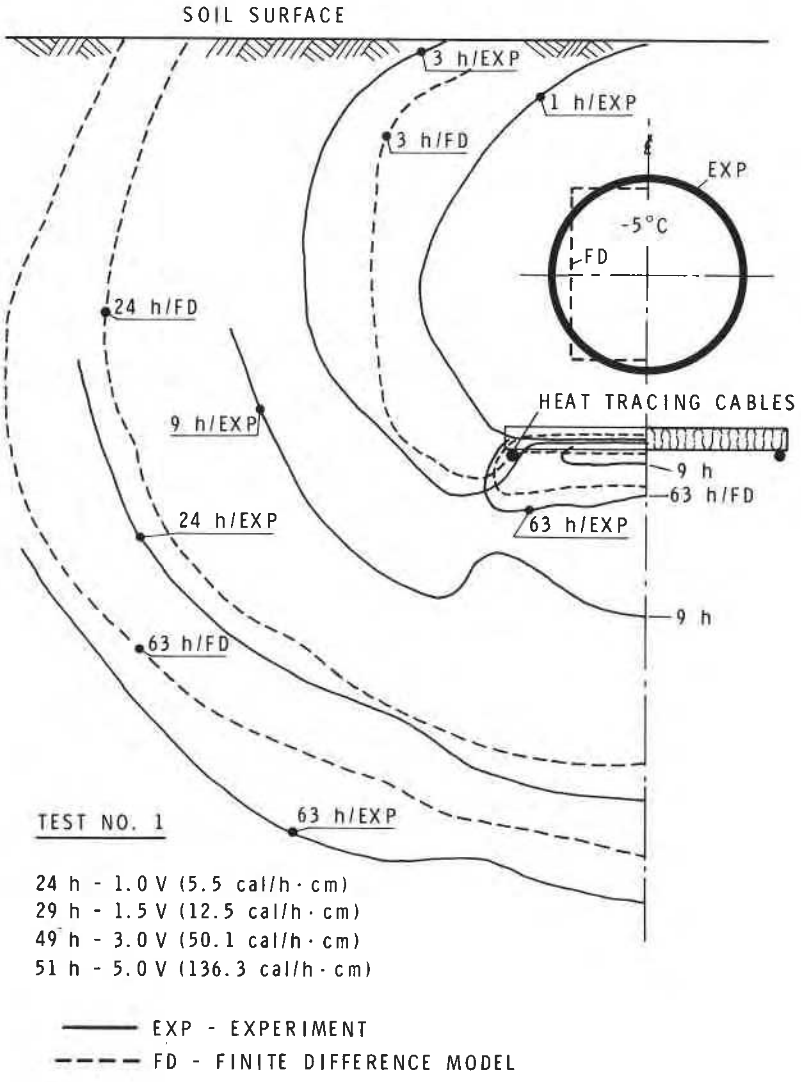

Fig. 5. Comparison of experimental and numerical results for tests No. 1 during first 63 h.

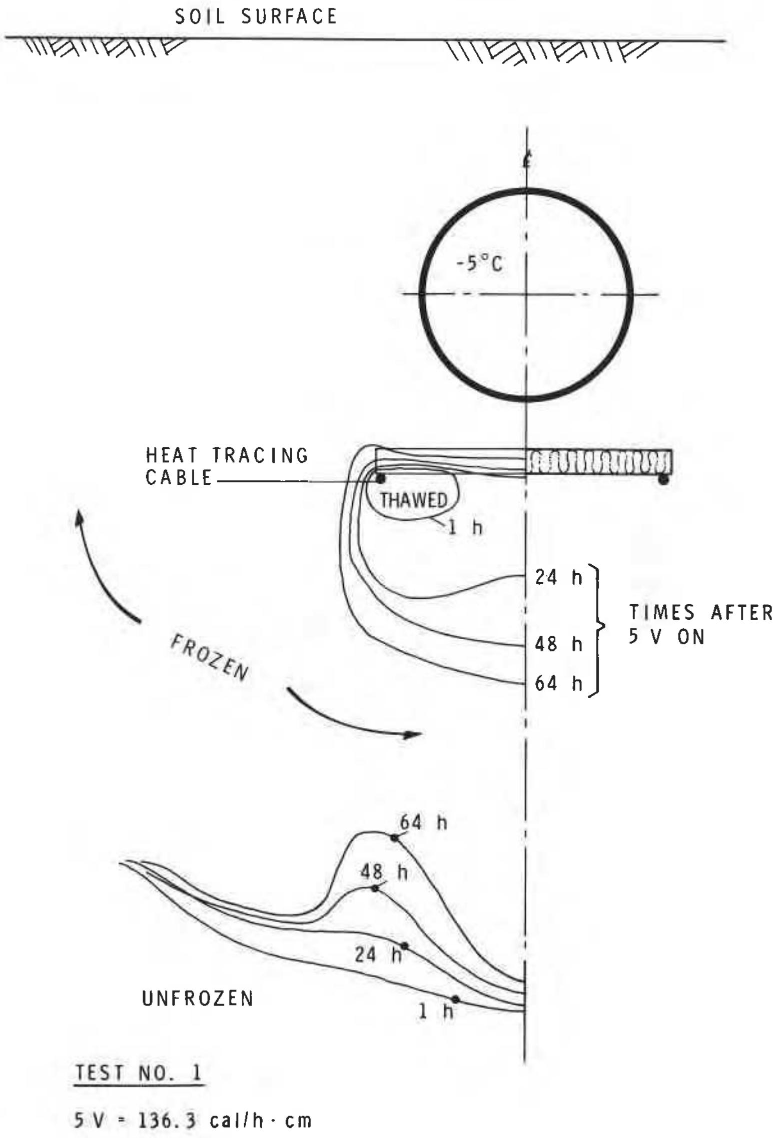

Fig. 6. 0°C isotherms during test No. 1 after application of 5 V.

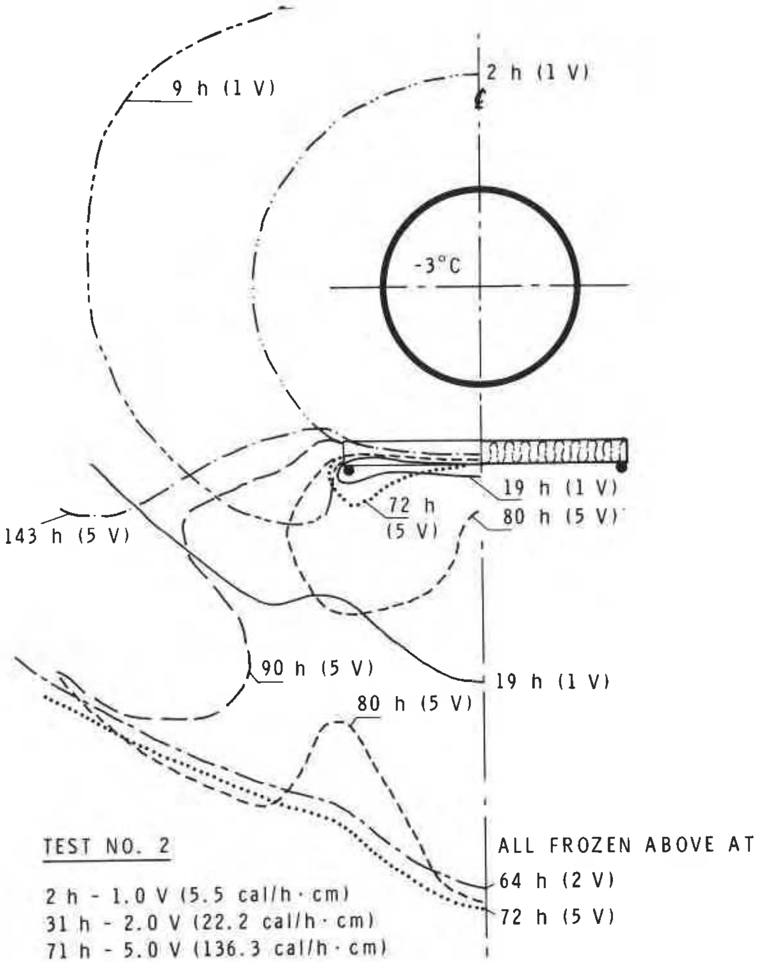

Fig. 7. 0°C isotherms during first 143 h in test No. 2.

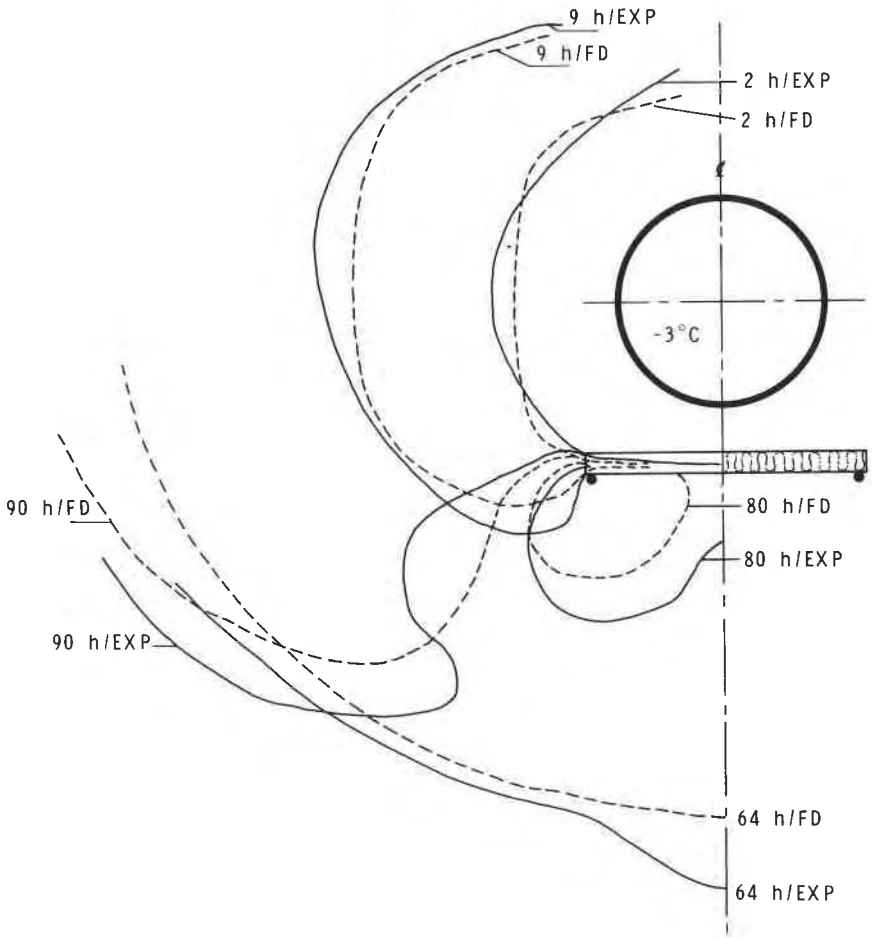

Fig. 8. Comparison of experimental and numerical results for test No. 2.

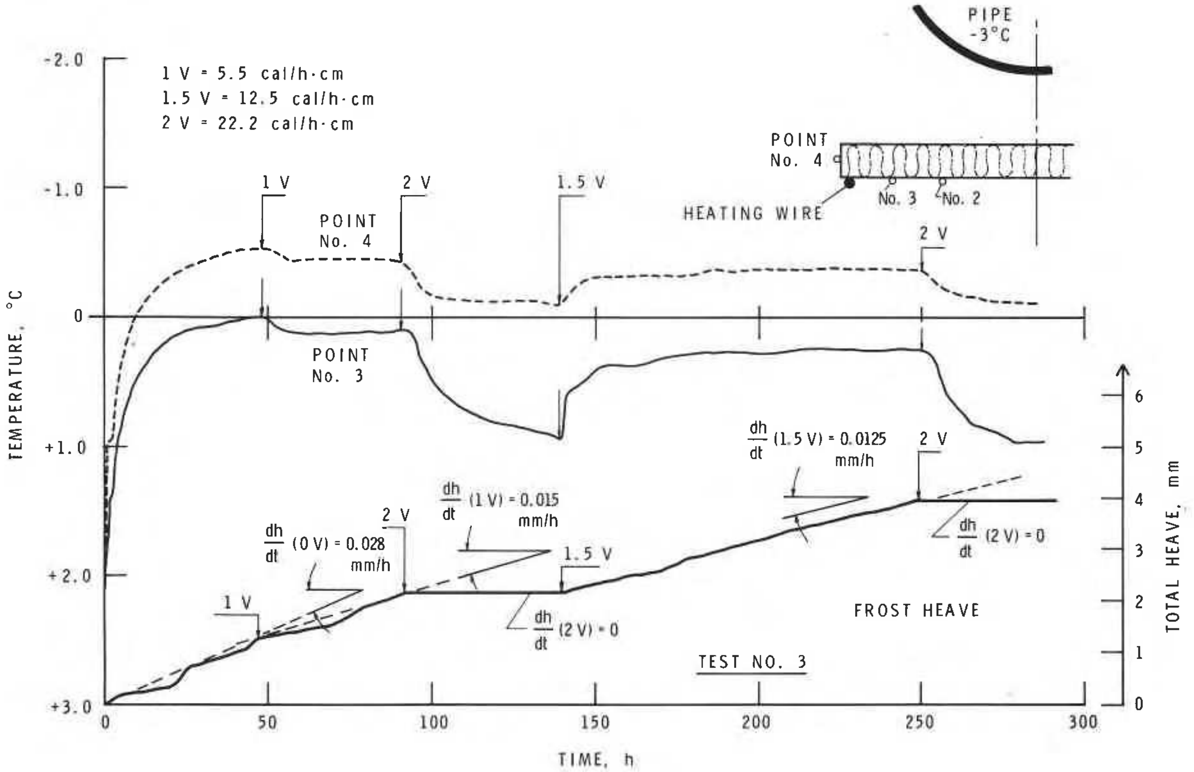

Fig. 9. Heating regime during test No. 3 (Niagara silt).

the rate of 0.0125 mm h^{-1}. By increasing the voltage later (250 h) to 2 V, the frost heave was stopped. Again this particular test demonstrated that the heave can be controlled by activating rather small heat sources in critical locations.

Figure 10 shows the growth of the frost bulb around the pipe as well as the effect of the heat of tracing on frost penetration. The first three measured positions for the 0°C isotherm (at 0.5, 2.0 and 3.0 h) illustrate the supercooling effect commonly found in the initial stages of freezing frost-susceptible soils. The frost bulb (together with a thick ice lens around its perimeter) is smaller than in the previous tests as the latent heat is considerably larger in silts than in sands. This is due to the larger amount of initial moisture in silts, but primarily results from the additional latent heat associated with the large amount of migratory water. Even though this incoming water was measured and ice lens growth observed, no quantitative conclusions can yet be made.

As has already been mentioned, the present model cannot as yet predict moisture transfer induced by freezing. Test No. 3, therefore, was not simulated.

CONCLUSIONS

These results indicate that the frost heave of a chilled pipeline can be successfully controlled by using heat-tracing cables. The experimental work, particularly that performed on highly frost-susceptible Niagara silt, shows that even a degree of frost heaving can be controlled to achieve economic optimum, together with structural integrity. Such an optimum could be based on a balance between the cost of refrigeration and transporting the gas at more economic higher densities.

The mathematical modelling of the first two tests dealing with soil freezing around a chilled pipe, together with the operation of the heat-tracing cables,

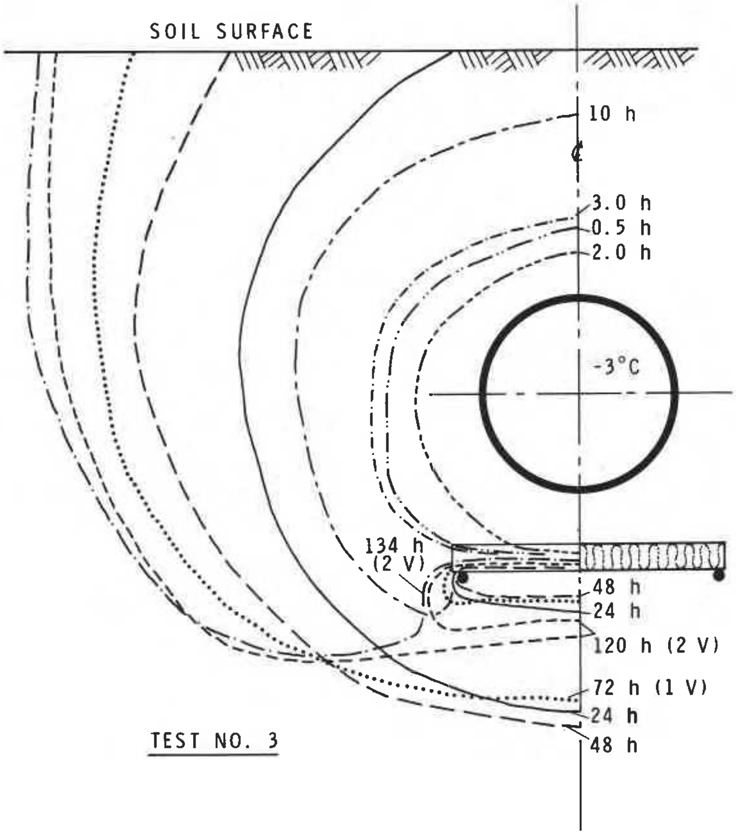

Fig. 10. 0°C isotherms during test No. 3.

shows, as one would expect, good agreement between theory and experiment (Figs. 5 and 8). Prediction of heat flow with time, particularly under the insulation and around cables, is of practical importance. On the basis of this model one can produce a number of designs of varying geometric configuration. The results presented here demonstrate the importance of heat sources and insulation in forcing the heat extraction to a more horizontal direction. This, in turn, causes much less harmful vertical ice lens growth. A parametric study of this nature could result in finding the economical system for a given soil and pipeline operating conditions.

Since a practical engineering approach to controlling frost heave is not yet available, it is very difficult to arrive at a design with a prescribed coefficient of safety. The use of heat-tracing cables would provide a certain degree of insurance against such uncertainty. There are indeed problems associated with heating wires (for example, their protection, power supply, and power control along the line), but is there a simpler, less expensive and, especially, a safer solution? The work described in this paper is continuing; future endeavours will be: to derive a mathematical theory of frost heave (Svec 1981); to determine the influence of geometric configuration of insulation; and to model real situations. Some results of the last two studies listed have been reported (Svec 1980).

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REFERENCES

Anderson, D.M., Tice, A.R., and McKim, H.L. (1973), The unfrozen water and the apparent specific heat capacity of frozen ground, North Am. Contribution to the 2nd Int. Conf. on Permafrost, Yakutsk, U.S.S.R. Nat. Acad. of Sci.: 289–294.

Beskow, G. (1974), Soil Freezing and Frost Heaving with Special Application to Roads and Railways, Translated by J.O. Osterberg, Tech. Inst., Northwestern University.

Dirksen, C. and Miller, R.D. (1966), Closed-system freezing of unsaturated soil, Proc. Soil. Sci. Soc. Amer., 30: 168–173.

Hoekstra, P. (1966), Moisture movement in soils under temperature gradients with the cold side temperature below freezing, Water Resources Res., 2: 241–250.

Kaplar, C.W. (1954), Freezing test for Evaluating relative frost susceptibility of various soils, CRREL Tech. Rep., 250, June 1974, Hanover, N.H.

Kersten, M.S. (1949), Laboratory research for determination of the thermal properties of soils, final report, Engng Experimental Station, University of Minnesota.

Penner, E. (1958), Pressure developed in a porous granular system as a result of ice segregation, Highway Res. Board Rep. 40 (Water and its Conduction in Soils), Washington, D.C.: 191–199.

Penner, E. (1967), Heaving pressures in soils during unidirectional freezing, Can. Geotech. J., 4: 398–408.

Ruckli, R. (1950), Der Frost im Baugrund, Springer-Verlag, Vienna.

Stone, H.L. (1968), Iterative solution of implicit approximations of multidimensional partial differential equations, SIAM J. Numer. Anal., 5(3): 530–558.

Svec, O.J. (1981), Chilled gas pipeline – frost heave design, Proc. ASCE Specialty Conference, "The Northern Community – A Search for a Quality Environment", Seattle, WA, April 1981.

Svec, O.J. (1981), A mathematical model for frost heave, in preparation.

Taber, S. (1929), Frost heaving, J. Geol., 37: 428–461.

Taber, S. (1930), The mechanics of frost heaving, J. Geol., 38: 303–317.

Weeler, J.A. (1973), Simulation of heat transfer from a warm pipeline buried in permafrost, presented to 74th Nat. Mtg AIChE, New Orleans.

Williams, P.J. (1967), Properties and behaviour of freezing soils, Norwegian Geotech. Inst., Publ. No. 72.

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