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by

W. A. Slusarchuk

Division of Building Research, National Research Council of Canada

and

G. H. Watson and T. L. Speer

Mackenzie Valley Pipe Line Research Limited, Calgary, Alberta

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Instrumentation Around a Warm Oil Pipeline Buried in Permafrost[1]

W. A. SLUSARCHUK
Division of Building Research, National Research Council of Canada, Ottawa, Canada
G. H. WATSON
Mackenzie Valley Pipe Line Research Limited, Calgary, Alberta
AND
T. L. SPEER
Mackenzie Valley Pipe Line Research Limited, Calgary, Alberta

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A section of an uninsulated pipeline, 90 ft (27.4 m) long and 2 ft (0.61 m) in diameter, was buried in ice-rich permafrost at the Mackenzie Valley Pipe Line Research Limited Inuvik Test Facility. Oil at 160 °F (71 °C) was circulated through the pipe from July 1971 to January 1972 causing a thaw bulb to develop around it.

Instrumentation was placed around the pipe to measure temperature, settlement, and pore-water pressure. Temperatures near the ground surface and at depth were measured using thermistors as the sensing element. Settlement was monitored by spiral foot gauges and by taking elevations at the ground surface and on rods welded to the pipe. Pore pressures were measured by gas-operated and Casagrande-type piezometers. Selection, fabrication, and installation of this instrumentation are discussed.

On a enterré un tuyau de pipe-line non isolé de 90 pieds (27.4 m) de longueur et de deux pieds (0.61 m) de diamètre dans du pergélisol riche en glace au centre d'essais d'Inuvik de la Mackenzie Valley Pipe Line Research Limitée. On a fait circuler dans le tuyau de l'huile à 160 °F (71 °C) de juillet 1971 à janvier 1972, ce qui provoqua la formation d'un bulbe de dégel autour du pipe-line.

On a disposé des instruments autour du pipe-line afin de mesurer la température, le tassement et la pression interstitielle. On a mesuré les températures près de la surface du sol et en profondeur au moyen de thermistors. On a vérifié le tassement au moyen de jauges à semelle en spirale ("spiral foot gauge") et en mesurant les niveaux à la surface du sol et sur les barres soudées au tuyau. On a mesuré la pression interstitielle au moyen de piézomètres actionnés au gaz et de type Casagrande. On examine la question du choix, de la fabrication et de l'installation de ces instruments.

In March 1971 Mackenzie Valley Pipe Line Research Limited decided to construct their second warm oil pipeline facility for testing under northern conditions. This line was to be buried in permafrost so that the results would complement previous studies of pipelines built on piles and in a gravel berm. The previously used site at Inuvik was suitable for the test because ice-rich permafrost was present and the terrain was flat. In addition, facilities to heat and circulate oil at any desired temperature were already present.

The main purpose of the test was to obtain data on how an ice-rich permafrost foundation would perform when a pipeline operating at 160 °F (71 °C) was buried in it. Following discussions between Mackenzie Valley Pipe Line Research Limited and the Division of Building Research a joint project to instrument the foundation was undertaken. The parameters to be measured were temperature, settlement, and pore-water pressure. This paper reports on the design, fabrication, testing, and installation of the instrumentation.

Test Facility

The test facility is located on relatively flat terrain 2 miles north of Inuvik, Northwest Territories, approximately 1 mile east of the east channel of the Mackenzie River. A typical soil profile at the site is as follows: moss and brown to black peat underlain by approximately 6–10 ft (1.8–3.1 m) of brown clayey silt, then approximately a 5–9 ft (1.5–2.7 m) layer of grey gravel and sand with 15–30% fines, and finally a layer of mainly grey fine-grained soil which extends to depths exceeding 30

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ft (9.2 m). A generalized soil profile with description of soil strata, frozen bulk unit weight, and water content is given in Table 1.

A gravel pad approximately 4 ft (1.2 m) in thickness and 50 ft (15.2 m) in width was on the permafrost at the location selected to bury the pipe. A backhoe was used to dig a trench through the gravel pad and into the virgin soil to a depth of approximately 2 ft (0.6 m). The uninsulated pipe, 90 ft (27.4 m) in length and 2 ft (0.61 m) in diameter, was bedded on, and backfilled with, sand. The organic material and gravel fill were then replaced and levelled.

Risers welded to each end of the pipe were joined to a 6-in. (0.15 m) diameter line which was connected to the main tank of warm oil. This line was supported on temporary cribbing so that it could be lowered as the buried pipe settled when the permafrost thawed.

The central portion along the pipe was instrumented as shown in Fig. 1. Selection of the position of the instruments was made with reference to results of a computer program developed to predict the progression of the thaw front. In total 46 thermistors, 11 settlement gauges, 19 gas-operated piezometers, and six Casagrande-type piezometers were used in the intensively instrumented area. Figure 2 shows the test section after the instruments were installed but before the hot oil began to circulate through the pipe.

Oil at approximately 160 °F (71 °C) began circulating through the pipe on July 22, 1971. Baffle plates placed at both ends of the buried pipe induced turbulent flow and kept the temperature of the pipe uniform. Operation of the heat exchanger was interrupted on October 1, 1971 and the oil temperature dropped to approximately 38 °F (3.3 °C) by November 3, 1971 at which time oil at 160 °F (71 °C) was again circulated. Oil flow was terminated in January 1972 and freezeback occurred. The mean annual air temperature at Inuvik is approximately 15 °F (−9.4 °C) and the amplitude of the annual variation in mean monthly air temperature is about ± 40 °F (± 22 °C). The initial temperature conditions (July 21, 1971) at the test site are given in Table 2.

Temperature

Although thermocouples and resistance-temperature devices (R.T.D.) were considered, thermistors were used to measure temperature because they could be integrated easily into the existing system at the site. Atkins precision interchangeable thermistors (P99-3) were used and the data acquisition equipment was matched to the resistance characteristics of these thermistors so that temperatures, in degrees Fahrenheit, were given directly on a digital readout. Temperatures were recorded twice a day with an accuracy of ± 0.5 °F (± 0.28 °C).

The thermistors were soldered to a two-wire shielded cable. Silicone rubber was applied to the thermistor and ends of the leads, and shrinkable tubing approximately 3 in. (0.1 m) in length was placed over top for protection.

As shown on Fig. 1 and in Table 3, 10 thermistors (T99–T108) were located at the surface of the test section. They were anchored to the ground by a small metal wire placed over the lead about 2 in. (0.05 m) away from the thermistor. The thermistor and lead were covered with sand to a depth of approximately 1/16 in. (0.002m). The other thermistors were placed in the thermistor – piezometer probes (described later), with a thermistor adjacent to the tip of each gas-operated piezometer. Additional thermistors were placed along the probes; their depths below surface are given in Table 1.

Settlement

Spiral foot gauges were installed in the foundation to monitor settlement at several depths. A schematic drawing showing typical details of the gauges is given in Fig. 3. The gauges were similar to those used successfully in the dykes at the Kelsey Generating Station in Manitoba (Johnston 1965).

One-inch-diameter steel reinforcing bars were welded to the top of the buried pipe at both ends and the middle, *i.e.* SR1, SR3, and SR5 as shown in Fig. 1. These bars were used as settlement rods to determine the vertical movement of the pipe. Elevations were taken on top of the settlement gauges and rods every 2–4 days. Ground surface elevations were taken periodically and an extensive series of elevations was taken July 21, 1971, September 1, 1971, and July 11, 1972.

Figure 4 shows a cross-sectional view of the initial location of the gauges in relation to the position of the pipe and layers of soil in a typical profile. Gauges S1, S2, S3, and S4 were installed just below the organic cover to monitor the settlement near the original ground surface. Three vertical arrays of gauges were used to obtain the settlement of the various soil layers. Array 1 (S7, S8)

TABLE 1. Generalized soil profile at site

Depth below surface (ft)	Designation of soil stratum	Frozen bulk unit weight (lb/ft)	Water content (%)
0–4.5	Gravel fill	—	—
4.5–5.0	Compressed organics	—	—
5.0–6.0	Silty clay (organic)	70	190
6.0–6.5	Ice (trace of silt)	59	Very high
6.5–9.0	Ice with silt inclusions	77	117
9.0–13.0	Silt and ice	89	80
13.0–below	Gravelly till	126	—

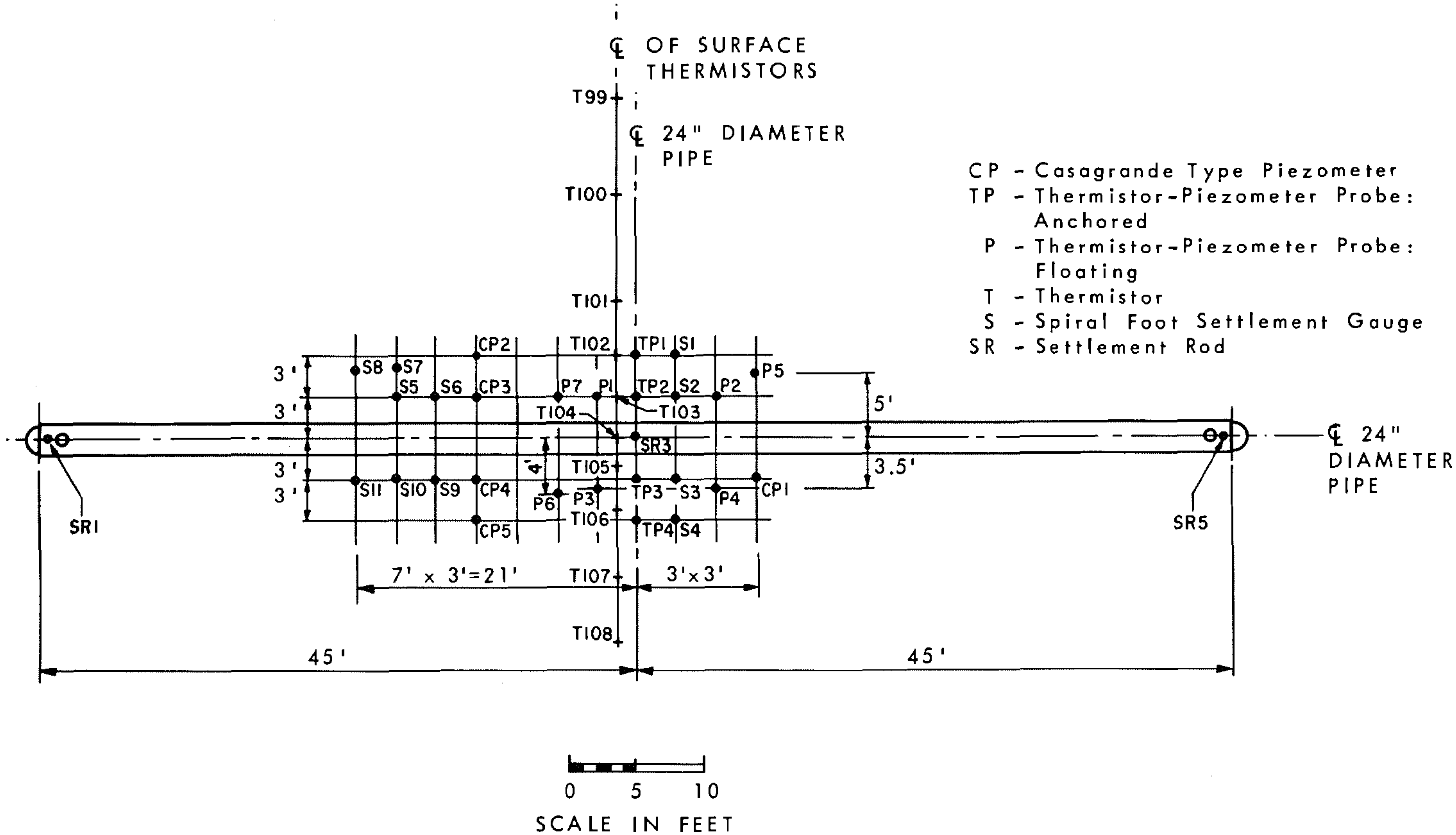


FIG. 1. Plan of instrumentation around buried pipe.

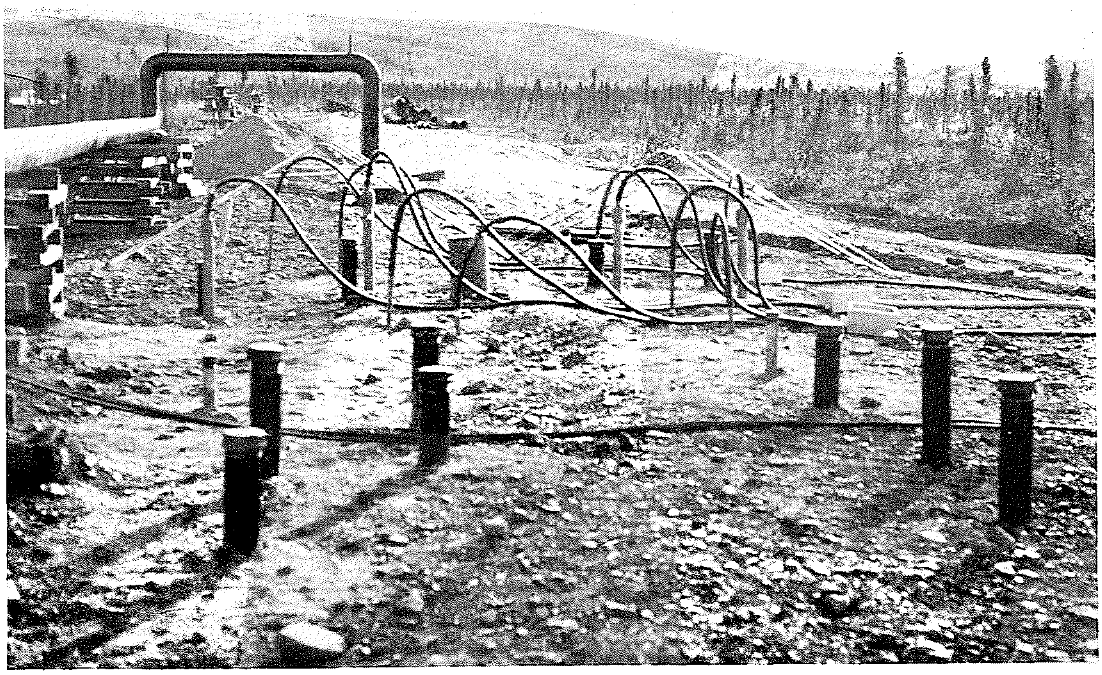


FIG. 2. Test section after installation of instruments.

TABLE 2. Initial temperature distribution at site July 21, 1971

Depth below surface (ft)	Temperature (°F)
0.04 (surface)	70.0
1.0	61.2
3.0	45.9
5.5	31.1
8.5	27.5
11.5	24.2
13.5	23.3
14.0	22.8

was placed approximately 5.5 ft (1.7 m) from the center line of the pipe. Array 2 (S2, S5, S6) was placed 3 ft (0.9 m) from the center line of the pipe on the same side as array 1. Array 3 (S3, S9, S10, S11) was placed approximately 3 ft (0.9 m) from the center line of the pipe on the side opposite array No. 2.

Pore-water Pressure

Piezometers were installed to determine whether excess pore pressures were generated when the ice-rich permafrost melted. Thawing around the pipe was expected to occur rapidly with subsequent settlement of the foundation. The experiment was scheduled to stop after the thaw front had penetrated into the gravelly material, which was at a depth of 13 ft (4 m). It was known, therefore, that large pore pressures would not be present during thawing. Literature on methods of monitoring pore pressures under these conditions was not available so a program was initiated to select, develop, and test instrumentation for this application, subject to five general guidelines.

1. Pore-water pressures were to be measured at the thaw front (*i.e.* as the 32 °F (0 °C) isotherm passed by the piezometer tip) as well as within the thaw bulb. This meant that the piezometers had to be installed in holes in the permafrost and that they must not be damaged during subsequent freezeback. It was desirable to be able to measure these pressures with an accuracy of ±0.5 ft (±0.15 m) of water or better because of the small pressures involved.

2. The elevation of the piezometer tips was to be known at all times because the foundation was expected to settle more than 3 ft (0.9 m) in a few months.

3. The level of the water table across and along the thaw bulb was to be measured so that the amount of excess pore pressure, if any, could be determined.

4. The piezometer was to be durable under Arctic conditions.

5. The availability and delivery date of the piezometers and the associated readout equipment had to mesh with laboratory testing and installation deadlines. The test loop was scheduled to be in operation by the middle of July 1971.

Selection of Piezometers

It was difficult to select the piezometer because of the limited information on measurement of pore pressures in thawing perma-

TABLE 3. Elevation of piezometers and thermistors

Probe	Piezometer	Thermistor	Instrument elevation (ft)	Depth below surface (ft)
TP 1		T 71	115.5	1.0
		T 72	113.5	3.0
	PZ 1	T 73	111.0	5.5
	PZ 2	T 74	108.0	8.5
	PZ 3	T 75	104.5	12.0
TP 2		T 76	116.1	0.7
		T 77	114.1	2.7
		T 78	113.1	3.7
		T 79	111.1	5.7
		T 80	108.6	8.2
	PZ 4	T 81	108.1	8.7
		T 82	105.6	11.2
	PZ 5	T 83	105.1	11.7
TP 3		T 84	115.9	1.0
		T 85	113.9	3.0
		T 86	112.9	4.0
		T 87	110.4	6.5
		T 88	108.9	8.0
	PZ 6	T 89	108.4	8.5
		T 90	106.4	10.5
	PZ 7	T 91	105.9	11.0
		T 92	103.4	13.5
	PZ 8	T 93	102.9	14.0
TP 4		T 94	115.7	1.0
		T 95	113.7	3.0
	PZ 9	T 96	111.2	5.5
	PZ10	T 97	108.2	8.5
	PZ11	T 98	105.2	11.5
Surface thermistors		T 99	—	
		T100	—	
		T101	—	
		T102	—	
		T103	—	
		T104	—	
		T105	—	
		T106	—	
		T107	—	
		T108	—	
P 1	PZ12	T111	110.6	6.0
P 2	PZ13	T112	108.2	8.5
	PZ14	T113	105.2	11.5
P 3	PZ15	T114	110.7	6.0
P 4	PZ16	T115	106.6	10.3
P 5	PZ17	T109	110.2	6.5
P 6	PZ18	T116	106.3	10.5
P 7	PZ19	T110	106.0	10.6

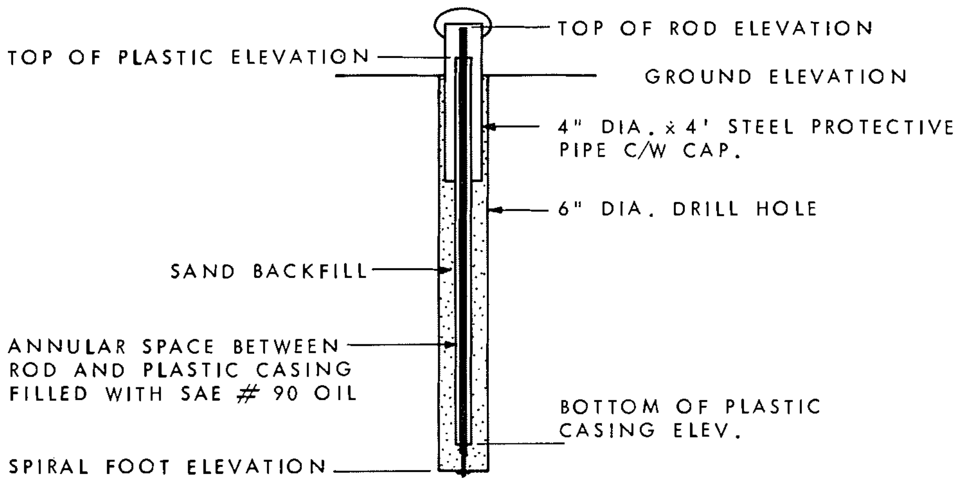
frost. With regard to the guidelines the following types of piezometers were considered.

Standpipe Type

This consists of a buried porous tip connected to the surface by a small diameter pipe, (Casagrande 1949). This type has the following advantages: simple design, gauge house not required, and proven use for more than 25 years. Its disadvantages are: a slow response time, possible errors due to the introduction of air, inability to record negative pressures, and need for an antifreeze fluid in Arctic conditions.

Closed Hydraulic System

This system was developed to overcome accuracy problems associated with air intrusion and to shorten the response time compared with the open tube piezometer (Daehn 1962; Bishop *et al.* 1964). Its advantages are: rapid response if air-free, ability to record negative pressures, and allows de-airing of the piezometer tip. The following are the disadvantages: requires a heated gauge house, sensitive to the elevation of the gauge house (particularly for low or negative pore pressures), fragile and thus sensitive



INSTALLATION NO.	TOP OF ROD	ROD LENGTH	SPIRAL FOOT EL.	TOP OF PLASTIC EL.	LENGTH OF PLASTIC	BOTTOM OF PLASTIC ELEV.	GROUND ELEV.
S1	117.50	5.71	111.79	116.77	4.22	112.55	116.37
S2	117.97	5.73	112.24	116.95	4.20	112.75	116.62
S3	118.03	5.71	112.32	117.08	4.21	112.87	116.79
S4	118.26	5.72	112.54	117.23	4.22	113.01	116.82
S5	117.96	10.22	107.74	117.07	8.70	108.37	116.71
S6	118.13	13.21	104.92	117.12	11.72	105.40	116.63
S7	118.28	8.22	110.06	117.30	6.72	110.58	116.67
S8	117.77	12.19	105.58	116.85	10.71	106.14	116.44
S9	118.09	10.21	107.78	117.27	8.70	108.57	116.79
S10	118.32	12.21	106.11	117.44	10.71	106.73	116.59
S11	118.24	15.71	102.53	117.30	14.21	103.09	116.51

FIG. 3. Spiral foot settlement gauges.

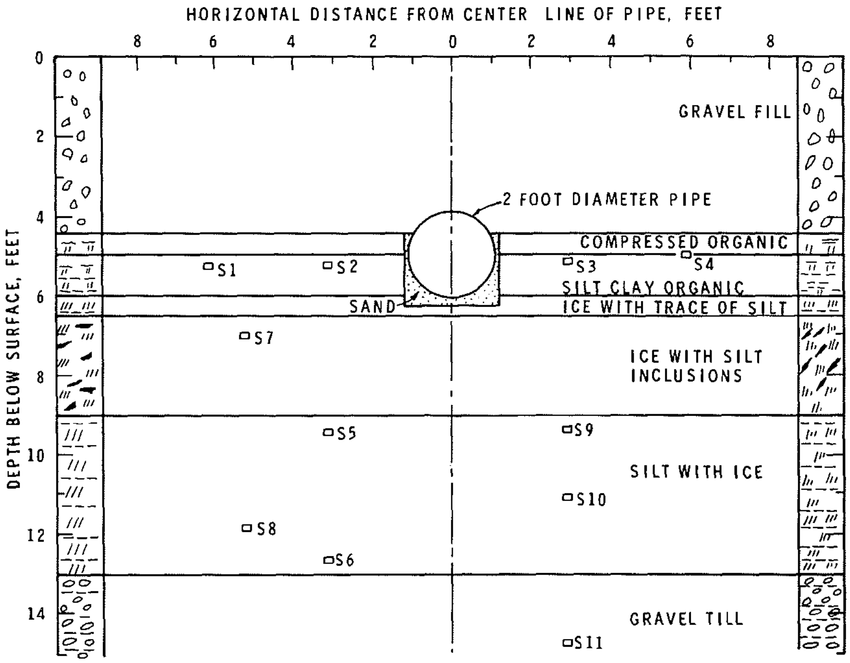


FIG. 4. Cross-sectional view of original position of settlement gauges.

to Arctic conditions, and requires an antifreeze liquid for circulation in the hydraulic system.

Electrical Diaphragm Instruments

In the majority of these instruments, the pore pressure against a thin metal diaphragm is measured electrically by means of strain gauges, vibratory wire gauges, or piezoelectric crystals (Terzaghi 1943; Plantema 1953; Muhs 1954).

These gauges have the advantage of almost instantaneous response and do not require fluid in the system and, therefore, are not as susceptible to Arctic conditions. In general, their main disadvantage is caused by errors that may arise due to calibration drift.

Pneumatic and Hydraulic Instruments

This type of piezometer has been developed within the past few years in America (Warlam and Thomas 1965) and in Europe (Lauffer and Schober 1964). This instrument operates by balancing the pore pressure on the soil side of the diaphragm with a known fluid pressure which may be supplied by gas or oil injected into a cavity on the other side of the diaphragm. Its advantages are: a rapid response time, the recorder level independent of the tip level, generally less expensive than the electrical type, and elaborate instrument house not required.

None of the piezometers considered could meet the criterion of immediate response upon thawing and still be able to withstand the freezeback of the backfill in the bore hole around it. To overcome this problem the tip of the piezometer was housed in a compartment that was filled with a solution (ethylene glycol) that would not freeze at the lowest temperatures of the local permafrost. Continuity of the fluid phase between the compartment and the soil had to be maintained.

The piezometer selected for the basic system was the P1020 pneumatic piezometer manufactured by Terra Tec. It functions by the application of gas (nitrogen) pressure through a closed loop system to balance the pore pressure acting on the sensing element. This element consists of a single bellows assembly which is sensitive to small displacements so that response time is minimized.

It was decided to use this type of piezometer for the following reasons:

1. It had been used successfully in frozen dyke foundations in northern Manitoba (Gupta and Marshall 1972);
2. Manufacturers' specifications indicated that it was possible to measure small pressure heads with this type of piezometer;
3. The tip or sensing unit was small and therefore convenient for use in a multiple assembly;
4. A tip which had a preload was available, thus allowing the monitoring of negative pore pressures; and
5. This type of instrument, complete with readout equipment, was available on short notice. This allowed time to run a laboratory testing program prior to installation.

Casagrande-type piezometers were selected for monitoring the level of the water table. A few gas-operated piezometers and three wells were also used to determine the position of the water table across and along the buried pipe.

Elevation Control of Piezometers

As mentioned previously, elevation control of piezometers at all times was essential. The methods that were considered to accomplish this were:

1. The use of a 'network' of settlement gauges to give contoured settlement;
2. The use of rigid rods attached to instrument assemblies extending to the surface and thereby allowing direct elevation measurements; and
3. The use of long rigid instrument probes founded in the permafrost below the depth of the thaw bulb.

Each of these methods had limitations which were recognized but their full implications were unknown. The 'interpolation' method using settlement gauges was not considered to be sufficiently accurate as a basic system to monitor the settlement of the other instruments. It would also lead to considerable expense for drilling and installation. Thermal disturbance was also a possibility.

The use of rigid rods attached to each instrument assembly appeared attractive except that again there would be a large number of holes with the associated higher cost and possible thermal disturbance. In addition, the analysis would be complicated by having the piezometer tips settling throughout the experiment.

The third method of using rigid instrument probes founded beneath the thaw bulb in the frozen gravel had the advantage of maintaining a fixed-grid at known elevations and, in addition, several instrument units could be mounted within the one assembly at varying depths thus reducing the number of holes required. This system had the disadvantage of having an unknown amount of frictional down drag on the probes as the foundation thawed and settled.

In view of the problems associated with all of these methods, it was decided that the rigid instrument probes would be used with a limited number of instruments utilizing the other systems as back-up.

To meet the requirements of sturdiness and constant known elevation, it was necessary to develop a probe that would have not only a high degree of reliability and precision, but also be sufficiently durable to withstand large ground settlements around it. The design developed for the thermistor–piezometer probes allowed a number of pressure and temperature sensors to be housed in a tough, protective cover. This cover was sufficiently rigid to maintain instruments at constant elevations with the probe base fixed in the frozen strata below.

Materials with a low thermal conductivity were used for these probes to minimize disturbance of the temperature regime around the pipe.

Basic Piezometer Unit

The basic piezometer unit consisted of a gas-operated sensing element, a compartment in which to house the element, and a port through the wall of the compartment. A thermistor was positioned adjacent to the sensing element to measure its temperature. Figures 5 and show 6 the basic unit unassembled, and partially assembled.

The design of the ports was given considerable attention because it was necessary that the compartment be kept saturated prior to, during, and after installation of the assembly in a bore hole to ensure a 'hard' pressure system so that a rapid response would be obtained as the permafrost thawed.

A series of small holes, 0.01 in. (0.003m) in diameter drilled at one level around the compartment was a possible solution that was investigated. It was quickly abandoned, however, because any tilting or jarring allowed the fluid to drain out of the compartment even though no drainage occurred if the unit was maintained in a fixed up-

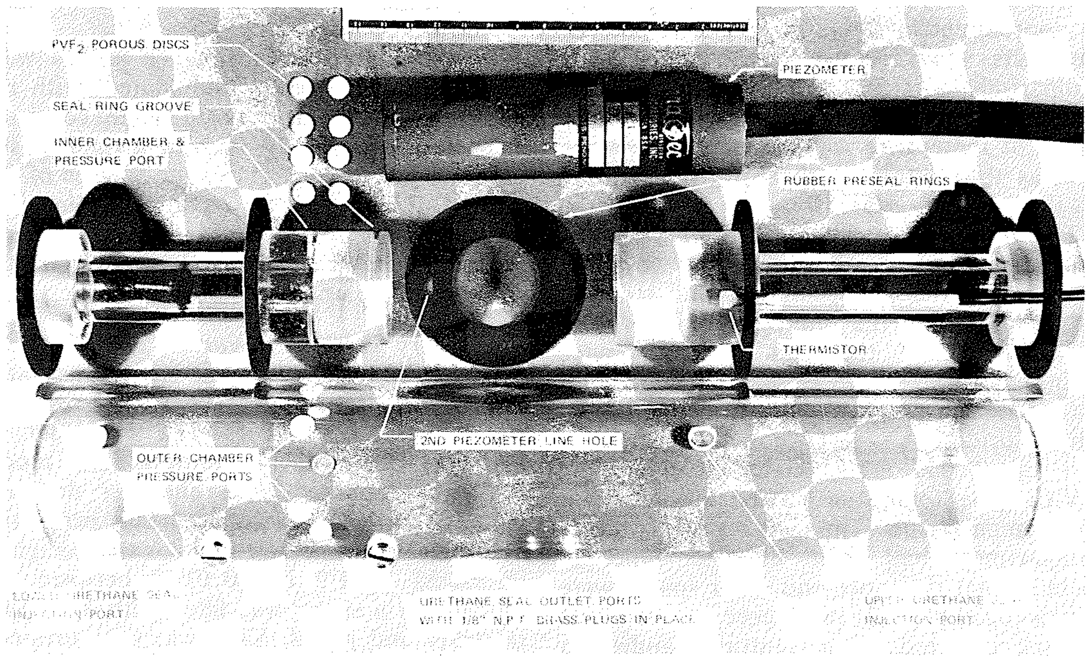


FIG. 5. Basic piezometer unit unassembled.

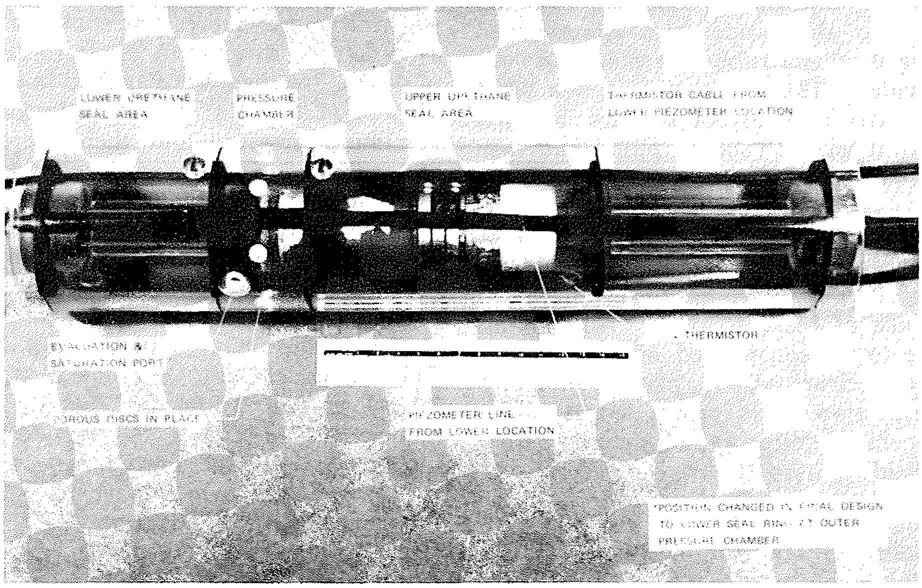


FIG. 6. Basic piezometer unit partially assembled.

right position. Next a series of 1/4 in. (0.006m) diameter holes was drilled in the wall and 1/16 in. (0.002m) thick porous discs were inserted into these holes. When the hydrostatic head was small (several inches) no drainage occurred. The porous plastic material had an average pore size of 25 μm with a porosity of approximately 80%. In the final design the ports were located at the top of the compartment so that the average head on the discs was only 1/8 in. (0.003m). The center of these discs was located at the same level as the bottom of the bellows assembly of the sensing element.

The geometrical configuration of the compartment was greatly influenced by the proposed fabrication techniques and strength requirements of the multiple unit probes. The outside of the compartment (outer casing) consisted of a 2.5 in. (0.06m) diameter, schedule 40, P.V.C. pipe (polyvinylchloride). An inner core consisting of a 1 in. (0.025 m) diameter, schedule 80, P.V.C. pipe formed a compartment within the compartment. The walls of this inner compartment had small diameter holes in them so that the inner and outer spaces were joined together. This inner core was required because it acted as a central mandrel to which the various components of the unit could be secured and then slipped into the outer casing during fabrication. The top and bottom of the compartment were formed by casting urethane rubber in place between rubber sealers. The compartment was filled with a water and glycol mixture by first evacuating it with a vacuum pump and then sucking in the mixture by releasing the vacuum.

A full-scale model (Fig. 6) was built to test techniques for assembly, evacuation, and saturation as well as to evaluate the performance of the instrument. All sections that were to be constructed of P.V.C. were made from clear acrylic plastic to allow visual inspection. This model led to many improvements in design and fabrication details of the field units.

Thermistor–Piezometer Probes

The multiple thermistor–piezometer probes formed the main pore pressure monitoring system and were anchored at depth in the gravelly permafrost. They consisted of two or three basic piezometer units housed together with the piezometer tips approximately 3 ft (0.9m) apart. The compartments housing each tip were sealed off from each other by urethane rubber plugs which were cast in place. A three-piezometer probe is shown in Fig. 7.

A few thermistor–piezometer probes were not anchored at depth but 'floated' with the settling ground. This back-up system consisted of a piezometer at the base of a rigid plastic tube which extended above the surface of the ground. This tube was used for elevation measurements but it also protected the piezometer and thermistor leads. Figure 8 shows the components of the probe.

Laboratory Testing Program

The basic piezometer unit model was tested in the laboratory to check its response to known applied pressures. In order to simulate bore hole conditions the model unit was mounted in a chamber designed for testing fluid displacement properties of oil and gas reservoir rock. A space slightly in excess of 1/2 in. (0.01m) between the model and a sleeve was filled with a mixture of water and glycol. Sand was then dropped into this mixture and tamped. Each end was sealed off with a bentonite plug and end caps. The system was connected to an accurate variable pressure source and tested at pressures from 0 to 30 ft (0 to 9.2 m) of water. Pressures were applied in increments of 5 ft (1.5 m) of water increasing to the maximum pressure and then decreasing to atmospheric. This procedure was carried out twice and then some random pressure increments were applied. In all cases the unit responded immediately to the changes in pressure; the pressures given by the piezometer gauge readout equipment agreed well with the changes in the applied stress. This indicated that the general design, fabrication, evacuation, and saturation techniques were adequate to provide a 'hard' system in the basic piezometer unit.

Because of the manufacturer's mode of fabrication, there was an initial preload stress on the bellows of the model P1020 piezometers. This value had to be subtracted from the number shown on the piezometer gauge readout to obtain the actual pore-water pressure. It was necessary therefore to have reliable values of the preload stress for each piezometer. The specifications that the manufacturer forwarded with the piezometers gave constant values for the preload stress and indicated that the accuracy was ±0.15 p.s.i. (±0.01 kg/cm²).

At first the preload values of only a few piezometers were checked, following the procedure recommended by the manufacturer. The values obtained by this procedure varied considerably from the values given by the manufacturer (see Table 4). From the experience gained while testing the basic piezometer unit model it was observed that a preload value could be obtained by subtracting the known applied pressure from the piezometer reading. This procedure was followed maintaining a temperature of 75 °F (24 °C) and some typical results are shown in Table 5. Another series of preload tests was run at approximately 25 °F (−4 °C) to observe the effects of temperature. Some temperature dependence was present in all piezometers.

Field Preparation of Probes

Each piezometer unit was filled with a mixture of water and glycol and tested for preload pressure just prior to installation in the foundation. The ports in the wall of the compartment were sealed by wrapping with teflon pipe thread tape and a layer of 1/16 in. (0.002 m) butyl rubber, which was then clamped in place. A three-way valve was connected to the compartment, a vacuum pump and a reservoir

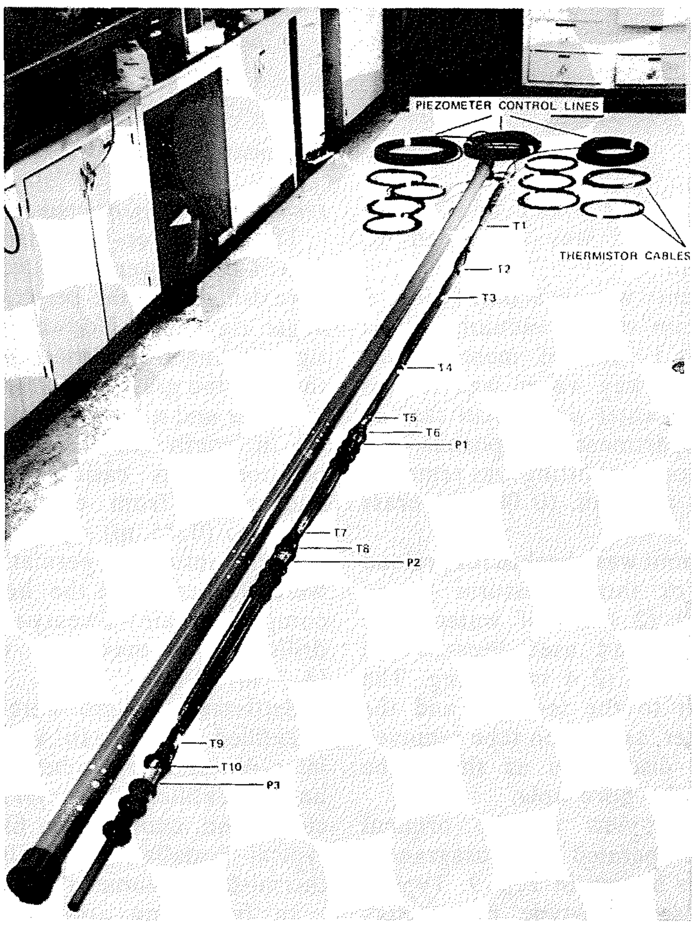


FIG. 7. Three piezometer probe prior to final assembly.

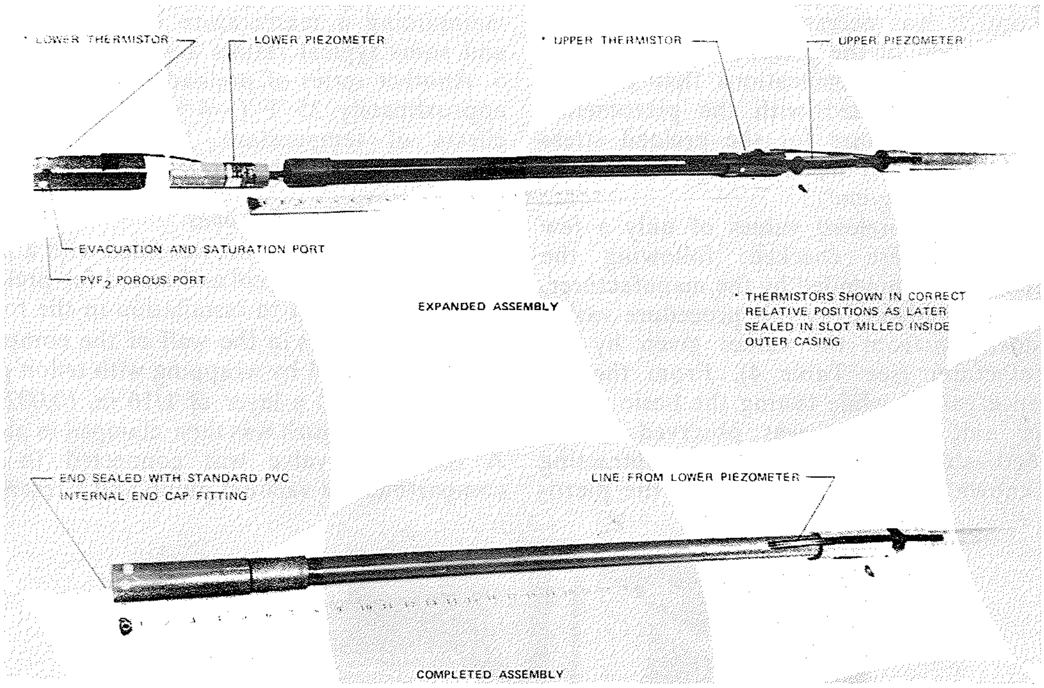


FIG. 8. Modified single piezometer probe.

filled with a mixture of water and glycol. A vacuum manometer was connected to the vacuum system.

The compartment was evacuated for a minimum of 15 min and a vacuum of less than 0.004 in. (0.1 mm) of mercury was obtained. The three-way valve was turned and the mixture of water and glycol rapidly saturated the compartment and porous disc ports. The saturation port fitting was removed and replaced with a 1/8 in. (0.003 m) brass plug.

The piezometer unit was checked for preload pressure at two or three pressures up to approximately 7 ft (2.1 m) of water. This was the maximum head used because the workshop had an 8 ft (2.4 m) ceiling. The probes were taken to the test site and the clamps, butyl rubber, and teflon tape removed from the porous disc ports as the probe was inserted into the bore hole.

A cross-sectional view of the original position of the gas-operated and Casagrande-type piezometers is shown in Fig. 9. Typical details of the Casagrande-type piezometers are shown in Fig. 10.

Installation of Instruments

The thermistor–piezometer probes and settlement gauges were installed in bore holes that were drilled into the permafrost by a Texoma auger rig and a Nodwell Mounted Mayhew rig. An auger was used to drill a pilot hole through the gravel pad and compressed organic layer and a 10 in. (0.25 m) casing 5 ft (1.5 m) in length was installed and rotated into position. This casing was to stop water and gravel from entering the boring. A 5.75 in. (0.15 m) diameter bit was utilized to drill into the permafrost. The cuttings were flushed from the hole by injections of compressed air. Twenty-seven borings were drilled to a maximum depth of 15.5 ft (4.7 m).

Settlement gauges were set in place and backfilled with clean sand (Fig.3). Thermistor–piezometer probes were set in place and backfilled in layers with bentonite, clean sand, and random fill. Figure 11 shows typical installation details of two of the thermistor–piezometer probes.

In backfilling around the thermistor–piezometer probes a precooled mixture of

TABLE 4. Results of preload pressure. Tests at atmospheric pressure

		Max. deviation		Average (ft water)					Max. deviation		Average (ft water)		
Piezo. No.	No. of readings	Below	Above	Lab.	Terra Tec	Difference	Piezo. No.	No. of readings	Below	Above	I.O.L. lab.	Terra Tec	Difference
521	9	0.5	1.0	10.0	7.4	2.6	531	8	0.3	0.6	11.3	12.8	−1.5
522	7	0.2	0.4	15.6	15.5	0.1	532	8	0.3	0.4	12.7	13.5	−0.8
523	5	0.1	0.1	11.5	11.2	0.3	533	8	0.8	0.4	11.0	12.5	−2.5
524	7	0.2	0.9	11.6	12.0	−0.4	534	5	0.2	0.1	17.1	14.5	2.6
525	8	0.3	0.6	15.4	15.5	−0.1	535	5	0.2	0.1	14.0	14.0	None
526	7	0.5	0.4	17.5	15.5	2.0	536	7	0.5	0.0	12.5	12.5	None
527	5	0.1	0.1	10.5	9.3	1.2	537	5	0.0	0.0	3.5	4.2	−0.7
528	25*	1.2	0.6	15.8	16.5	−0.7	538	8	0.8	1.1	16.8	15.5	1.3
529	6	0.5	0.2	9.9	9.4	0.5	539	6	0.3	0.8	11.7	10.0	1.7
530	6	0.2	0.1	12.1	10.8	1.3	540	5	0.2	0.3	12.2	10.3	1.9

*Readings taken at different hours over a period of 3 days.

glycol and water (freezing temperature of 10 °F (−12 °C)) was first poured into the bottom of the hole. Sand was poured down the hole around the probe and tamped in layers approximately 6 in. (0.15 m) thick with a 1×2 in. (0.025 ×0.051 m) wooden

TABLE 5. Typical laboratory preload pressure test results

	Applied load (ft of water)								
	3 ft		6 ft		12 ft		20 ft		
Piezometer number	Reading (ft of water)	Preload (ft of water)	Reading (ft of water)	Preload (ft of water)	Reading (ft of water)	Preload (ft of water)	Reading (ft of water)	Preload (ft of water)	Average preload (ft of water)
TP 2	13.0	10.0	16.0	10.0	22.5	10.5	30.7	10.7	
533	13.0	10.0	16.1	10.1	22.5	10.5	30.7	10.7	
Top	13.0	10.0	16.0	10.0	22.6	10.6	30.7	10.7	10.3
TP 4	19.1	16.1	22.4	16.4	28.2	16.2	36.5	16.5	
534	19.0	16.0	22.3	16.3	28.2	16.2	36.5	16.5	
Bottom	19.0	16.0	22.3	16.3	28.2	16.2	36.5	16.5	
	19.0	16.0							16.2
TP 4	16.0	13.0	19.0	13.0	25.1	13.1	33.3	13.3	
535	16.0	13.0	19.0	13.0	25.2	13.2	33.2	13.2	
Middle	16.0	13.0	19.0	13.0	25.2	13.2	33.3	13.3	13.1
SP 6	15.5	12.5	18.3	12.3	24.5	12.5	32.6	12.6	
536	15.3	12.3	18.1	12.1	24.5	12.5	32.7	12.7	
	15.3	12.3	18.1	12.1	24.5	12.5	32.6	12.6	12.4

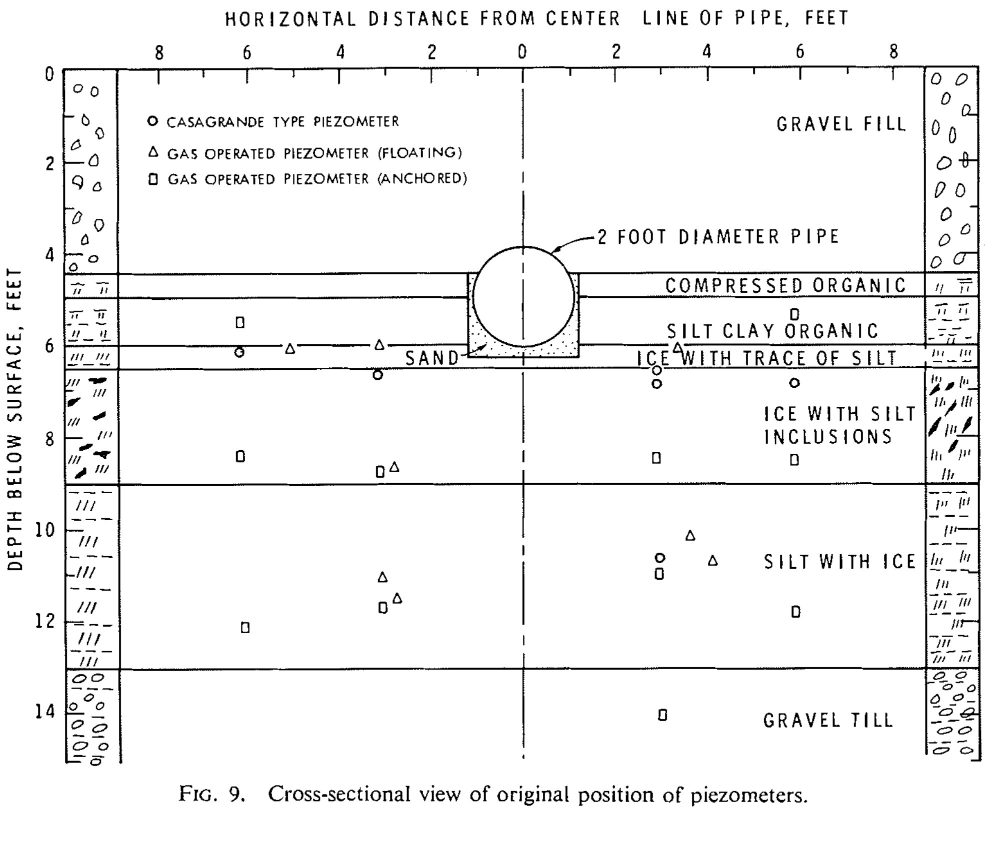
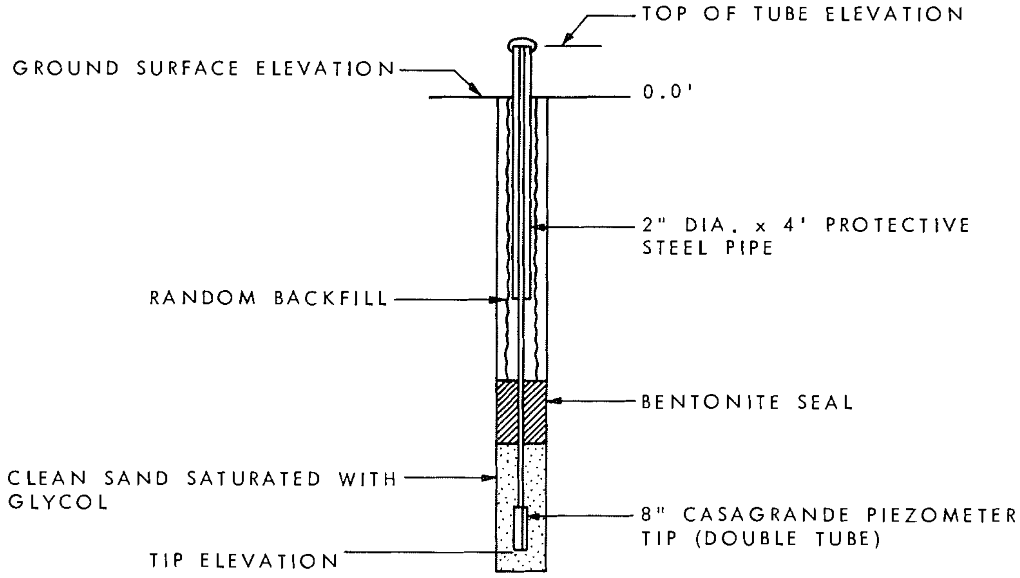


FIG. 9. Cross-sectional view of original position of piezometers.

staff. The sand pack was placed so that 9 in. (0.23 m) of sand was on each side of the tip of the piezometer. Bentonite had been previously wetted with water and rolled into balls about 1 in. (0.025 m) in diameter. These balls were dropped down the hole one by one and continuously tamped to form a seal approximately 1–1.5 ft (0.30–0.46 m) thick above the sand pack. As shown in Fig. 11 this sequence was repeated so that each piezometer in the probe had a sand pack around it and a bentonite seal above it.

The thermistor and piezometer leads coming out of the top of the probes were placed in flexible metal tubes for protection. These tubes were secured to the top of the probes and ran to a small heated instrument shack located adjacent to the test section. The piezometer leads were attached to a board inside the shack for convenience during testing. The thermistor leads entered a junction box that was connected to the data acquisition equipment located in the main instrument trailer.



INSTALLATION NUMBER	DATE	ELEVATIONS TOP OF TUBE	GROUND SURFACE	TIP	BENTONITE SEAL
CP-1	15 JULY 1971	117.85		109.85	110.8 - 111.8
CP-1A	1200	117.76	116.89	105.79	107.3 - 109.6
CP-2	13 JULY 1971 1630	117.27	116.43	109.27	111.0 - 112.0
CP-3	13 JULY 1971 1700	117.78	116.64	109.78	111.0 - 112.0
CP-4	14 JULY 1971 1500	117.92	116.88	109.92	111.3 - 112.3
CP-5	14 JULY 1971 1600	117.55	116.65	109.55	111.2 - 112.2

FIG. 10. Casagrande-type piezometers.

Discussion

Temperature

The performance of the thermistors was excellent. They were sturdy and reliable as evidenced by the fact that all of them worked throughout the testing period. The accuracy of the temperature measurements was considered to be adequate for this type of study.

Additional thermistors in the instrumentation area would have proved helpful in establishing more accurately the position of the thaw bulb, particularly the sides. Thermistors could also have been positioned adjacent to the foot of the settlement gauges to determine when the thaw front passed by, instead of having to interpolate from temperature points located several feet away.

Settlement

The experience gained in the use of spiral foot settlement gauges in other projects in permafrost proved very helpful in ensuring that the performance of the gauges was satisfactory. One problem which arose that had not been previously mentioned in the literature was that of bowing of the rods and the plastic tubes around them. This was due to the two-dimensional aspect of the thaw bulb in that movement did not occur only in the vertical direction, but

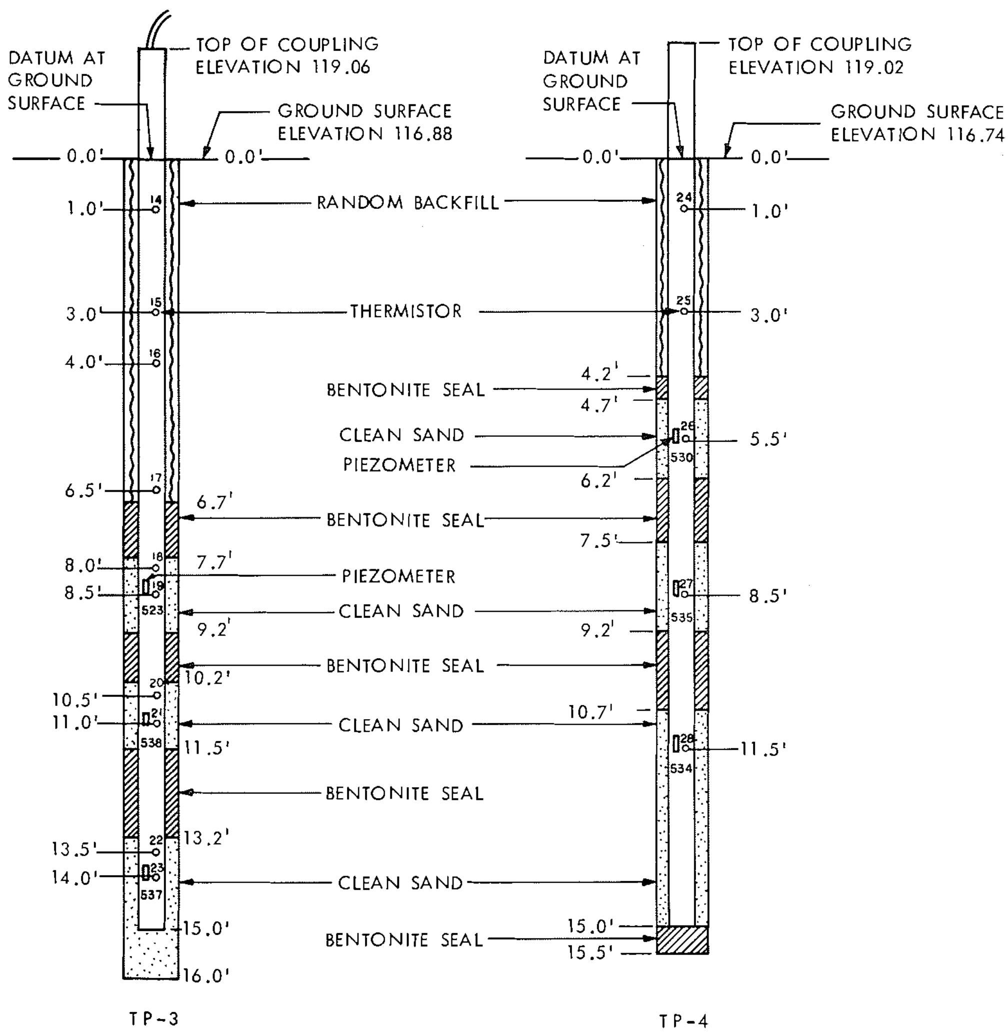


FIG. 11. Detail of thermistor–piezometer probes.

the material tended to slough in towards the buried pipe as well. The bowing caused some difficulties because it had to be considered in the analysis of the settlement data (Watson *et al.* 1973). The settlement rods welded to the top of the buried pipe did not bow during settlement.

Pore Pressure

Nineteen units were placed in the foundation and only one unit did not function properly. This unit was at the top of a multiple thermistor–piezometer probe and was located in an area where excessive settlement took place. The piezometer recorded large negative pressures for approximately the first 2 months even though the water table was above it during this time. The unit started to give more reasonable data in October and continued to do so for the remainder of the test.

The thawing front moved by the various piezometers at different rates. It moved quickly past the piezometers located near the pipe and relatively quickly past those at depth close to the center line of the pipe. The piezometers at the edges of the thaw bulb thawed out slowly. In all cases, however, the rapid increase in pore pressure at each piezometer was associated with the presence of the thaw front (Fig. 12). Because of the different rates of advance of the thaw front relative to the piezometers the pore pressures generally reached their maximum value during a period of 1–7 days (Watson *et al.* 1973).

It is estimated that the accuracy of the pore-water pressure measurements was approximately $\pm$ 1.0 ft (0.3 m) of water even though it was planned to be measured to an accuracy of $\pm$ 0.3 ft ($\pm$0.09 m) of water. The main reason for this was the difficulty associated with determining the preload pressure on each tip for this type of piezometer.

Three methods were used in an attempt to achieve elevation control of the piezometers: (1) contoured settlements determined by the spiral foot gauges; (2) 'floating' piezometers that settled with the thawing foundation; and (3) piezometer probes anchored at depth in the permafrost. The contoured settlement method was not successful because the variability of the ice content of the permafrost was such that

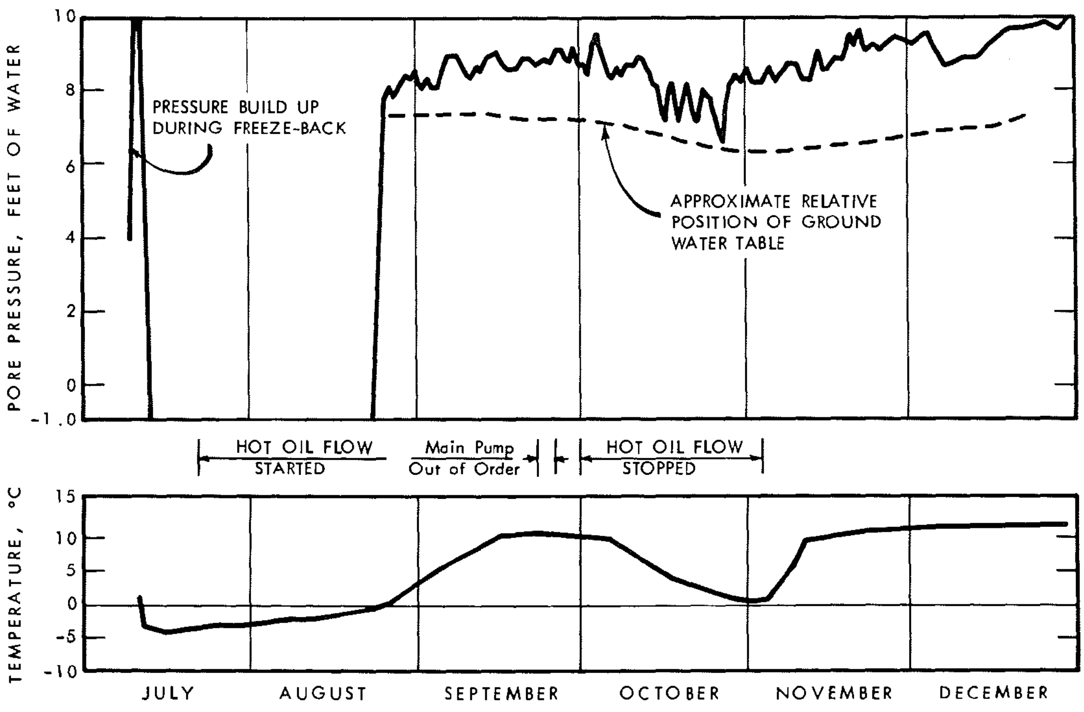


FIG. 12. Pore pressure and temperature readings (TP2 at 11.7 ft).

interpolation from the settlement gauges to the piezometers could not be done easily or with reasonable accuracy. The floating piezometer method suffered because the datum tubes coming to the surface bowed during the test. In addition it was difficult to analyze the data because consideration always had to be given to the relative positions of the piezometers and the water table, both of which were moving. The anchored piezometers appeared to give the most reliable information.

The use of multiple thermistor–piezometer probes had an advantage over a number of single unit probes as the distance between piezometers in a probe was accurately known. This permitted the calculation of a hydraulic gradient between any two piezometers with an accuracy of the same order as that of the pressure measurements. This calculation could be done very simply and without knowledge of the amount of settlement at any point or the level of the water table.

When the probes were installed, the sand pack around each piezometer was saturated with a mixture of water and glycol. This was done to prevent large pressures from developing around the piezometer during freezeback. This was satisfactorily accomplished for all installations except the first. In this case seepage into the bore hole from the unfrozen surface organic layer was not adequately controlled by the casing and the bottom of the hole was filled with water. During freezeback the pressure around the piezometer increased over a period of 1 day from approximately 4 ft (1.2 m) of water to 56.8 ft (17.3 m) of water. On the second day the pressure was greater than the upper limit of the readout gauge. On the third day after installation the pressure was back down to approximately 4 ft (1.2 m) of water (Fig. 12).

The level of the water table was measured with Casagrande-type piezometers and water wells. Six Casagrande-type piezometers were placed in the foundation and only one did not operate satisfactorily. This one was placed much lower into the permafrost than the others. For these piezometers to work the tip and the standpipe had to be located within the thaw bulb. The level of the water table in the wells was measured by taking an elevation to top of the water.

Conclusion

The number, position, and performance of the temperature and settlement instruments were generally adequate for the purposes of this experiment. Additional temperature points located at the edges of the thaw bulb and at the foot of the settlement gauges, however, would have been helpful. Some problem in interpretation of the settlement data arose because of the bowing of the settlement rods. This problem could be overcome if settlements at depth could be obtained without the use of rods leading to the surface. This is not easily done without introducing other complications.

The general design philosophy of the basic piezometer unit proved to be adequate for the conditions encountered. The piezometers responded quickly when the thaw front passed by and continued to perform for the duration of the test. Loss of data due to malfunctioning or breakage was very limited. The basic piezometer unit was equally adaptable to the single or multiple thermistor–piezometer probes. It is recognized that additional research is required to improve the accuracy of preload values for these piezometers if more precise pore pressures are needed.

Elevation control of the piezometers in the thawing foundation was critical because of the large settlements. The contoured settlement profiles proved to be inadequate. The 'floating' probe system was better but not as satisfactory as the 'anchored' probes. The anchored probe design is compatible with the use of more than one piezometer per probe.

The multiple probe concept has some advantages over the single unit design. The hydraulic gradient between any two units on a probe can be obtained without knowledge of settlement or location of the water table. The relative position between units is fixed and accurately known. In addition, fewer holes need to be drilled during installation to obtain equivalent instrument density, and therefore thermal disturbance and installation costs are reduced.

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BISHOP, A. W., KENNARD, M. F., and VAUGHAN, P. R. 1964. Developments in the measurement and interpretation of pore pressures in earth dams. Trans. 8th Int. Congr. Large Dams, **2**, pp. 47–72.

CASAGRANDE, A. 1949. Non-metallic piezometer for measuring pore pressures in clay. *Appendix to* Soil mechanics in design and construction of Logan Airport. J. Boston Soc. Civ. Eng. **36**(2), pp. 214–221.

DAEHN, W. W. 1962. Development and installation of piezometers for the measurement of pore-fluid pressures in earth dams. Field testing of soils. Am. Soc. Test. Mater., S.T.P. 322, pp. 8–17.

GUPTA, R. C., and MARSHALL, R. G. 1972. Kettle Generating Station — earthwork instrumentation. Presented at the 25th Can. Geotech. Conf., Ottawa, Canada. Dec. 7–8, 1972.

JOHNSTON, G. H. 1965. Permafrost studies at Kelsey Hydro-Electric Generating Station; Research and instrumentation. Natl. Res. Counc. Can. Publ. No. 7943.

LAUFFER, H., and SCHOBER, W. 1964. The Gepatsch Rockfill Dam in the Kauner Valley. Trans. 8th Int. Congr. Large Dams, **3**, 635–659.

MUHS, H. 1954. Measurement of pore-water pressure in open ground particularly in earth dams. Bau-Masch. Bautech. **7**, pp. 65–70.

PLANTEMA, G. 1953. Electrical pore water pressure cells: some designs and experiences. Third Int. Conf. Soil Mech. Found. Eng. **1**, pp. 279–282.

TERZAGHI, K. 1943. Measurement of pore-water pressure in silt and clay. Civ. Eng. **13**, pp. 33–36.

WARLAM, A. A., and THOMAS, E. W. 1965. Measurement of hydrostatic uplift pressure on spillway weir with air piezometers. Instruments and apparatus for soil and rock mechanics. Am. Soc. Test. Mater., S.T.P. 392, pp. 143–151.

WATSON, G. H., ROWLEY, R. K., and SLUSARCHUK, W. A. 1973. Performance of a warm oil pipeline buried in permafrost. To be presented at the 2nd Int. Conf. Permafrost, Yakutsk, U.S.S.R.