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Some Problems of Solid and Liquid Waste Disposal in the Northern Environment

Technology Development
Report EPS-4-NW-76-2

Northwest Region
November, 1976

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SOME PROBLEMS OF SOLID AND LIQUID WASTE DISPOSAL IN THE NORTHERN ENVIRONMENT

A series of 4 reports

Edited by

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Environmental Protection Service
Department of the Environment
Northwest Region

for the

Environmental-Social Program
Northern Pipelines

Technology Development
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The data for these reports were obtained as a result of investigations carried out under the Environmental-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development, Government of Canada. While the studies and investigations were initiated to provide information necessary for the assessment of pipeline proposals, the knowledge gained is also useful in planning and assessing highways and other development projects.

The research was carried out under contract for the Arctic Land Use Research Program, Northern Natural Resources and Environment Branch, Department of Indian Affairs and Northern Development. The views, conclusions and recommendations expressed herein are those of the authors and not necessarily those of the Department.

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WORKCAMP SEWAGE DISPOSAL
WASHCAR - INCINERATOR COMPLEX
FT. SIMPSON, N.W.T.

by

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Northwest Region
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This study was made possible through funds provided under the Arctic Land Use Research (ALUR) Program of the Department of Indian Affairs and Northern Development, and the Federal Activities Environmental Branch (FAEB) Program of the Environmental Protection Service (EPS), Environment Canada. The study was part of the overall FAEB program to assess various waste treatment facilities at federal activities in the north.

The federal Department of Public Works (DPW) permitted evaluation of the test facilities at two work camps and provided useful comments on operations of the facilities (Appendix B).

The contributions of numerous individuals in EPS are gratefully acknowledged. Mr. Richard A. Fahlman and Mr. A. C. Edwards performed much of the initial work in the study and prepared an interim report. Mr. R. Aldi and Mr. B. R. Croft performed stack tests on incinerator emissions and prepared two stack testing reports. Mr. R. Martin assisted in preparing weekly summaries of the data. The contributions of many other individuals are also greatly appreciated.

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*Available from the authors or from the Manager, ALUR Program, Northern Natural Resources and Environment Division, DINA, Ottawa.

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1. SUMMARY

Construction camps which may proliferate along the proposed Mackenzie Valley pipeline and highway, will be faced with water supply and wastewater disposal problems. Conventional camp facilities may not offer satisfactory solutions to these problems in cases where water supply costs are high and where conventional wastewater treatment facilities are difficult to construct. Therefore, the need exists to develop alternative wastewater collection systems which require minimum amounts of water, and wastewater disposal systems which are influenced little by geotechnical constraints on site development and which provide a high standard of environmental protection.

This study investigates the use of water-saving facilities and an incinerator for disposal of concentrated wastewater as alternatives to conventional systems at northern workcamps. The test facility consists of a washcar trailer and an incinerator trailer connected by an insultated pipe. In the washcar, water-saving facilities consist of vacuum toilets and associated equipment, recirculating chemical toilets, a pump to recirculate used wash-water from a holding tank to the toilets, and a sauna. Laundry, shower, and urinal facilities also are included in the washcar. In the incinerator trailer, equipment includes a black water holding tank, a macerator to grind up the contents, and a 90 litre per hour waste incinerator with associated equipment.

It was determined that vacuum toilets used at least 90% less water than conventional, flush toilets and decreased water requirements for the washcar by an estimated 35% to 90 litres per capita per day. Chemical toilets could not be evaluated properly because of inaccessible leakages. The quantity of black water generated was estimated to be 5 litres per capita per day, roughly 50% greater than the quantity of water supplied to the toilets. It was demonstrated that vacuum systems in washcars can operate with a minimum of daily operator attention.

Incineration of black water appeared to be an effective means of black water disposal. Particulate emissions from the incinerator were 74 to 82 mg/m^3 and nitrogen oxide emissions were 70 to 127 mg/m^3. Predicted ground level concentrations of pollutants from stack emissions were well below Environment Canada's proposed maximum acceptable levels. During incineration, some operational problems were encountered, the main one being attributed to a faulty macerator. The estimated annual operating cost (1973-74) for incineration of black water, including amortized capital cost, is $0.15 per litre.

It is concluded that operation of a washcar-incinerator complex is feasible. However, the economic feasibility must be examined on a case by case basis, particularly in view of the high capital and operational costs of incineration.

Needs for further study include investigation of modifications to a washcar to achieve additional water savings, characterization of grey water, and additional assessments of black water incineration.

RÉSUMÉ

L'approvisionnement en eau et l'élimination des eaux usées poseront certains problèmes dans les chantiers de construction qui parsèmeront le tracé du pipeline et de la route de la Vallée du Mackenzie. Les solutions traditionnelles peuvent ne pas convenir en raison des coûts élevés de l'approvisionnement en eau et de la construction d'installations classiques de traitement des eaux usées. Par conséquent, il y a lieu de concevoir des installations sanitaires consommant peu et des modes d'épuration peu sensibles aux contraintes géotechniques des sites et protégeant en même temps l'environnement de façon adéquate.

La présente étude porte sur un sanitaire économisant l'eau et sur un incinérateur disposant des eaux usées concentrées, à substituer aux installations habituelles des chantiers de construction du Nord. Le module expérimental groupe deux caravanes, l'une servant de salle d'eau et l'autre abritant l'incinérateur, reliées par un tuyau isolé. Dans la première se trouvent les appareils courants: lessiveuses, douches, sauna, urinoirs, toilettes munies de chasses à vide et toilettes à vidange chimique circulatoire. Un système de pompage permet d'accumuler l'eau de lessive pour l'acheminer ensuite vers les toilettes. La deuxième caravane contient un réservoir d'eaux noires, un macératuer pour en broyer la contenu et un incinérateur pouvant brûler 90 litres de résidus à l'heure ainsi que les accessoires de ces appareils.

On a déterminé que les chasses à vide utilisaient au moins 90 p. 100 moins d'eau que les chasses ordinaires et qu'elles réduisaient de 35 p. 100 la consommation d'eau de la caravane qui s'établissait à 90 litres par personne et par jour. Les toilettes à vidange chimique ne se sont pas prêtées à une évaluation adéquate à cause de fuites inaccessibles. La production d'eaux noires a été estimée à 5 litres par personne et par jour, soit environ 50 p. 100 de plus que le volume d'eau libéré par les chasses. On a démontré que les systèmes à vide exigent très peu d'entretien.

L'incinération a paru efficace pour disposer des eaux noires. Les émissions de particules ont varié de 74 à 82 mg/m^3 et celles d'oxydes d'azote, de 70 à 127 mg/m^3. Au niveau du sol, les concentrations estimatives de polluants s'échappant de la cheminée se sont révélées bien inférieures aux limites acceptables proposées par Environnement Canada. L'incinérateur n'a pas toujours fonctionné parfaitement, à cause, surtout, d'un macérateur défectueux. Le coût estimatif annuel d'exploitation (1973-1974) de cet appareil, y compris l'amortissement des immobilisations, a été de $0.15 par litre.

Les chercheurs ont conclu que l'exploitation d'installations sanitaires couplées à un incinérateur est réalisable. Toutefois, il y a lieu d'étudier les incidences économiques de chaque cas, les coûts d'immobilisation et d'exploitation de l'incinérateur étant particulièrement élevés.

En plus d'estimer encore plus minutieusement l'incinération des eaux noires, il faudrait faire des études plus poussées, notamment sur les modifications à apporter au sanitaire en vue de réduire encore davantage la consommation d'eau, et approfondir les caractéristiques des eaux grises.

2. INTRODUCTION

Conventional wastewater facilities at northern construction camps consist of gravity collection systems discharging to lagoons, seepage pits, or holding tanks served by pump-out trucks. These systems may not be economically feasible nor environmentally acceptable at some workcamp sites for the following reasons:

1. Gravity collection systems require large amounts of water to convey small quantities of waste from their respective fixtures to the point of treatment and may be very expensive to operate in view of the high cost of supplying water to isolated workcamps.

2. Sewage lagoons may be expensive to construct and may not operate satisfactorily because of cold climate and poor site conditions such as unavailability of fill material for berm construction, poor drainage, shallow water table, and permeable soil.

3. In areas of permafrost, lagooning may be complicated further by the presence of ice wedges or high ice content soils, and by the problem of thermokarst development.

4. The disposal of lagoon effluent also may be a problem if no suitable receiving stream or lake is nearby.

5. Adverse soil conditions such as permafrost, seasonally frozen ground and impermeable soil may limit the applicability of seepage pits.

6. With respect to holding tank wastes, some measure of wastewater treatment is required before ultimate disposal to the environment.

It is evident that there is a need for practical alternatives to the conventional methods for collection and disposal of workcamp wastewater. Therefore, a study of one such alternative was undertaken and is the subject of this report.

The study involved an assessment of a washcar with various water-saving facilities and an assessment of an incinerator for disposal of concentrated wastewater (black water). The water-saving facilities in the washcar are comprised of three vacuum toilets, two chemical recirculating toilets, and a pump for recycling used washwater from a collection tank to the toilets. A sauna is included also since originally it was thought to be a water-saving device. Photographs of the washcar and incinerator are presented in Figures 1 to 3. Schematic diagrams of the water supply system, the wastewater collection system, and the incinerator are shown in Figures 4, 5 and 6, respectively.

Fig. 1 Interior of washcar, sauna entrance in background

Fig. 3 Feces incinerator furnace

Fig. 2 Exterior of incinerator trailer

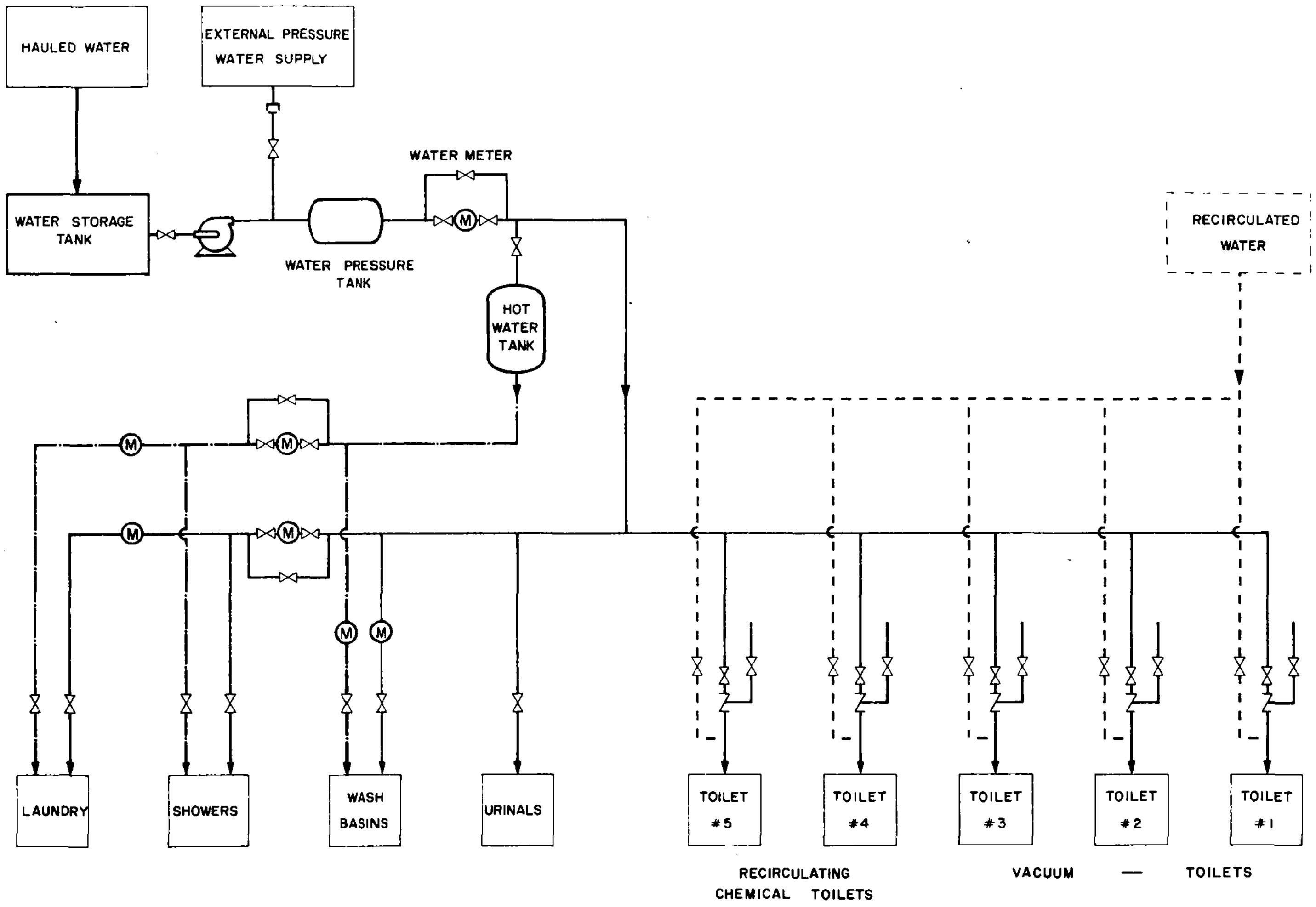

FIGURE 4 SCHEMATIC DIAGRAM OF WATER SUPPLY SYSTEM FOR WASHCAR

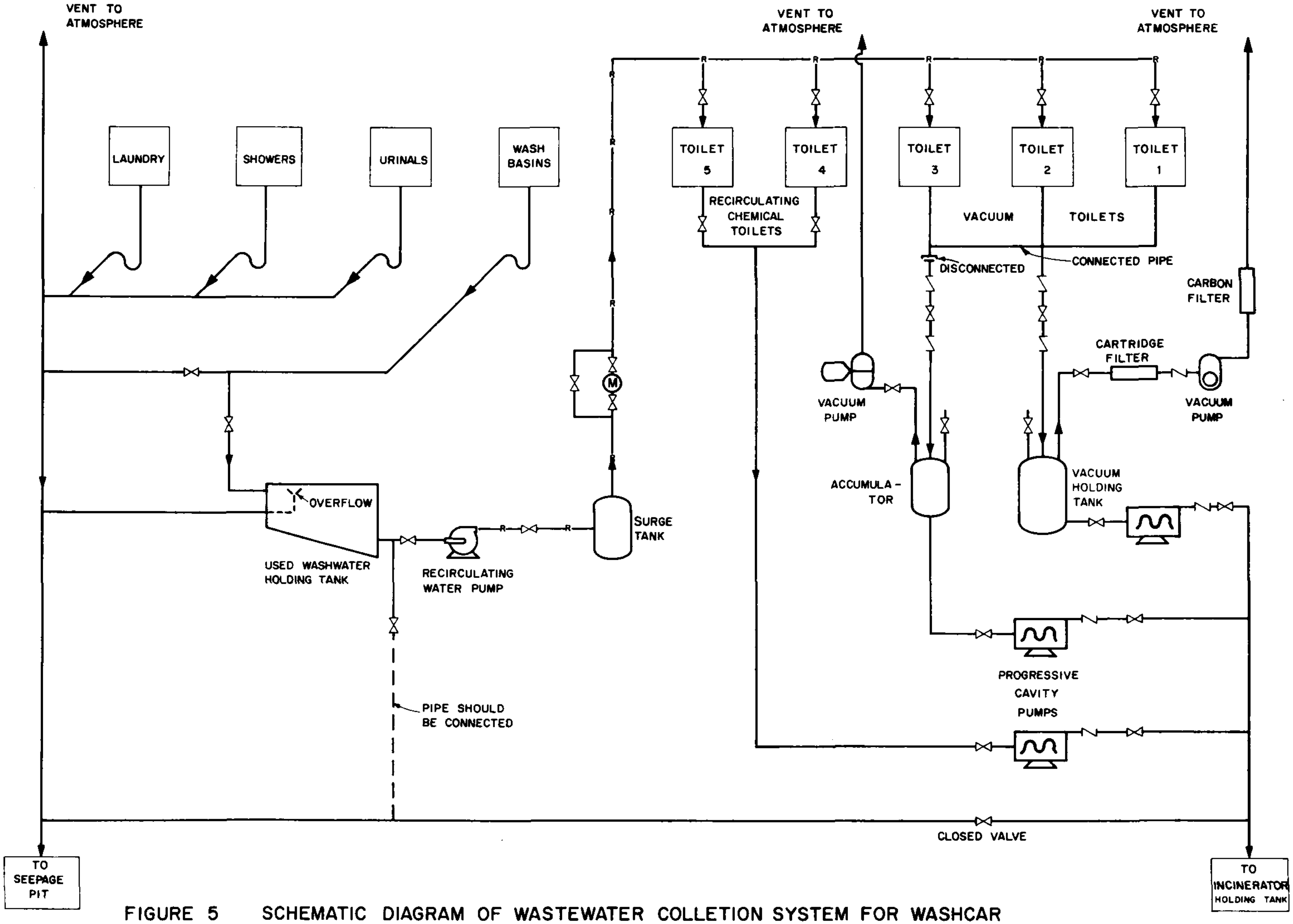

FIGURE 5 SCHEMATIC DIAGRAM OF WASTEWATER COLLETION SYSTEM FOR WASHCAR

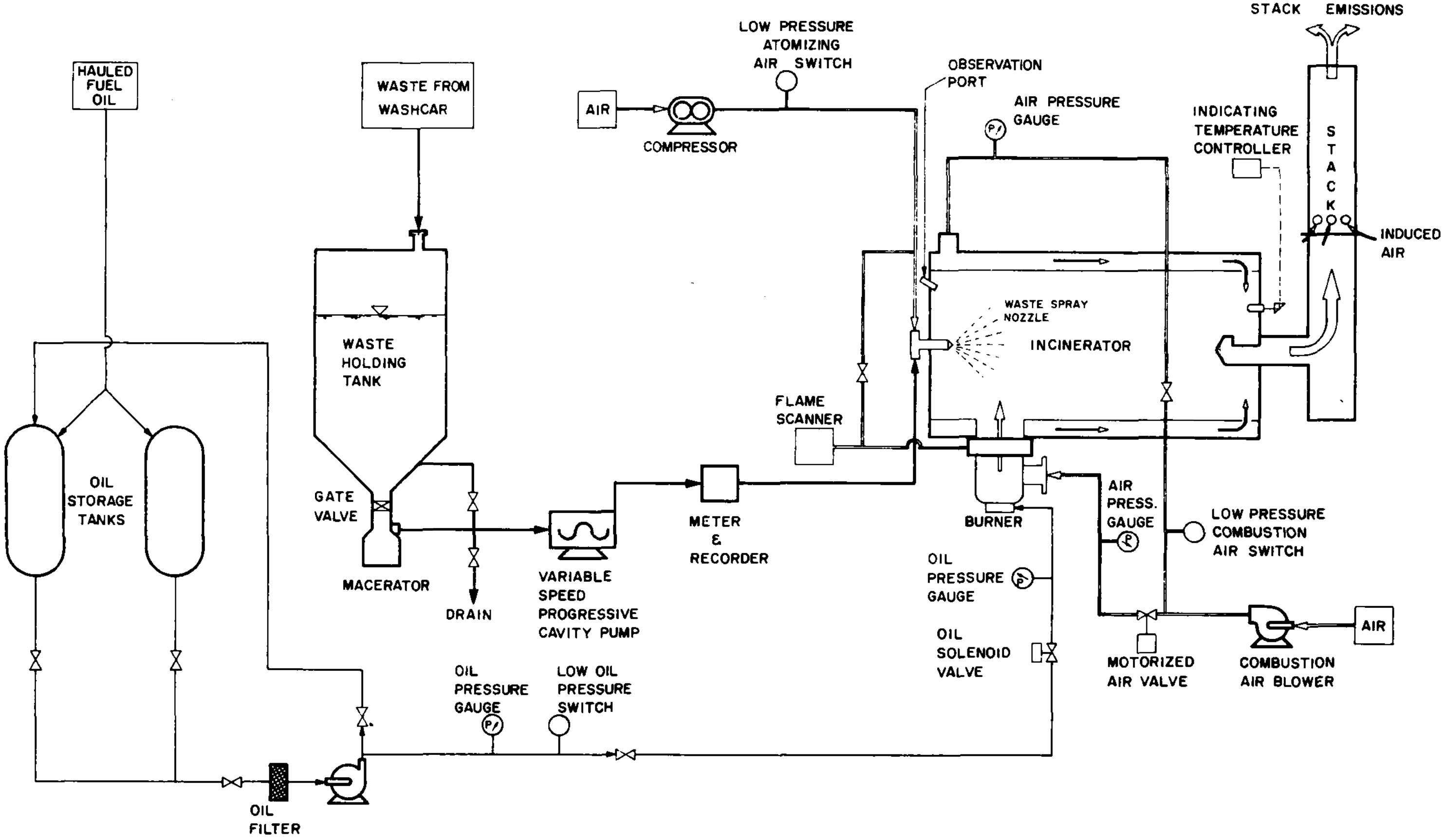

FIGURE 6 SCHEMATIC DIAGRAM OF FECES WASTE INCINERATOR

The main objectives of the study were as follows:

1. To assess the vacuum and chemical toilets by determining their water-saving capabilities, operational requirements, reliability, and acceptability as alternatives to conventional facilities.
2. To determine the water distribution budget for a washcar.
3. To determine operational requirements and stack emissions associated with incineration of black water, and to predict the effects of black water incineration on ambient air quality.
4. To determine the economic and operational feasibility of a washcar-incinerator complex for northern workcamps.

3. CURRENT STATE OF KNOWLEDGE

The use of a vacuum collection system and an incinerator for black water disposal is a relatively new concept in Sanitary Engineering. A number of investigators (Averill and Heinke, 1973; Miholits, 1961; Baribo, 1957) have proposed that such a system may be applicable particularly in northern areas.

A vacuum collection system and incinerator were installed in Wainwright Alaska as part of the Alaska Village Demonstration Projects (Reid, 1973). The vacuum system was used to collect wastes periodically from recirculating chemical toilets, located in a central complex. These wastes were fed to an incinerator along with honey bucket wastes, water and wastewater process sludges, and solid wastes. Some of the waste heat from the incinerator was re-claimed with heat exchangers. Unfortunately, fire destroyed the entire central complex before much operating data was obtained; however, the limited results did appear promising.

4. STUDY AREA

In conjunction with the Federal Department of Public Works (DPW), two workcamp sites on the Mackenzie Highway near Ft. Simpson, N.W.T. were selected to study the washcar-incinerator trailer complex (Figure 7). The sites were considered representative for typical workcamps.

From September, 1973 to December, 1973 the complex operated at DPW Workcamp #1, located approximately three kilometres from the town of Ft. Simpson. During this period. During this period the workmen were transferred gradually to the DPW Workcamp at Mile 320, approximately 32 kilometres northwest of Ft. Simpson. Since the population at Workcamp #1 became insufficient to assess the complex properly, the trailers were moved to the Mile 320 Workcamp in January, 1974 and remained there until project completion in November, 1974. The move allowed evaluation of equipment mobility and ease of reinstallation after transport.

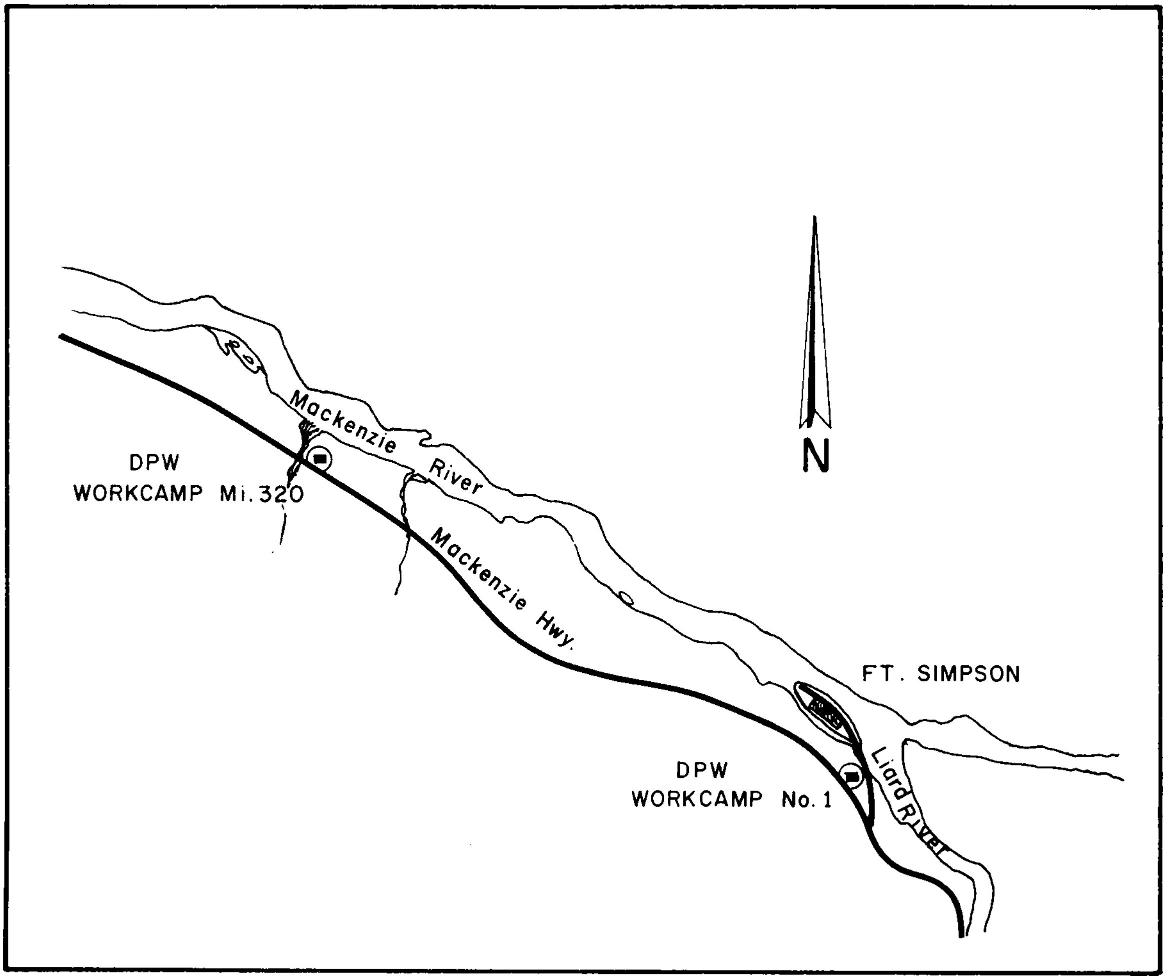

FIGURE 7. LOCATION PLAN OF DPW. WORKCAMPS

5. METHODS AND SOURCES OF DATA

Initially, one operator was hired specifically to operate the washcar-incinerator complex and record daily observations. There were several personnel changes in this job with consequent disruptions in the study. For the time periods during which no operator was present, data on the washcar operation was recorded when visits were made by personnel from the Environmental Protection Service District Office in Yellowknife, usually once per week. Operator duties and requirements are presented in Appendix A.

When sewage was incinerated, the general operating data were recorded. On two of these occasions, stack samples were taken to assess the air pollution potential of black water incineration.

5.1 Normal Operating and Maintenance Data

Worksheets were filled out daily when operator manpower was available. Recorded data included all meter readings, camp population and any comments pertaining to the operation and maintenance of the washcar.

Initially, water meters were installed in the washcar to measure the following:

1. Total water consumption
2. Shower and laundry water consumption (two meters, hot and cold)
3. Quantity of recycled water from the holding tank below the wash basins to the vacuum toilets.

In May 1974, water meters were installed in the washcar to measure the following consumptions:

4. Laundry water consumption (two meters, hot and cold)
5. Wash basin water consumption (two meters, hot and cold)

Flush counters were installed on the toilets to record the number of flushes. From records obtained over a short period of time during which wash water was recycled, the unit water consumption of the vacuum toilets was determined. The data on flush counts was used to estimate water consumption by the vacuum toilets during non-recycle operation.

Knowing the preceding consumption rates, water consumption for the showers and the urinals could be determined through simple arithmetic calculations as follows:

Shower water consumption equals (2) - (4)

Urinal water consumption equals (1) - (2) - (5) - Toilet water consumption.

Power meters were installed to measure total power consumption by the washcar and by the incinerator trailer. An estimate of power consumption by the sauna was made by shutting off the sauna November 6 - 12, 1974 and comparing the power requirement to that under full load conditions, October 25 - 31, 1974.

With respect to measurement of oil consumption, no meters were installed for this purpose in the washcar or incinerator trailer. It was planned to obtain information on oil deliveries to the individual oil tanks; however, no records of this information were kept, unfortunately. Oil consumption rate by the incinerator trailer was estimated by dipping the oil tanks and noting the drop in level of the oil over a six hour period.

5.2 Incineration Data

When sewage was incinerated, general operating data was recorded as follows:

1. Incinerator temperature
2. Waste flow rates
3. Power Consumption
4. Fuel Pressure
5. Combustion air pressure (air blower)
6. Atomizing air pressure (air compressor)
7. Comments on operation of incinerator

Stack emission tests were carried out by the Air Pollution Control Section, Environmental Protection Service, Northwest Region on April 4 - 9, 1974 and October 4 - 7, 1974. (Aldi and Croft, Nov./74; Croft, Dec./74). The samples were analyzed for total particulates, hydrocarbons, sulfur dioxide, and nitrogen oxides except that sulfur dioxide samples were omitted during October, 1974 because of insufficient feed.

Data on air pollutant emissions were used to predict their effects on ambient air quality under various atmospheric stability conditions and wind speeds ranging from 1.0 to 12.0 metres per second.

6. RESULTS

For the latter part of the study period (August 19 to November 19, 1974) two additional washcars were operated by DPW because of a larger camp population. The DPW washcars had separate wastewater systems of a conventional nature and were not included in the study. The study took place over 265 days, during which time daily camp population ranged from about 5 to 45 men with an average of 18 men.

6.1 Vacuum and Chemical Toilets

Data on toilet flush counts are summarized in Table 1 for various operating time periods. It is quite evident from this table that, with respect to frequency of use, the vacuum toilets were far superior to the chemical toilets; and, of the vacuum toilets, one brand (Toilets 1 and 2) was preferred to the other brand (Toilet 3). It is worthy of note that, while the vacuum toilets were preferred overall to the chemical toilets, one segment of the men - those who had always resided in the Northwest Territories - would use only the chemical toilets.

With respect to water-saving capabilities of the vacuum toilets, it was determined by metering recycled wash water that the vacuum toilets used an average of 1.6 litres per flush. This compares favorably to 25 litres per flush approximately for conventional flush toilets and represents more than a 90% water reduction. Data on the total number of flush counts is incomplete because only four counters were installed on the toilets. For estimating purposes, it is assumed that the frequency of use of Toilet 5 was the same as for Toilet 4, since both were the same type. With this assumption, the toilet usage was approximately two flushes per capita per day. Therefore, complete use of vacuum toilets would result in a lower water demand, approximately 45 litres per capita per day less than normal.

Maintenance problems experienced with the toilets and associated equipment are illustrated in Table 2. Toilets 1 and 2 operated quite satisfactorily. Toilet 3 experienced numerous breakdowns despite being connected to the vacuum system for Toilets 1 and 2. Toilets 4 and 5 had few breakdowns, however, they operated for a much shorter time than the vacuum toilets because leaks in the chemical toilets were inaccessible for repair. It is speculated that the leaks must have occurred either in the holding tanks or in the plumbing.

6.2 Washcar

Data on water consumption by various facilities in the washcar are summarized for various time periods within which test conditions were reasonably stable (in Table 3).

The results for August 19 to November 19, 1974 cannot be considered representative of typical washcar usage because the DPW washcars also were open during that time. However, this is the only period during which the water consumption for each facility could be determined, since additional water meters had been installed and the total-water meter was operational. Data for the previous operating period,

TABLE 1 TOILET FLUSH COUNTS AND WATER CONSUMPTION

Dates	Number of Flushes for Toilet Numbers				Total Number of Flushes for Vacuum Toilets 1, 2 and 3	Water Consumption for Vacuum Toilets, litres	
	1	2	3	4		Actual[a]	Estimated[b]
Sept. 14 - 20/73[c]	103	106	--[d]	42	--	660	
Sept. 21 - Oct. 27/73	482	319	212	135	1013	1630	
Oct. 28 - Dec. 4/73	403	252	54	85	709		1100[e]
Feb. 19 - April 17/74	781	577	324	147	1682		2700
May 18 - June 28/74	153	152	32	out of order	337		540
Aug. 19 - Nov. 19/74	428	537	124	out of order	1143		1800

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a. Actual, metered water consumption consisting of recycled water from the wash basins.
b. Estimated water consumption based upon data for Sept. 21 - Oct. 27/73.
c. Number of flushes for chemical Toilet 5 was 10, Sept. 14 - 20/73.
d. No flush counter installed on Toilet 3.
e. Includes 210 litres of recycled water from wash basins.

TABLE 2 EQUIPMENT BREAKDOWNS

Cause of breakdown	Number of occurrences	Toilets affected 1	2	3	4	5
Vacuum pump motor vibrated loose, disengaging the gear between the motor and pump.	1	X	X	X		
Vacuum release valve on Toilet 3 did not seal after flushing.* Air leaked into vacuum system for three days until the vacuum pump seized.	1	X	X	X		
Toilet 3 plugged because of a constriction in the vacuum line.	10			X		
Toilets became dry because of a leak.	2				X	X
Recirculating pump plugged and waste material did not break down.	1					X

* Vacuum release valve did not seal on numerous other occasions, but the problem was corrected before vacuum system failure by manually pushing the valve with a long probe.

TABLE 3 WATER CONSUMPTION FOR FIXTURES IN WASHCAR

Dates	Description	Operating Time	Average Daily Camp Population	Water Consumption, litres						Unit Water Consumption litres/cap/day
				Laundry	Showers	Wash Basins	Urinals	Toilets[a]	Total	
Sept. 14-20/73	DPW Workcamp #1: Start-up period. Flush counters on Toilets 1,2, 4 & 5. Recycled wash water to Toilets 1-3.	7	25	11,400		3,800		660	15,200	86
Sept. 21- Oct. 27/73	DPW Workcamp #1: Flush counters on Toilets 1-4. Recycled wash water to Toilets 1-3.	37	15	35,200		20,000		1,630	55,800	100
Oct. 28- Dec. 4/73	DPW Workcamp #1: Recycled 210 litres of wash water to Toilets 1-3.	38	10	16,400		15,500		1,100	32,800	86
Feb. 19- April 17/74	DPW Workcamp at Mile 320: No recycling	57	21	59,200		33,000		2,700	94,500[b]	77
May 18- June 28/74	DPW Workcamp at Mile 320: Total water meter bypassed. Additional meters installed.	37	6	18,700	1,000	3,180		540		
Aug. 19- Nov. 19/74	DPW Workcamp at Mile 320: Other DPW Washcar was open. Consumption Values are low.	89	25	56,200	8,200	11,900	12,000	1,800	89,800[c]	41

a Data from Table 1. Water consumption for chemical toilets is negligible.

b Includes estimated 25,000 litres for March 27 - April 8.

c Includes estimated 7,700 litres for Sept. 28 - Oct. 4.

May 18 to June 28, 1974, was incomplete because the total-water meter was bypassed for a considerable portion of the time. Also, camp population was low at that time, averaging six men per day.

The estimated average water budget for the washcar is presented in Table 4 and is based upon the following information and assumptions:

1. Data from August 19 to November 19, 1974 shows that the ratio of water distribution between laundry and showers is 82:18, and between wash basins and urinals is 50:50.
2. It is assumed that the data on ratio of water distribution in (1) can be applied to the September 14, 1973 to April 17, 1974 period, when fewer water meters had been installed and only the test washcar was open.

TABLE 4 ESTIMATED WATER BUDGET FOR WASHCAR

Facility	Water Usage	
	Litres/cap/day	% of Total
Laundry	43	50
Showers	10	11
Wash Basins	15	18
Urinals	15	18
Toilets	3	3
TOTAL	86	100

The sauna in the washcar was poorly accepted by the men, who generally preferred showers instead. The few men who did use the sauna usually alternated between the showers and sauna for a considerable time, and possibly used more water than if just showers had been available. An examination of power requirements by the washcar, with and without the sauna operating, revealed that total requirements averaged 143 kwh per day, and partial requirements (with sauna off) averaged 76 kwh per day. Therefore, the sauna required 67 kwh per day, or 47 per cent of the total power load for the washcar.

During transport of the washcar from Workcamp #1 to Mile 320, extreme difficulty was experienced in negotiating a steep, short grade (approximately 5% grade, 300 metres long) and sharp corners (at entrance to Mile 320 workcamp).

6.3 Incineration

Three samples of black water were taken and analysed (Table 5) at different times during the study period.

TABLE 5 RESULTS OF BLACK WATER SAMPLE ANALYSES

Constituent	% of Weight			
	Sample 1	Sample 2	Sample 3	Average
Water	99.00	99.01	99.24	99.08
Solids	1.08	0.99	0.76	0.94
Combustibles	0.89	0.69	0.51	0.69
Ash	0.19	0.30	0.25	0.25
Nitrogen	0.15	0.002	0.002	0.05
Sulphur	0.012	0.030	0.030	0.024

Number 2 fuel oil was fed to the incinerator at a constant rate of 23 litres per hour, which was determined by dipping the oil supply tanks. An analysis of the oil, provided by the manufacturer, is shown in Table 6.

TABLE 6 FUEL OIL CHARACTERISTICS

Type	Number 2, P40
Heating Value	37, 000 kJ/l*
Specific Gravity	0.8-0.81 kg/l*
Sulphur Content	0.037 % by weight
Ash Content	Nil

* SI Unit

Various logs of incinerator runs were recorded and representative logs are reported in Appendix C* for October 6 and October 7, 1974, respectively. Also on those dates, stack samples were taken and the analyses are presented in Table 7. Sulphur dioxide levels could not be determined because of insufficient feed to permit continued incineration and sampling.

Maximum ambient air concentrations of particulate and nitrogen oxide pollutants were predicted to be well under acceptable levels. Calculations by Croft (1974), using Brigg's plume rise equation and the Pasquill-Gifford dispersion method (Turner, 1970) indicate maximum ground level particulate concentrations of 5.8 $\mu g/m^3$ (one hour average) and nitrogen oxide concentrations of 7.5 $\mu g/m^3$ (one hour average). Environment Canada's proposed maximum acceptable levels are 120 $\mu g/m^3$ (24 hour average) for particulates and 400 $\mu g/m^3$ (one hour average) for nitrogen oxides. The preceding calculations were based upon input data in Table 8.

Power requirements by the incinerator trailer averaged approximately 8.3 kwh per hour when incinerating and 0.2 kwh per hour when not incinerating.

Operation of the incinerator seldom ran smoothly, due mainly to a faulty macerator. This and other problems are itemized as follows:

1. The macerator frequently overheated and shut off automatically. Incinerator controls were such that the macerator could not be re-started unless the incinerator was first shut down.

2. The flame scanner sometimes would not detect a flame after start-up of the incinerator. This resulted in automatic shut-down of the incinerator. The problem was diagnosed as poor positioning of the scanner such that the influent waste spray obscured light from the scanner. The scanner was relocated perpendicular to the waste inflow.

3. In the new position, the flame scanner sometimes failed to operate. This problem was caused by a coating which formed over the glass on the scanner and thereby prevented light penetration to the sensing device. The problem was rectified by cleaning the scanner and ensuring that the compressor was turned on before other equipment, so that compressed air would maintain the glass free of coating substances.

4. The incinerator shut down automatically soon after start-up. This problem was traced to an over-supply of air by the blower after a change from fall to winter operation, and was corrected by decreasing the volumetric air flow rate to account for the denser, colder air.

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*Appendix C is available from the authors or the Manager, ALUR Program, DINA, Ottawa.

TABLE 7 INCINERATOR STACK EMISSIONS, OCTOBER 6-7, 1974[a]

Constituent	Parameter	Stack Emissions[b] (range)
Particulates (2 samples)	Weight per unit volume of stack gas.	74 - 82 mg/m^3
	Weight per unit time	14 - 15 mg/s
	Weight per unit weight of waste incinerated.	550 - 600 mg/kg
	Hydrocarbons	47 - 87%
	Sulphur	1.6 - 2.0%
Nitrogen oxides (4 samples)	Weight per unit volume of stack gas.	70 - 127 mg/m^3
	Weight per unit time	14 - 24 mg/s
Other gases	Water vapor	9.6%
	Carbon dioxide	4.2%
	Oxygen	13.5%
	Nitrogen	71.8%
	Carbon monoxide	Not detected
	Argon	0.9%
		100.0%

a Stack gas temperature: 430 - 460°C

Volumetric flow rate: 0.187 - 0.190 m^3/s

b Results are for standard conditions: 760 mm Hg pressure and 25°C temperature.

TABLE 8 GENERAL INCINERATION DATA

Gas Exit Temperature	430°C
Ambient Air Temperature	10°C
Exit Velocity	10 m/s
Stack Diameter	0.25 m
Stack Height	6.1 m
Particulate Emissions	14 mg/s
NOx Emissions	18 mg/s

7. DISCUSSION

7.1 Vacuum and Chemical Toilets

Vacuum toilets were preferred to chemical toilets by the majority of workers. The chemical toilets were very large and cumbersome, and had a high, formidable step. Thus, preference for vacuum toilets may not have existed if different chemical toilets, such as the smaller ones used by airlines, had been tested.

The vacuum toilets clearly demonstrated their water-saving capabilities as compared to conventional flush toilets. The greater than 90% reduction in water requirements was significant from both the water supply and black water disposal aspects. Operating problems, which were frequently experienced with one of the vacuum toilets, should serve as a warning that not all vacuum systems are alike. Care must be taken in evaluating different brands of vacuum systems before a selection is made. This study demonstrated that vacuum systems can perform reliably with a minimum of daily operator attention.

The chemical toilets were not evaluated with respect to water-saving capabilities because of their limited use and operational problems. It would be expected, however, that chemical toilets would contribute more to water saving, and ultimately lower incineration costs, than vacuum toilets because of the lower water usage of chemical toilets (approximately 0.17 litres per flush, or 50% of vacuum toilet requirements, according to advertisements by chemical toilet manufacturers).

7.2 Washcar

The average water consumption in a conventional workcamp was shown by Forgie (1975) to be 150 litres per capita per day. Of this quantity, 25 litres per capita per day was attributed to kitchen requirements and 125 litres per capita per day to washcar requirements. These water-use figures closely support the results for the Ft. Simpson washcar, that is, 86 litres per capita per day, considering the 45 litre reduction in water used by vacuum toilets.

The use of the sauna in a workcamp for water-saving purposes is seriously questioned. This, together with the sauna's lack of general acceptance and high power consumption, appear to make saunas impractical at workcamp locations.

Other modifications to the conventional washcar design should be considered for water-saving purposes. In particular, the high water consumption by automatic washing machines, which accounts for 50% of washcar requirements, possibly could be reduced by installing wringer washers. More and better use could be made of water recycling. Odor problems experienced with recycling water from the wash basins to the toilets were caused by improper construction of the wash-water holding tank. Recycling of wash-water to urinals also could be considered and may result in a 20% reduction in total water requirements. Any deficiencies in available quantities of recycled water could be supplemented by recycling water from showers as well as wash basins. Furthermore, the use of vacuum urinals with recycled water should be considered. It appears that it may be possible, through some of these additional modifications, to reduce water requirements by a washcar to 45 litres per capita per day. The benefits that accrue from any such reduction may include not only lower water supply costs, but also lower wastewater treatment and disposal costs.

7.3 Incineration

Incineration of black water proved feasible from an operational point of view. However, because little use was required of the incinerator, its $35,000 capital cost (1973 cost, including trailer and related equipment) cannot be justified economically in this study. The incinerator was designed for a maximum loading rate of 90 litres per hour at an operating temperature of 700 to 830°C. Actual incineration rates reached the design level after a 2-1/2 hour warm-up time. During the 265 day study period, an estimated 13,000 litres of black water was incinerated over 150 hours (86 litres per hour).

Production of black water was approximately five litres per capita per day, 1.5 times greater than the flush water used by the vacuum toilets. The amount of chemical toilet wastes incinerated was insignificant.

Black water, quite feasibility, could be incinerated for an average of 40 hours per week at a rate of 90 litres per hour. On a long term basis, the incinerator could serve a camp with more than 100 men. It is evident that the incinerator was under-utilized by a factor of 10 and that a smaller incinerator could have done the job. Under full-load conditions the incinerator should require no more than 20 hours of operator attention per week. Estimated operating costs are in the order of $0.15 per litre (Table 9). The cost of black water incineration should not be considered by itself, but also in conjunction with other factors such as lower grey water disposal costs and higher standards of environmental protection. It is conceivable that incineration may be the only practical and acceptable sewage disposal method at workcamps with adverse geotechnical or environmental conditions.

The reduction in the quantity of black water through the use of vacuum toilets is particularly significant with respect to the effect on the cost of incineration. To incinerate ordinary, raw sewage would be impractical because of its large volume and low concentration. Black water incineration is much more feasible because of its relatively higher solids concentration and smaller volume. Further concentration of black water through some type of pre-treatment also might be considered before incineration to achieve overall cost reductions. A 20-fold increase in solids concentration of black water would lower incineration costs correspondingly, that is, from $0.75 per capita per day to less than $0.04 per capita per day. The reduced incineration cost would have to be compared to the additional pre-treatment cost to determine which alternative is economically preferable.

TABLE 9 ESTIMATED 1973-74 ANNUAL COSTS FOR BLACK WATER INCINERATION AT 100 MAN CAMP[a]

Item	Quantity	Unit Cost	Annual Cost
Operator	800 hr.	$8.00/hr.	6,400
Maintenance & Repair	Say 10% of capital cost		3,500
Fuel Oil	40,000 litres	$0.11/litre	4,400
Electric Power	14,000 kwh	$0.15/kwh	2,100
Amortized capital costs (10 yr. @ 10%)			5,700
		Total	$22,100

Estimated unit operating cost = $22,100/144,000 litres = $0.15/litre (including amortized capital cost).

---

a <u>Assumptions regarding incinerator operation</u>:

1. Workcamp is open 40 weeks per year.
2. Black water incineration time = 40 hours per week.
   Incinerator warm-up and cool-down time = 4 hours per week.
   Total "ON" time = 44 hours per week.
3. Fuel oil flow rate = 23 litres per hour.
4. Power consumption = 8 kwh per hour.
5. Black water feed rate = 90 litres per hour.

The incinerator in this study was not fully evaluated because of the small volume of black water generated. However, preliminary tests on stack emissions indicate that the resulting ambient air concentrations of pollutants are far less than Environment Canada's proposed maximum allowable levels. Nevertheless, it would be worthwhile to determine the effects of various operational changes on incinerator performance and to evaluate operational requirements over a longer time period. In particular, the effect of incinerator operating temperatures on stack emissions, operating costs, and equipment durability should be assessed. Also, various aspects of incinerating chemical toilet wastes, as well as more concentrated black water (after pre-treatment), should be investigated.

8. CONCLUSIONS

The following conclusions, with respect to sewage collection and disposal at northern workcamps, are summarized from the study:

1. Vacuum toilets are preferred to chemical toilets by most workers; however, chemical toilets which resemble conventional toilets more closely may prove just as acceptable.
2. Native northerners may not accept vacuum toilets unless the operation of these toilets is briefly explained and technically demonstrated.
3. Vacuum toilets use about 1.6 litres water per flush or at least 90% less water than conventional flush toilets. These water savings may be beneficial with respect to water supply costs and black water disposal costs.
4. Vacuum toilets decrease water requirements for a washcar by an estimated 45 litres per capita per day or by 35%.
5. Vacuum sewage systems can operate reliably with a minimum of daily operator attention; however, some brands may not operate satisfactorily.
6. A washcar, utilizing vacuum toilets, has a total water requirement of about 90 litres per capita per day distributed approximately as follows:

Laundry	50%
Showers	11%
Wash Basins	18%
Urinals	18%
Toilets	3%
	100%

7. The use of recycled wash water in toilets and urinals may be economically feasible if fresh water supply costs are high.
8. A sauna is not suitable with respect to water-saving capabilities, power requirements, and general acceptance.
9. Black water incineration appears feasible from an operational view point.
10. Quantities of black water generated from vacuum toilets are estimated to be five litres per capita per day.

11. Annual costs (operator wages, maintenance and repairs, fuel, power, and amortized capital costs) for black water incineration are in the order of $0.15 per litre of sewage incinerated or, on a per capita basis, $0.75 per capita per day. This cost could be reduced by pre-treating the black water to increase the solids concentration and decrease the volume to be incinerated.

12. Disposal of black water by incineration may be the only acceptable and practical alternative for disposal when adverse geotechnical or sensitive environmental conditions exist.

13. Semi-skilled personnel are required to maintain vacuum sewage systems and black water incinerators.

14. A washcar which is 20 metres long cannot be manouvered easily around sharp corners encountered at workcamp sites and may be too heavy to pull up steep inclines.

15. A washcar - incinerator complex appears feasible, operationally. The question of economic feasibility, particularly for incineration, must be resolved on a case by case basis. It appears that the high capital and operating costs of incinerators may limit their use to sites having adverse geotechnical conditions for conventional systems and/or sites requiring exceptionally high standards of environmental protection.

9. IMPLICATIONS AND RECOMMENDATIONS

This study has demonstrated that there are alternatives to the conventional washcar facilities, wastewater collection systems, and wastewater disposal systems for northern construction camps. Low water-use facilities, vacuum collection systems, and black water incinerators may gain acceptance, in some cases, because of economic and environmental requirements. These non-conventional systems should result in increased flexibility in selection of sites for proposed workcamps that would otherwise be hindered by climatic, geotechnical and environmental constraints. The increased flexibility in choice of workcamp sites indirectly could result in reduction of pipeline or road construction costs.

Recommendations regarding the use of water-saving facilities, vacuum collection systems, and black water incinerators are summarized as follows:

1. Potential users of vacuum toilets should be given a brief explanation of their operation in order to avoid misconceptions that could lead to non-acceptance of the facilities.

2. Semi-skilled personnel should be hired and trained primarily to operate and maintain the systems. The balance of their time could be devoted to other camp duties.

3. Vacuum systems and black water incinerators should be designed with consideration to the type of operator and operating problems expected at northern workcamps. Controls should be well-identified and kept to a minimum. Equipment should function reliably and automatically with little operator attention, and should be provided with back-up systems and alarms in case of malfunction. Duplicate equipment should be provided in most instances.

4. Grinding of sewage solids prior to incineration should be accomplished by a macerator designed to operate under a head or by one placed under little or no head.

5. Trailer sizes should be governed by mobility requirements.

6. Site selection for workcamps should be made after considering all of the alternatives for wastewater systems. Each site and wastewater alternative should be analyzed with respect to overall economics, practicability, and environmental requirements.

7. The use of one mobile incinerator to serve several workcamps should be considered when distances between camps are not prohibitive.

10. NEEDS FOR FURTHER STUDY

1. Further modifications should be made to a washcar to achieve additional water savings. The following could be investigated:

    - -foot pedal-operated taps for wash basins
    - -spring taps for wash basins
    - -smaller wash basins
    - -water-conserving nozzles for showers
    - -wringer washers instead of automatic laundry machines
    - -recirculating pumps from showers to urinals and to toilets
    - -vacuum urinals

2. Collection and disposal requirements for urinal wastes should be studied.

3. Information on volumes and characteristics of kitchen wastes would be desirable. Garburators could be installed for food wastes which could be fed with black water to an incinerator.

4. Grey water characterization, treatment and disposal studies are required.

5. Further studies should be conducted on a black water incinerator to test its durability, assess its performance, and determine operating costs more completely.

6. Addition of honey bag wastes and solid wastes, as well as black water, to a modified incinerator could be considered.

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APPENDIX A

OPERATOR DUTIES AND REQUIREMENTS

OPERATOR DUTIES

Operator duties necessary for proper maintenance of the Ft. Simpson washcar-incinerator complex are summarized as follows:

Washcar:

1. Maintain records on the quantity of water remaining in the water holding tank and order water deliveries as required.
2. Check the water system daily for leaks.
3. Check the vacuum system daily for leaks.
4. Check the operation of vacuum and chemical toilets daily.
5. Check the oil in the vacuum pump and add oil when necessary. Change the oil every two weeks.
6. Maintain records on toilet flush counts to estimate the quantity of accumulated black water in the vacuum holding tank. Pump the contents from the vacuum holding tank to the incinerator holding tank when required.
7. Make minor repairs and adjustments to equipment as required.
8. Replace cartridge and carbon filters every six months.
9. Maintain an adequate supply of duplicate equipment and spare parts.

Incinerator:

When incineration is required, the sequence of operations is as follows:

1. Open all fuel oil supply valves.
2. Switch on the master electrical switch to the incinerator.
3. Press fuel pump button and check pump gauge (should read 100 psig).
4. Clean flame scanner lens with a cloth and screw the scanner into position.
5. Start the air compressor and adjust the pressure to 20 psig.
6. Open the gate valve at the bottom of the black water holding tank and the recycle valve to the holding tank.

7. Start the macerator.
8. Wait for the PURGE COMPLETE light to come on.
9. Push the IGNITION button and hold until ignition occurs. This is indicated by the fire eye.
10. Open all valves before and after the sewage pump.
11. When the incinerator temperature reaches 1500°F, start the sewage pump at the lowest speed and periodically increase the pump speed (by the screw attachment) so that the 1500°F temperature is maintained.
12. When all sewage has been incinerated, shut off all equipment except the compressor and combustion air blower for 15 minutes, to allow the incinerator to cool.

GENERAL OPERATOR REQUIREMENTS

1. The operator must be familiar with the operating principles of vacuum and water systems and incineration.
2. He must know how to operate, maintain, and repair small pumps, motors, water heaters, and furnaces.
3. He should be able to solder copper pipe.

APPENDIX B

COMMENTS
BY
DEPARTMENT OF PUBLIC WORKS
ON
WASHCAR-INCINERATOR COMPLEX

Public Works Canada Travaux publics Canada

January 30th, 1975
Our File Number: 9305-52-330

Mr. J. Slupsky
Environmental Protection Service
Environment Canada
10th Floor, 10025 Jasper Avenue
EDMONTON, Alberta

EXPERIMENTAL WASHCAR - INCINERATOR UNIT,
MILE 320, MACKENZIE HIGHWAY

In response to a request made by yourself some time ago, I am herewith presenting some comments obtained from our field staff with regard to the use of the experimental washcar - incinerator unit that has been at our Mile 320 Camp since approximately February, 1973. As previously pointed out, your own staff have been directly responsible for the operation and maintenance of the unit during that period of time and will be your best source of information on the technical aspects of the unit and its operation. We are only in a position to provide you with some generalized comments on the unit from a user's point of view.

Of the five toilet units in the washcar, the two units towards the back or sauna end of the trailer appear to be the most popular and frequently used. From our understanding of the various problems that arose with the operation of the unit, I believe that these two units were also found to be the easiest to keep in working order. The other three toilet units were seldom used even when they were functioning particularly the two elevated units towards the front of the trailer. My own impression of the middle unit was that it was found less attractive by the apparent complexity of the controls associated with its use. Aside from any of the mechnical difficulties that might have been experienced with the operation of the unit, it was our impression that the vacuum toilets were definitely a water saving feature. Except for the need for a central vacuum system, it is my impression that this type of toilet unit is more compact and versatile for a mobile washcar as opposed to the conventional toilet unit with the attached water closet. As a point of interest, it was found that a number of native people staying in the camp would not use the vacuum toilets.

The storage tank underneath the sinks to provide for re-use of sink water in the toilets would appear to be of doubtful benefits unless some of the bad features could be corrected or overcome. Over a three month period there was an indicated saving of 75 gallons

..../2

of water by using this system, however the stagnant water under the sinks resulted in a bad odor given off into the washcar unit and the system was subsequently disconnected. Even if the odor problem can be overcome, it would appear that a more significant water saving would have to be realized to justify the relatively complex storage tank and plumbing associated with it.

Although automatic washers are found very convenient by the staff, they are not compatible with the overall water saving objective of the washcar unit. These should be replaced with conventional wringer washers unless automatic washers are available with a water consumption comparable to that of a wringer washer. We have, also, found some indications in the camps that with the convenience of the automatic washers some employees put through needlessly small loads, thereby aggravating the water consumption problem. With conventional wringer washers there is probably more of a tendency on the part of the employees to minimize the number of loads that they wash, thereby making it more desirable from a water saving point of view.

The sauna in the experimental unit was enjoyed by most employees in the camp, however here again it is not compatible with the water saving objective of the unit because of the increased amount of water used in the showers. There is also a high power demand by the sauna, however this is probably not too critical if such a demand is also necessitated by the incinerator unit and the electrical systems can be arranged in such a manner so that both demands do not occur simultaneously.

Since the incinerator unit itself had no direct effect on the operation of the washcar unit, we are in no position to make any comments on the incinerator unit from a user point of view. It does, however appear that even if some of the mechnical problems with the unit can be overcome there would still be a very high capital outlay for the purchase and operation of such a unit as well as the significant increase in the power source required in a camp having such a unit. The benefits of incinerating sewage as opposed to other possible forms of disposal would have to be quite large to economically justify such an installation. I believe that some concentration of effort towards water saving devices within the washcar is justified, however serious consideration should be given to adoption of a less complex, more economical, and more realistic form of sewage disposal.

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Southern Mackenzie Roads
Western Region

SHREDDED SOLID WASTE DISPOSAL

by

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Technology Programs

Northwest Region
Environmental Protection Service
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GLOSSARY:

Terms and Definitions

^{o}C	- degree Celcius
cm,cm^2	- centimetre, square centimetre
kg	- kilogram
kPa	- kilopascal
kw	- kilowatt
l	- litre
m,m^3	- metre,cubic metre
%	- percent
raw refuse	- refuse prior to shredding
refuse	- synonymous with 'solid waste'
RPM	- revolution per minute
shredded solid waste	- solid waste which has passed through a mechanical shredding process
solid waste	- the solid portion of discarded materials. Includes: garbage, rubbish, ashes, street refuse, abandoned vehicles, sewage treatment solids (See Table B-1, Appendix "B")
tonne	- 1000 kilograms

RÉSUMÉ

La nature et l'étendue de l'étude ainsi que ses objectifs par rapport à la construction du pipeline apparaissent dans le document. Celui-ci donne aussi un aperçu de l'état actuel des connaissances sur le déchiquetage des déchets solides et situe l'expérience. La source des données et les méthodes de cueillette sont indiquées et les résultats, notés et examinés. Enfin les chercheurs tirent des conclusions; ils font état des implications, des recommandations ainsi que des études ultérieures qui pourraient s'imposer à l'avenir.

Les travaux entrepris jusqu'ici indiquent qu'il est possible d'opérer le déchiquetage des déchets solides dans les conditions défavorables du Nord. De plus, les températures élevées atteintes dans les parcelles expérimentales de sol recouvertes par les déchets solides déchiquetés indiqueraient une décomposition bactérienne de ceux-ci.

Dans ces parcelles, le pergélisol a dégelé plus profondément que dans les parcelles témoins et il n'avait pas encore commencé à regeler en février 1975.

L'étude indique les caractéristiques de fonctionnement du matériel et propose quelques changements mineurs.

On a noté la présence de certains animaux, plus particulièrement de corbeaux et, probablement, de renards, de belettes et de loups.

1.0 SUMMARY

The general nature and scope of the study as well as its objectives are discussed with respect to general relationships of the study to pipeline development. A resumé of the current state of knowledge of shredded solid waste is presented and the project study areas outlined. The methods and sources of data are indicated and the results noted and discussed. Conclusions are stated and implications, recommendations and needs for future study suggested.

To date the project has shown that shredding solid waste under adverse northern conditions is feasible. Furthermore, because of high temperatures which have occurred within the shredded solid waste study plots, there is strong indication that there was bacterial decomposition of the shredded solid waste occurring within the plots.

The permafrost beneath these plots thawed deeper than the control plot and has not yet begun to refreeze at this time (February, 1975).

Equipment operation characteristics are pointed out and minor design changes suggested.

Some wildlife use has been noted in the form of ravens and possibly fox, weasel and wolf, as well.

2.0 INTRODUCTION

2.1 General Nature and Scope of Study

Pipeline workcamps, and workcamps in general in Canada's north, will require special methods of treatment and disposal of their generated wastes in order to protect the natural environment of the area. The general objective of this project has been to develop a viable alternate method of solid waste disposal in the north, to replace open dumps and uncontrolled burning of solid waste. Special emphasis has been placed on promoting degradation of shredded solid waste, discouraging degradation of the permafrost regime beneath shredded solid waste, and discouraging wildlife use of solid waste.

2.2 List of Objectives

The project's objectives in more detailed form are:

1. to determine the feasibility of shredding solid waste under northern conditions;
2. to determine optimum conditions to encourage thaw and degradation of the organic waste materials;
3. to determine optimum conditions to prevent thaw and degradation of the permafrost underlying the shredded solid waste;
4. to determine the optimum characteristics for cover material;
5. to determine the effects of leachate and run-off on soil characteristics;
6. to determine the degree of attraction of wildlife to shredded solid waste.

The majority of these objectives can be met only by a long term study lasting several years.

2.3 General Relationship to Concerns about Pipeline Development

Any licence given to institute development, such as pipeline construction, will include a requirement to minimize the environmental impact of constructing and operating the pipeline and associated facilities. Part of minimizing this impact will be to minimize pollution of the land, air and water by the wast products generated in the construction process. Liquid (sewage) and solid wastes will have to be treated to satisfy these requirements.

In areas where conventional landfill sites cannot be safely operated because of permafrost, lack of suitable cover material or boggy conditions, and where open burning is considered to be environmentally hazardous, it will be necessary to utilize an alternate solid waste disposal method. This alternate method must not encourage wildlife to use the solid waste as a food source.

3.0 RESUME OF CURRENT STATE OF KNOWLEDGE; SHREDDED SOLID WASTE

3.1 General

The process of shredding solid waste to achieve size reduction is also known as impacting, shearing, tearing, grinding, milling, pulverizing and flailing. Shredding, however, is the most commonly used term and generally refers to any mechanical unit that accomplishes the dry liberation, size reduction and homogenization of solid waste. Solid waste shredders normally use a combination of techniques including impacting, tearing and shearing (NCRR, 1973). Three types of equipment are used in shredding solid waste: (a) rotating-drum types which use a wet pulverizing technique, (b) hammermills, and (c) rasping machines (Flintoff & Millard, 1969). A hammermill was used in this project.

3.2 Hammermills

The term "hammermill" describes any machine in which a number of flailing hammers are used to strike the material as it falls through the machine, or as the material rests on a stationary surface. The basic arrangement of a hammermill (Figure 1) consists of a horizontal rotor carrying fixed discs, through which are pivoted groups of hammers which are either fixed or free swinging. There is usually a frame or casting with an inlet above the hammers, as well as an outlet area beneath the hammers. Impact plates and occasionally shredding teeth are fitted in the casing, and a grate is usually fixed at the outlet area. The spacing of the grate bars, which controls the maximum product size, varies from 6.3 to 10 cm, with 7.6 cm being common (Flintoff & Millard, 1969; NCRR, 1973).

When the material to be shredded is fed into the hammermill, primary reduction occurs when the material is truck by the hammers. Further reduction takes place as the material is pinched between the hammers and the grate bars. Oversize material usually remains in the hammermill until it is reduced to a size small enough to pass through the grate bar openings. In the usual range of grate bar spacings, paper material is shredded to a 0.5 to greater than 2.6 cm size; rock, glass, wood and metal cans to a 0.5 cm size (Pollock, 1974). Many hammermills are fitted with a ballistic rejection system to prevent damage to the machine, or operator injury by unshreddable materials.

Even large hammermills cannot shred tramp metal, tires, and bundles of textiles. Most hammermills have difficulty shredding carpets, plastic containers (which simply elastically deform), and plastic sheeting (which wraps around and jams the hammers) (NCRR, 1973). Machinery parts, wet ashes, and glass cause heavy wear on the hammers. Explosive materials should not be shredded.

3.2.1 Design Factors for Hammermills

The three main design factors for hammermills are rotor speed, horsepower, and grate bar openings. Rotor speeds generally range from

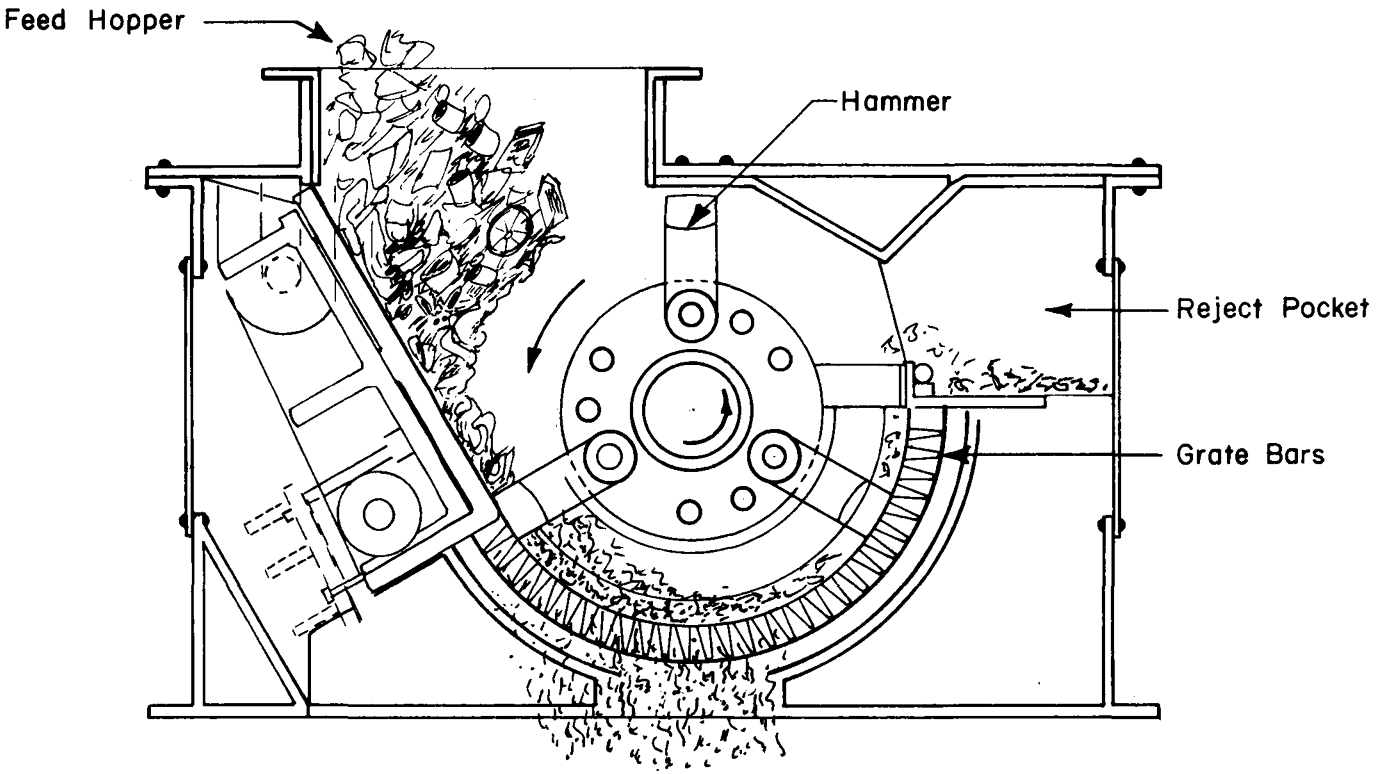

Figure 1 TYPICAL HAMMERMILL

850 to 1350 RPM in most municipal shredding operations (NCRR, 1973). In larger plants, generally classed at 5 to 30 tonnes per hour, 4.48 to 4.85 kilowatts (kw) per tonne per hour is used to estimate power requirements (Flintoff & Millard, 1969). The capacity of a hammermill is a function of the final product size as governed by the grate bar openings, i.e., as the product size decreases so does the capacity of the hammermill. The product size is also a function of the refuse composition, its moisture content, and the degree of wear on the hammers: as the percent moisture increases the product becomes finer, and as the hammer wear increases the product becomes coarser (Pollock, 1974). Furthermore, as the product size decreases the rate of decomposition increases (APWA, 1970).

Although rating capacity by tonnes per hour is convenient, it may be misleading because in actuality the capacity is a function of both density and volume of the material fed into it. A more realistic rating might better be in cubic metres per hour (Flintoff & Millard, 1969).

3.3 Volume Reduction

Shredding of solid waste reduces its volume by 20 to 50% on the basis of true volume (Flintoff & Millard, 1969; NCRR, 1973). The weight of the shredded material alone will cause considerable settlement, and a pressure of only 6.9 kilopascals (kPa) may reduce the shredded volume by nearly 50% (Flintoff & Millard, 1969). A comparison of densities of unprocessed raw refuse and shredded solid waste is presented in Table 1.

TABLE 1. Density Data

Reference	Type of Compaction	Density (kg/m^3, wet wt) Unprocessed Raw Refuse	Density (kg/m^3, wet wt) Shredded Solid Waste	Percent Increase in Density over Unprocessed
Pollock, 1974	None	186	229	23
Pollock, 1974	34.5 kPa No Vibration	297	449	51
Pollock, 1974	34.5 kPa With Vibration	333	492	48
NCRR, 1973	Baled	251	545	54

3.4 Practices

According to one report (NCRR, 1973) it may be better, in terms of final settling and decomposition, to place uncompacted shredded solid waste in layers less than one metre thick, and to allow each layer to settle naturally three to six months before the next lift is added. Settlement is usually uniform and, in general, is three or four times as fast as that of "raw" refuse, being complete in five years. Vehicles have no problem driving over compacted or settled shredded solid waste (APWA, 1970), and in at least one case shredded solid waste has been used to construct access roads within landfill sites with better results than available soil material (Pollock, 1974).

European design of shredded solid waste disposal sites call for smooth final surfaces, with a minimum of 4:1 slopes, fences around the site, and control of runoff to prevent ponding (NCRR, 1973).

Shredded solid waste may be applied to the soil as a mulch/fertilizer (Webster, 1973). Application rates in one study were 28 kg shredded solid waste per square metre of soil (Webber and King, 1973). Although there was some uptake of metals by the crops grown, the levels did not reach toxic concentrations.

Shredded solid waste may also be used as feed to suspension type incinerators. Furthermore, because of its homogenous nature, shredded solid waste is a good feed for air and magnetic sorters which separate out glass, metals, and plastics for recycling.

3.4.1 Cover Requirements

Without cover on shredded solid waste, there is supposedly increased surface water infiltration which results in accelerated decomposition and, therefore, increased leachate production. Daily cover is usually not used in Europe, where they have extensive shredding operations, unless the site is within 100 metres of any houses (NCRR, 1973). Even in these cases cover is only applied to improve public opinion, and not to solve any problems with odor. There is little odor associated with shredded solid waste, except when raw or wet pulverized solid waste is placed in the site and begins to decompose. Although a dense volunteer vegetation growth on uncovered shredded solid waste has been reported after a 3 to 5 year period (NCRR, 1973), or even 1 to 2 years (Pollock, 1974), it may be best to apply a final cover and seet it to grass as aesthetic safeguard (NCRR, 1973).

There is generally little blowing of shredded solid waste, because (1) the particles become entangled with each other, (2) each exposed particle presents a small target for the wind and (3) once the material is in place a crust similar to papier mache forms on the surface within a few weeks. Winds up to 97 kilometres per hour have been experienced, with only "minor problems" encountered (Pollock, 1974).

3.5 Effects of Shredded Solid Waste on Flies and Vermin

Flies are not associated with shredded solid waste (APWA, 1970). The shredding action within the hammermill kills almost 100% of the fly larvae (Pollock, 1973, 1974). Where there are flies around a shredded solid waste site, there are usually less than would be associated with a freshly-plowed field (NCRR, 1973).

Rodents cannot live in average shredded solid waste because the concentration of organics 7.5% (wet weight), is too low to serve as a food source (Pollock, 1973). Rodents have been seen at times in European shredded solid waste sites, but not for feeding purposes (NCRR, 1973). Seagulls have been attracted to shredded solid waste for heat, and possibly for food. Although small seed-eating birds have found food in shredded solid waste, their population was no greater than for any landfill or common dump (NCRR, 1973).

3.6 Fencing, Site Maintenance and Safety Precautions

All raw refuse storage areas must be maintained and cleaned at the end of each day to prevent vector problems. Fencing was recommended around the raw refuse storage area to prevent the spreading of blowing paper and plastics. Furthermore, it may be desirable to fence the entire shredded solid waste site to keep any blowing paper and plastics in, as well as to keep people out (NCRR, 1973).

A personnel shield to protect the operator from rejected or exploding materials and a fire extinguisher were recommended for any solid waste shredding operation (Pollock, 1973). A complete back up disposal system was further recommended in the event that the shredder is inoperable (Pollock, 1973).

3.7 Decomposition of Shredded Solid Waste in the Arctic

Little is known about the decomposition of shredded solid waste in an Arctic environment. One study (Straughn, 1972) indicated that raw refuse discharged to landfills in an arctic or subarctic environment would be preserved for an indefinite period of time, i.e., the material would remain frozen year round and no decomposition would occur.

Attempts to encourage decomposition in these landfills (Cohen, 1973) through aeration of the material, the addition of moisture and the addition of sewage sludge as a micro-organism source had little effect. Water at 60°C was pumped into the landfilled raw refuse as a source of heat and moisture, but still no decomposition occurred. Cohen (1973) suggested that in the North large amounts of heat would be required if the decomposition process was to be completed in the ground and that, as an alternative, surface disposal could be used to approximate composting.

4.0 STUDY AREAS

4.1 Feasibility

General feasibility of shredding solid waste under adverse northern conditions, i.e., Arctic weather conditions, was to be evaluated. Characteristics of shredding frozen solid wastes were to be compared to shredding unfrozen solid wastes. Operator training and safety requirements were to be developed.

4.2 Equipment Evaluation

In conjunction with evaluating the feasibility of shredding solid waste, evaluation of the shredding equipment used was necessary. Equipment modification and additional requirements were to be noted for future design modification.

4.3 Volume Reduction

The degree of volume reduction which results from shredding solid waste was to be determined. Furthermore, the effects of compaction and natural settlement on the landfill volume requirements were to be noted so the data could be eventually used to estimate actual land requirements for workcamp shredded solid waste disposal.

4.4 Thermal Regime

The effects of applying solid waste to the surface of permafrost soil were to be determined by monitoring the thermal regime within and below the various shredded solid waste plots. Data were to be used to determine how degradation of the permafrost below shredded solid waste can be minimized.

4.4.1 Cover and Insulation Requirements

Cover material requirements for shredded solid waste with respect to promoting degradation of the shredded solid waste and minimizing leaching by precipitation were to be determined. An insulative layer of woodchips on top of shredded solid waste was to be used in an attempt to promote degradation of the shredded solid waste. Similarly, a layer of woodchips between shredded solid waste and the permafrost was to be used in an attempt to prevent degradation of permafrost.

4.5 Wildlife Use

A program of monitoring the shredded solid waste plots for wildlife use was to be set up in co-ordination with the Northwest Territories Game Management Department. Additional observations were to be noted by the project operators where possible.

5.0 METHODS AND SOURCES OF DATA

5.1 Project Location

The field location for the project was at Inuvik, N.W.T., at 68° 22' N and 133° 43' W, which has an environment intermediate between arctic and subarctic, with continuous permafrost soil. The actual test site was located approximately 3.22 kilometres north of Inuvik and 0.4 kilometres from the present Inuvik refuse dump (Figure 2).

The site area, 73.2 metres by 73.2 metres, was cleared from a lightly burned stand of spruce, birch and aspen situated on a complex of mineral soil hummocks separated by shallow, moss-filled trenches. The hummocks are composed of a dense, sticky, grey-brown clay-silt showing little or no soil profile development. Some hummocks have mineral soil exposed at the surface, but most are covered with a thin layer (less than 5 cm) of humus, mosses and lichens. The hummocks are generally one to two metres across, whereas the trenches between are 30 to 80 cm wide and about 35 cm deep. The trenches are moss filled and underlain by wedges of peat extending well below the base of the natural active layer, the layer of soil which is subject to annual freezing and thawing (Heginbottom, 1973).

Plot centers were laid out with 19.8 metres between centers and 16.8 metres from the site edge. The plots were circular. Using thermal regime data calculated by Dr. R. Edwards and Dr. D. Thornton, Environmental Protection Service, 9.1 metre diameter plots were selected. Plot depths were set at 1.22 metres of shredded solid waste.

Plots were to be loaded as shown in Figure 3. Plots "2" and "3" were part of an associated ALUR project re: woodchips.

5.2 Equipment

The two main pieces of equipment used for the project, the shredder and the conveyor, were supplied by Jeffrey Manufacturing, Montreal. The shredder consisted of a Jeffrey Model 30 AB hammermill, equipped with grates sized to give a nominal 7.6 cm product and powered by a Lister HR6, six cylinder, 56 kw at 1800 RPM, air-cooled diesel engine, all mounted on a heavy duty utility trailer. The conveyor trailer consisted of a rubber belted conveyor driven by a Lister SRIA, single cylinder, 4.5 kw at 1800 RPM, air-cooled diesel engine, through a Radicon gear reducer.

The working configuration of the two units is shown in Figure 4. The conveyor was designed to fit beneath the shredder and had a hopper which directed shredded solid waste from the hammermill onto the conveyor belt.

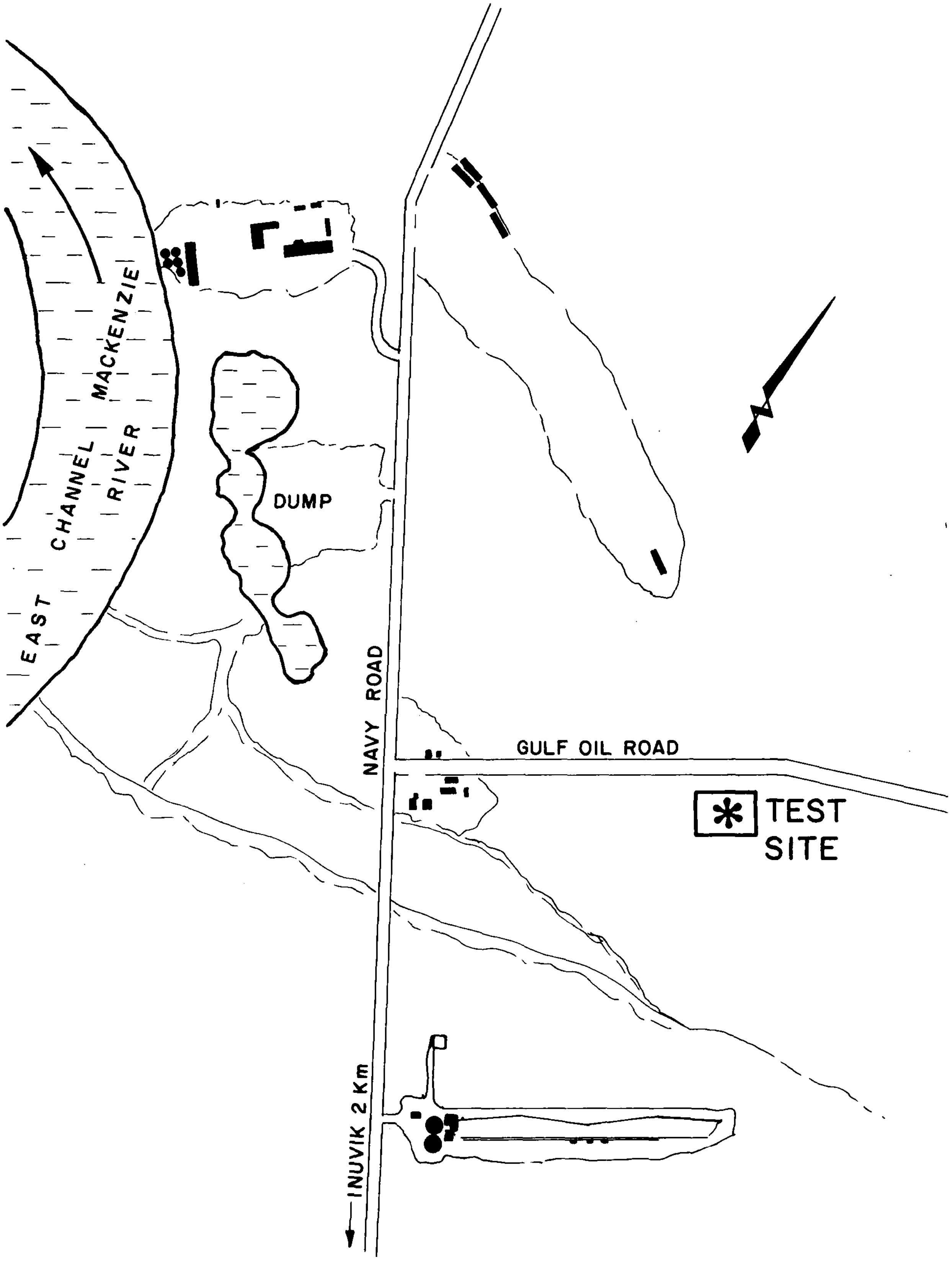

FIGURE 2 TEST SITE RELATIVE TO INUVIK NWT.

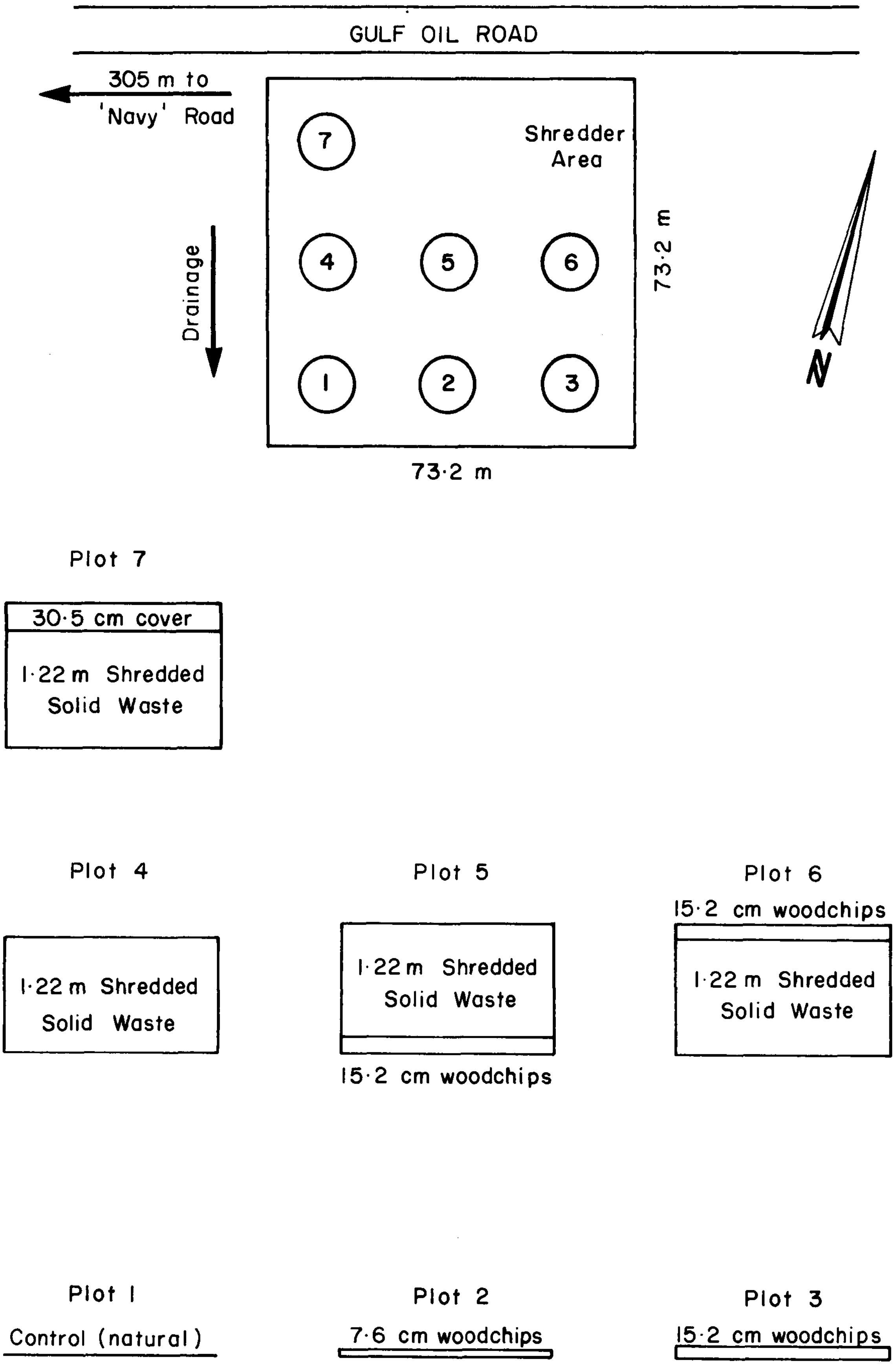

Figure 3 TEST SITE AND PLOT LAYOUT

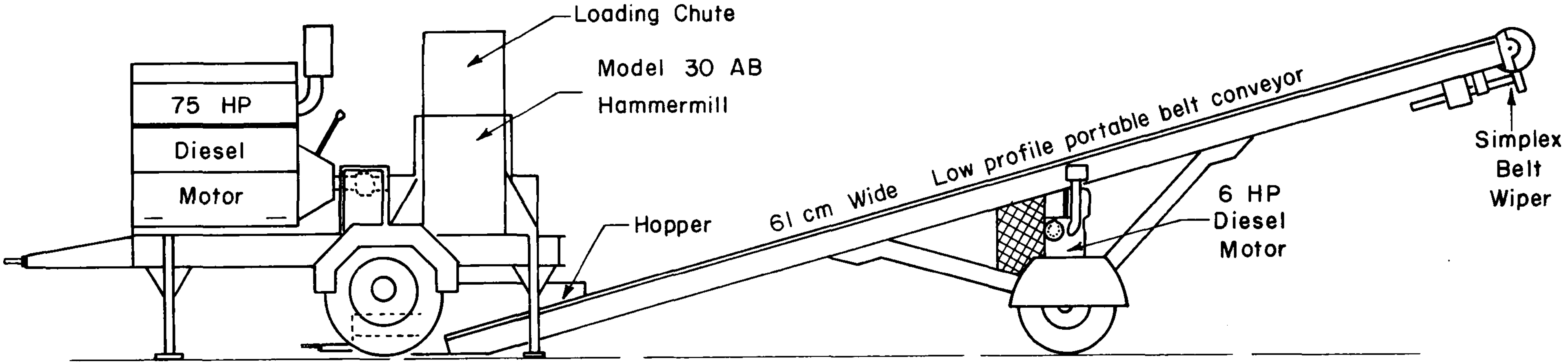

Figure 4 WORKING CONFIGURATION OF SHREDDER AND CONVEYOR

5.3 Procedure

As the Inuvik town administration encouraged the burning of household refuse, weekly residential collection of solid waste contained generally only burnt tin cans and ashes. Household refuse could, therefore, not be used, and as an alternate source the "Institutes" were used as a raw refuse source (Table 2).

The town's Department of Public Works (DPW) trucks brought the refuse to the test site and dumped it on the ground by the shredder. During the period February to May, 1974, an average volume of 34.7 m^3 per day of raw refuse was delivered to the site and shredded. In the period October to December, 1974, raw refuse was delivered to the site and shredded at an average rate of 35.2 m^3 per day.

To shred this material with a two man crew, one man loaded the shredder while the other brought unbroken plastic bags containing paper, cans, bottles, food, etc.; cardboard boxes full of loose refuse and small or broken and folded cardboard boxes to the shredder loading platform. The conveyor loading hopper was checked and cleaned of any accumulation of shredded material and shredded solid waste shovelled away from the end of the conveyor by either man.

When it was possible to hire an additional man, the third man primarily shovelled shredded solid waste away from the end of the conveyor and bent, folded, or cut large cardboard boxes into sizes which would fit into the shredder loading chute easily.

When the pile at the end of the conveyor became too large and hindered the shredding operation, it was moved to the various plot sites by a bucket equipped, rubber tired front-end loader. This loader dumped the shredded solid waste on the plots as directed by the shredder operator, and then compacted it with the bucket of the loader at a calculated rate of 0.3 kgf/cm^2.

5.3.1 Sampling

Shredded solid waste samples were obtained by taking five approximately equal volume, random shovelfulls of refuse from the pile at the end of the conveyor. Soil samples were taken at the time of temperature probe-hole drilling. No "leachate" samples were taken as originally planned because (1) the precipitation is low and, more importantly, (2) it was thought that digging a trench to collect the sample would be more detrimental to the permafrost than the shredded solid waste would be with respect to leachate contamination.

5.3.2 Temperature Probes and Thermal Regime

The temperature probes consisted of lengths of 2.54 cm PVC pipe in which thermistors were placed at 30.5 cm intervals and the pipe filled with zonolite insulation. The probes for plots "1", "2" and "3" were 3.05 metres in length and contained 10 thermistors, whereas the

TABLE 2. Inuvik Solid Waste - Type and Source

Source	Refuse Type
Inuvik General Hospital	Food scraps, juice and formula cans, paper, disposable diapers, cardboard boxes.
Anglican and Roman Catholic School Hostels	Food scraps, 100 oz. and smaller tin cans, paper, cardboard boxes, clothing, liquid foods, e.g. soup.
CFS Inuvik	Food scraps, food cans, beer cans and boxes from messes. Cardboard boxes, whole vegetables and fruit from the Canex.Bags of waste paper from offices. Oil cans from workshops.
The Bay	Paper, cardboard boxes, whole vegetables and fruit.
Town Arena	Soft-drink and beer cans, liquor bottles, plus food scraps, cans, paper, etc. after banquets, dances, etc.

Shredded solid waste will be analyzed for: Crude fibre content, moisture content, ash, volatile percentage, carbon nitrogens, total water soluble solids (including Na, Cl NH_3, Org-N, PO_4, SO_4, COD) and trace elements (Cr, Ni, Cu, Cd, Zn, Sn, K, Mn).

probes for plots "4", "5", "6" and "7" were 4.27 metres in length and contained 14 thermistors. The holes in the plots for the probes were drilled in the centers in May, 1974. Probes were set in these holes by packing them in with available soil so that the uppermost thermistor was 30.5 cm above the final plot surface. Readings have been taken weekly since June, 1974 with a Model 3F01 Atkins meter.

5.3.3 Phasing of Shredding

The original calculations for the length of time required to shred enough material for each plot had been based on an assumed per capita solid waste contribution rate of 2.27 kg per day. This figure had been obtained from the available literature and was applicable to combined municipal and industrial solid wastes in southern locations. The figure was too high for Inuvik, especially in view of the fact that most of the residential solid waste in Inuvik is burned before it is collected.

As a result, enough material for only 2.25 plots was shredded in the period February to May, 1974, before the ground became too soft to move the material from the end of the conveyor to the plots with the front-end loader. The remaining quantity of shredded solid waste for 1.75 plots was shredded in October to December, 1974 period.

6.0 RESULTS

6.1 Comments on Shredding Solid Waste

The hammermill-shredder unit generally did a good job of shredding all materials fed to it. Paper and cardboard were ripped into small pieces, tin cans were bent and ripped into unrecognizable pieces, and wood was shattered into splinters. Glass was shattered into a fine powder or crystals. Plastic garbage bags which commonly become entangled in hammermill bars in warmer weather, shattered into pieces in cold weather and caused no problems.

Major problems in shredding were represented by cans and large cardboard boxes. Cans were often propelled out of the inlet chute because the rubber mats provided to prevent this did not function properly. Large cardboard boxes were separated, cut, folded, stacked and then loaded into the shredder.

Cloth, e.g. rags and clothing, were not shredded well by the hammermill. It was only partially ripped and before it could pass through the shredder outlet, it caught on the hammers and continued to go around in the shredder, jamming the hammers in most cases. This necessitated shutting the shredder off and removing the cloth from the hammers.

Batteries (flashlight type) became projectiles when struck by the hammers and for "safety's sake" were not added to the shredder if possible.

Leather boots and shoes caused a great deal of noise as they were struck by the hammers. Although most of the material was eventually shredded, chunks were often rejected out the inlet chute opening. It may have been better, with respect to safety, to completely reject these materials by hand before shredding.

Clear plastic sheeting used to wrap pallets of food stuffs, etc. for a shipment did not shred easily. Due to its lightness, it was blown away from the hammers and therefore, heavier material had to be added after the sheeting to aid its shredding.

During warm weather, greater than -12°C, most of the vegetables and food scraps (including soups) were unfrozen (had never been frozen) before shredding. This material went through the mill very quickly in a large wet clump. Afterwards, the grates beneath the hammers often clogged as the wet material mixed with cardborad. This problem was very significant because the hammermill did not operate properly unless the grates were open. As manual cleaning was physically impossible, the solution to clear the grate openings was to load a large bag (or box) of beer and soft drink cans into the mill. This had a relative "laxative" effect and normal operations could be resumed shortly thereafter.

The shredded solid waste was generally dry and light because the vegetable matter remained frozen during cold weather operation and therefore, did not release moisture to be subsequently absorbed by the paper/

cardboard material. As proof of this dryness, a fire started once in the shredded solid waste at the end of the conveyor, possibly ignited by a hot can (the result of hammer impact).

At colder temperatures, less than -28°C, the conveyor belt was polished by the action of frozen vegetable matter and the Simplex belt wiper. The co-efficient of friction which resulted was too low to enable shredded solid waste to be carried up the conveyor unaided. Clumps of this shredded solid waste had to be helped up the conveyor by pushing them with a stick. The need for small belt flights was indicated at these times by the fact that the slight height of the belt connector was enough to pick material out of the skirtboard hopper unaided.

At temperatures greater than -28°C and with less wiper pressure, the belt became dirty with finely shredded organic and glass materials. This made the belt rough enough that all shredded solid waste was conveyed away from the shredder with no problems.

The shredded solid waste could stand at greater than 45° angle of repose uncompacted and vertically after compaction. Wind did not have a great effect upon the shredded solid waste, once the loose material had blown off the pile, due to interlayering. The wind did blow the shredded solid waste off the conveyor at times until a makeshift cardboard wind screen was erected along the length of the conveyor.

6.2 Equipment Evaluation

The factory shredding rate of 909 kg to 1364 kg per hour (hand fed) was impossible to attain under actual conditions due to jamming of bags, boxes, etc. in the inlet chute; to obtain the suggested figures continuous feeding is necessary. Actual raw refuse shredding time was 5 hours per day at a rate of 6.9 m^3 per hour during the February to May, 1974 period. During the October to December, 1974 period the shredding time averaged 4.2 hours per day (partially due to the increasing darkness) at the rate of 8.3 m^3 per hour.

Neither the shredder or the conveyor motor would start at cold temperatures, less than -17.8°C, without being heated by a portable propane torch. At colder temperatures, -40°C, it took four hours to warm the shredder motor enough so it could be turned over fast enough to start; at -24.4°C heating time was down to 25 minutes. At all cold temperatures it was necessary to "jump" the shredder battery with the truck battery and use an aerosol starting fluid to start the shredder motor.

(It was pointed out by heavy equipment operators in Inuvik that all their starting systems are 24V DC rather than the 12V DC as supplied with the shredder.)

The conveyor had a crank start motor which required at least one half to three quarters of an hour of heating before it was loose enough to start at colder temperatures (less than -17.8°C). A shredder battery-powered electric starting motor was purchased for this motor, reducing the heating time required for starting to less than ten minutes, even at the coldest temperatures.

The conveyor belt had no lateral guides which, when combined with a build up of a fine, shredded fuzz material on the main rollers, resulted in eratic side-to-side movement of the belt. There were no flights on the conveyor belt to carry the shredded material up the belt, as needed, when the belt was polished.

The motors in both units generally ran very well and required only minor routine maintenance. At no time was the conveyor's SR1A motor overloaded although the shredder's HR6 motor was at times, e.g. when processing bags of magazines or other dense materials.

Fuel consumption for the shredder motor was 3.04 litres per hour at 1000 RPM, the overnight idling speed during cold weather (less than -17.8°C) and 5.5 litres per hour at the 1800 RPM shredding speed. The conveyor motor used approximately 4.54 litres of fuel per five hours of operation.

The main equipment fault was the lack of an effective projectile rejection system. Heavy rubber belts were supplied in the inlet chute to prevent such rejections but because they were not resilient at cold temperatures the first time they were used in Inuvik (-40°C) they were bent out of the way and have remained so for the remaining time. As a result material could be rejected out of the inlet chute, creating a danger to the equipment operators (See Section 6.4).

6.3 Volume Reduction

Volume reduction was based on the raw volume of the refuse or solid waste. This volume was measured while the raw refuse was in the collection truck, prior to any processing. It was not the true volume of the raw refuse, however, because it included the volume of empty boxes, cans, etc.

On this basis, volume reduction during the February to May, 1974 period was approximately 8.5:1, where "1" represents the volume of uncompacted but shredded solid waste and "8.5" represents the "raw" volume of the raw refuse. Similarily, during the October to December, 1974 period volume reduction was approximately 9.8:1, where "1" represents the volume of compacted, in place, shredded solid waste and "9.8" represents the "raw" volume of the raw refuse.

By October, 1974, the shredded solid waste on plots "4" and "7" had settled approximately one foot since May, 1974.

6.4 Safety Equipment

During operation of the shredder, the need for safety equipment to prevent injury to the operator(s) became evident. The major requirement was protection of the operator from material ballistically rejected out

TABLE 3. Required Safety Equipment

Item		Reason
1(a)	Safety Goggles (Winter use)	Tin cans, glass, other metals rejected through the inlet chute.
(b)	Face Screen (Summer use)	Same as above but frosts up during winter use.
2.	Sound Muffs	Motor noise, hammermill-impacting noise.
3.	Air Filter/ Respirator Mask	To prevent inhalation of cardboard fuzz glass dust, disposable diaper material, ashes, etc.
4.	Hard Hat	Flying tin cans, metal objects, etc. rejected through the inlet chute.
5.	Fire Extinguishers	Putting out any fires in shredded refuse.

of the inlet chute. Table "3" lists the required safety equipment for operation of this shredder.

6.5 Thermal Regime

Thermal regime data for plots "1", "4", "5", "6" and "7" are plotted in Figures A-1, A-2, A-3, A-4 and A-5 (Appendix "A"), respectively, for the period June, 1974 to January, 1975.

6.5.1 Plot "1" Control

For the control plot, plot "1", the freeze/thaw interface depth increased at an approximately constant rate from June until September, 1974. At this time, the ground surface began to re-freeze downwards and thereby decreased the rate of lower thawing.

Although the ground near the surface was well frozen by October 8, 1974, the ground temperatures remained relatively constant until mid-December, 1974. The lower freeze/thaw interface, which had decreased to approximately 160 cm by late November, began to re-freeze upwards early in December; by December 15 the ground was completely frozen.

6.5.2 Plot "4": 1.22 m - Shredded Solid Waste

When the first temperature readings were taken in June, 1974, the temperature in the middle layer of the shredded solid waste on plot "4" was off scale on the meter, i.e., greater than 48.9°C, indicating bacterial action was occurring. Cooling of this layer began near the end of June, possibly due to a temperature kill-off of some of the bacteria. The temperature of the shredded solid waste/ground interface was approximately 12°C in the June to September, 1974 period, 4°C on December 28 and 2°C on January 18, 1975 (less than 0.15 m of shredded solid waste remained unfrozen, however).

Thawing of the ground was slower to start than the control plot, and remained at a relatively constant rate from June to mid-September, 1974, at which time it began to slow. The maximum depth of thaw was reached by the end of December, 1974, at 180 cm below the initial ground surface.

Cooling in the top of the shredded solid waste accelerated near the end of August, 1974 and re-freezing began from the top down in late September, 1974. Although the top layer of the soil cooled in the 2°C to 10°C range, there is no sign of any re-freezing upwards from the bottom at this date (February, 1975).

6.5.3 Plot "5": 0.15 m - Woodchips and 1.22 m - Shredded Solid Waste

The 0.15 m of woodchips which were on plot "5" over the summer (1974) retarded subsurface thawing. There was little increase in the depth of thaw beyond the initial amount during the summer months. By approximately September 10, 1974, the maximum depth of the freeze/thaw interface was reached at 107 cm, or approximately 50 cm shallower than the control plot. The plot started to freeze down from the top and up from the bottom on approximately the same date, September 25, 1974. The ground was completely frozen by November 14, 1974.

The first shredded solid waste was added to the plot on November 19, 1974. Because both the shredded solid waste and the ground were frozen, no bacterial action started and therefore there was no internal plot heating. The -2°C isotherm has continued at a relatively constant level, although the -1°C isotherm took a sharp decline December 4, 1974.

6.5.4 Plot 6: 1.22 m - Shredded Solid Waste and 0.15 m - Woodchips

There was approximately 0.15 to 0.3 m of shredded solid waste on plot "6" over the summer, June to October, 1974. There was a fairly slow rate of thawing of the permafrost during this period, with the maximum depth of the freeze/thaw interface reached near the end of November, 1974 at 175 cm below the ground surface.

The ground had begun to re-freeze from the top down late in September, but as shredded solid waste was added to the plot early in October the ground warmed slightly. By the time the final shredded solid waste was added November 19, 1974, the plot was warming considerably, apparently due to bacterial action. This continued during late November and early December, 1974, with internal shredded solid waste temperatures reaching 40°C plus even though the mean air temperatures during this time ranged from -25°C to -39°C.

At the time of the last readings (January 21, 1975) the plot was much warmer than either plot "4" or "7", which previously had been 40°C plus in their middle shredded solid waste layer. The shredded solid waste-ground interface temperature on January 21, 1975 was 6°C.

6.5.5 Plot "7": 1.22 m - Shredded Solid Waste and 0.3 m - Cover

As for plot "4", when the first temperature readings were taken in June, 1974, the temperature in the middle layer of plot "7" was off scale on the meter, i.e., greater than 48.9°C, indicating bacterial action was occurring. This middle layer began to cool approximately August 1, 1974, possibly due to a temperature kill-off of some of the bacteria as well as because of colder weather. The temperature of the shredded solid waste-ground interface was approximately 17°C during the June-September, 1974 period, 10°C on November 27, 6°C on December 17, 2°C on January 8, 1975 and 0°C on January 16, 1975. All the shredded solid waste was frozen by January 16, 1975.

Although the ground below the plot had initially been slower to thaw than the control plot, it has continued to thaw downwards longer than the control plot. By January 21, 1975 the ground had thawed to 150 cm below the original ground surface, with no trend of re-freezing upwards from the bottom evident at this date (February, 1975). The addition of fill to the plot top on November 19, 1974 has had no effect to date.

6.6 Wildlife Use

The Northwest Territories Game Management authorities were unable to assist in monitoring the plots for wildlife use. All wildlife use observations were made by the project operators.

Ravens were commonly observed foraging both in the shredded solid waste and in the raw refuse (when available). Although this did occur during the working day, it occurred more often at times when the equipment was shut off and the site vacated.

One of the project operators in the October to December, 1974 period observed weasel and fox tracks and marks where these animals had dug in the shredded solid waste; whether or not they found anything to eat could not be determined. The same operator also reported that a wolf appeared to be periodically investigating the test site early in December, 1974.

7.0 DISCUSSION

A detailed report of the equipment operation which included all the minor faults, etc., which were not included in this report, was sent to the equipment manufacturer, Jeffery Manufacturing, as a means of feedback so that they could upgrade future equipment design.

From the thermal regime data available to date (January 21, 1975) it appears that the insulative properties of the shredded solid waste delayed initial thawing of the permafrost below the plots. This thawing, on the other hand, was continued deeper and for a longer time than that of the control plot. This is due in part to the same insulative properties hindering re-freezing of the permafrost from the top down, as well as because of heat generated within the plot by bacterial action.

With at least 150 cm of permafrost soil remaining unfrozen under plots "4", "6" and "7" at the date of the last readings (January 21, 1975), and only three or four months left before spring break up, these plots may not completely re-freeze this year.

When break up occurs, the shredded solid waste on plots "4", "6" and "7" will have to thaw before any bacterial action can begin. It remains to be seen what the effect upon underlying permafrost below plots "4", "6" and "7" will be. It is possible that because there has been some bacterial action already future bacterial action, i.e., summer, 1975, will be of a decreased nature and that the effect upon the permafrost will be decreased.

When the shredded solid waste is eventually decomposed to a stable form, the permafrost regime will stabilize. This stabilized regime may be different from that of the control plot.

Because of the shredded solid waste on plot "5" being frozen when it was added, no bacterial action occurred. Plot "5" will, therefore, be one year behind either plot "4" or "7" in terms of bacterial decomposition of the shredded solid waste and its effect upon the thermal regime. Future thermal regime data from plot "5" will show whether or not the layer of woodchips beneath the shredded solid waste will insulate the permafrost from any generated heat.

8.0 CONCLUSIONS

Shredding solid waste under northern climatic conditions is physically feasible. Cold weather actually improved shredding by making the food easier to shred without clogging the grates, as well as by making the shredding operation more pleasant for the operator by eliminating most of the odors associated with solid waste. The particular pieces of equipment used could have been improved by installing a projectile rejection system on the hammermill and small flexible flights on the conveyor belt. For general workcamp installations the hammermill used was felt to be undersized with respect to ease in loading.

Volume reduction is considerable and would enable considerable landfill area savings to be realized when compared to raw refuse requirements. Better compaction of the shredded material than that obtained in this project could be easily obtained by using readily available construction equipment, e.g., a Caterpillar-type crawler tractor, to compact each lift. Further landfill savings could be realized by utilizing the natural decomposition/settlement of the shredded material to best advantage by phasing the placement of material, i.e., by allowing one lift to settle for approximately three months before the next lift is started.

Contrary to the results of studies of decomposition of solid waste in sanitary landfills in the north (Straughn, 1972; Cohen, 1973), there were indications of bacterial decomposition of the shredded solid waste in plots "4", "6" and "7" as evidenced by the high temperatures in the middle of the shredded solid waste. The permafrost below these plots is being degraded due to the combination of the heat within the plots and the insulative properties of the shredded solid waste which are preventing normal re-freezing. Continued monitoring is necessary.

Assessment of wildlife use was inconclusive because of the lack of formal, professional monitoring. Ravens did appear to be feeding on the shredded solid waste, although this is not considered to be a serious problem for workcamp installations.

9.0 IMPLICATIONS AND RECOMMENDATIONS

Shredding solid waste is a viable alternate method of waste disposal which is applicable to workcamp use. Care would have to be taken to prevent the degradation of the permafrost below the shredded solid waste.

A larger hammermill than that used for this project and a conveyor with small flights are recommended for workcamp use. A shelter around the equipment would improve winter operating conditions.

For workcamp use, raw refuse would have to be shredded the same day as it was generated to discourage wildlife attraction as a food source when stored unprocessed. Fencing around the shredder units and disposal area may help to discourage any wildlife use, e.g., by bears.

Although cover material may not be necessary to promote degradation of the shredded material, it may be advisable to obtain suitable cover material and seed the plots to some type of native or suitable grass as an ecological safeguard.

Provision would have to be made for disposal of non-shreddable items, e.g., a pit to be covered over after use.

Thorough operator training and provision of the necessary safety equipment would be necessities to protect the integrity of the shredding equipment in any pipeline workcamp installation.

10.0 NEEDS FOR FURTHER STUDY

A controlled wildlife monitoring study is needed. Of special interest would be use by larger animals, either directly for food or indirectly for food through smaller animals which may begin to inhabit the shredded solid waste. The Northwest Territories Game Management Department has expressed some informal interest in putting the shredder in a workcamp on the MacKenzie/Dempster highway for the purpose of wildlife monitoring.

A continuation of the temperature monitoring is necessary, as is the sampling of the shredded solid waste to determine its rate of decomposition. Further controlled studies of shredded solid waste could determine the effect of (1) the depth of the shredded solid waste and (2) the application of sewage treatment sludge to the shredded solid waste plot as a nutrient and bacteria source, on material degradation and the thermal regime.

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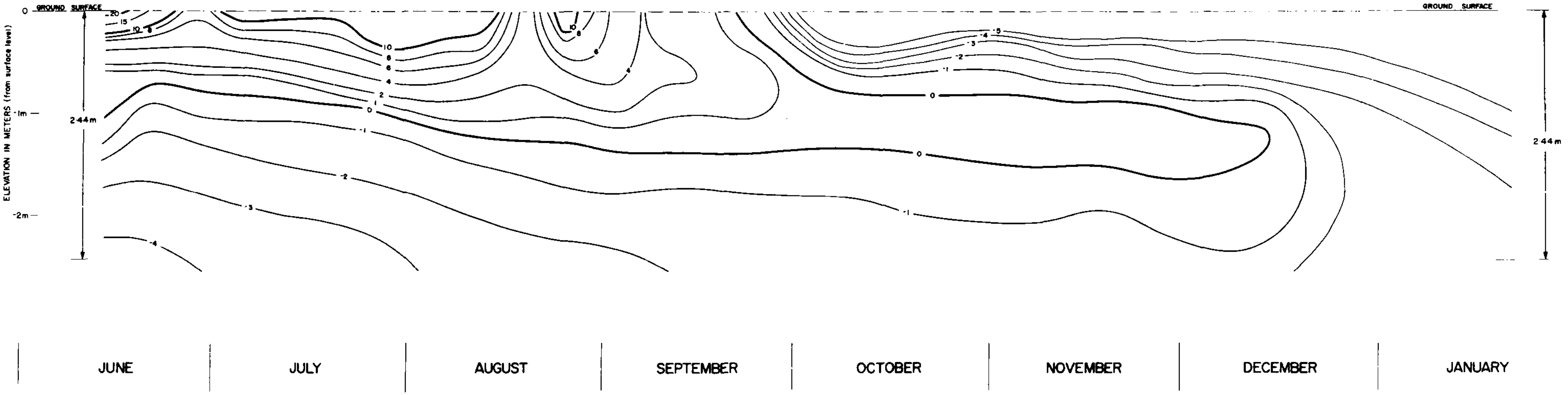
APPENDIX "A"

TEMPERATURE PROFILES

TEMPERATURE PROFILE:
PLOT 1 (°C Isotherms)



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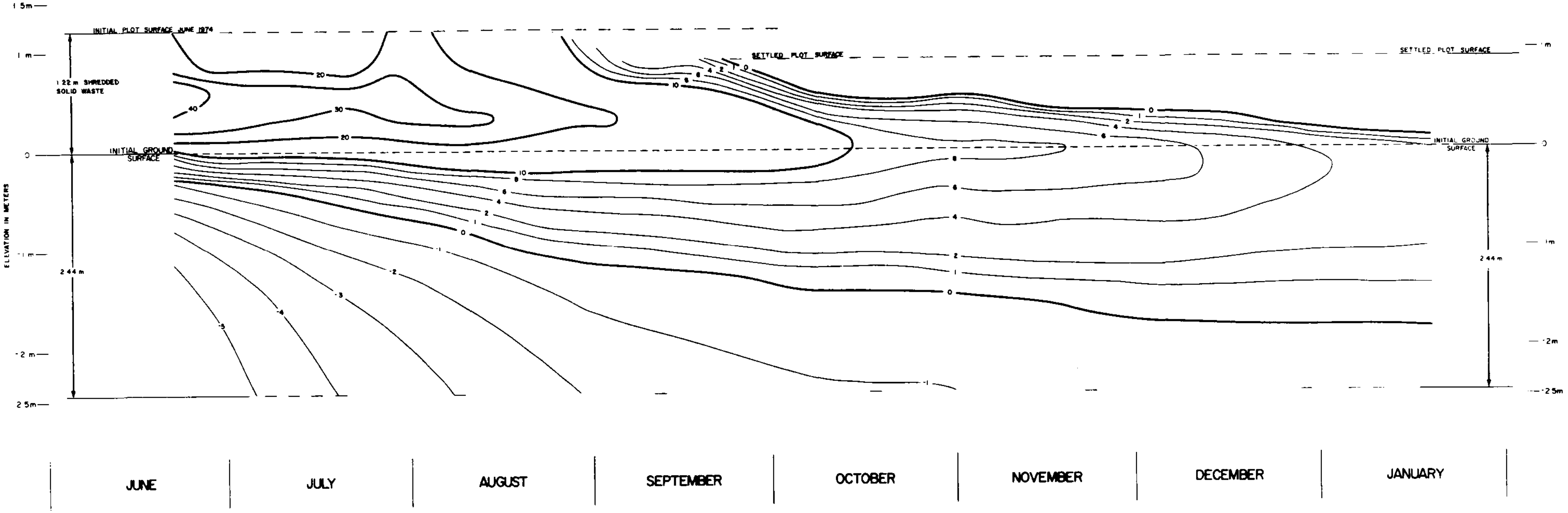
PLOT 4 (°C Isotherms)



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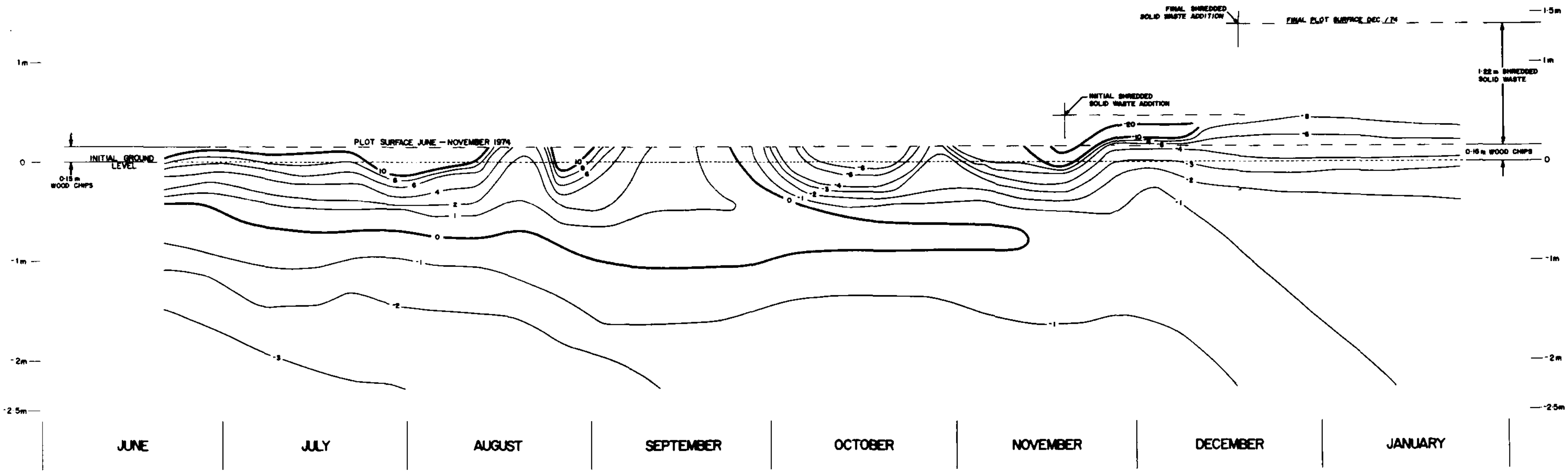
PLOT 5 (°C Isotherms)



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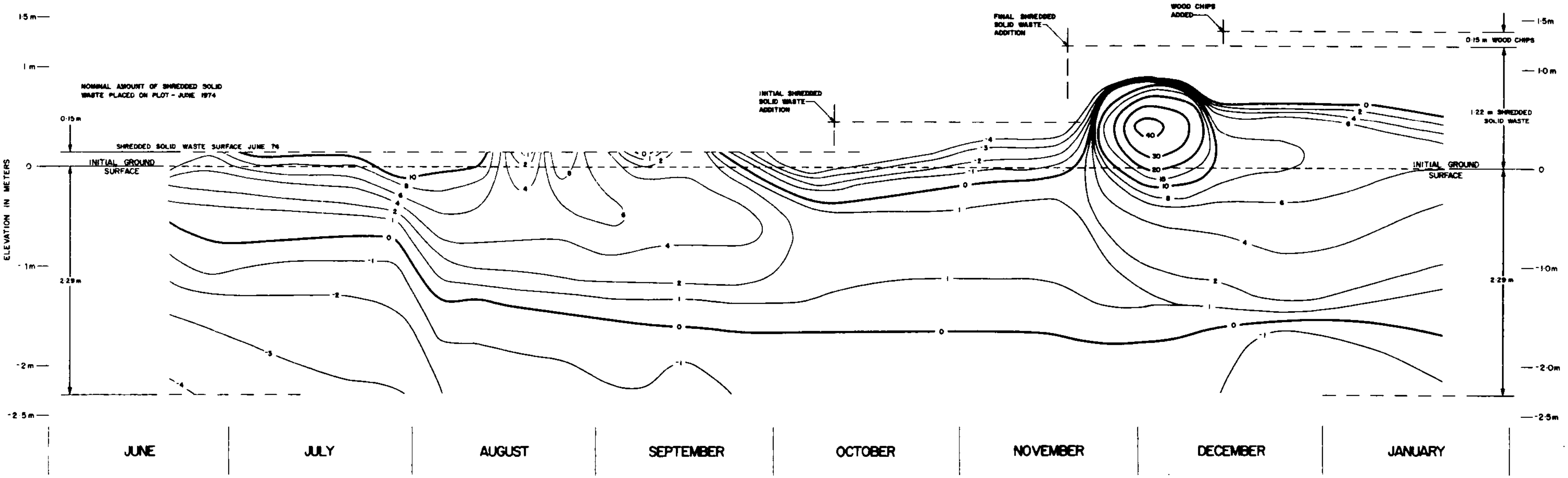


APPENDIX "B"

SOLID WASTE CLASSIFICATION

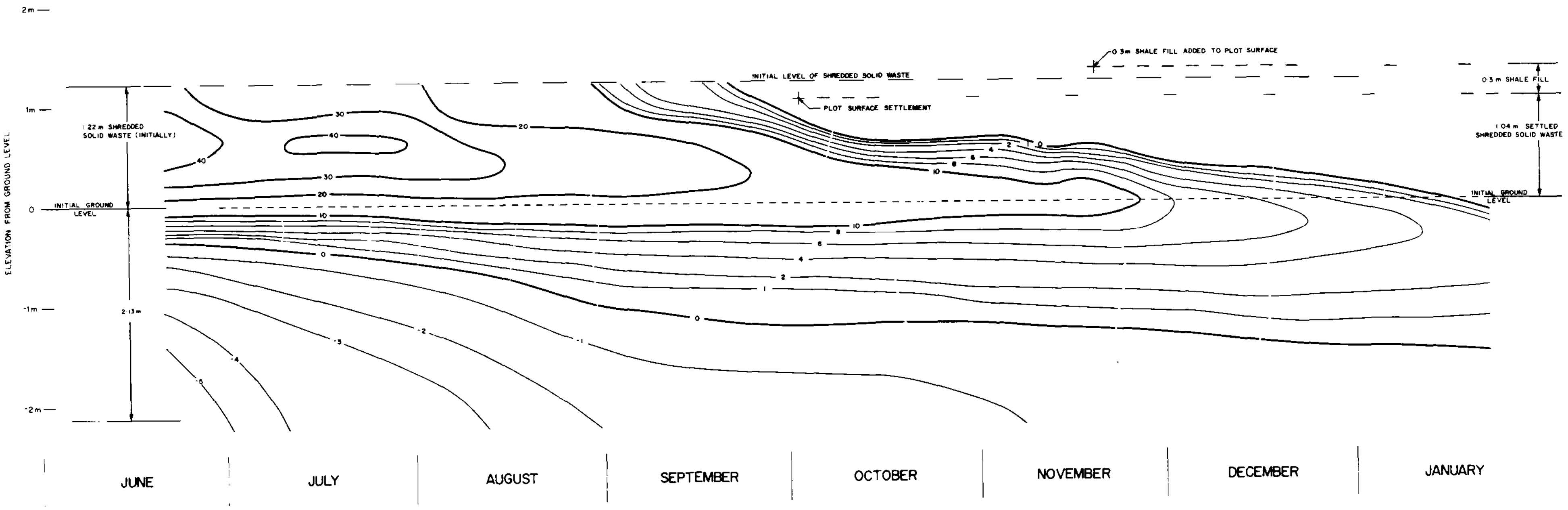
Table B-1 (After APWA, 1970)

REFUSE MATERIALS BY KIND, COMPOSITION, AND SOURCES

Kind		*Composition*	*Sources*
Refuse	Garbage	Wastes from preparation, cooking, and serving of food; market wastes; wastes from handling, storage, and sale of produce	Households, restaurants, institutions, stores, markets
	Rubbish	Combustible: paper, cartons, boxes, barrels, wood, excelsior, tree branches, yard trimmings, wood furniture, bedding, dunnage	
		Noncombustible: metals, tin cans, metal furniture, dirt, glass, crockery, minerals	
	Ashes	Residue from fires used for cooking and heating and from on-site incineration	
	Street Refuse	Sweepings, dirt, leaves, catch basin dirt, contents of litter receptacles	Streets, sidewalks, alleys, vacant lots
	Dead Animals	Cats, dogs, horses, cows	
	Abandoned Vehicles	Unwanted cars and trucks left on public property	
	Industrial Wastes	Food processing wastes, boiler house cinders, lumber scraps, metal scraps, shavings	Factories, power plants
	Demolition Wastes	Lumber, pipes, brick, masonry, and other construction materials from razed buildings and other structures	Demolition sites to be used for new buildings, renewal projects, expressways
	Construction Wastes	Scrap lumber, pipe, other construction materials	New construction, remodeling
	Special Wastes	Hazardous solids and liquids: explosives, pathological wastes, radioactive materials	Households, hotels, hospitals, institutions, stores, industry
	Sewage Treatment Residue	Solids from coarse screening and from grit chambers; septic tank sludge	Sewage treatment plants; septic tanks

TEMPERATURE PROFILE:

PLOT 7 (°C Isotherms)



ENVIRONMENTAL PROTECTION SERVICE
ENVIRONMENT CANADA

DISPOSAL OF CONCENTRATED WASTES IN NORTHERN AREAS

by

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UNIVERSITY OF TORONTO

April 1975

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1.0 SUMMARY

1.1 Concentrated Human Waste

(1) The composition of collected human waste (faeces + urine) in general was reasonably constant. Some variation in solids, COD and alkalinity was observed. In large part, this variation was due to analytical problems; some part of the variation appears to come from the inherent variability of human excrement. The studies carried out on human waste quantities and strengths agree reasonably well with literature values.

(2) The concentrated nature of the human waste introduces certain analytical problems, which can cause random distortions and errors in the individual values measured. However, the average values and overall effects determined on the basis of these values are definitive, and allow judgements to be made on the effectiveness of the treatment systems investigated.

1.2 Anaerobic Pit

(1) The anaerobic pit, which operated under simulated permafrost conditions at -5^{0}C, merely served as a holding tank. No biological activity was observed during the operation of the pit at -5^{0}C in Phase I or Phase III. When the pit was operated at +5^{0}C (Phase II) for about three months to simulate summer conditions, insignificant changes in the values of the physical-chemical parameters were observed.

The sole significant change was a fourfold increase in the production of volatile acids. A significant increase in the heterotrophic bacterial population was observed during the latter part of the Phase II operation. No increase of psychrophilic bacteria was noticed.

After a one year study, it can be tentatively concluded that the current practice of disposal of human waste (honey-bag waste) in sludge pits in the permafrost regions, is not a satisfactory method for waste disposal and presents a potential threat to public health and the environment. To safeguard against environmental and public health hazards, certain improvements in the existing sludge pit disposal method are warranted. The location of the site, the soil conditions, topography, and whether or not the sludge pits are lined with plastic sheets are important considerations.

(2) Freezing reduced the numbers of all types of microorganisms. Among indicator organisms, the coliform group was more severely affected than the faecal streptococci, which indicates that the latter may be a better bacterial indicator of faecal pollution in cold regions.

(3) Solids determinations were found to be of little significance because of urine hydrolysis and large losses when the sample

was dried and ignited. Similarly, calorific measurements do not show promise of being a reliable parameter in the analysis of high strength wastes.

(4) When the unit was later operated at a higher temperature, freezing of wastes did not prevent the 'acid-formation' stage of the anaerobic process.

(5) Anomalous physical-chemical results were obtained in Phase III operations of the pit at -5°C due to the "salting-out" effect.

1.3 Anaerobic Digestion

(1) Anaerobic digestion of concentrated human wastes is possible. Based on the results of the study to date, we believe that it is important to inoculate the digester with "seed" previously developed from concentrated waste digestion, in order to have a reasonably short lag period. Once the lag period is over, suitable microflora which are active and can function even under high concentration of ammonia nitrogen (4,000 mg/l) and volatile acids (10,000 to 20,000 mg/l) inhabit the digester. The temperature of operations should not be below 10°C. Dilution of the wastes decreases the lag period and increases the rate of gas production. Further work, now under way, is expected to provide the information necessary for the statement of design criteria on detention time, and on required further treatment of supernatant effluent.

(2) In Reactor No. 2 (20°C) the increasing rate of gas production and the percentage of methane (50%) in the digester gas indicated the development of methane bacteria, which have different physiological characteristics than methane bacteria present in conventional anaerobic digesters which treat sewage sludge.

(3) Anaerobic digestion of concentrated human waste at 10°C (Reactor No. 1) could be accomplished in part. A low temperature (10°C) could bring the digestion up to "acid-formation" phase. Reactor No. 1 could not reach "gas-formation" phase even after almost one year of operation. This has been attributed mainly to the lack of inoculum (seed) and , to a lesser degree, to low temperature.

(4) pH variations in the anaerobic reactors were moderate, which indicates that the high alkalinity present did maintain a well-buffered system in the reactors.

(5) Volatile acids, gas production and its composition appear to be the most suitable indicators of the anaerobic digestion of concentrated human wastes.

(6) The low temperature (10°C) in Reactor No. 1 created a selective environment for the psychrophilic bacteria, as is shown by the fact that they increased with time from about 10 to 25% in the feed to almost 100% of the total bacterial counts in the reactor

contents. The percentage of psychrophilic bacteria in Reactor No. 2 (20°C) stayed constant at about 10 to 25% of the total bacterial counts.

(7) The survival of indicator organisms seemed to be temperature dependent. Both coliforms and faecal streptococci survived longer at 10°C (Reactor No. 1) than at 20°C (Reactor No. 2). The viability of faecal streptococci was found to be much longer than that of coliforms in the anaerobic reactors.

(8) After an initial unsteady period of 4 to 8 weeks after the start of the reactors, approximately the same numbers of heterotrophic facultative anaerobic bacteria were found in both Reactor No. 1 (10°C) and in Reactor No. 2 (20°C).

(9) Dilution of the concentrated human waste (1:1) in Reactor No. 3 shortened the lag period for gas production and increased the rate of gas production. Dilution caused a distinct improvement in anaerobic digestion, but greater ratios of dilution are required for practical use. The results obtained in Reactor No. 3 are confirming this. Further studies along these lines are in progress.

RÉSUMÉ

1.1 Les déchets humains concentrés

(1) En général, la composition des déchets humains recueillis (fèces et urine) s'est révélée assez constante. Toutefois la teneur en matières solides, la D.C.O. et l'alcalinité ont varié quelque peu; cela était dû en grande partie à des difficultés d'ordre analytique mais aussi à la variabilité caractéristique des excréments. Les quantités et concentrations correspondent assez bien aux valeurs publiées ailleurs.

(2) La concentration des excréments entraîne certaines difficultés d'analyse donnant lieu à des distortions et des erreurs aléatoires dans les mesures isolées. Toutefois, les moyennes et les effets globaux dérivés de ces mesures sont sûrs et permettent de juger de l'efficacité des installations d'épuration étudiées.

1.2 La fosse anaérobie

(1) La fosse anaérobie soumise à des conditions simulées de pergélisol à -5°C a servi simplement de collecteur. A cette température, aucune activité biologique n'y a été observée (phases I et III); par ailleurs, on n'a constaté que des variations aléatoires des valeurs des paramètres physico-chimiques à $+5^{\circ}$C (phase II) au cours de trois mois de conditions estivales simulées.

Le seul changement significatif a été une augmentation quadruple de la production d'acides volatils. Un accroissement notable de la population des bactéries hétérotrophes s'est manifesté au cours de la dernière partie de la phase II. Aucune multiplication de bactéries psychrophiles n'est apparue.

Après un an d'étude, on peut conclure provisoirement que la méthode actuelle d'éliminer les excréments humains (les sacs à miel enfouis dans des fosses à boues) dans les zones de pergélisol ne convient pas et menace à la fois la santé et l'environnement. Comme mesure de protection, certaines améliorations s'imposent. Les conditions du sol, la topographie, l'emplacement des fosses et le fait qu'elles soient doublées ou non de feuilles de plastique sont des facteurs importants.

(2) Le gel réduit le nombre de tous les types de micro-organismes. Parmi les indicateurs bactériens, il touche plus fortement le groupe des coliformes que celui des streptocoques fécaux; par conséquent, ces derniers pourraient plus sûrement indiquer la pollution fécale dans les régions froides.

(3) Les analyses des matières solides se sont révélées peu utiles à cause de l'hydrolyse de l'urine et des pertes importantes subies au cours du séchage et de la combustion. De même, les mesures calorimétriques n'ont pas semblé constituer un paramètre fiable dans l'analyse des excréments très concentrés.

(4) Ultérieurement, à une température plus élevée, le gel des excréments n'a pas emêché le stade dit de formation d'acides de l'anaérobiose.

(5) Des effets physico-chimiques anormaux se sont produits au cours de la phase III, à -5°C, à cause de l'effet de "relargage".

1.3 La digestion anaérobie

(1) La digestion anaérobie des excréments humains concentrés est possible. D'après les résultats obtenus jusqu'ici, nous croyons qu'il importe d'ensemencer le contenu du digesteur avec une partie du "ferment" résultant de la digestion précédente afin de réduire la période de démarrage. Lorsque la digestion est amorcée, une microflore appropriée se répand dans le digesteur; elle est active même à des concentrations élevées d'azote ammoniacal (4000 mg/l) et d'acides volatils (10,000 à 20,000 mg/l). La température minimale de fonctionnement est de 10°C. La dilution des excréments réduit la période de démarrage et accélère la production de gaz. D'autres travaux en cours devraient fournir les renseignements permettant de formuler les critères déterminant la période de séjour des matières fécales et le traitement supplémentaire à faire subir à la liqueur de surface.

(2) Dans le réacteur n° 2 (20°C), la production accélérée de gaz et le pourcentage de méthane (50 p. 100) dans les gaz du digesteur ont indiqué que les bactéries méthaniques présentes différaient physiologiquement de celles qui se trouvent dans les digesteurs anaérobies classiques traitant les boues résiduaires.

(3) A 10°C, la digestion anaérobie des excréments humains concentrés (réacteur n°1) ne s'est faite que partiellement. A cette basse température, la digestion a atteint le stade de la formation d'acides. Cependant elle n'est par parvenue à la gazéification, même aprés un an. Les chercheurs ont surtout attribué ces résultats à la quantité insuffisante de "ferment" et, à un degré moindre, à la basse température.

(4) Les variations de pH dans les réacteurs anaérobies ont été modérées, indiquant que l'alcalinité élevée a réussi à maintenir un ensemble de conditions bien équilibré.

(5) La présence d'acides volatils, la production de gaz et leur nature semblent être les indicateurs les plus convaincants de la digestion anaérobie des excréments humains concentrés.

(6) La faible température (10°C) dans le réacteur n°1 a créé un environnement sélectif favorable aux bactéries psychrophiles; leur nombre s'est en effect accru en fonction du temps, à partir de 10 à 25 p. 100 dans les excréments introduits jusqu'à près de 100 p. 100 de la population totale de bactéries dans le réacteur. Le pourcentage de bactéries psychrophiles dans le réacteur n°2 (20°C) est demeuré constant s'établissant entre 10 à 25 p. 100 de la population totale.

(7) La survie des organismes indicateurs a semblé liée à la température. Les coliformes et les streptocoques fécaux ont survécu plus longtemps à 10°C (réacteur n°1) qu'à 20°C (réacteur n°2), mais la viabilité des seconds était supérieure.

(8) Au terme d'une période d'ajustement initiale de quatre à huit semaines aprés la mise en usage des réacteurs, on a trouvé approximativement le même nombre de bactéries anaérobies hétérotrophes aléatoires dans les réacteurs n°1 (10°C) et 2 (20°C).

(9) La dilution des excréments humains concentrés (1:1) dans le réacteur n°3 a hâté le début de la production de gaz et l'a accélérée par la suite. Elle a aussi nettement amélioré la digestion anaérobie, mais une dilution plus accentuée serait nécessaire en pratique; c'est ce que confirment les résultats obtenus dans le réacteur n°3. D'autres études en ce sens sont en cours.

2.0 INTRODUCTION

This study is a continuation of work started in October, 1973. A report entitled "Preliminary Report on Disposal of Concentrated Wastes in Northern Areas" covers the work completed by March, 1975. This was published in Report No. 74-10, Environmental-Social Committee Northern Pipelines, Task Force on Northern Oil Development, in July, 1974. The preliminary report was written in two parts: Part I - Collection and Disposal Systems for Concentrated Wastes, and Part II - Laboratory Investigation of Decomposition of Human Wastes in Permafrost. The present report covers the extension of the laboratory investigation during the period April, 1974 to February, 1975. Both of the reports, which complement each other, should be read. It is expected that this study will continue during the next year, but it is subject to the availability of funds.

3.0 EXPERIMENTAL SET-UP AND ANALYTICAL METHODS

The experimental set-up of the anaerobic pit and batch anaerobic reactors has been continued as described by Heinke (1974). Analytical methods used are those described by Heinke (1974) as well as those described below.

3.1 Anaerobic Pit

The operation of the anaerobic pit has been as follows: concentrated waste was originally added at the rate of 5-8 litres per week for 9 weeks until the pit was almost full. Thus, the pit contained approximately 60 litres of waste. The pit was operated at -5°C for 4-1/2 months. In order to study the effect of temperature change on the performance of the anaerobic pit, the temperature of the unit was changed daily by 1°C for 10 days, and was held at +5°C for 3 months to simulate summer conditions. After this, the procedure was reversed and the temperature returned to -5°C. The anaerobic pit is presently in its 15th month of operation.

3.2 Anaerobic Reactors

The operation of the anaerobic reactor, described by Heinke (1974), has been continued at 10°C. At present the reactor is in its 14th month of operation. It is referred to from now on as Anaerobic Reactor No. 1 (10°C).

Two additional anaerobic reactors were operated at 20°C. The operations were as follows:

Anaerobic Reactor No. 2 (20°C): A 10 litre glass bottle was filled with 7 litres of concentrated human waste, seeded with 1 litre of digested sludge and operated at 20°C. The contents were mixed by a magnetic stirrer. Gas collection and analytical tests performed were as described by Heinke (1974).

Anaerobic Reactor No. 3 (20°C, Diluted Waste): A 15 litre glass bottle was filled with 9 litres of human waste which had been diluted with water on a 1:1 ratio, seeded with 1 litre of digested sludge, and mixed by a magnetic stirrer. Gas collection and analytical tests performed were as for other reactors.

3.3 Analytical Methods (Additional)

3.3.1 Gas Composition

Gas composition was determined by gas chromatography. The unit used was a Carle Instruments Inc. Model 8500 Basic Gas Chromatograph, which contains two columns (a 24 ft. 40% DC 200 on Porapak 2, and a 6 ft. Molecular Sieve 5A). One millilitre samples were used for the gas analyses. The chromatograph was operated at a temperature of 50^{o}C and a gas pressure of 1.4 kg/cm^2. The carrier gas was helium. The helium flow rate was maintained at 20.0 ml/min. The recorder chart speed (time scale) was set at 2.5 cm/min.

3.3.2 Volatile Acids:

In the preliminary experiments the Column - Partition Chromatographic method as described in Standard Methods (1971) was used for volatile acids estimation, but was found to be unsuitable because the results obtained were erratic and the variation in replicate samples was very high. Therefore, the volatile acids were determined by the direct steam distillations method (Sawyer, 1960). 1-5 ml clear samples, acidified to pH 1.0, were taken in a distillation flask. The distillation flask was then attached to a steam distillation unit. About 100 ml of distillate, which was collected in a flask, was titrated with standard 0.2N NaOH reagent to the phenolphthaline end point. Care was taken to avoid aeration of the sample.

4.0 RESULTS AND DISCUSSION

Results obtained on the concentrated waste feed, anaerobic pit mixed liquor, and anaerobic reactor mixed liquor are presented and discussed under the following headings:

- 4.1 Physical-Chemical
  - 4.1.1 Volume and Composition of Human Waste Feed
  - 4.1.2 Temperatures
  - 4.1.3 pH and Alkalinity
  - 4.1.4 Solids
  - 4.1.5 Chemical Oxygen Demand
  - 4.1.6 Nitrogen
  - 4.1.7 Calorific Value
  - 4.1.8 Volatile Acids
  - 4.1.9 Gas Production
- 4.2 Bacteriological
  - 4.2.1 Feed Waste
  - 4.2.2 Anaerobic Pit
  - 4.2.3 Anaerobic Reactor No. 1
  - 4.2.4 Anaerobic Reactor No. 2

4.1. Physical Chemical Results and Discussion

4.1.1 Volume and Composition of Human Waste Feed

Concentrated human waste was fed to the anaerobic pit weekly over a 9-week period (February-April, 1974) at a reasonably uniform rate of about 5 to 8 litres per week, to a total volume of 60 litres. The collection procedure and composition of contents of the batch anaerobic reactors were both quite similar to those for the anaerobic pit.

The physical-chemical composition of the concentrated human waste which was fed to the anaerobic pit and reactors is shown in Table 1.

4.1.2 Temperature

The temperature of the contents of the anaerobic pit, of the soil surrounding the pit, and of the 3-batch anaerobic reactors was

TABLE 1

COMPOSITION OF HUMAN WASTE - RESULTS OF ANALYSIS

Date	pH	Alk. mg/l $CaCo_3$	Mixed Waste COD mg/l	Total Solids mg/l	Total Volatile Solids mg/l	Dissolved Solids mg/l	Dissolved Volatile Solids mg/l	Mixed Waste: Nitrogen			Phosphorus as PO_4 mg/l.	Calorific Value Cal/g	Centrifuged Supernatant COD mg/l.
								TKN mg/l	NH_3-N mg/l	Organic-N mg/l			
12-2-74	8.80	-	110,880	79,980	63,415	53,620	44,760	7,580	3,700	3,880	3,500	4,340	44,880
19-2-74	8.85	16,400	134,820	83,250	66,410	38,720	27,120	8,230	3,530	4,700	3,400	4,260	-
26-2-74	8.90	17,800	110,220	75,850	59,170	37,550	25,450	8,180	3,920	4,260	4,000	-	46,990
5-3-74	8.76	15,000	125,630	83,440	67,740	41,070	29,660	8,620	4,370	4,260	4,250	4,380	54,910
12-3-74	8.85	17,000	121,700	85,030	67,220	43,310	30,340	8,400	4,370	4,030	3,500	4,330	61,280
19-3-74	8.85	13,600	102,080	75,560	56,680	36,600	21,980	9,520	4,060	5,520	-	-	42,240
26-3-74	8.60	14,400	104,840	80,220	63,110	37,010	24,890	-	-	-	-	4,060	50,860
2-4-74	8.62	11,900	80,750	65,990	50,290	33,140	20,910	7,280	3,470	3,810	-	4,130	39,980
9-4-74	8.80	14,800	102,280	73,960	58,300	32,500	21,170	7,600	3,900	3,690	3,500	3,830	46,970
Mean	8.78	14,990	110,360	78,140	61,370	39,290	27,360	8,070	3,920	4,150	3,730	4,190	48,510
Std. Deviation ±	± 0.11	± 1,740	± 15,820	± 5,980	± 5,770	± 6,360	± 7,380	± 520	± 340	± 316	± 370	± 200	± 2,200

determined regularly. There was no variation amongst the pit, soil and ambient temperatures. Temperatures of the anaerobic reactors were the same as ambient temperature in the early part of the experiment. However, later on the temperature in the reactors was slightly (0.5°C - 1°C) higher than the ambient temperature.

4.1.3 pH and Alkalinity

(a) Anaerobic Pit: (Figure 1)

The pH of the mixed liquor during the operation of the pit at -5°C (Phase I) remained between 8.6 and 8.9, and the total alkalinity between 15,000 and 22,000 mg/l as $CaCo_3$. During the 3-month operation of the pit at +5°C (Phase II), the pH dropped by 0.3 to 0.5 units and remained between 8.0 to 8.6, and the total alkalinity ranged between 15,000 - 20,000 mg/l as $CaCo_3$. During Phase III when the pit temperature was again lowered to -5°C and held at this temperature for 4-1/2 months, the pH remained between 8.0 and 8.3 and the total alkalinity remained between 20,000 and 22,000 mg/l as $CaCo_3$.

The frozen conditions which lead to the non-homogeneity of the sample collected may also have been partly responsible for the fluctuation in alkalinity values. The drop in pH values in Phase II was probably due to the accumulation of volatile acids.

(b) Anaerobic Reactor No. 1 (10°C) (Figure 2)

The pH in Anaerobic Reactor No. 1 (10°C) dropped by 0.3 units in the first week of operation. In the subsequent few weeks the drop in pH was about 0.1 - 0.2 units per week, until it levelled off in the range of 7.0 - 7.7. During the 12 months of operation of the reactor the pH dropped by 1.5 - 2.0 units. Total alkalinity increased in the first three weeks from 14,800 mg/l to 17,600 mg/l in the third week. From the third week onward, it started decreasing to 13,000 - 14,000 mg/l where it stayed throughout the subsequent operation of the reactor.

In view of the fact that alkalinity and NH_3-N tend to increase pH, whereas volatile acids and dissolved carbon dioxide lower pH, the drop in pH in the early few weeks of operation was surprising. It appears that it was a result of the accumulation of volatile acids and dissolved CO_2, while the increase in alkalinity was due to the increase in the NH_3-N concentration (Figure 14). Unfortunately, volatile acid results are not available for the early part of the operation because of analytical difficulties. However, volatile acids were measured successfully after 6 months' operation. About 12,000 - 14,000 mg/l of volatile acids were present during the subsequent 6 months' operation of the reactor.

In summary, pH and alkalinity did not show any significant change, which indicates poor digestion of the concentrated waste in the reactor operating at 10°C.

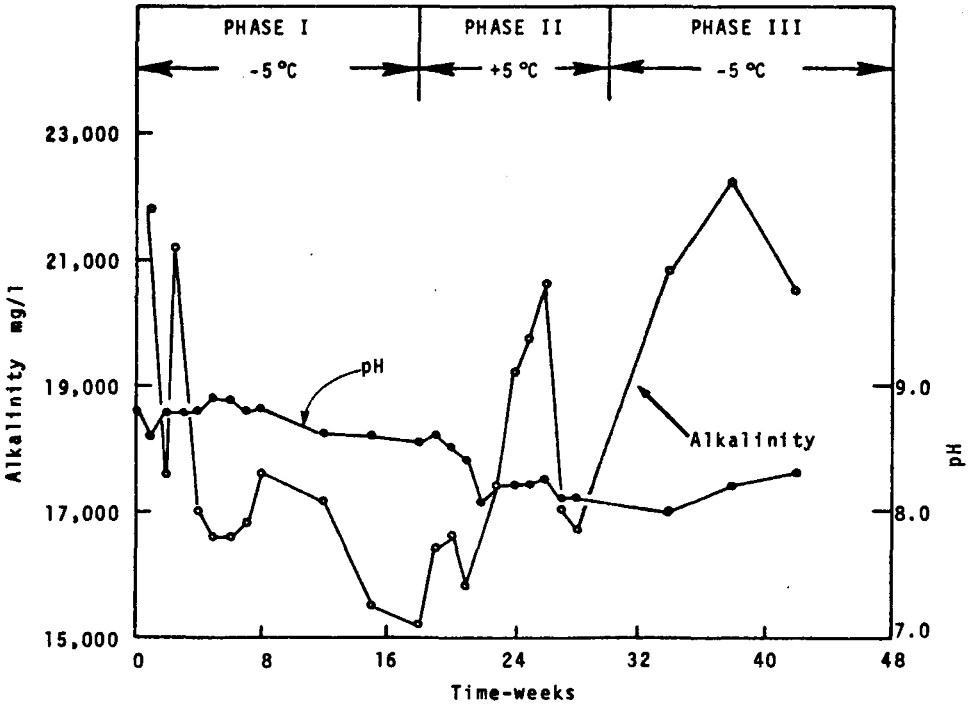

FIG.1 pH AND ALKALINITY IN ANAEROBIC PIT

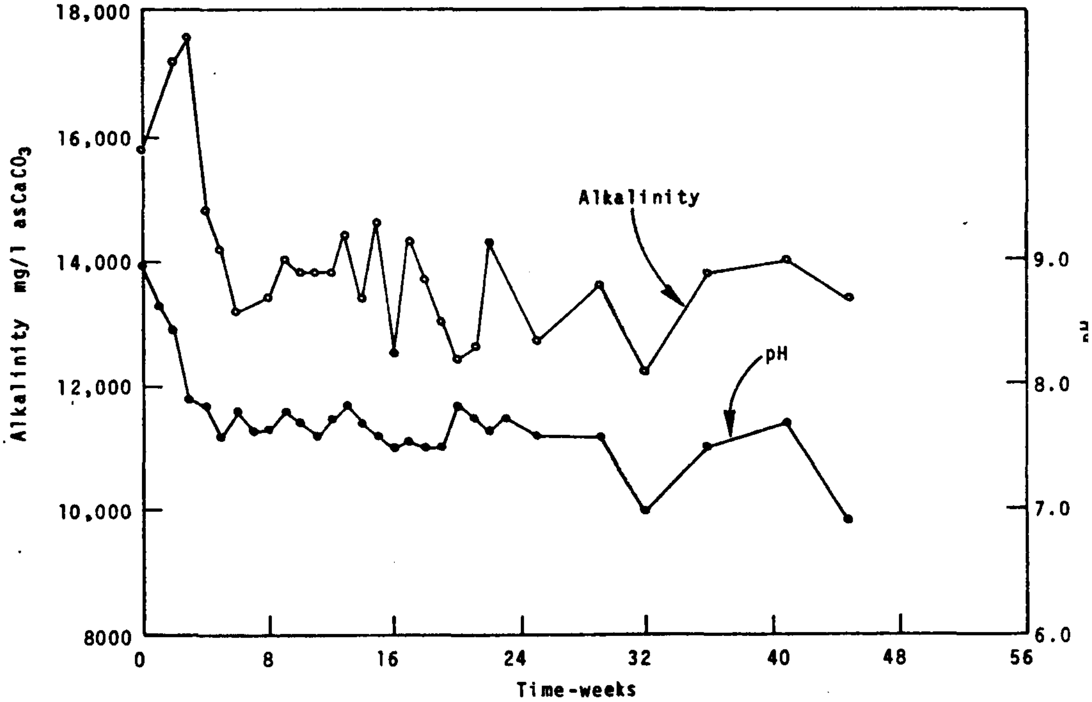

FIG.2 pH AND ALKALINITY IN ANAEROBIC REACTOR No.1 (10 °C)

(c) Anaerobic Reactor No. 2 (20°C) (Figure 3)

The pH dropped by about 1.0 unit in the first two weeks of operation. This was followed by a slow continuing drop. By the end of the 16th week, pH had dropped by a total of 1.8 units to 7.0. By the 27th week it had started to increase again. The decrease may be attributable to the accumulation of volatile acids which were present in the range of 17,000 - 20,000 mg/l from the 16th week to the 27th week. The alkalinity remained between 14,000 mg/l and 16,000 mg/l up to the 16th week of operation. From the 16th week onward it started increasing and reached 17,400 mg/l in the 27th week. These increases in pH and alkalinity values accompanied the increased rate of gas production (Figure 17).

(d) Anaerobic Reactor No. 3 (20°C - Diluted Waste (Figure 4)

The reactor contained wastes diluted 1:1. The pH dropped by 0.3 - 0.5 units in the first two weeks of operation. This was followed by a slow decrease. The overall decrease in pH was about 1.7 units up to the 8th week of operation. The pH then started to increase and reached 7.8 at the end of the experiments (24th week). The total alkalinity did not change significantly during the early part of the operation, up to the 11th week (range 7,000 - 8,000 mg/l). From the 11th week onward it started increasing and reach about 13,000 mg/l.

The average pH values and their range observed in this study were as follows:

	Average pH	pH Range
Anaerobic pit (-5°C) Phase I	8.67	8.6-8.9
Anaerobic pit (+5°C) Phase II	8.20	8.1-8.4
Anaerobic pit (-5°C) Phase III	8.18	8.0-8.3
Anaerobic Reactor No. 1 (10°C)	7.53	6.8-8.9
Anaerobic Reactor No. 2 (20°C)	7.75	7.1-8.9
Anaerobic Reactor No. 3 (20°C) 1:1 dilution	7.67	6.8-8.4

By comparison, other studies on anaerobic digestion of human waste and night soil report the following pH values:

Snell (1943)	pH range 7.5 to 8.7 in a batch anaerobic digester for human excreta operating at 25°C.

and

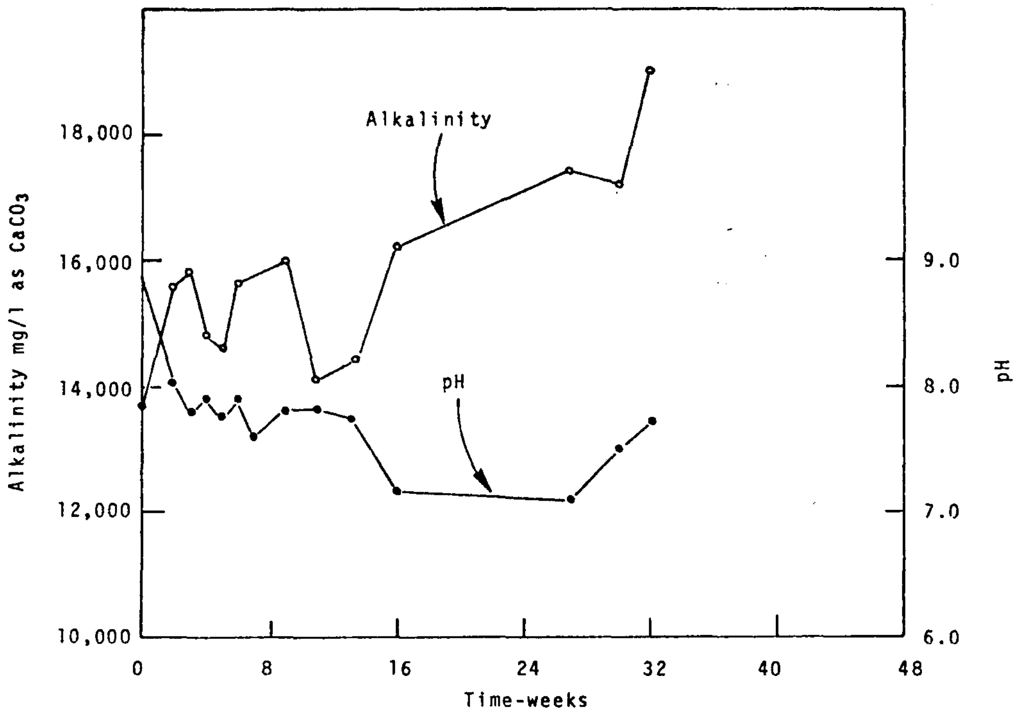

FIG.3 pH AND ALKALINITY IN ANAEROBIC REACTOR No.2 (20 °C)

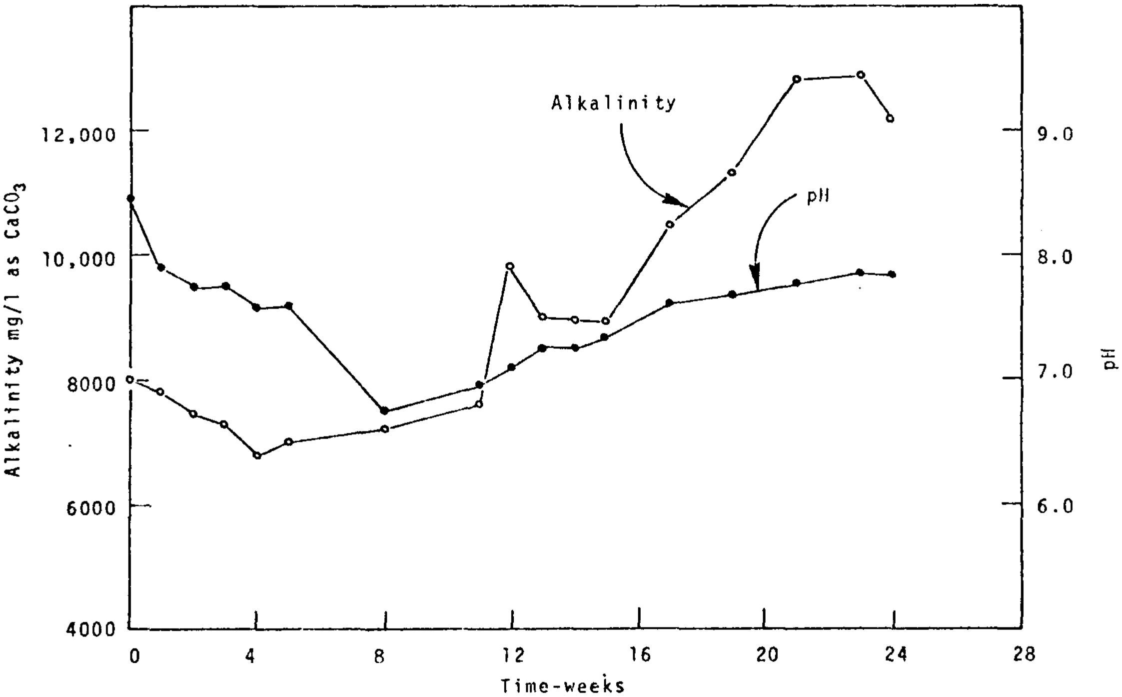

FIG. 4 pH AND ALKALINITY IN ANAEROBIC REACTOR No.3 (20 °C)
(Diluted Waste)

Matsumoto and Endo (1965): pH 8.3 to 8.5 in a batch anaerobic digester for night soil operating at 30°C.

4.1.4 Solids

(a) Anaerobic Pit: (Figure 5)

Considerable fluctuation in solids measurements of the pit mixed liquor is evident, especially during the period the pit was operated at -5°C (Phase I) (76,510 ± 12,190). Solids measurements did not fluctuate as much while the pit was being operated at ± 5°C (Phase II), (64,620 ± 550).

During the 3 months operation of the pit at +5°C (Phase II), no trend of significant changes in solids concentrations was evident. During Phase III when the pit temperature was reversed to -5°C and held for a 4-1/2 month period, the solids values showed unexpected results. Total solids and total volatile solids appeared to decrease, while dissolved solids showed an increase in values. These values are probably inaccurate due, in a large part, to the fact that suspended solids settled to the bottom, and only frozen supernatant from the upper layers of the pit could be sampled during Phase III operation.

(b) Anaerobic Reactor No. 1 (10°C) (Figure 6)

Total solids, as well as volatile solids, started decreasing slowly during the early weeks of operation. This slow decrease continued up to 6 months of operation. However, no change seemed to occur during a further 6 months of operation. Total solids decreased from an initial value of 67,500 mg/l to a mean value of 54,000 mg/l, and total volatile solids decreased from 53,000 mg/l to a mean value of 41,000 mg/l in 6 months of operation. Dissolved solids decreased from an initial value of 44,000 mg/l to 25,000 mg/l, and dissolved volatile solids from an initial value of 37,000 mg/l to 15,000 mg/l in the first week of operation. This rapid decrease in dissolved solids may have been due to the hydrolysis of urea present in the urine, since a similar decrease in organic-nitrogen was observed (Figure 14). Urea is hydrolysed at a good rate at lower temperatures under anaerobic conditions (Halvorsen et al, 1969). After the initial large decrease dissolved solids and dissolved volatile solids remained fairly constant at average values of 23,600 mg/l and 15,000 mg/l respectively during the 12 months of operation. These results indicate that the digestion in the reactor was very poor.

(c) Anaerobic Reactor No. 2 (20°C) (Figure 7)

A rapid reduction in all the solids values was observed in the first 2-3 weeks of operation. This was followed by a slow decrease. During the 6 months of operation, a substantial reduction was observed.

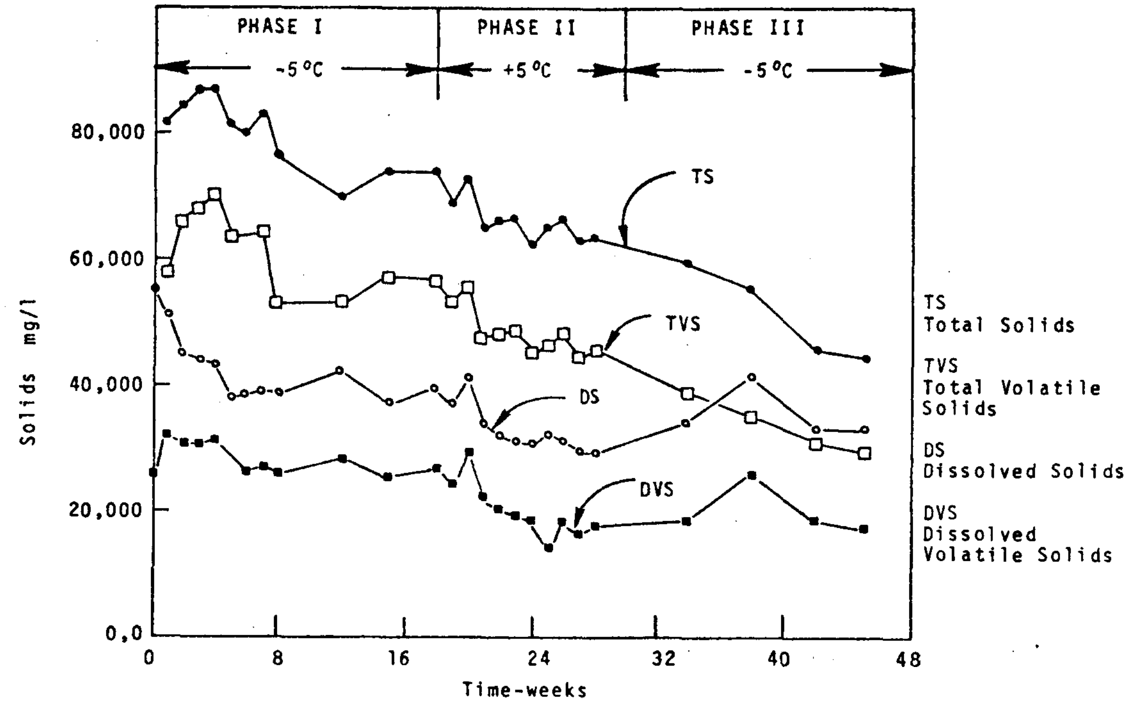

FIG.5 SOLIDS CONCENTRATIONS IN ANAEROBIC PIT

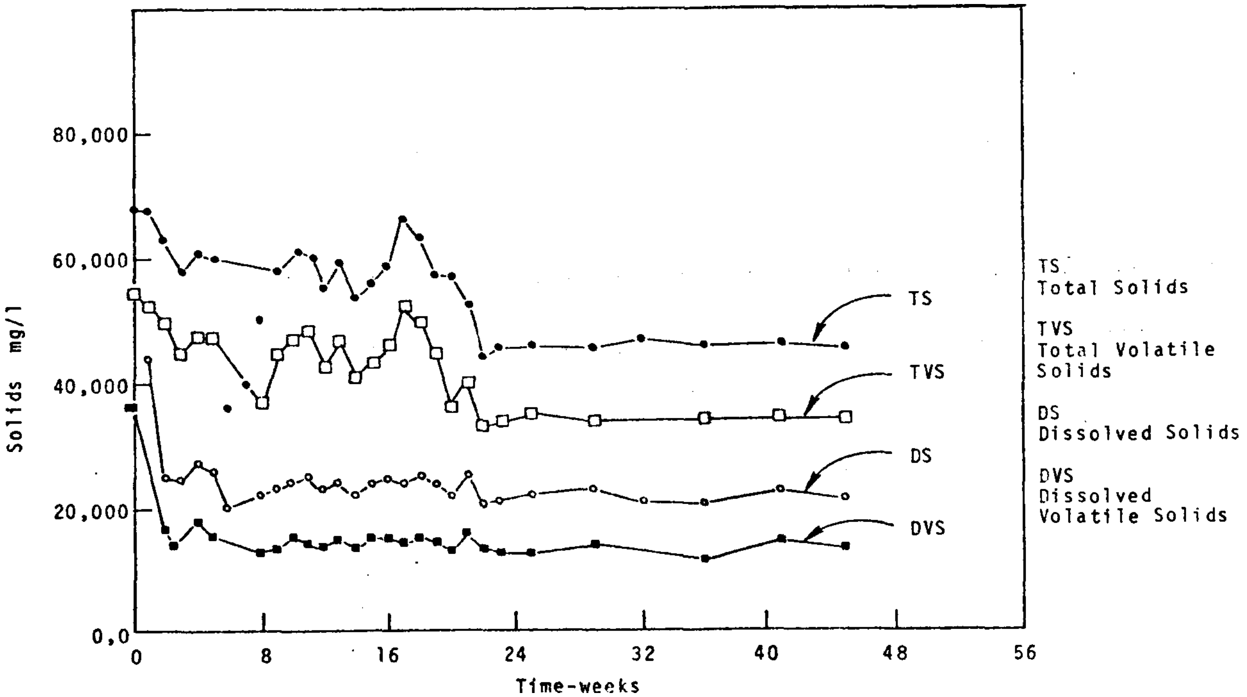

FIG.6 SOLIDS IN ANAEROBIC REACTOR No 1 (10 C)

Total solids, total volatile solids, dissolved solids and dissolved, volatile solids decreased by about 27%, 45%, 24% and 42%, respectively.

(d) Anaerobic Reactor No. 3 (20°C - Diluted Waste) (Figure 8)

A rapid reduction in total solids and total volatile solids occurred in the first 4 weeks of operation. This was followed by a slow decrease. During the entire 6 months of operation of the reactor, the total solids and total volatile solids decreased by about 35% and 40%, respectively. The decrease in dissolved solids and dissolved volatile solids was not as great as that in total and total volatile solids.

4.1.5 Chemical Oxygen Demand (COD)

(a) Anaerobic Pit: (Figure 9)

Only the centrifuged supernatant of the pit contents was used for COD determinations to avoid errors resulting from the non-homogeneity of the mixed liquor samples.

Like the solids values, the COD values also showed considerable fluctuation when the pit temperature was held at -5°C (Phase I) (59,000 ± 3,600). However, in Phase II (+5°C), the fluctuations in COD values were less noticeable (51,230 ± 550). The results indicate that no microbial activity took place in the pit at -5°C. During Phase II (+5°C), a rapid reduction in COD values occurred. The COD value dropped from 62,000 mg/l to about 50,000 mg/l in 2 weeks. This observation was very puzzling at first since it gives the impression that the reduction in COD values is a result of microbial activity, which is highly unlikely at the low temperatures which occurred during the first 2 weeks of operation in Phase II. On examination of supernatant COD values of feed waste (mean value 48,500 mg/l) in Table 1, it is of interest to note that the supernatant COD values in Phase I had increased from 42,000 mg/l to about 59,000 ± 3,600 mg/l. It appears that this rapid increase in supernatant COD values in Phase I resulted from freezing of a portion of the pit, which will increase the concentration of dissolved material in the unfrozen portion. Similarly, the decrease in supernatant COD values in Phase II appears to have been caused by thawing and the resulting dilution of the reactor contents.

These results also suggest that no microbial activity occurred at -5°C and that the operation of the pit at +5°C (Phase II) did not produce significant changes in the pit mixed liquor as a result of biological activity.

(b) Anaerobic Reactor No. 1 (10°C): (Figure 10)

COD determinations were made on centrifuged supernatant for all reactors. There was no indication of COD reduction during the 12 months of operation of the digester. It must be remembered, however, that the COD test lacks somewhat in precision for an individual determination, especially in the analysis of very high strength waste. The

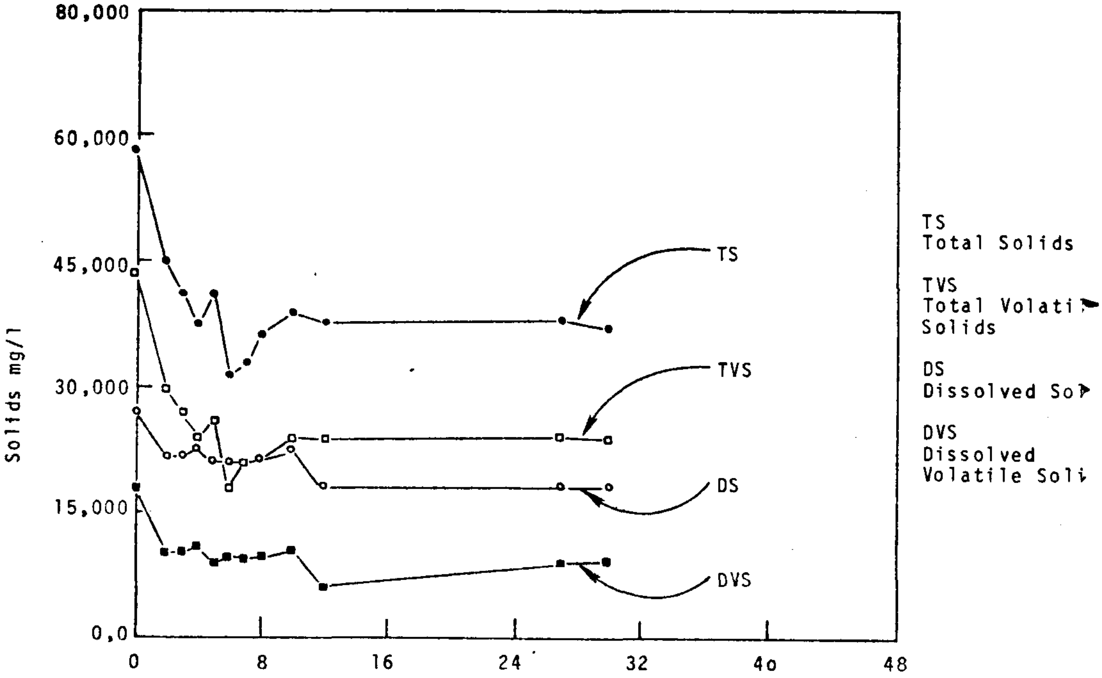

FIG.7 SOLIDS IN ANAEROBIC REACTOR No 2 (20 °C)

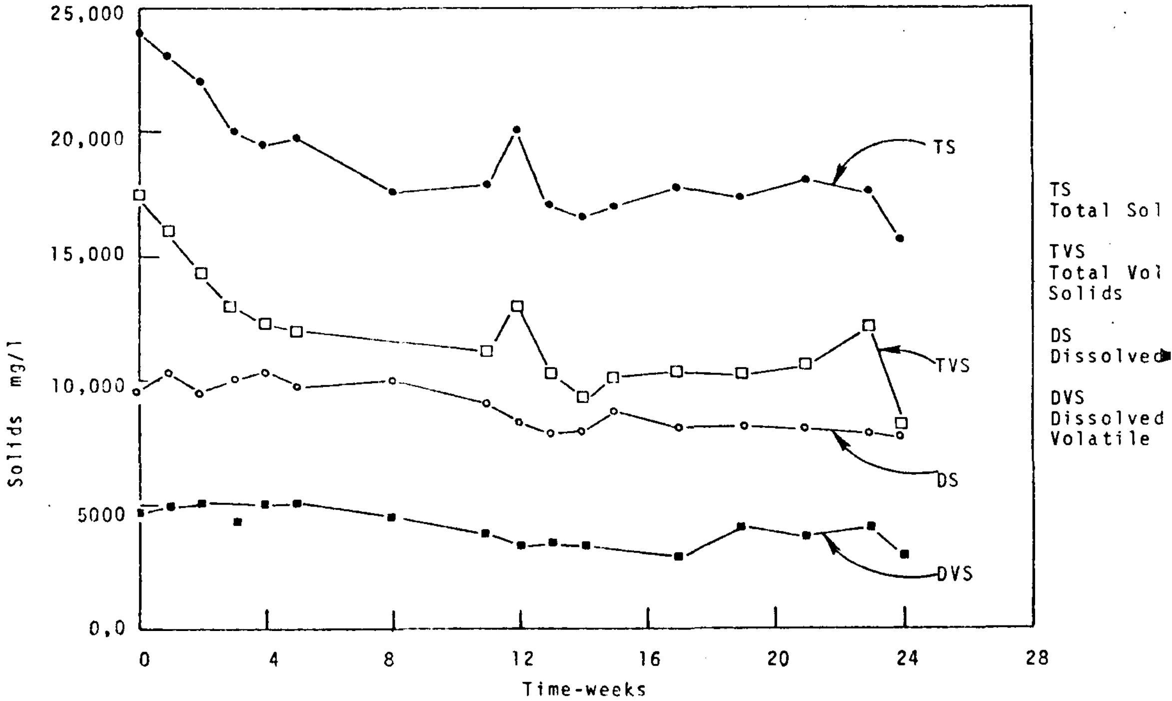

FIG.8 SOLIDS IN ANAEROBIC REACTOR No 3 (20 °C) Diluted Waste.

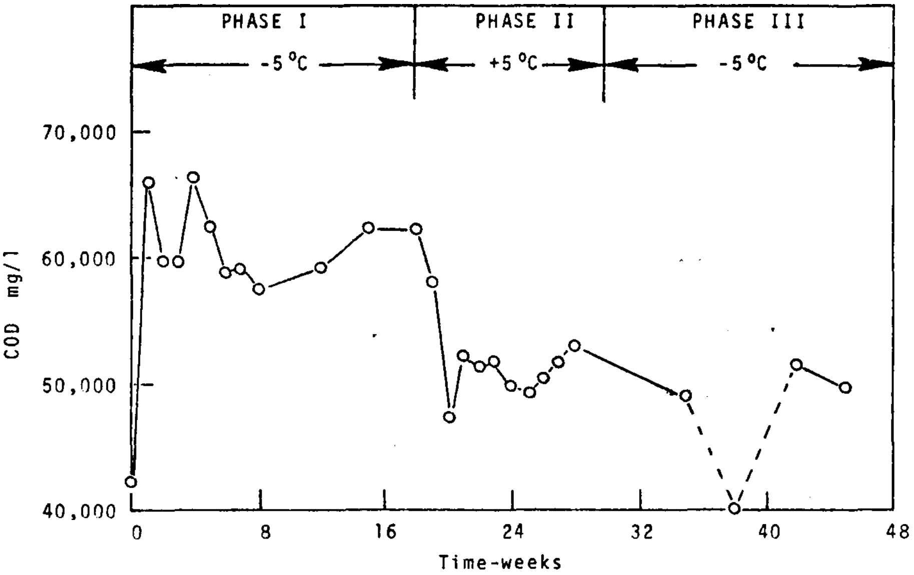

FIG.9 MIXED LIQUOR SUPERNATANT COD IN ANAEROBIC PIT

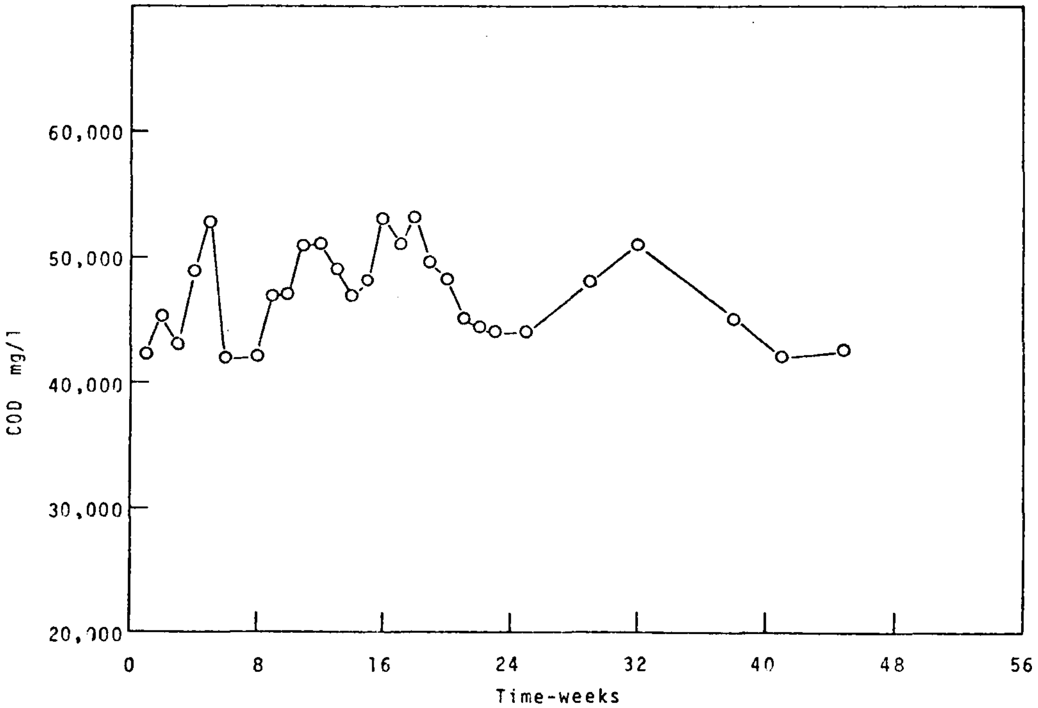

FIG.10 MIXED LIQUOR SUPERNATANT COD IN ANAEROBIC REACTOR No.1

results indicate that the digestion in this reactor was very poor.

(c) Anaerobic Reactor No. 2 (20°C): (Figure 11)

COD values did not show any change during the first 8 weeks of operation of the reactor. From the 8th week onward, however, a decrease in COD values was evident. About a 38% reduction in COD values had occurred by the end of the 32nd week, indicating that the increased digestion in this reactor was due in fact to the higher temperature.

(d) Anaerobic Reactor No. 3 (20°C - Diluted Waste): (Figure 12)

During the first 4-8 weeks of operation, the values of supernatant COD increased from an initial value of 15,000 mg/l to 21,000 mg/l, due to the biological conversion of particulate organic matter to a dissolved form. From the end of the 8th week the COD values started decreasing, and this decrease continued until the experiment was terminated. At the end of the experiment, the supernatant COD was about 5,000 mg/l, while the mixed liquor COD was about 12,000 mg/l. During the experimental period of 24 weeks, about a 72% reduction in mixed liquor COD occurred (see Table IX).

4.1.6 Nitrogen

(a) Anaerobic Pit: (Figure 13)

Total Kjeldahl nitrogen and NH_3-N were regularly determined in the pit mixed liquor centrifuged supernatant (Figure 13). It was reported in the preliminary report (Heinke, 1974) that about two-thirds of the total nitrogen in the pit content was in the NH_3-N form, although only one-half of the total nitrogen in the feeds was in the NH_3-N form. These proportions stayed approximately constant, throughout the 4-1/2 month period of pit operation, at -5°C (Phase I). Since other parameters measured in this study indicated no biological activity of any kind in the pit, this change in proportion, from feed to mixed liquor, may have been the result of a physical phenomenon, perhaps the effect of freezing and thawing of the wastes as previously discussed for COD.

During the three months of operation of the pit at +5°C (Phase II), organic nitrogen values dropped from mean values 2,870 ± 270 mg/l to mean values 1,420 ± 180 mg/l. Corresponding increases in NH_3-N occurred. This indicates that organic nitrogen was biologically converted to NH_3-N. Hydrolysis of urea is known to occur at a good rate at low temperature under anaerobic conditions (Halvorson et al, 1969).

NH_3-N values increased further during Phase III, when the pit temperature was held at -5°C. This increase appears to have been due to freezing of wastes. No such increase was observed in the organic nitrogen values, which were present only in small quantities and not appreciably affected by freezing of wastes.

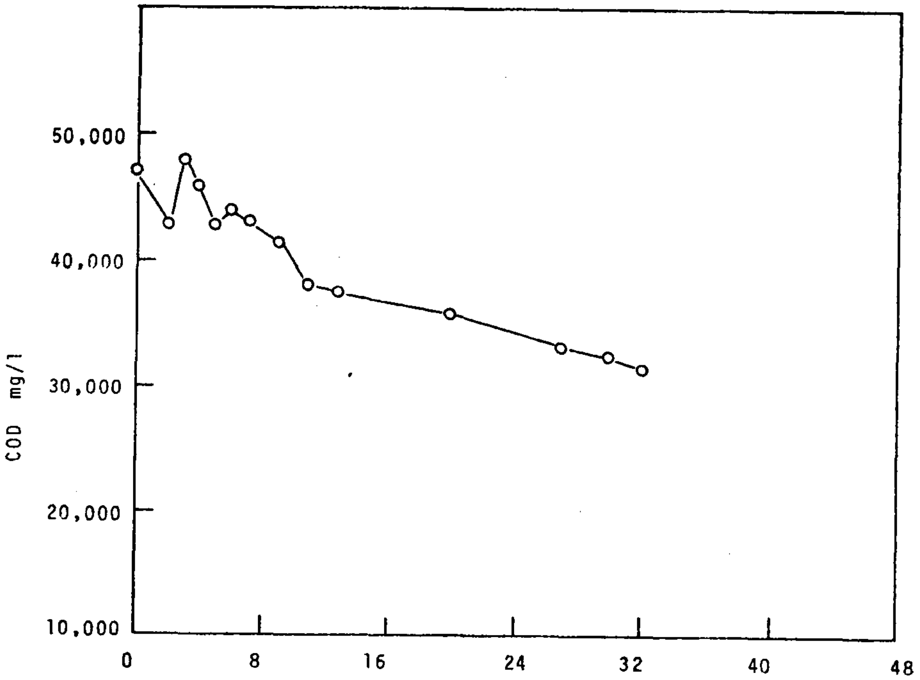

FIG.11 MIXED LIQUOR SUPERNATANT COD IN ANAEROBIC REACTOR No.2

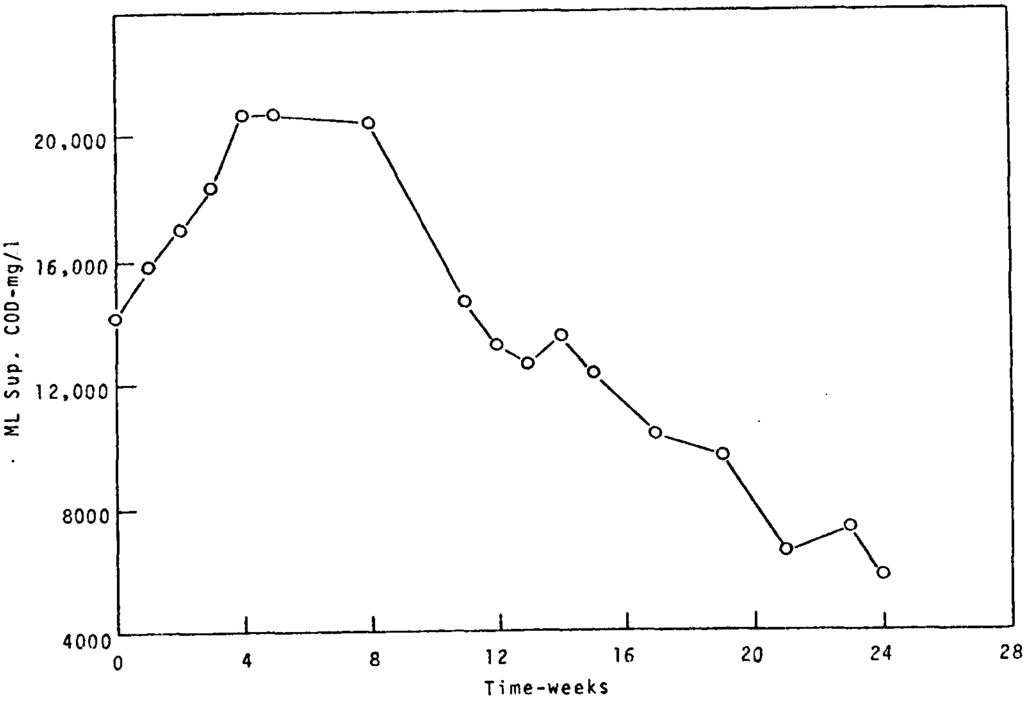

FIG.12 MIXED LIQUOR SUPERNATANT COD IN ANAEROBIC REACTOR No.3
(Diluted Waste)

(b) Anaerobic Reactor No. 1 (10^{o}C): (Figure 14)

Within 2-3 weeks of the start of the operation of the reactor, organic nitrogen values decreased by half. This corresponded with a simultaneous increase in NH_3-N, which indicated that organic nitrogen is biologically converted to NH_3-N. The decrease in organic nitrogen may be attributed partly to the hydrolysis of urea. From the 8th week onward, the organic nitrogen values stayed at a constant level of 1,160 ± 180 mg/l throughout the 12 month period. The average value of NH_3-N stayed at 4,290 ± 190 mg/l throughout.

(c) Anaerobic Reactor No. 2 (20^{o}C): (Figure 15)

Organic nitrogen values decreased rapidly within the first 2 weeks of operation, followed by a slow decrease up to the 12th week, after which time they stayed constant. This decrease in organic nitrogen values was accompanied by a simultaneous increase in NH_3-N values. The average value of NH_3-N was 5,350 ± 220 mg/l.

(d) Anaerobic Reactor No. 3 (20^{o}C - Diluted Waste): (Figure 16)

Unfortunately, no nitrogen determinations were made in the first two weeks, when most of the conversion of organic nitrogen occurred. Thereafter, the degradation of organic nitrogen was slow and rather insignificant. After the first two weeks, the average NH_3-N value was 2,420 ± 139 mg/l during the operation.

4.1.7 Calorific Value

The calorific values of the feed waste and the mixed liquor of the anaerobic pit and reactors were determined weekly. Average results and standard deviations are shown in Table 2.

TABLE 2 CALORIFIC VALUES OF WASTES AND MIXED LIQUOR

	Calorific Value, cal/g dry weight	
	Average	Std. Dev.
Feed Waste	4190	200
Anaerobic Pit (-5^{o}C)	4190	80
" " (+5^{o}C)	3990	130
" " (-5^{o}C)	-	-
Anaerobic Reactor No. 1	4480	230
" " No. 2	3750	355
" " No. 3	3420	230

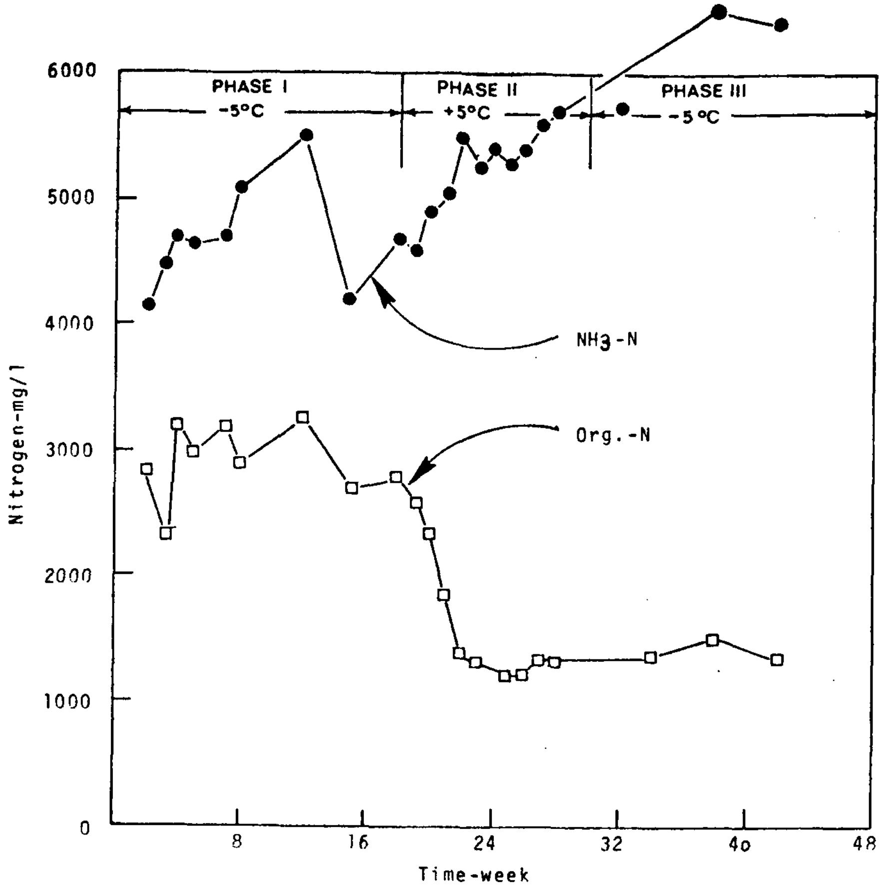

FIG.13 NH_3-N AND ORGANIC-N IN MIXED LIQUOR SUPERNATANT OF ANAEROBIC PIT.

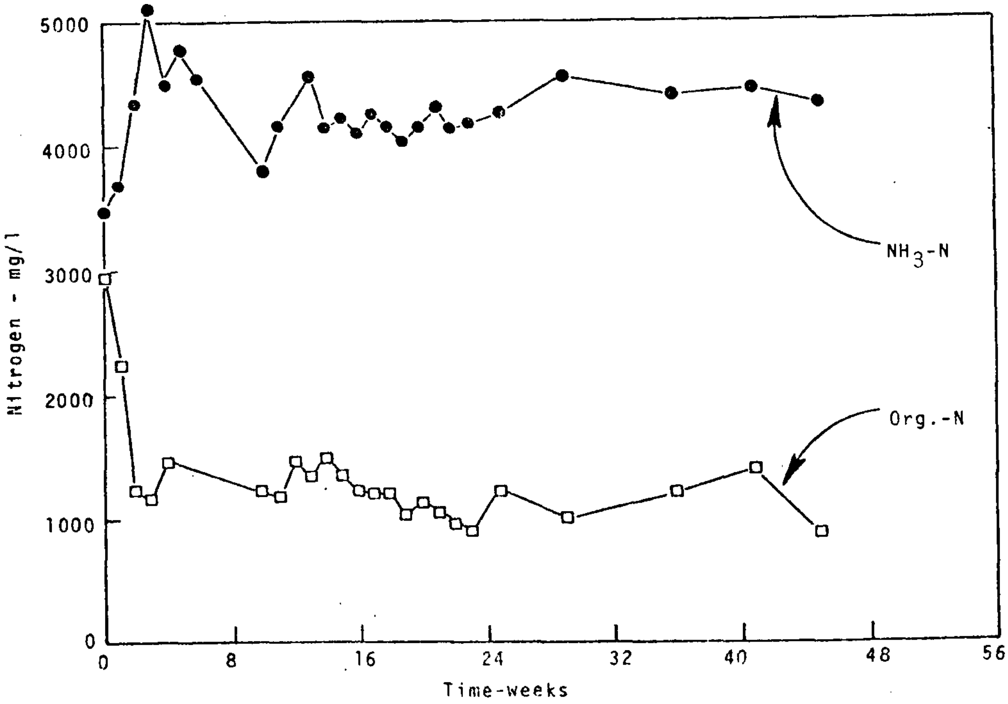

FIG.14 NH_3-N AND ORGANIC-N IN MIXED LIQUOR SUPERNATANT OF ANAEROBIC REACTOR No.1

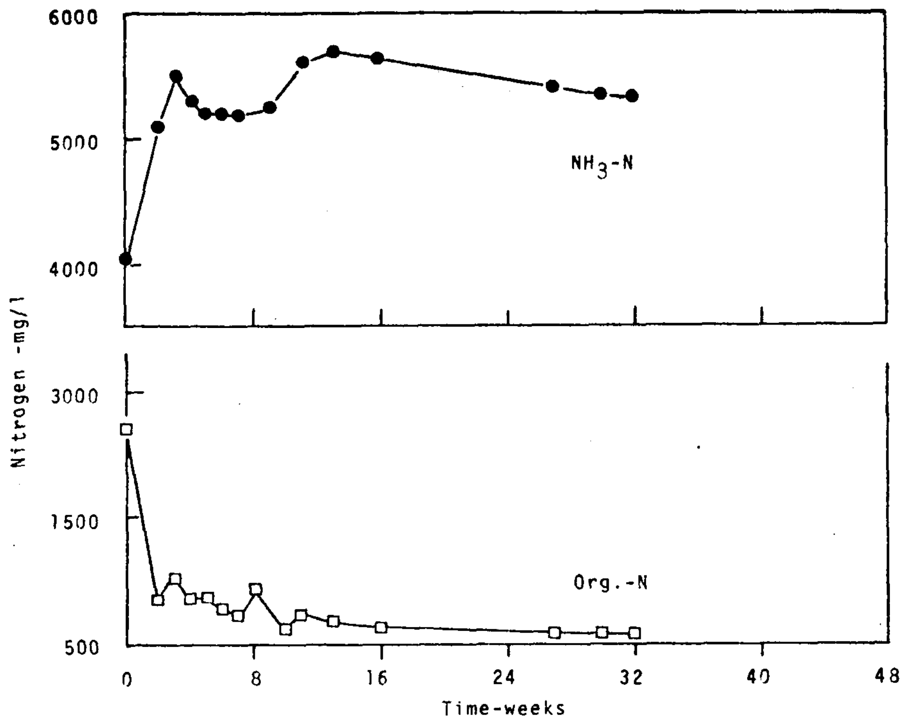

FIG.15 NH_3-N AND ORG.N IN MIXED LIQUOR SUPERNATANT OF ANAEROBIC REACTOR No.2

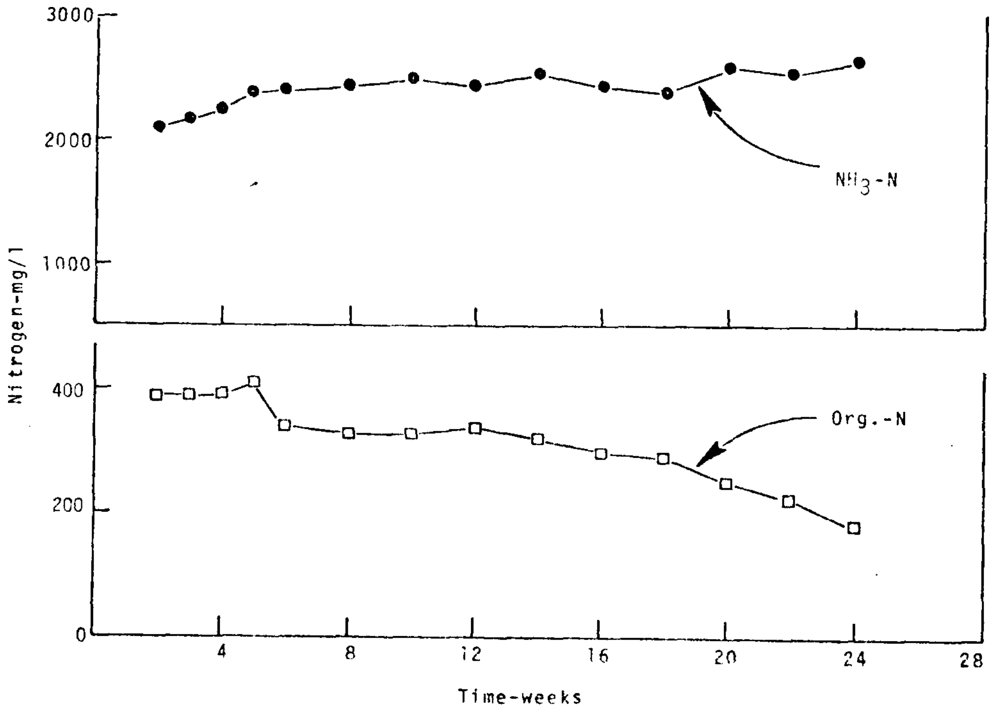

FIG.16 NH_3-N AND ORG.N IN MIXED LIQUOR SUPERNATANT OF ANAEROBIC REACTOR No3. (Diluted Waste)

No significant correlation between the observed calorific values and any other parameters studied was evident. Therefore, the determination of the calorific values was discontinued several months ago.

4.1.8 Volatile Acids

(a) Anaerobic Pit

The determination of volatile acids was started in the latter part of the Phase II operation of the pit (Table 3). It can be seen that considerable concentrations of volatile acids had accumulated in the anaerobic pit during Phase II operation. The value of volatile acids in the feed waste was about 2,500 mg/l and the volatile acids, measured between the 27th and 31st week (Phase II), were in the range of 10,000 mg/l, which indicates a fourfold increase.

It is highly unlikely that any increase in volatile acids occurred in the pit during Phase I at -5^{o}C, since other parameters measured indicate that no biological activity was taking place under the frozen conditions.

During Phase III operation of the pit at -5^{o}C, volatile acids increased further. This increase in volatile acids has been attributed to freezing of part of the contents resulting in higher concentrations in the unfrozen part.

(b) Anaerobic Reactor No. 1 (10^{o}C)

The determination of volatile acids which was carried out from the 32nd week onward showed that about a fivefold increase in the values of volatile acids occurred in the reactor (Table 3). No significant change in the volatile acids concentrations seemed to occur in the final 4 months of the reactor's operation. This corresponds with other parameters measured in this study, further indicating that the digestion in this reactor was very poor.

(c) Anaerobic Reactor No. 2 (20^{o}C)

The determination of volatile acids was made from the 16th week onwards (Table 3). In the 16th week, volatile acids concentration was around 20,000 mg/l, which indicated an eightfold increase. This was followed by a slow decrease, which suggests that digestion was taking place slowing in the reactor.

(d) Anaerobic Reactor No. 3 (20^{o}C - Diluted Waste)

Volatile acids were measured from the 8th week onward (Table 3). In the 8th week, the concentration of volatile acids was about 10,000 mg/l, which indicated an eightfold increase. The volatile acids started decreasing rapidly, and had diminished to about 300 mg/l at the end of the reactor operation in the 24th week.

TABLE 3

VOLATILE ACIDS IN MIXED LIQUORS OF ANAEROBIC PIT AND ANAEROBIC REACTORS

(Values expressed in mg/l as Acetic Acid)

Time in Week	Anaerobic Pit		Reactor No.1 (10°C)	Reactor No.2 (20°C)	Reactor No.3 (20°C) 1:1 Dilution
0*	2,500	Phase I	2,500	2,500	1,260
8	-		-	-	9,120
11	-		-	-	7,830
12	-		-	-	6,675
13	-		-	-	5,100
14	-		-	-	5,100
15	-		-	-	4,725
17	-		-	19,620	3,900
19	-	Phase II	-	-	3,060
21	-		-	-	1,845
23	-		-	-	640
24	-		-	-	375
27	-		-	18,600	
28	10,740		-	-	
30	-		-	16,950	
32	-	Phase III	13,740	17,700	
34	15,840		-		
36	-		12,300		
38	15,300		-		
41	-		11,875		
42	13,425		-		
45	-		13,800		
48					

*Note: Average of 5 Feed Waste Samples.

4.1.9 Gas Production (Figure 17)

(a) Anaerobic Reactor No. 1 (10°C)

Gas production was measured at intervals at room temperature and pressure (Figure 17). Reactor No. 1 showed a very long lag period of about 20 weeks in gas production, and thereafter gas production continued very slowly. The total amount of gas produced in the reactor during the 12 months of operation was about 3.0 l/kg of volatile solids. Gas analyses were also conducted, and it can be seen that methane was present in trace amounts only (Table 4). These results, together with other parameters measured in this study, clearly indicate the poor performance of the digester.

(b) Anaerobic Reactor No. 2 (20°C)

The rate of gas production was very erratic during the first 24-26 weeks (Figure 17). Thereafter, the rate of gas production increased steadily. It appears that the methane formers were acclimatizing during the first 24-26 weeks period, and it would be logical to consider this as a lag period. The analyses of gas conducted on the gas sample collected during Week 20 revealed that the gas produced contained only 15.0% methane and about 46% CO_2 (Table 4). The gas from the sample collected during Week 30 contained about 50% methane. The toral amount of gas produced by the end of the 32nd week was about 100 l/kg v.s. (Table 9).

(c) Anaerobic Reactor No. 3 (20°C - Diluted Waste)

The rate of gas production during the first 8 weeks of operation was erratic. This was followed by a steady increase (Figure 17). The maximum rate of gas production of about 50 l/kg v.s./week was reached during Week 15, and gas production stayed in the range of 50-60 l/kg v.s./week up to the 22nd week. From the 22nd week onward, the rate of gas production decreased very rapidly and reached about 7.0 l/kg v.s./week by the 24th week. It stayed at this rate until the end of the reactor operation during the 25th week. The total amount of gas produced during the entire period of 25 weeks of operation of the reactor was about 360 l/kg v.s.

The analyses of gas samples collected during the 6th and 22nd week are shown in Table 4. Gas produced furing the lag period contained about 13% methane, while that evolved (generated) during the maximum rate of gas production (22nd week) contained about 75% methane. The latter figure indicates proper digestion.

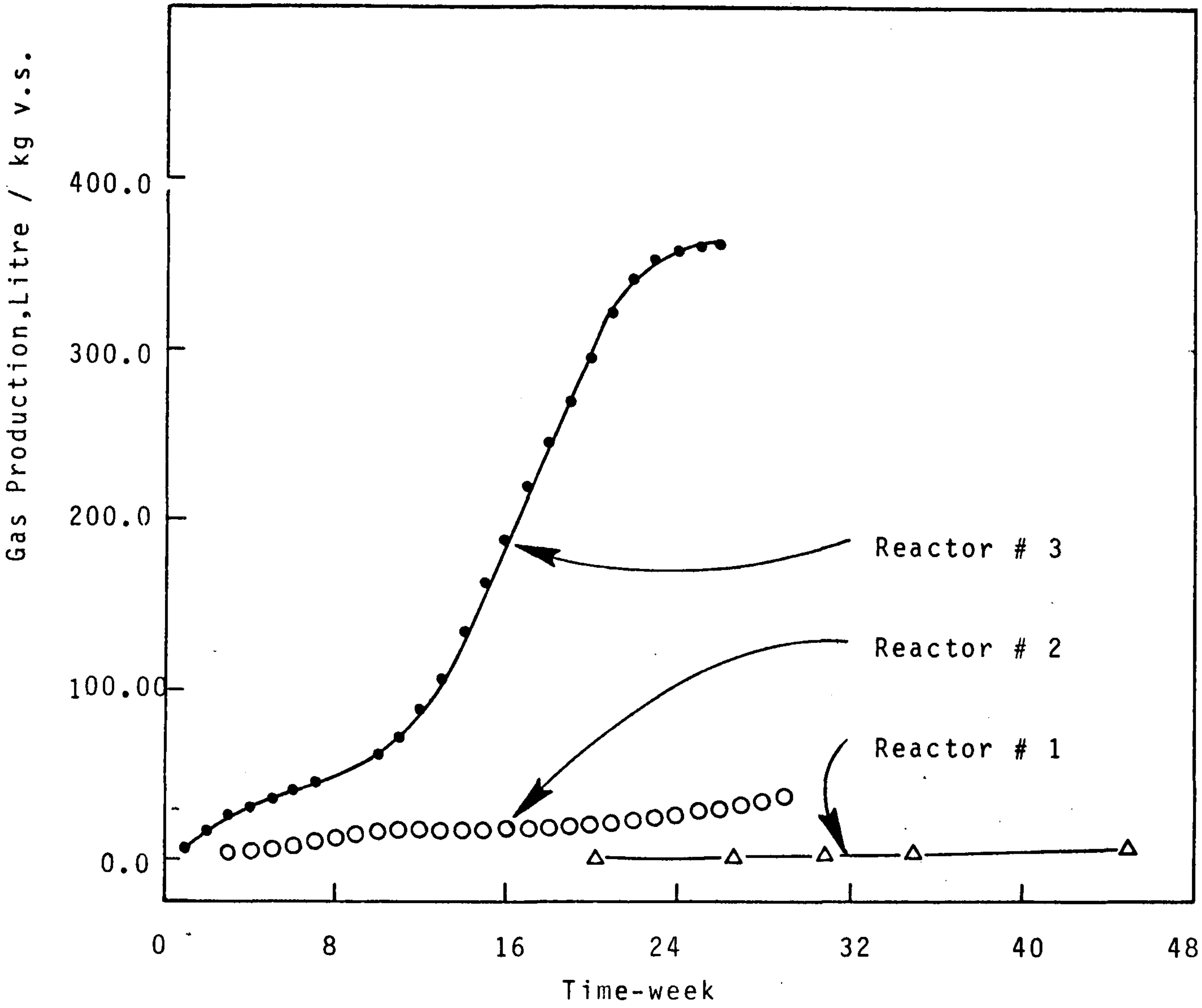

FIG.17 CUMULATIVE GAS PRODUCTION

TABLE 4 COMPOSITION OF REACTOR GAS

Gas	Reactor No. 1 Gas % by volume	Reactor No. 2 Gas % by volume		Reactor No. 3 Gas % by volume	
	during 40th week	during 20th week	during 30th week	during 6th week	during 22nd week
Methane	Traces	14.4	50.2	12.8	74.75
Carbon dioxide	13.3	46.4	35.3	6.7	15.93
Oxygen	1.3	6.6	2.3	1.3	2.00
Nitrogen	85.0	32.7	12.2	79.2	7.32

4.2 Bacteriological

4.2.1 Feed Waste

The numbers of all types of bacterial enumerated in feed waste (Table 5) were lower than the numbers normally found in human waste. Since the feed waste was stored at -5°C for one week prior to bacteriological testing, the low bacterial counts are not surprising. In order to assess the effect of freezing on bacteria in concentrated human excrement, an experiment was conducted. About 1 litre of fresh human excrement (faeces + urine) was collected. Following initial examination, an excrement sample was well mixed and then divided into two 1-litre plastic bottles and stored at -5°C and -25°C, respectively. Samples were removed for bacteriological examination after 24 hours, 48 hours and 1 week (Tables 6 and 7). The tables show that, in general, all types of bacteria diminished considerably after 24 hours' freezing. A further appreciable drop occurred during a second 24 hours of freezing, and a smaller decrease occurred after one week of frozen storage. Reductions in coliforms were noted to be 90 per cent and 99.99 per cent after 24 hours of freezing at -5°C and -25°C, respectivley. After one week's freezing, the coliforms counts reduced to 99.99% at -5°C, and 100% at -25°C. The coliforms counts (43/ml) obtained after one week's freezing at -5°C (Table 4) were much lower than the coliforms counts ($24 \times 10^3 - 15 \times 10^4$/ml) in the feed waste (Table 5). The lower coliforms counts could be attributed to the small volume (500 ml) of excrement used in the above experiment. In general, the results are in agreement with Fournelle (1942), who reported that freezing of sewage sludge (-13°C to -21°C) caused reductions in various bacterial types of between 95.2% - 99.6% in the first 24 hours of freezing. Higher reductions of faecal streptococci were obtained in this study (79.2% - 86.3% reduction) than by Fournelle, 1952, (65% - 72%) which could be due to the different nature of the waste he used.

TABLE 5 MICROFLORA IN HUMAN WASTE

Date	Aerobic Total Count 10^6/ml 20°C	Anaerobic Total Count 10^6/ml 20°C	Aerobic Total Count No /ml 2°C	Entero-cocci 10^6/ml 37°C	Coliform MPN/ml 37°C
19-2-74	4.6	-	20×10^3	2.5	24×10^3
26-2-74	7.1	1.91	37×10^4	0.56	11×10^4
5-3-74	5.4	-	44×10^4	0.34	15×10^4
12-3-74	7.5	2.0	-	0.75	8×10^4
19-3-74	6.3	1.85	30×10^4	1.0	10×10^4
26-3-74	-	-	-	0.69	8×10^4
2-4-74	6.7	1.7	13×10^4	0.57	11×10^4
9-4-74	5.0	2.1	35×10^4	0.44	15×10^4

TABLE 6 MICROFLORA IN FRESH HUMAN WASTE

Bacterial Types	Initial Counts 10^6/ml	Per cent of Total Counts*
Total aerobes	36.5	-
Total anaerobes	36.0	98.6
Psychrophiles	0.09	0.24
Total coliforms	240.0	-
Faecal streptococci	3.8	10.4

* Based on counts of the total aerobes.

TABLE 7

EFFECT OF FREEZING AND THAWING ON BACTERIAL POPULATION

BACTERIAL TYPES	TEMPERATURE			
	-5°C		-25°C	
	Counts/ml	Reduction Per cent	Counts/ml	Reduction Per cent
AFTER 24 HOURS:				
Total aerobes	18.3×10^{6}	50.0	11.3×10^{6}	69
Total anaerobes	-	-	19.0×10^{6}	47.5
Psychrophiles	4.5×10^{4}	50.0	-	-
Total coliforms	24.0×10^{6}	90.0	2400	99.99
Faecal streptococci	78.0×10^{4}	79.2	$53. \times 10^{4}$	86.3
AFTER 48 HOURS:				
Total aerobes	15.7×10^{6}	64	6.0×10^{6}	83.7
Total anaerobes	-	-	-	-
Psychrophiles	-	-	-	-
Total coliforms	24.0×10^{6}	90	240	99.99
Faecal streptococci	74.0×10^{4}	80.1	27.0×10^{4}	92.0
AFTER 1 WEEK:				
Total aerobes	6.45×10^{6}	82.3	1.32×10^{6}	96.1
Total anaerobes	7.35×10^{6}	79.1	2.05×10^{6}	99.1
Psychrophiles	17.0×10^{3}	81.1	6.0×10^{3}	93.3
Total coliforms	43	99.99	0.0	100.0
Faecal streptococci	25.7×10^{4}	93.3	15.4×10^{4}	96.0

4.2.2 Anaerobic Pit

The results of bacterial counts in the pit samples are shown in Figures 18 and 19. During the operation of the pit at -5°C (Phase I), the microflora generally existed in the same range as was found in the feed waste up to 8-10 weeks, except for total coliforms, which disappeard almost completely in 16 weeks. However, during the subsequent 6 weeks of Phase I, the numbers of all the types of bacteria enumerated started to decrease. This trend continued for another 4 weeks, even when the pit was being operated at +5°C (Phase II). However, after another 4 weeks of incubation at +5°C (Phase II), there was a sudden increase in aerobic and anaerobic bacterial numbers and the counts reached 8 x 10^6/ml.

Faecal streptococci (Figure 19) showed a steady decrease throughout the entire operation of the pit.

Psychrophilic bacterial counts gave very erratic results. This may be attributable to the freezing effect. The bacterial colonies after 2 weeks incubation at 2°C were observed to be very tiny in comparison with the colonies grown under similar conditions from other anaerobic reactors. It appears that bacterial cells exposed to freezing take a long time to recover under a low temperature (2°C).

Bacterial counts confirm the physical-chemical results which indicated that the anaerobic pit during the operation at -5°C was serving just as a holding tank and that no biological activity occurred under such conditions. Pit performance did not exhibit a significant change when the temperature was raised to +5°C (Phase II).

4.2.3 Anaerobic Reactor No. 1 (10°C)

The results of bacterial counts in the mixed liquor of the anaerobic Reactor No. 1 are shown in Figures 20 to 22. Total aerobic counts (Figure 20) appeared to decrease during the first week of operation; however, from the second week onward, the bacterial numbers started increasing. This trend continued up to the 5th week, but was followed by a drop in the 6th week, and then levelled off. No significant changes in aerobic bacterial numbers occurred throughout the subsequent 12 month operation of the digester (range 25 x 10^6/ml - 216 x 10^6/ml).

Anaerobic bacterial counts followed a pattern similar to that of the aerobic counts, except that the anaerobic bacterial counts were lower than the total aerobic counts (Figure 20). Similar results were obtained from all the samples, irrespective of their source. Though this is in agreement with other investigators (McKinney _et al_, 1958, McCarty _et al_, 1962), these results may be considered doubtful since the incidence of a large number of obligate anaerobic bacteria in faeces, sewage and sewage treatment processes has been demonstrated by modern culture techniques (Zubrycki and Spaulding, 1962; Post _et al_, 1967, and Toerien _et al_, 1967). Following the techniques of Toerien and Siebert (1967), the obligate anaerobic bacteria were enumerated in

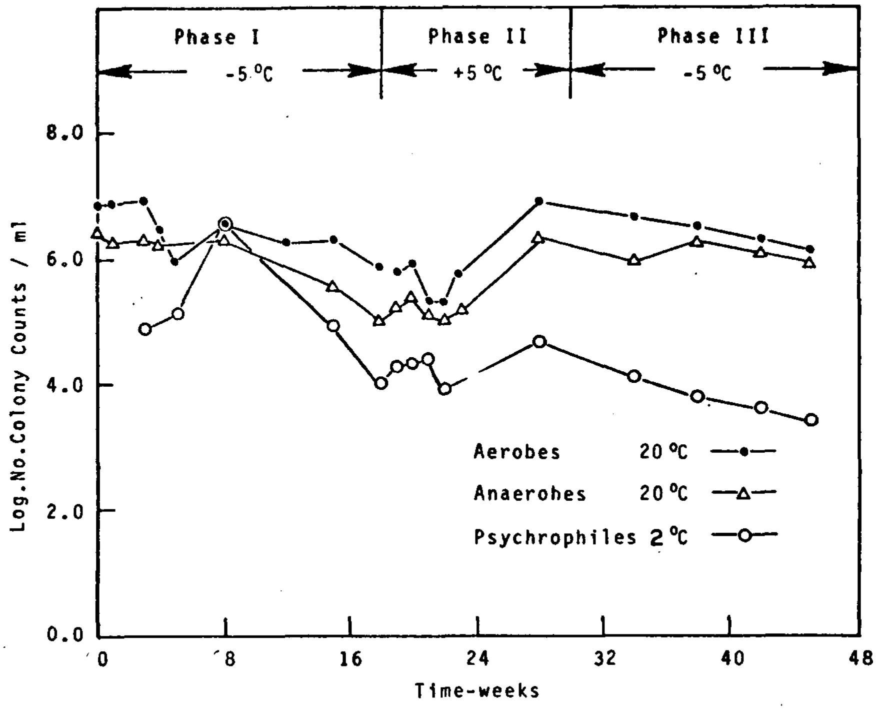

FIG.18 HETEROTROPHIC MICROFLORA IN ANAEROBIC PIT

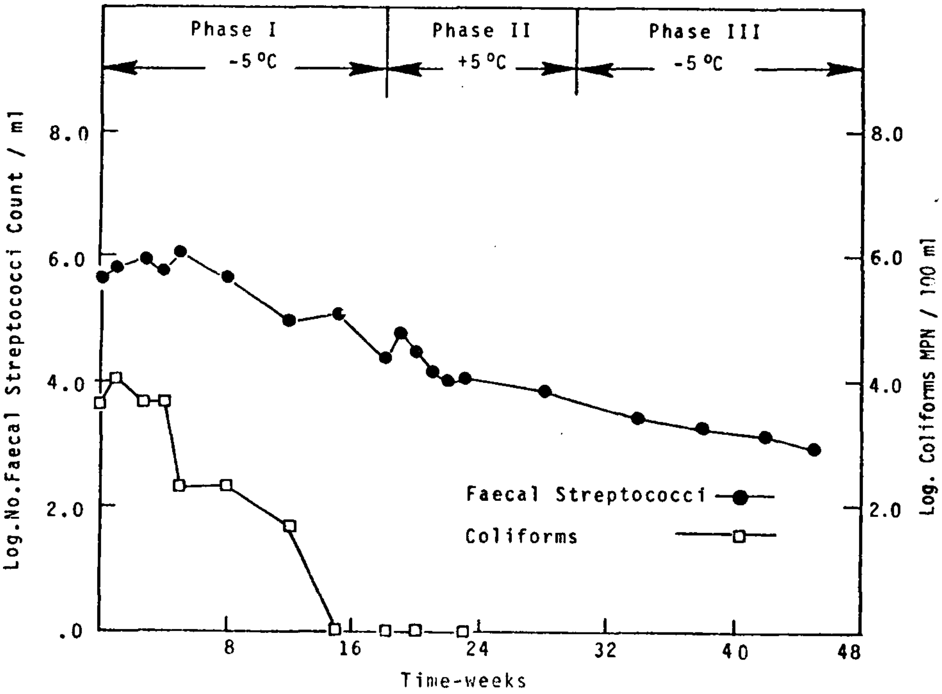

FIG.19 INDICATOR ORGANISMS IN ANAEROBIC PIT

the mixed liquor. Although the counts were slightly higher than those obtained by the conventional anaerobic jar method, the numbers were lower than the total aerobic counts. These modern techniques for enumerating anaerobic bacteria (Toerien and Siebert, 1967) require sample collection as well as dilution under strictly anaerobic conditions (through the use of a syringe). Due to the thick nature of the waste samples used in this study, the hypodermic syringe could not be used for the collection or the dilution of the samples. Therefore, the anaerobic bacteria were enumerated by the standard plate count method. The obligate anaerobic bacteria are extremely sensitive to oxygen. It seems likely that the obligate anaerobic bacteria were damaged during the collection or dilution of the samples, which were done under aerobic conditions. The low anaerobic counts obtained in this study were due to the absence of obligate anaerobic bacteria in the Petri plates.

Psychrophilic bacteria (Figure 21) started increasing in the first week of operation, and reached 60 x 10^6/ml by the 4th week. From the 4th week onward, the counts stayed in the range 6 x 10^6 to 138 x 10^6/ml during the subsequent 12 months of reactor operation. The average count of psychrophiles during this 6 month period was 41.6 x 10^6/ml, which is similar to the average total aerobic counts (20°C) (41.7 x 10^6/ml) calculated for the same period of 6 months (Figure 20). This indicates that the environment in the reactor became selective in favour of the psychrophilic bacteria, and that any physiological activity of the organisms inhabiting this reactor represented a measure of psychrophilic activity.

Total coliforms (Figure 22) increased in the first few weeks of operation of the reactor. This increase corresponded with the increase in other bacterial counts. This is not surprising, since some members of the coliform group are known to multiply outside human intestines. After the 3rd week of operation, the coliform counts reached 24 x 10^4/100 ml when they started to decline, and they disappeared after 3 months. This indicates that the viability of coliform organisms at 10°C is longer than at -5°C. Our results are in agreement with the literature.

Faecal streptococci started to decrease slowly from the beginning of the experiment. Even after 12 months of operation of the reactor, these organisms were present in the range of 3.5 x 10^3/ml to 4 x 10^6/ml. They are known to be somewhat resistant to adverse temperature, chemical and other environmental changes; accordingly, they survived in this anaerobic digester.

When the reactor reached the gas-formation phase, two samples were tested to enumerate the methane-forming bacteria by MPN method (Siebert & Hatting, 1967). Unfortunately, both times the results were negative. This was rather surprising in view of the fact that gas was being produced at the time when samples were collected for the tests. However, the analysis of the gas revealed a highly abnormal composition. Methane gas was present only in traces, which, together with the fact that only a small amount of gas was formed (3 litres/kg v.s.), indicated that methane-forming bacteria were present in very small

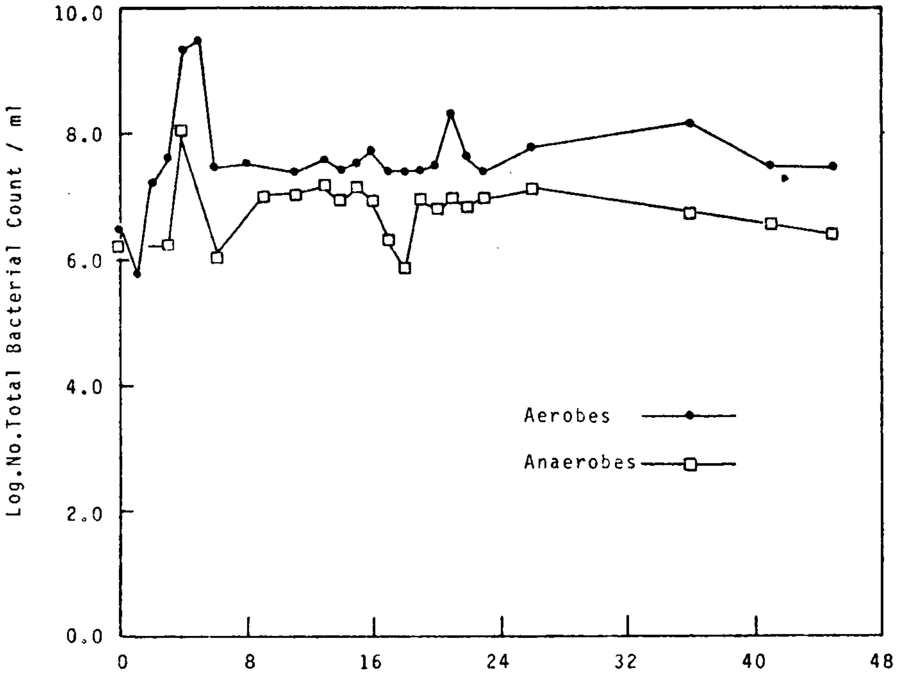

FIG.20 HETEROTROPHIC MICROFLORA IN ANAEROBIC REACTOR No 1

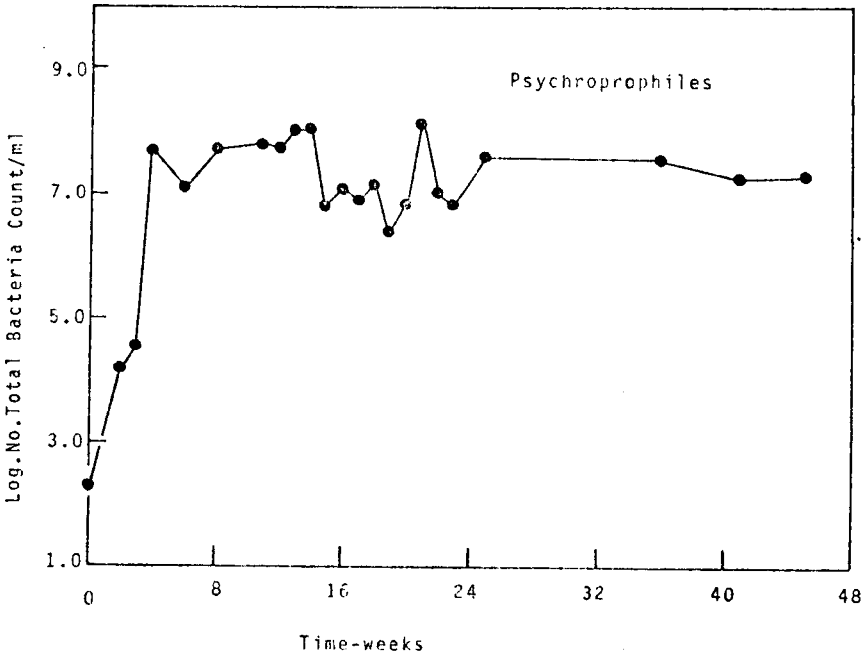

FIG.21 PSYCHROPHILES IN ANAEROBIC REACTOR No.1

5.0 GENERAL DISCUSSION

5.1 Anaerobic Pit

The concentrated, frozen nature of the waste introduced certain analytical problems, which could have caused random distortions and errors in the individual values measured. However, the average values and overall effects are definitive and therefore indicate the effectiveness of the treatment system investigated. The various parameters monitored in this study indicate that no change in all the operational parameters occurred during the 4-1/2 month operation of the pit at -5°C in Phase I, or during the later 4-1/2 month operation at -5°C in Phase III of the study. The physical-chemical results, together with bacteriological results, indicate that no biological activity occurred in the anaerobic pit operated under simulated permafrost conditions, and that the waste pit merely served as a holding tank.

Once the temperature of the pit was raised to +5°C to simulate summer soil temperature, and the pit was held at that temperature for 3 months, a slow, insignificant change showed in most of the values measured, except those for volatile acids. This slow change was noticeable after a lag period of 5-6 weeks. The pit contents took about 4 weeks to thaw completely. The pH of the mixed liquor dropped from a mean value of 8.67 to 8.2 (Figure 1) during the operation of the pit at +5°C in Phase II. This decrease in pH values was accompanied by a fourfold increase in volatile acids. This is a clear indication of biological activity in the pit, similar to the "acid-forming" phase in anaerobic digestion, when complex organic compounds are digested to yield fatty acids under conditions of low redox potential. Although redox potential was not monitored in this study, the accumulation of volatile acids indicates that the conditions in the pit were anaerobic. It is highly unlikely that further decomposition of fatty acids to methane gas and CO_2 occurred in the pit. This is further substantiated by the absence of methane-forming bacteria in the pit sludge. In the literature, methane formation has been reported at low temperature, but the slow rate requires longer detention time (Rudolfs, 1927; Fair and Moore, 1934, 1937; McGhee, 1968). It appears that the operational period at +5°C was not long enough for the development of the methane-forming bacteria. The high concentration of NH_3-N (4,000-5,000 mg/l) may have been another additional inhibitor to the development of methane bacteria.

When the temperature of the pit was reversed to -5°C, and held at this temperature for a further 4-1/2 months, no actual change seemed to occur in all the parameters measured. From the physical-chemical results and the bacteriological data, it is evident that the current practice of disposal of human waste in sludge pits in permafrost regions does not appear to be a satisfactory method, for environmental as well as public health safety reasons. More adequate treatment and better disposal methods are desirable for those small northern communities which are still using the "honey-bags" system of disposal. It would be, however, unrealistic to suggest the adoption of sewer systems and sophisticated waste treatment facilities, especially for numbers and could not be detected with the MPN method used in this study.

4.2.4 Anaerobic Reactor No. 2 (20°C)

Total aerobic counts (Table 8) dropped in the first week of operation. Subsequently there was an increase in numbers. After 5 weeks, the total bacterial counts decreased and then levelled off. No significant changes in bacterial numbers occurred in the subsequent weeks of digester operation. This trend was similar to that of Reactor No. 1 (10°C). After reaching stable conditions, the bacterial counts in both the reactors were approximately in the same range. Anaerobic bacterial counts were erratic and were lower than the total aerobic bacterial counts. Psychrophilic bacteria ranged from 68 x 10^3/ml to 2.28 x 10^6/ml In comparison with the numbers of the psychrophilic bacteria (6 x 10^6/ml - 138 x 10^6/ml) in anaerobic Reactor No. 1 (10°C) (Figure 21), these counts are very low. This was not surprising since the temperature of this reactor was kept at 20°C.

TABLE 8 MICROFLORA IN ANAEROBIC REACTOR NO. 2 (20°C)

Date	Aerobic Total Count 10^6/ml (20°C)	Anaerobic Total Count 10^6/ml (20°C)	Aerobic Total Count 10^6/ml (2°C)	Enterococci 10^6/ml (37°C)	Coliform MPN/100 ml (37°C)
24-5-74	5.6	1.81	0.43	0.54	10 x 10^4
11-6-74	2.9	0.49	0.36	0.014	460
18-6-74	4.3	0.56	0.73	0.008	0.0
25-6-74	35.0	0.60	2.28	0.002	0.0
2-7-74	54.0	2.29	1.19	0.008	0.0
9-7-74	77.5	1.47	0.77	0.005	-
16-7-74	17.0	2.30	0.068	0.013	-
30-7-74	25.	-	0.070	0.004	-

Total coliforms decreased very rapidly and could not be detected ater a 2 week period of reactor operation. This indicates that the survival of the coliform organisms is shorter at higher temperatures. As reported earlier, the survival time of coliforms has been observed to be 12 weeks at 10°C under anaerobic conditions which agrees with the literature.

Faecal streptococci ranged from 40 x 10^2/ml to 54 x 10^4/ml. The reductions in number started very slowly from the first week of operation. A comparison of these results with those obtained in the anaerobic Reactor No. 1 (10°C) apparently indicates that the viability of these bacteria is greater at 10°C than at 20°C. This suggests that faecal streptococci would be a more suitable indicator of faecal pollution in cold regions than coliforms.

Methane-forming bacteria were estimated in the mixed liquor when the digester reached the gas-forming phase. Methane bacteria were present in the range of 11 x 10^2 to 24 x 10^2/g volatile suspended solids (v.s.s.). These bacterial counts were far lower than the literature values of 50 x 10^3 to 200 x 10^3/g v.s.s. (Siebert and Hatting, 1967). The low numbers of the methane bacteria present in the reactor explain the poor performance of the digester at this stage of operation. Since these bacteria are of vital importance in the successful operation of anaerobic digesters, the small methane bacteria population also explains the low recovery of methane gas (14-50%) and the small amount of total gas produced in the digester (100 l/kg v.s.).

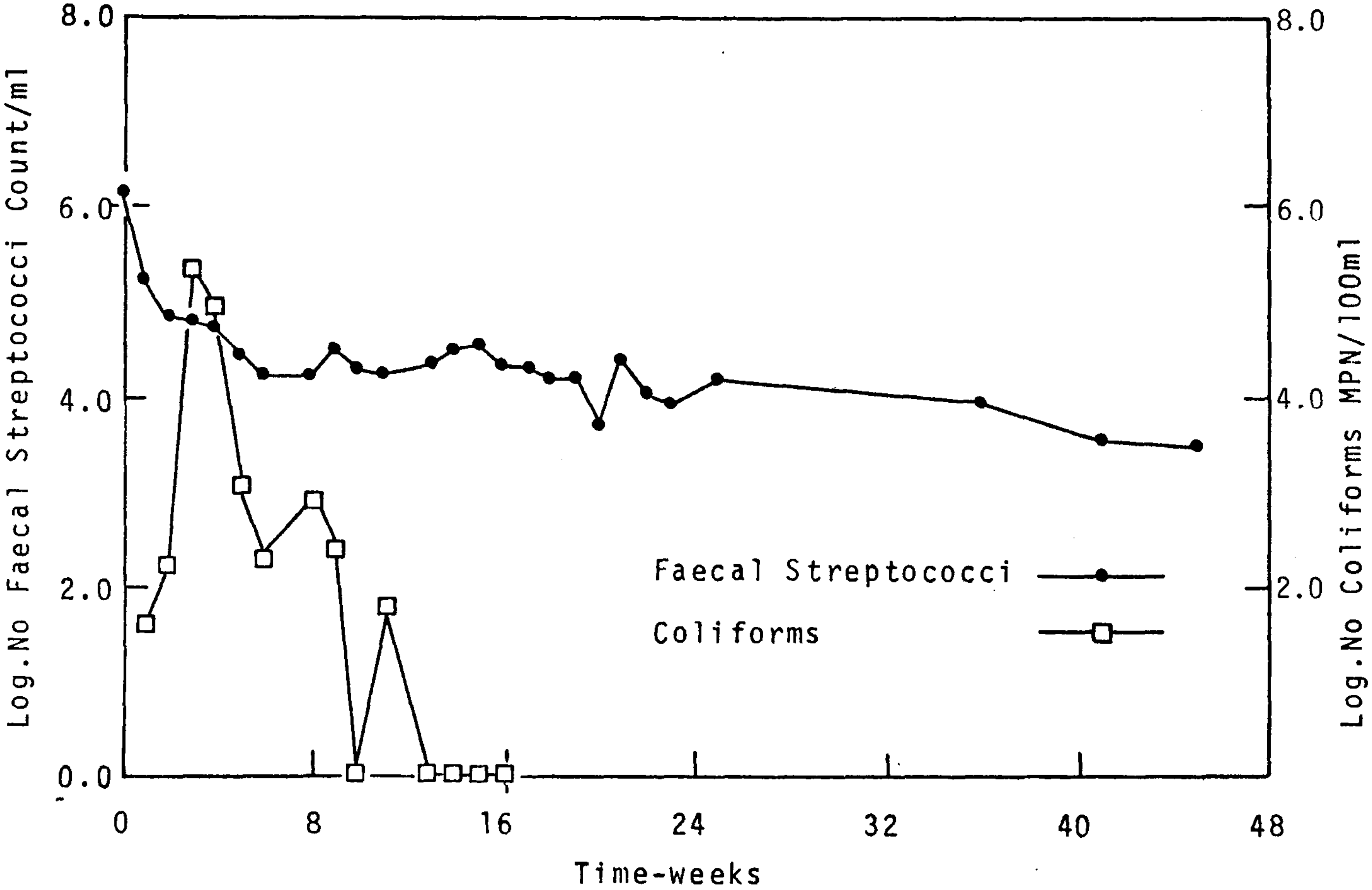

FIG.22 INDICATOR ORGANISMS IN ANAEROBIC REACTOR No.1

settlements which are not likely to grow much in the future. At the present time, from a sanitation point of view, proper collection and disposal methods are of higher priority than highly efficient treatment methods. The current sludge pit disposal method, though inadequate insofar as treatment efficiency is considered, seems to be a reasonable solution under the present circumstances. Nevertheless, to safeguard against environmental and public health hazards, certain improvements in the existing sludge pit disposal method are needed. Soil condition and topography are important considerations in sludge pit location, aesthetically and practically. The lining of sludge pits with plastic sheets is recommended to prevent seepage through soil and to limit the pollution of ground and surface waters.

5.2 Anaerobic Reactors

5.2.1 Anaerobic Reactor No. 1 (10°C)

Considering all the parameters monitored, the results indicate that the reactor did not perform properly and that the reactor was in an unbalanced condition, as is apparent by the accumulation of high concentrations of volatile acids (Table 3). The high concentrations of volatile acids in the reactor, together with appreciable numbers of acid-formers (4×10^7/ml), suggest that the "acid-formation" phase of anaerobic digestion was not affected much in this reactor under the experimental conditions, and that the activity of acid-formers is substantial. However, the second phase - "methane formation" of anaerobic digestion was drastically affected in this reactor. The long lag period of 20 weeks in gas production, small amount of gas produced (3.0 l/kg v.s.), presence of methane in traces, together with negative counts of methane bacteria, suggest that the growth of methane bacteria was inhibited in the reactor. The literature on the inhibition of methane production is voluminous and often confusing. The pH, high concentration of volatile acids (>3,000 mg/l), ammonia nitrogen (>1,250 mg/l) as well as many heavy metals, have been reported to inhibit gas production in the conventional anaerobic digestion of sewage sludge (Maline, 1965; Golueke, 1958; Snell, 1943; McCarty, 1964a, 1964b; Boyko, 1974; Anonymous, 1974). However, the anaerobic digestion of night soil has been reported to occur at an acceptable rate under environmental conditions different from those normally considered optimum for methane production (Iwai et al, 1962; Kaibuchi, 1961; Matsumoto and Endo, 1965). It is extremely difficult to point out the factor, or factors, which inhibited the digestion in this reactor. High volatile acids do not appear to be responsible, since volatile acids themselves are not toxic to methane production, but are toxic indirectly through a reduction in pH (below 6.4) (McCarty et al, 1962). In this reactor, the pH range was between 7.6 - 7.8, which falls within the pH range (6.4 - 7.8) under which methane formers are more active (Golueke, 1958; Snell, 1943). The data recorded during anaerobic digestion of night soil by Matsumoto and Endo (1965) indicate good gas production at pH between 8.3 and 8.6. Retarding effects of ammonia and ammonium ions on the anaerobic digestion in human excrement have been reported (Snell, 1943). Urea, $(NH_4)_2CO_3$, $(NH_4)_2SO_4$ and NH_4NO_3 retarded gas production; however, $NH_4H\ CO_3$ did not have any detrimental effects on digestion as long as the pH was below 7.6 (Snell, 1943). In view of these facts, it seems likely that high concentration of ammonia nitrogen and ammonium ions may have been responsible for the inhibition of gas production in this study. The low temperature (10°C) and the lack of inoculum (seed) may have had an additional effect on the development of the methane bacteria.

5.2.2 Anaerobic Reactor No. 2 (20°C)

It is premature to make any conclusive judgments on the performance of this reactor, since the experiment is still in progress.

Gas production started after 10 days, and a slow, erratic rate of gas production (1.0 - 9.28 l gas/kgm v.s./week) continued up to the 28th week (Figure 17). After the 28th week, the rate of gas production started increasing (29.5 l/kg v.s./week during the 31st week). This indicates the development of a specialized population of methane bacteria, which had different physiological characteristics from those present in conventional anaerobic digesters treating sewage sludge. Other parameters monitored also indicate that this reactor is tending towards a normal digestion stage.

The results obtained so far, including a steady increase in gas production rate, are promising and indicate that comparable treatment efficiency is likely to be achieved as the experiment progresses. This suggests that concentrated human waste may be treated by anaerobic digestion, provided suitable microflora responsible for the production of gas, the methane bacteria, are active in these different environmental conditions and are present in adequate numbers in the reactors.

5.2.3 Anaerobic Reactor No. 3 (20°C - Diluted Waste)

Based upon the results of monitoring the various parameters, it is evident that the dilution of the concentrated waste (1:1) reduced the magnitude of inhibition encountered in Reactor No. 2. Dilution of the concentrated waste not only shortened the lag period in gas production (from 20 to 8 weeks), but increased the rate of gas production (from 29.5 to 60.0 l/kg v.s./week), the total amount of gas produced (360 l/kg v.s.), and the % COD removal (72.2%). Gas produced during the period of maximum rate of gas production contained about 60-75% methane and 30-35% CO_2. These values are very similar to those obtained during the normal digestion of sewage sludges when the gas contains 65-70% methane and 25-30% CO_2 (Boyko, 1974). The total gas yield (360 l/kg v.s. added) obtained from this reactor is lower than the total gas yield of 550-570 l/kg v.s. reported to be achieved in digestion of night soil at temperature range between 30°C - 40°C (Matsumoto and Endo, 1965). Since temperature exerts an important regulating influence on the rate of metabolism, the low gas yield obtained in this study may have been due to the lower temperature (20°C) at which this reactor was operating.

Considering all the parameters, i.e., pH, alkalinity, COD, solids, total gas production, rate of gas production and volatile acids, the results obtained for Reactor No. 3 showed a distinct improvement in digestion over those obtained for Reactors No. 1 and No. 2. For purposes of comparison of all three reactors, some of the parameters measured are shown in Table 9. The digestion may be further improved upon higher dilutions of the concentrated waste. Experiments on this are now being carried out.

TABLE 9

COMPARISON OF VARIOUS REACTORS

Reactor	pH		Alkalinity mg/l		% Soluble COD Reduction	% Reduction		Maximum Gas Production Rate l/kg v.s./week	Total Gas Produced	
	Initial	Digested Mixed Liquor	Initial	ML Super.		T.S.	V.S.		l/kg v.s.	Time Weeks
No. 1 (10°C)	8.98	7.5 - 7.8	14,800	12,400-14,300	Not significant	20.8	24.5		3.0	48
No. 2 (20°C)	8.88	7.1 - 7.8	13,700	14,100-17,400	38.0	27.8	45.4	29.5	100.0	32
No. 3 (20°C) 1:1 dilution	8.4	7.0 7.84	8,000	7,000-12,800	72.2	37.4	55.5	60.0	360.0	25

6.0 RECOMMENDATIONS FOR FURTHER STUDY

1. Disposal of Human Wastes in Anaerobic Pit in Permafrost:

It is recommended that the anaerobic pit be continued in operation for at least one more year along its present lines, and that measurements now taken be continued at monthly intervals. The cost of this is expected to be quite small.

2. Anaerobic Digestion:

It is recommended that further laboratory studies on semi-continuous anaerobic digestion under low temperature conditions be started to establish design criteria and operating conditions for future installations. Pilot plant studies in a northern community will be required once laboratory studies are completed. This should be carried out for concentrated wastes ('honey-bag' wastes), as well as diluted wastes (vacuum sewer wastes).

3. Physical and Chemical Treatment:

The supernatant from an anaerobic digestion system contains high concentrations of dissolved materials and requires additional treatment prior to final disposal. This may be accomplished by physical-chemical treatment such as lime-precipitation.

It is recommended that studies should be carried out on lime-treatment of the supernatant at the laboratory scale, and eventually at a pilot plant scale.

4. Effect of Chemical Additives on Anaerobic Digestion:

Chemical additives are generally used to control odour for bucket-toilets. Proprietary brands are generally used which contain a bacterial inhibitor such as phenol or cresol, a perfume and a caustic compound. These chemicals are likely to affect anaerobic digestion.

It is recommended that a thorough search be carried out into the nature of proprietary brands commonly used. The possible effect of the use of these chemical inhibitors on anaerobic digestion should be studied. If anaerobic digestion is inhibited by these chemicals, then a substitute for use in bucket-toilets should be found.

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WASTE IMPOUNDING EMBANKMENTS IN PERMAFROST REGIONS:
THE SEWAGE LAGOON EMBANKMENT, INUVIK, N.W.T.

by

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For

TECHNOLOGY PROGRAMS
TECHNICAL BRANCH
ENVIRONMENTAL PROTECTION SERVICE
DEPARTMENT OF ENVIRONMENT
NORTHWEST REGION

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1. SUMMARY

In permafrost regions, thaw bulbs exist beneath those bodies of water which maintain a mean annual bottom temperature above the freezing point of water. Many permafrost soils have an excess ice content, therefore, settlement and instability problems may result if water is impounded and creates such a thaw bulb. As well, the relatively warm impounded fluid will have a thermal influence on the surrounding ground. Of particular interest is the increase in the seasonal thaw depth in the foundation soils under the embankment. This will be greater at the upstream sections and may result in settlement, stability and/or seepage problems depending on the soil conditions, topography and surface temperatures. In very cold regions it is possible to maintain a frozen core naturally within the embankment, thus minimizing these problems. In warmer permafrost and the discontinuous permafrost regions, active or passive measures may be required to reduce the thermal perturbation as a result of the lagoon and/or allow for any detrimental thawing.

The literature pertaining to water reservoir construction and other arctic engineering projects provides valuable background information, but there is little recorded on the performance of low, wide impoundment embankments similar to those required for sewage lagoons. A field study site was set up at the existing embankment of the Inuvik, N.W.T. sewage lagoon which has apparently performed satisfactorily for 17 years. The soils are typical of much of the Mackenzie Delta silt, with excess ice contents of 70% v/v near the surface organic layer and decreasing with depth. Thawing has resulted in approximately 1.5 m of settlement, however, this has been primarily only a maintenance problem.

Soil samples were obtained and thermistors were installed to monitor the thermal regime within and beneath the embankment. At this time just over one year's data have been collected. It shows that the 2.5 m thick gravel embankment and approximately 1.5 to 2.0 m of the foundation soils thaw each year, but these completely refreeze by early January. Under the lagoon itself, however, a permanent thaw bulb is indicated. Although there is potential for seepage through the pervious-when-thawed embankment, the low hydrostatic head at the study site discourages this. At a nearby location, where the embankment height is higher, there was evidence of some seepage.

A modified steady state and a finite element transient state analysis, which incorporated a surface heat balance, were performed and the results reported. Evaluation of these was hampered by the unreliability of the measured near-surface temperatures. The agreement was, however, generally good and adequate for engineering calculations. As well, they provide a quantitative understanding of the processes at work at this site, and indicate how further simplifications may be used to achieve reasonable results.

From the Inuvik lagoon case history and other related arctic engineering works, field study and theoretical results allow us to make a number of general comments with respect to lagoon and embankment construction in permafrost regions.

RÉSUMÉ

Dans les régions de pergélisol, des poches de dégel existent sous les nappes d'eau dont la température moyenne annuelle du fond est supérieure au point de congélation. Le pergélisol, dans bien des cas, contient trop de glace et cela peut provoquer des affaissements et créer des conditions instables si l'endiguement des eaux donne lieu à de telles poches. De plus, la température relativement plus élevée des eaux captives à des répercussions thermiques sur le sol environnant, notamment un dégel saisonnier plus profond sous les levées. La profondeur du dégel s'accentue en amont et peut entraîner un affaissement, des conditions instables ou des infiltrations, selon l'état du sol, la topographie et la température superficielle. Dans les régions très froides, le noyau de la levée peut demeurer gelé, atténuant ainsi les problèmes évoqués plus haut; cependant, dans les régions plus chaudes et celles ou le pergélisol est discontinu, des mesures actives ou passives peuvent s'imposer pour minimiser les perturbations thermiques dues à la présence du bassin et (ou) pour compenser tout effet nuisible de dégel.

Les publications traitant de l'aménagement des réservoirs et d'autres travaux de génie dans l'Arctique donnent de précieux renseignements de base; cependant, elles nous éclairement assez peu sur les levées aplaties qui conviennent aux bassins de stabilisation. Une étude de la levée actuelle de celui d'Inuvik (T. du N. -O.) s'est poursuivie; la digue s'est apparamment bien comportée depuis 17 ans. Le limon typique d'une grande partie du delta du Mackenzie y contient près de 70 p. 100 de glace en volume près de la couche organique superficielle. Cette proportion décroît cependant avec la profondeur. Le dégel y a causé un affaissement d'environ 1.5 m, mais cela n'a nécessité que quelques travaux d'entretien.

Il y a un peu plus d'un an, on a prélevé des échantillons de sol et installé des thermistors dans et sous la levée afin d'en étudier le régime thermique. Les données obtenues jusqu'ici indiquent que la digue de gravier de 2.5 m de hauteur et le sol du fondement jusqu'à environ 1.5 à 2.0 m de profondeur dégèlent chaque année et regèlent complètement vers le début de janvier. Toutefois, sous le bassin même on a décelé une poche permanente de sol dégele. La faible charge hydrostatique existant à cet emplacement empêche l'eau de filtrer à travers la levée que le dégel rend perméable. Dans une localité voisine, une levée plus haute a manifesté des signes d'infiltration.

Sous des conditions d'équilibre thermique superficiel, on a procédé à l'analyse d'un état d'équilibre modifié et à une autre d'une situation transitoire mais dont les éléments étaient définis; les résultats en sont donnés dans le rapport. Leur évaluation a souffert de ce que la mesure de la température superficielle était peu fiable; toutefois les lectures concordaient assez bien, de sorte qu'elles ont pu servir aux calculs techniques. Les analyses ont également éclairé les aspects quantitatifs des processus à l'oeuvre à cet endroit et ont indiqué comment d'autres simplifications mèneraient à des résultats acceptables.

Grâce à l'historique du bassin d'Inuvick et à d'autres travaux connexes de génie effectués dans l'Arctique, l'étude sur le terrain et les résultats théoriques suggèrent certains commentaires généraux sur la construction de bassins et de levées dans les régions de pergélisol.

2. INTRODUCTION

Accompanying rapid development and expansion in the Canadian North, is a need for sound waste management for both permanent and transient communities. In the past, oxidation ponds have provided satisfactory treatment for domestic wastes at a number of communities in western and northern Canada. Because of the low-cost, dependable treatment capabilities and ease of operation, such systems are likely to continue to be an important method of waste treatment in the North.

In permafrost regions, bodies of surface water create an appreciable perturbation in the ground thermal regime. In particular, thaw bulbs exist beneath those water masses which maintain a mean annual temperature above the freezing point. Since many permafrost soils are unstable when thawed, the creation of thaw bulbs beneath and adjacent to impounded water may create structural and seepage problems for the containing embankments.

The structural problems are essentially twofold. Firstly, the differential settlement created by uneven consolidation of the underlying thawing soil tends to produce cracks and fissures in the embankment above. Secondly, as the thaw front advances within a high-ice-content soil, relatively large volumes of water may be released which, unless allowed to escape, could result in the generation of excess pore-water pressures. Such a situation could/might lead to a drastic reduction in soil shear-strength in the thawing zone and contribute to the danger of embankment failures.

Other areas of arctic engineering projects which encounter similar problems include water storage reservoirs, roadway embankments adjacent to or causing the impoundment of shallow water bodies, heated buildings with "active" foundation design, buried large diameter hot pipelines and others. In addition to requirements of structural stability, waste impounding embankments should be impermeable to ensure the necessary protection of public health and the environment.

The field work for the overall project was separated into two stages: firstly, examination of an existing embankment to determine the long-term state of such a structure; secondly, monitoring of a site immediately before, during and after construction of a lagoon. To implement the first stage of the project, the embankment of the existing lagoon at Inuvik, N.W.T. was selected for study.

The object of this study is to observe the thermal regime within and adjacent to the lagoon embankment which, apparently, has performed adequately for almost twenty years. Temperature measuring thermistors were embedded in the embankment and its foundation to a depth of 11 m, to a depth of 60 m in one hole adjacent to the embankment, and along the bottom of the lagoon. Soil samples from the bore-holes were analyzed. At this time just one year's temperature data have been collected and analyzed.

Theoretical steady state and transient state thermal models were utilized to generate mathematical predictions of the measured temperature data, and gain a quantitative understanding of the processes at work at this site. This will greatly assist in the design of future wastewater impoundment lagoons, and similar arctic engineering projects in this and other permafrost areas.

This report is a continuation of an earlier preliminary report by Dr. D. Thornton (1974).

3. RESUME OF CURRENT STATE OF KNOWLEDGE

Lagoons as a waste treatment process for cold regions have been studied and design requirements established. However, there is little documented experience with lagoon and embankment construction experience in permafrost regions.

Thermokarst lakes present a natural occurring analogy to waste water impoundment, while the few water storage dams constructed in permafrost regions provide valuable design and construction information. Relevant information from these sources, along with that from other permafrost, thermal and geotechnical research and northern construction, can be used indirectly to review lagoon embankment design and construction problems and techniques.

3.1 Lagoon Sewage Treatment

Sewage lagoons have ben utilized extensively, and almost exclusively, for municipal sewage treatment in arctic and sub-arctic communities. They are a flexible and reliable method of obtaining economical yet adequate sewage treatment, particularly in locations where it is unlikely that there will be trained operators or supervisors (Grainge and Cameron, 1975).

Lagoon sewage treatment ponds are on the first rung of the ladder of controlled biological degradation processes. The environment is virtually beyond the control of the designer, and only the physical factors such as depth and loading can be controlled to a degree (Marais, 1970). Waste stabilization is achieved through a complex, non-steady state ecological system, therefore,lagoon design has generally been based on past experience and limited bio-engineering adaptation. The use of sewage lagoons in the "south" has been well documented (e.g., Barson, 1973; McKinney et al, 1971),and Clark et al (1970) have reviewed many of the existing cold region lagoons. Dawson and Grainge (1969) and Grainge and Cameron (1975) have presented design criteria for lagoons, and Grainge et al (1973) have extended these to cover their use for work camps in the North.

The use of lagoons in cold regions influences the physical design in two ways. Firstly, due to ice cover and reduced sunlight during the winter, wastewater must be stored until the summer and discharged after adequate treatment is obtained. Storage capacity must therefore be large, and one year's storage capacity is generally recommended. A thick ice cover must also be included in the volume design, and lagoons should be at least deeper than the maximum ice thickness expected. However, for good treatment results during the sunlight period the lagoon should have a large surface area and be relatively shallow to allow light penetration. Both the storage and treatment aspects must be considered. Secondly, the long duration of cold temperatures reduces the rate and amount of biological decomposition. This is important in the case of anaerobic decomposition of bottom sludge. The build-up of sludge will necessitate large storage capacity and/or more frequent removal by dredging. Generally, for all but very small installations a two cell system has been recommended. The first is a deep, short retention cell, where most of the sludge will settle out and decompose anaerobically. The second is a long retention cell, where the algae-bacteria symbiotic relationship in the presence of sunlight provides secondary treatment. The small primary cells should be 3 to 8 m deep, while large facultative secondary cells should be operated at 1.0 to 1.5 m depth in summer and provide adequate storage capacity during winter.

There are a number of lagoon waste treatment systems that may be used in the North. Aerated lagoons are mechanically supplied with air (oxygen) and can therefore discharge through the year. They are deeper and smaller in surface area, therefore embankments may be higher, and the pond will be warmer than large, naturally aerated lagoons as earlier described. Tertiary treatment or "polishing" lagoons may be used in conjunction with other treatment methods, and emergency lagoons may be required as back-up to more sophisticated wastewater treatment plants in case of system failures or overloading, resulting in insufficient treatment.

These factors, and others, will influence the physical design and operation of lagoon systems, and therefore establish criteria for embankments, overflow structures and other appurtenances. All aspects of design must be consistent with the objective of low cost and maintenance, while providing adequate waste stabilization for nuisance control, protection of water supplies, and minimizing detrimental impact on the receiving waters.

3.2 Thermokarst Lakes

Thermokarst topography is created by the thawing of ice-rich ground. This may be as a result of natural disturbances, including climatic changes and fires, or man-induced surface thermal regime alterations, such as vegetation removal or damage and water or wastewater impoundment. A common thermokarst feature are thaw lakes. These are widespread in central and northern Alaska (e.g., Anderson and Hussey, 1963; Tedrow, J. C. F., 1969) and in northern Canada, especially in the Mackenzie Delta (Mackay, 1971), and other areas.

The study of the causes and formation of natural thermokarst features, including thaw lakes, is important in the physical and mathematical predictions of the thermal and physical perturbation resulting from wastewater impoundment in high ice content soils. For example, Johnston and Brown (1964) have observed the distribution and temperatures of the permafrost surrounding a thaw lake in the Mackenzie Delta, and thermal regime has been mathematically estimated by Brown *et al* (1964).

3.3 Water Storage Dams in Permafrost Regions

A number of water reservoirs have been constructed in the permafrost regions of North America and Russia, and some of the information and experience gained is useful in designing wastewater impoundment embankments. Water reservoirs are usually large and deep so as to provide sufficient storage or hydraulic head. Seepage through a water reservoir may be allowable.

Bogoslovsky _et al_ (1963) have described a number of water storage dams in permafrost regions. They are generally broken down into those that maintain, or even aggrade, the permafrost within and under the embankment, and those that allow foundation thawing but consider all aspects and consequences of thawing. Mean annual air temperature, foundation and embankment materials available, scale of construction, and other factors must be considered in this design decision. A few examples are examined below to illustrate the techniques that have been utilized.

In the discontinuous permafrost zone, the best documented dams are the Hess Creek Dam which is located about 80 km north of Fairbanks, Alaska (Rice and Simoni, 1963; Kitzie and Simoni, 1972) and the Kelsey and Kettle Generating Stations in northern Manitoba (Johnston, 1969; Macpherson _et al_, 1970). At the former location (mean annual air temperature -4°C) a 25 m high dam impounded water, but the reservoir was drained each fall to promote refreezing of the summer-thawed soil. As well, a refrigeration system was installed at the base of the embankment to ensure freeze-back and bonding at the interface of the frozen foundation gravels and the central core of the summer-placed hydraulic fill, and to ensure positive freeze-back of the sheet pile cut-off wall installation trench. Twenty years of intermittent operation have not appreciably thawed the permafrost foundation under the embankment center-line and settlement has been very small. The embankment itself does not freeze completely, even during extremely cold winters. The method of operation at this site is a major factor in the foundation thermal regime and embankment performance.

At the Kelsey Hydro Generation Site (mean annual air temperature -5°C), it was considered impractical to preserve the discontinuous permafrost. Foundation soil properties varied considerably over short distances and large differential settlements were expected. Removing all of the high ice content soils and refrigeration was considered too expensive and time-consuming. Therefore, the embankments were constructed extremely wide and made of non-cohesive, self-healing soils to allow for limited differential movement and minor foundation failures without severe fissures. As well, high ice content soils were removed to limit the expected settlement to 1.5 m. Seepage through the embankment is a major contributor to foundation thawing caused by sensible heat transported by the water. The high permeability of the soils allows rapid dissipation of excess pore water pressure, thereby improving stability. This process was further encouraged by the inclusion of drains beneath the dykes. Allowance was made for the estimated settlement by super-elevation of the dyke crest at the time of construction, however occasional remedial work is required to maintain the design freeboard. Maximum settlements of nearly 2.1 m have been experienced, but by careful design and maintenance the integrity of the dykes has been maintained.

A number of embankments have been constructed in the discontinuous permafrost region to contain and decant mine tailings waste. Two such dykes at Yellowknife (mean annual air temperature -5°C) were studied by Roy et al (1973). These were constructed, in stages, of very highly-permeable crushed rock, and no instability problems developed in the embankment or the thawed foundation. A high seepage rate was a major contributor to foundation thawing and resulted in considerable settlement where fine-grained and organic soil were present. Where no seepage occurred, dyke movement was small or negligible. Temperature readings indicate that a large thawed zone exists through and under dykes for the majority of the year. Roy recommends that future tailings dykes be made impervious, perhaps by the use of compressed peat core which would be fairly impervious and have low thermal conductivity.

Biyanov (1965) describes a water storage dam constructed on continuous permafrost at Irelyakh, U.S.S.R. (mean annual air temperature -8.2°C). Ice content in the foundation soils reached 60% at some locations, and considerable subsidence and instability would result if these were thawed. Therefore, permafrost preservation was considered essential and porous thaw bulb beneath the existing river channel had to be frozen to prevent seepage. The dam was constructed of thawed material which will have completely frozen naturally in an estimated 30 years, but artificial freezing of the core and bonding to the permafrost foundation is facilitated by the installation of vertical ducts. Cold air is forced through these during the winter, and the "thermal inertia" of the dam is sufficient to maintain the frozen conditions through the warm period. The sequence of operation is then repeated. Seepage would be very dangerous, therefore for added safety an impervious core was constructed and a frozen cut-off wall is maintained by refrigeration. The 20 m high dam was constructed during 1961 to 1963, and the core was completely frozen artifically during the 1963-64 winter before filling that spring. Thawing beneath the upstream slopes is inevitable, an estimated 10 m in 50 years. Therefore, these were constructed with quite flat slopes (1:4) and were made of flexible non-cohesive soils.

In very cold regions artificial refrigeration may not be required. Fulwider (1973) has described a wide, 3.6 m high water storage dam at Thule, Greenland (mean annual air temperature -11.4°C) constructed of pervious material, and based on the premise that soil in the central part of the embankment would remain frozen through the year. Temperature readings collected between 1952 and 1959 indicated that an impervious permafrost core was created. Two winters were required to establish a stable thermal regime in the original 3.6 m high dam, and about the same time period was required again after the embankment was raised by approximately 2.4 m. The water level should be maintained below the elevation of the bottom of the thawed (active) layer in the embankment, which was approximately 1.8 m, however, this was not strictly adhered to at this site. Fulwider speculated that embankments as high as 6 m would completely freeze-back in one winter and maintain an impervious frozen core when used to impound water. For greater heights and/or warmer locations, he suggested construction in stages over several years, to ensure dependable, natural freeze-back of the foundation and embankment.

A natural frozen core dam was also proposed for Asbestos Hill in Northern Quebec (mean annual air temperature -8.3^{o}C) (Hahn and Sauer, 1968). The 14 m water storage dam would be built, in winter, of local pervious materials which would be placed in shallow layers and allowed to freeze. Alternatively, the core section could be built up of ice blocks frozen together on site. In both cases the slopes would be of soil, and a thick layer of moss insulation would be located on the crest and exposed slopes to reduce summer thawing. Foster (1974) has considered earthfill dams for domestic water storage for communities in the eastern Arctic where only granular soils are available, but is concerned that the core may not freeze completely and seepage zones may remain. An impervious liner on the upstream face would prevent seepage through the embankment, but not the foundation material. Other systems, such as refrigeration, are expensive, therefore he favours the construction of large cut-and-fill type earth reservoirs, which would have reduced hydrostatic head and be completely lined with an impermeable membrane. Imperial Oil Ltd. (1974) have reviewed the use of impermeable lines, and other dyking techniques, to contain petroleum product spills in the North.

3.4 Thaw Consolidation

In permafrost regions most of the total settlement of embankments is a result of the thawing of ice lenses and inclusions, and the remainder results from consolidation of the thawed soil and perhaps the embankment itself. The settlement, per unit thickness of thawed soil, can be crudely estimated from the visual ice volume content, however, the frozen and thawed dry unit weight and moisture content of soil samples can be effectively and expediently used to estimate settlement (Crory, 1973). This method has been used by Speer et al (1973) to predict thawing and resulting differential settlement along a linear disturbance, in their case, a buried warm oil pipeline. Brown and Johnston (1970) have incorporated a simple time-dependent moving thaw front into a similar ice volume-related settlement technique, and closely approximated the settlement of an embankment where seepage was the major contributor to thawing.

In many cases a more complete analysis of consolidation is required, particularly in non-free-draining soils. This area has been investigated by Tsytovich et al (1965) and Zaretskii (1968), and others. Morgenstern and Nixon (1971) have developed a one-dimensional theory of thaw consolidation, based on the Terzaghi theory of consolidation, and the thaw front prescribed by a solution to the heat conduction in solids such as the Newmann problem (e.g., Carslaw and Jaeger, 1959; Anderson and Morgenstern, 1973). This has also been extended to a more general thaw rate condition, which is particularly important in non-one-dimensional thawing (Nixon and Morgenstern, 1973). Other related papers have considered the factors that influence the thawing of frozen soils, which is very important in the thaw-consolidation model (Nixon and McRoberts, 1973). Layered systems have also been studied by Nixon (1973) and Nixon and Morgenstern (1973) have considered the implication of residual stress in the thawed soil.

3.5 Stability

Concern in the design of relatively low wastewater impoundment embankments in permafrost regions is primarily related to foundation bearing capacity and stability when thawed. Two areas of interest are beneath the embankment and the pond created.

Frozen soils and soil-ice mixtures are generally strong enough to support heavy loads. However, when high ice content soils thaw, relatively large quantities of water may be released and settlement occurs as the water is squeezed from the soil. If the rate of generation of excess water exceeds the discharge capacity of the soil, settlement is impeded and excess pore pressure will develop. The shear strength of the supersaturated soil is greatly reduced and stability is impaired. Understandably, the greatest stability problems are encountered when fine-grained, low permeability, high-ice-content soils thaw.

Morgenstern and Nixon (1971) have shown that the excess pore pressures and the degree of consolidation are dependent on the thaw consolidation ratio (R). This parameter is a measure of the relative rate of thawing, and possible excess water generation, with the permeability and compressibility of the thawed soil. For most cases, this parameter is the relative rate of generation and expulsion of excess pore fluids. The papers offering extensions to the thaw-consolidation theory, mentioned in the previous section, also contain appropriate extensions of the thawing pore pressure theory. These include general thaw rates, layered systems and residual stress. The thaw-consolidation theory was used to predict settlement and pore pressures, resulting from the operation of a warm oil test pipeline at Inuvik. There was extremely encouraging agreement between the theoretically predicated and the actual measurements (Nixon and Morgenstern, 1973).

Tsytovich (1958) states that subsidence of frozen soil when it thaws, caused by rapidly occurring loss of foundation bearing capacity and resulting in the soil being squeezed out laterally from underneath the foundation, is a major cause of the deformation of structures. Lachenbruch (1970) outlined how a thaw bulb created by a warm oil pipeline may, under certain conditions, induce liquification and the flow of the thawed cylinder on relatively flat slopes. The literature on the stability of thawing slopes, and some case histories, have been reviewed by McRoberts and Morgenstern (1974).

McRoberts (1972) has utilized the work on excess pore pressure to formulate estimates of the factor of safety for the stability of thawing slopes. He shows that natural or artificial changes that increase the rate of thaw and/or increase the excess pore pressure contribute to slope instability. Northern Engineering Services Co. Ltd. (1974) have extended this to include the effects of an insulating layer and free draining surcharge loading.

3.6 Thermal Models

Prediction of the natural and disturbed ground temperatures as a result of natural and man-made disturbances, such as the construction of an embankment and lagoon, are very important in permafrost regions. In particular, permafrost thawing and the resultant thaw-consolidation and stability are very dependent on the total thaw and the rate of thawing.

Gold and Lachenbruch (1973) have recently reviewed the literature pertaining to the surface boundary and subsurface thermal conditions in permafrost regions. The thermal calculations and models can generally be classified as steady state or transient state, and the latter may be further sub-divided into problems including and excluding the effects of latent heat of fusion of soil moisture.

3.6.1 Steady State Conditions

Steady state conditions are those achieved after a long period (strictly speaking, infinite) during which the boundary conditions are unchanged. The thermal regime is therefore dependent on only the boundary thermal conditions and the ratio of thermal conductivities of the materials. Although steady state conditions rarely exist in nature, many complex problems can be estimated using these relatively easily calculated conditions. In steady state analysis the thermal components can be solved separately and then combined.

Carslaw and Jaeger (1959) present a number of closed-form steady state solutions to problems with geometrically simple boundaries and relatively homogenous materials. Brown (1963) has presented graphical solutions to a number of thermal problems in permafrost, including the isotherms beneath a warm building, river, lake or lagoon. This type of solution was used by Brown *et al* (1964) to estimate the temperatures beneath a small lake in the Mackenzie Delta which was thermally influenced by nearby rivers, lakes, and the geothermal gradient.

3.6.2 Transient State Conditions

Transient surface temperature conditions are the more common in nature and engineering problems. The actual surface boundary time dependence may, in some cases, be approximated by a step change in temperature or a simple periodic temperature fluctuation. Another major category of transient state solutions are those that consider the latent heat of soil moisture.

Solutions for step change in surface temperature conditions when latent heat is neglected are given in many references (e.g., Carslaw and Jaeger, 1959; Lachenbruck, 1957). Simple sine function periodic surface temperature variation about a mean temperature results in a thermal perturbation at depth. The attenuation and phase displacement of a periodic surface temperature fluctuation at depth in a homogenous, dry soil is given by Carslaw and Jaeger (1959), McKay (1971), and others. Lachenbruch (1959) has extended this to predict the damping of a periodic surface perturbation at different depths in a two- and three-layered soil system.

As moisture content in soil increases,the latent heat becomes dominant in thermal calculations. There are several empirical and semi-empirical techniques to calculate the depth of thaw (or frost) penetration. These assume a step change in surface temperature and can generally be classified as Stephan or Neumann solutions (for formal derivation see, e.g.,Carslaw and Jaeger, 1959; Jumikis, 1966; etc.) The former solution was originally developed for calculating the thickness of ice formation, but has been adapted for thaw calculations by including the soil structure and sensible heat (e.g., Carlson, 1952; Moulton, 1969). The Neumann solution involves the tedious solution of the transcendental equations, but it can be easily estimated graphically with the modified Berggren equation (Aldrich and Paynter, 1953) which can also be used to solve layered problems (Aldrich and Paynter, 1966). A similar solution that has fewer assumptions is presented by Nixon and McRoberts (1973). These solutions can be used to calculate one dimensional thawing such as under the centre of a large lagoon.

There is no analytical solution to a periodic surface temperature that includes the phase change of soils moisture. Lachenbruch (1959) does however present an indirect approximate technique. Berg (1973) utilized this in embankment design by reducing the surface thawing index by a factor determined by the latent heat of the soil and calculating an equivalent sine curve from this adjusted value, thereby reducing the problem to a non-latent heat solution.

3.6.3 Quasi-Static Solution

in some cases, such as during the formation of a large thaw bulb in frozen moist soil, the boundary between the thawed and frozen ground moves relatively slowly, and the non-steady state condition may be approximated by a series of quasi-static states. Utilizing this assumption and a step change in surface temperature, Porkhayev (1963) presents a graphically assisted solution to time dependent,two and three dimensional thawing under a warm building or lake. This could be used to estimate the thaw bulb progression with time as a result of wastewater impoundment. However, the periodic surface temperature and non-linear effects of freezing and thawing soils give erroneous results at the edges, which is the area of interest in embankment design.

3.6.4 Numerical Solutions

Many of the practical thermal problems encountered either do not have analytical solutions or they may be excessively cumbersome. Graphical and analog methods using fluid and electric analogies have been utilized, but computerized numerical methods are presently almost exclusively used. Berg (1973) reviewed twenty such finite difference and finite element computer programs related to soil thermal problems, and Goodrich (1973) has summarized many of the characteristics, advantages and limitations of numerical solutions.

All such programs must include the effect of latent heat to be useful in permafrost problems, and most take this into account over a temperature range, depending on the soil type. Some include the redistribution of moisture during phase change,and thermal influences from moisture movement may be indirectly incorporated. Temperature dependent soil properties are included in most models.

Finite element programs are particularly adapted to two-dimensional problems with complicated boundary geometry. The external boundary thermal conditions that can be imposed vary, but most models assume the surface temperature is a simple time function. The more complete models incorporate a surface energy balance, and some incorporate thaw-consolidation calculation and consideration. Specialized other features are available in some programs.

Numerical solutions are very versatile and may include many complex refinements, however, like any other mathematical solution they are limited by the quantity and reliability of input data and internal mathematical approximations. The random components of surface temperature conditions, and the non-homogeneous nature of soils and their thermal properties, must be considered when utilizing any thermal solutions for engineering design purposes. Presently, the limited availability of these programs, and the high cost involved in manpower and computing time, has limited their use to research and large design projects. However, for many engineering problems in permafrost regions, that have complicated geometric and temperature boundary conditions and internal soil thermal properties, particularly latent heat, numerical solutions offer the only practical solution.

4. STUDY AREA - BACKGROUND AND SITE INFORMATION

The embankment studied in the field investigation impounds the lagoon which serves the town of Inuvik, N.W.T. (68° 18'N, 133° 29'W). The original townsite was contemplated for a population of about 2,000 persons, but the present population is over 3,500. Oil and gas activities, including a pipeline down the Mackenzie Valley, would further accelerate growth of the town. Engineering investigations of the townsite have been made by Pihlainen et al (1956) and Pihlainen (1962). The physical geography of the area has been described by Mackay (1963) and thermal regime information was summarized by Judge (1973). There have also been many engineering and scientific investigations in the Inuvik and Mackenzie Delta areas which contain valuable specific information.

The Inuvik lagoon was constructed in 1957 north-west of the townsite and adjacent to the East Channel of the Mackenzie River (Figures 1 and 2). Impoundment was facilitated by building an embankment road around three sides of a natural depression and installing a wooden overflow weir at the natural drainage point. The lagoon has an irregular shape with a length of approximately 975 m and width of 90 to 225 m. The depth varies with bottom topography and season, but is generally 1.2 m. The surface area is approximately 110 hectares. Effluent from the lagoon discharges via a small creek at the north end of the lagoon and into the East Channel. The area was originally very swampy and no surface vegetation was removed before embankment construction and the filling of the lagoon.

A short embankment at the north-east end was constructed to deflect surface runoff from the lagoon, and in 1972 the embankment height was raised to increase the storage capacity. This second lift is indicated in the embankment cross section drawings and photographs (Photo 2).

The lagoon as a sewage treatment system has been studied by Dawson (1967), Jacobsen (1972), and Miyamoto (1972). The main objections to the lagoon have been a build-up of sludge at the inlet, increased loading leading to reduced efficiency, and encroachment of townsite residential and industrial development. Associated Engineering Services Ltd. (1973), in a report to Environment Canada, have studied alternative sewage treatment methods and recommended construction of a new lagoon system utilizing a few existing small lakes across the East Channel and slightly downstream from the present lagoon site. This was by far the lowest cost acceptable alternative, however, no action has yet been taken on their recommendations.

5. METHODS AND SOURCES OF DATA

5.1 Field Site

Near the end of October 1973, thermal probes were installed and representative soil samples obtained at the study site.

Three holes were drilled through the lagoon embankment to a depth of 12 m to install probes II, III and IV, and one hole 60 m deep was advanced 3.5 m from the downstream edge of the embankment for probe V (Figures 3 and 4). A further probe was also included, labeled I in Figures 3 and 4, to obtain temperature data from the upstream surface of the embankment and along the bottom of the lagoon. In total, 44 temperature stations were employed.

5.2 Instrumentation

Probes II, III and IV consist of Atkins PR 99-3 thermistors installed inside 2.54 cm diameter p.v.c. tubing filled with zonolite insulation. The two remaining probes consist of similar thermistors attached to a flexible p.v.c. cable reinforced by steel bracing wires. Since their installation, only one thermistor has failed.

Leads from the probes were channeled to termination boxes on the sides of the embankment. A meter may be connected to these boxes and each temperature station selected in turn. Temperature readings are made weekly to the nearest 0.28°C (0.5°F) by personnel from the Inuvik Research Laboratory.

5.3 Soil Samples

The holes were drilled using a Nodwell-mounted Mayhew 100 drill-rig and variations of soil and ground water conditions were noted. Representative samples of the subsoils were taken at intervals by pushing a 5 cm diameter split-spoon or 7.5 cm diameter, thick-walled Shelby tubes into the permafrost. Densities and moisture contents of these samples were determined in Inuvik. Samples of the 60 m deep test-hole consisted primarily of disturbed air-returned material.

The soil samples recovered from the drilling operations were analysed by standard laboratory procedures (particle size distribution, hydrometer tests and Atterberg index determinations). Moisture contents were obtained for all samples. Wet density, dry density and ice-content were obtained for the permafrost samples.

6. FIELD RESULTS

6.1 Subsoil Conditions

Three holes drilled through the embankment indicated the gravel layer was 2.5 m thick beneath the higher upstream section, and approximately 1.25 m thick near the lower downstream toe. Underlying the embankment gravel, a brown silt was present to the bottom of each test hole. It was apparent that the bottom portion of the gravel and approximately 0.6 m of the silt deposit was unfrozen. In fact, sloughing from this wet, unfrozen zone prevented sampling near the bottom of the two holes closest to the lagoon. The bore-hole in the undisturbed vegetated area adjacent to the embankment indicated a 0.3 m organic topsoil cover above the silt strata.

One of the recovered samples contained a 15 cm thick ice lens, although most of the ice in the fine-grain silt consisted of visible horizontal layers, varying from 1 - 13 mm in thickness. Near the bottom of the bore-holes, the ground ice was classified as non-visible, well-bonded with excess ice.

6.1.1 Soil Sample Classification and Parameters

The test hole logs, including the measured soil densities and moisture contents, are shown in Figures 5 to 8 (Underwood and McLellan & Associates, 1973) The major physical and thermal soil parameters for the recovered samples are summarized in Table 1.

The Inuvik silt deposit, which comprises the majority of the geologic sequence, was classified as a low plastic silt with a Unified Classification Symbol of ML. The Atterberg liquid limit for the silt varied from 20.4% to 33.9%, with an average value of 25.6%. This average indicates that the clay content is generally low and that the samples consisted primarily of silts. Hydrometer analysis indicated that the silt strata contained an average of 5% clay with a trace of sand, and that the remainder consisted of silt.

Below the 30 m level the average liquid limit was 33.7%, which indicates that the strata contains a greater clay content. A sample obtained from the 60 m level had a liquid limit of 42.4%, a clay content of 30%, and was classified as an organic clay of medium plasticity.

A summary of the soil gradation curves is presented in Figure 9. The cross-hatched area denoted by "A" represents the range of gradation curves for seven samples, collected from the four bore-holes at various depths between 2.5 and 8.0 m. Curve "B" is the gradation curve for an air returned sample recovered from the hole at probe V from a depth of 60 m.

The range of dry densities and excess ice contents obtained varied from 0.64 g/cm^3 to 1.56 g/cm^3 and from 42% to 79%, respectively. In general, the sampling indicated excess ice content of over 70% near the original ground surface; approximately 50% from 1.5 to 5 m depth, and decreasing below this. The deepest undisturbed sample was obtained at the 10.7 m depth, and it had an excess ice content of 40%.

The coefficients of permeability of the unfrozen gravel embankment and underlying silt were estimated to be in the order of 1 cm/sec and 10^7 cm/sec, respectively.

No samples were obtained of the embankment material, however, it was classified as coarse pit run gravel.

6.2 Air Temperature

The average and extremes of climatic data for the Inuvik airport from 1957 to 1971 have been summarized by Smith and Hwang (1973). The daily air temperatures for the study period (November 1, 1973 to October 31, 1974) were analysed and summarised. The mean temperature during this period was -11.08^{o}C, whereas the fourteen year average was -10.1^{o}C. Figure 10 illustrates the mean, maximum and minimum weekly temperatures during the study period (Table 2).

The air temperature may be mathematically represented by a Fourier series made up of annual, daily and random components. Lachenbruch (1959) has compared the effects of actual air temperatures with six-term harmonic analysis and simple sine curve approximations. He found that at a depth of 25 cm the resultant propagated temperature curves were very close. The simple sine curve requires a minimum of data and is easily and quickly calculated, therefore it is generally used to represent temperatures. The simple sinusoidal temperature variation about a mean may be represented by:

$$T_t = T_m + A \sin \left[360 \left(\frac{t + n}{p} \right) \right] \qquad (1)$$

where:

T_t = temperature at time t (^{o}C)

T_m = mean annual temperature (^{o}C)

A = equivalent amplitude (^{o}C)

t = time under consideration (days from the first of the year (January 1)

n = time phase term so that the temperatures may be related to the first of the year (days)

p = period (365 days)

Angle is in degrees. For radians replace 360 with 2π

The mean annual temperature is simply the arithmetic mean of the year's data. The equivalent amplitude may be obtained in two ways. The first method is to calculate the simple curve with the same number of cumulative degree-days above and below the freezing point. This freezing and thawing index method is cognisant of the critical role played by the freezing point in thermal calculations. The two amplitudes calculated will be only slightly different, and these may be averaged or recorded separately. The equivalent amplitude may also be calculated from the temperature mean deviation multiplied by $\pi/2$. This method will give answers very close to the previous method, and since it is easier to calculate it was used to obtain the equivalent amplitudes in Table 4.

The best fit of the minimum and maximum air temperatures during the study period were on January 21, 1974 (day 21) and July 20 (day 201), respectively. The air temperature may therefore be represented by the following simple sine curve approximation:

$$T_t = -11.1 + 23.8 \sin \left[360 \left(\frac{t - 111}{365} \right) \right] \qquad (2)$$

This curve is also plotted in Figure 10 and compares favourably with the actual weekly mean temperatures.

6.3 Surface Temperature

The relationship between air temperature and ground-surface temperature is extremely complex and several modes of energy transfer are involved (Scott, 1964). The large number of components and the complexity and time involved in measuring these has resulted in few examples where a complete analysis has been carried out (Scott, 1969). The most satisfactory and expedient method of establishing the upper boundary for thermal calculations appears to be by direct measurement of temperature near the ground surface (Gold and Lachenbruch, 1973).

Surface temperatures at the study site were measured weekly. This relatively long spacing and the fact that all readings would tend to be taken during the day-time will influence the results and reduce their reliability in representing the actual mean surface temperatures. The fact that the air temperature is measured at the Inuvik airport, which is about 15 km away, does not border the data Mackenzie Delta and is approximately 40 m higher in elevation, must be considered when applying these data to the study site.

The surface temperatures for various surface types are often roughly estimated from the air temperature and a surface factor "n". This factor has been calculated from the study site data (Table 3). There are two distinct surface conditions at the site. A relatively undisturbed, natural vegetated area is represented by Station 34. The mean temperature at this location is 6.9°C above the air temperature. This is primarily a result of a low surface factor (0.54) in the winter due to the insulating snow cover. The dark colour and other factors contribute to a summer surface temperature close to the air temperature.

The embankment is an exposed, dark, soil surface from which snow is not cleared in the winter. The measured winter surface factor was 0.83, which is less than would be expected from a cleared road surface, approximately 0.9 to 1.0, but much higher than the undisturbed site. This may be partially attributed to a higher snow density as a result of exposure, as well as snowmobiles and traffic, including the persons recording the temperatures along the embankment. These factors, however, could not completely account for the very cold near-surface embankment temperatures which responded almost immediately with, and equal to, fluctuations in the air temperatures. Probe II was examined and found not to contain the zonolite packing, thereby allowing air currents within the p.v.c. tube. The fact that probes II and IV protrude approximately 0.5 m above the surface, and each probe has a small metal termination box on top, would encourage the tube to act like a thermopile (e.g., Long, 1964; Miller, 1971). Since this natural one-way valve does not transfer heat during the period when the air temperature is greater than the ground temperatures, only the winter temperatures are thought to be unreliable. The summer surface factors of 1.36 to 1.50 agree well with other studies. For example, Berg and Aitker (1973) measured 1.40 for a dark gravel road surface on a test section of road near Fairbanks.

6.4 Lagoon Bottom Temperature

Thermistors located within the lagoon are at station numbers 2 to 7 (Figure 4). The temperature data analysis is presented in Table 4 and illustrated in Figure 15.

The water level of the lagoon was not measured, however, it varies through the year. The intermediate temperatures at Station 2 indicate that it was probably under the ice for part of the winter. The temperature measurements confirm that the bottom surface of the lagoon is irregular, and some of the thermistors were not anchored firmly on the bottom. If these stations are neglected, the mean bottom temperature is approximately 3.0°C and the amplitude is 8.1°C. The freezing and thawing indices are 360°C-days and 1385°C-days, respectively.

The mean bottom temperature is greater than the freezing point, therefore a permanent thaw bulb exists beneath the lagoon. However, the lagoon does freeze to the bottom, and further, each winter. Neither of these was directly measured. Interestingly, the thawing index on the bottom of the lagoon is roughly the same as the ground surface. The freezing index is, however, considerably reduced due to the high latent heat released by the freezing liquid.

The thermistors located on the lagoon bottom are a considerable distance from where the warm sewage influent enters the lagoon. The temperatures recorded indicate that the heat supplied by the influent sewage, and generated from biological activity, are not significant at the study location. Near the inlet these factors, primarily the former, may be important. Dawson (1967) recorded influent temperatures averaging 23°C during the summer and fall. However, at 350 m from the inlet the fluid temperatures were considerably cooled and approximately equal to the temperature of the effluent at the outlet, which is 975 m from the inlet. He also found that the lagoon froze to the bottom, and only a small channel which was under a hydrostatic pressure remained unfrozen through the winter.

6.5 Embankment and Ground Temperatures

The measured temperature data for the four probes at selected depths are plotted in Figures 11 to 14. The analysis of the weekly data for a one year period is presented in Table 4.

For the reasons given already, the near-surface and 0.61 m depth winter measurements for the embankment probes which are installed inside the p.v.c. tubes are not considered reliable.

The initial readings indicated some transient effects were created by the drilling. In particular, those holes in which sloughing of wet material occurred from the unfrozen zones showed anomalous temperature variations for about two weeks after the probes were installed. A simple calculation indicates that this is approximately the time taken for the wet material to freeze. Near the surface equilibrium conditions were soon reinstated, however at the bottom of the deepest hole (60 m) an estimated 100 days were required. The fact that the temperatures could only be recorded to the nearest 0.28°C (0.5°F) obscured this process, although it was evident.

The attenuation of the extreme air and surface temperatures at depth is illustrated by the ground temperature plots, and by the minimum, maximum and temperature range at each station (Table 4).

The mean temperature and the equivalent amplitude were calculated and presented in Table 4, so that the temperature data, in the form of a simple sine curve, may be reproduced for any station. The amplitude attenuation with depth, and particularly near the surface within the active layer, is apparent. The standard error of the mean is 0.04°C. However, at depths below which the amplitude is less than the temperature recording error of 0.28°C, the amplitude calculated is not statistically reliable. At depths below 20 m, at probe V, the temperatures are not symmetrical, partly indicating prolonged drilling perturbation. The mean temperatures indicate the thermal influences of the undisturbed, vegetated and embankment surface temperatures, the embankment materials, and the water body on the ground temperatures. They are useful in steady state temperature analysis and have been plotted in Figures 21 to 24 for such a comparison.

the lag time shown in Table 4 and Figure 15 is the displacement, in days, of the minimum temperature at the station in relation to the air temperature. The best fit sine curve was used to determine the minimum air temperature. However, thermistors near the surface may be responding to actual air temperatures. For these reasons, the lag times given are primarily for descriptive purposes and probably have an accuracy of plus or minus two weeks. The lag time to the maximum temperatures will not be the same as for the minimum temperature, due to the temperature-dependent thermal properties, but there are insufficient data at this time to present this.

The mean annual temperature, equivalent amplitude, and lag time for each station are shown in Figure 15.

The freezing and thawing indices calculated for each station are also included in Table 4. These show exponential reductions with depth similar to amplitude attenuation. The thawing index is zero below the active layer, while the freezing index reduces slowly below this. The warming influence of the lagoon is shown by a reduction in freezing indices in the probes closest to it.

6.5.1 Freezing Isotherm

In most permafrost considerations the freezing isotherm is of prime importance. Figures 16 to 18 purport to show the location of the 0°C isotherm during the thawing and freeze-back periods. The numbers used to identify the isotherms also indicate the number of weeks since the start of the study period. Generally, the movement of the isotherm is illustrated by plotting the location every two weeks.

Figure 16 indicates the first freeze-back during the study period. The mean air temperature fell below the freezing point on October 3, 1973, and the freezing front progressed into the embankment as shown, while the thawing front from the previous summer continued to descend slightly. As freezing progressed, the thawed zone can be seen to become pinched out and down in the direction of the lagoon. The embankment and soil beneath it were completely frozen by January 21, 1974, therefore a 110 day period had been required. Other isotherms, when plotted on a weekly basis, also showed the same pinching out and down phenomenon as a result of surface cooling.

Figure 17 purports to show the thawing during the summer of 1974. The thawing period began approximately May 10, 1974 and ended September 20, 1974, resulting in a duration of 130 days and thawing index of 1087°C-days. The thaw front progressed very rapidly through the relatively dry embankment material, particularly under the older section. The ice in the lagoon thawed in a short period of one to two weeks.

The initiation of the second freeze-back during the study period is shown in Figure 18. The near surface embankment froze quickly, but the freezing isotherm is retarded at approximately the level of the lagoon water surface. There were also heavy snowfalls at the end of October and in early November so that during November, although the air temperature was 3°C below the average, the surface temperature was 14.2°C above the previous year's. These factors may have caused the halt and retreat of the freezing front as shown. Unfortunately, damage to the temperature recording meter resulted in a long gap in the data, and further freeze-back isotherms could not be plotted. A rough comparison with the previous year (Figure 16) indicates that the freeze-back was retarded by approximately five to six weeks.

6.5.2 Deep Temperature Readings

Deep temperature readings were obtained from probe V. It is located 3.5 m from the embankment and the vegetated surface is relatively undisturbed. Thermistors are placed to a depth of 60 m.

Figure 19 shows the minimum, maximum and mean temperatures, as well as representative mean monthly temperature profiles. Only the mean temperature is plotted below 30 m because the temperature data collected may be unreliable due to the coarseness of the temperature readings and freeze-back errors.

The mean surface temperature recorded is cooler than the mean ground temperature if it is projected to the surface. This is probably due to non-linear effects in the active layer, and re-occurring errors due to non-random temperature recording times. The plot of the mean temperatures near the surface has a slight bow, indicating the thermal influence of the lagoon. At a depth of 22 m, the mean temperature appears to be primarily influenced by the geothermal gradient. The slope of the mean temperature between 22 m and 37 m is approximately 2.5°C/100 m. This is equal to the value estimated by MacKay (1967) and the value calculated by Smith (1972) from data reported by Brown et al (1964) at a study site in the Mackenzie Delta, but less than the 4.3°C/100 m reported by Judge (1973) for Inuvik.

Below 37 m the mean temperatures have a gradient of 6.9°C/100 m, which is higher than the other reported measurements. This steeper slope may be attributed to a number of causes, including a general climatic warming trend in this area in the last 100 years (Gold and Lachenbruch, 1973), historical shifts in the river channel (Smith and Hwang, 1973), and change in soil texture and therefore thermal conductivity.

The large water surface areas of the Mackenzie Delta and the East Channel also thermally influence the deep temperatures. This influence has been estimated by steady state equations in Appendix B and the results are included in Figure 19. It can be seen that the relatively close East Channel has a marked influence on deep temperatures and the thickness of the permafrost layer. In estimating for the Mackenzie Delta, it was assumed to be completely water-covered and infinite in width. However, even then, the thermal influence is not as significant, primarily due to its further distance away from probe V (Figure 1).

If the measured mean temperatures are extrapolated deeper, the permafrost is estimated to end at approximately the 84 m depth. Without the effects of the East Channel and the Mackenzie Delta, the permafrost would be approximately 100 m thick.

6.6 Thaw Consolidation and Stability

No measurements of settlement or pore pressures were taken during the study period or at any time since the embankment and lagoon were constructed. Settlement, however, can be estimated from the present location of the bottom of the gravel embankment and the bottom of the lagoon. If these were initially horizontal, the settlement has been approximately 1.5 m, which corresponds to 40 to 50% of the measured seasonal thaw depth under the embankment.

This rather large settlement has not resulted in appreciable foundation stability problems, although periodic maintenance is required.

7. THEORETICAL RESULTS

Two types of thermal models were utilized to predict thermal and physical consequences of lagoon construction at the Inuvik site. One was a modified steady state temperature analysis, and the other a sophisticated transient state finite element computer model.

7.1 Steady State Analysis

For simple steady state conditions the location of the 0°C, or other isotherm, is independent of the phase change and can be estimated from solutions presented in Appendix B. For the Inuvik conditions the results are shown in Figure 20. Note that near the surface there is little difference in the conditions whether an infinite or a 200 m wide lagoon was used. The geothermal gradient must be added to these results, however, near the surface it is relatively insignificant.

Strict steady state analysis cannot be used, since the 17 years of operation of the lagoon would not have been sufficient time for thermal equilibrium to be reached. A modified solution is therefore used.

For situations which have not yet achieved steady state conditions, the primary concern is the location of the transient thaw front. Below the central part of the lagoon, simple one-dimensional step change in surface temperature, thaw depth calculation methods can be utilized. The measured mean bottom temperature and estimated soil properties were used to estimate the thaw depth to be approximately 7 to 8 m after a 17 year period. Near the edge of the lagoon, steady state conditions will have been quickly achieved due to the periodic surface temperature. The 0°C isotherm at this location would be somewhere between that indicated by the steady state results and the lagoon thaw depth calculations (Figure 20). This freezing isotherm location can be geometrically estimated using the equations in Appendix 1, to calculate an equivalent lagoon width by setting the boundary temperature conditions and the thaw depth below the central part of the lagoon. For the Inuvik conditions this has been calculated (Figure 20).

The quasi-steady state analysis was carried out using a simple explicit finite difference technique to solve numerically the partial differential equations, which describe the time-independent heat conduction (Laplace's equation). It was assumed that all cross-sections of the lagoon and embankment are identical. This reasonably implies that there is negligible heat flow parallel to the lagoon edge, and thereby reduces the problem to consideration of two-dimensions only. To facilitate the convergence to a steady state solution, three consecutively finer grids simulating the embankment cross-section were utilized, culminating in a square lattice of 40 x 40 points, where each grid space equals 0.76 m. For large grids this technique is necessary.

In all numerical solutions the boundary temperature conditions are critical to the thermal predictions. The bottom boundary was calculated to be -2.8°C from the mean surface temperature (-4.0°C), plus the geothermal gradient (0.76°C at 30 m depth using 2.5°C/100) and the East Channel and Mackenzie Delta influences (0.46°C at 30 m depth from steady state calculations). The vertical boundaries were made adiabatic, and the embankment - lagoon interface location was chosen so that the equivalent lagoon width would result in the quasi-steady state solution location of the 0°C isotherm (Figure 20).

Predictions of three surface geometric and thermal boundary conditions are presented and the results compared to the measured mean annual ground temperatures. After these calculations were made, the errors in the measured winter near-surface embankment temperatures were discovered. The predictions are however presented as they were made. In the first case the boundary conditions simulated the actual field conditions (Figure 25). The geometry of the embankment was roughly estimated by the grid, as shown, and the measured mean surface temperatures were imposed. The ratio of the thermal conductivities of the underlying silt and the gravel embankment, whose geometry was approximated as shown in Figure 25, was assumed to be 0.67. Due to the large grid spacing, the organic layer could not be represented geometrically nor was an equivalent thermal resistance included, since the saturated peat would have a weighted average frozen and thawed thermal conductivity not much different than the silt. Of course, for transient state prediction the high latent heat of this layer is important. Using these conditions the predicted temperatures are plotted in Figures 21 to 24. The agreement with probe II, closest to the lagoon, is good. This indicates the usefulness of the equivalent lagoon width technique for quasi-steady state analysis. At probes III and IV, which are further away from the lagoon influence, the near-surface temperature predictions are too cold. This is somewhat expected due to non-linear effects within the active layer and measured surface temperatures. At greater depths the agreement is closer. At probe V these influences are also indicated near the surface, but at depth the predicted temperatures are warmer than measured. This would indicate, as expected, that the quasi-steady state assumption predicts too much perturbation at distances removed from the lagoon.

In order to reduce the influence of any near-surface boundary errors, a number of trials were run utilizing the measured mean temperatures from successively lower depths while adjusting the geometry of the grid respectively. The predicted temperatures were found to approximate the measured data more closely. One of these boundary conditions is shown in Figure 25 and the results are plotted in Figures 21 to 24. In this case the top boundary was chosen to correspond roughly to the bottom of the lagoon, and the embankment and the ground temperature was established as isothermal at -3.7°C, which is the average at that depth. Agreement for this case is excellent, with the only exceptions being near the surface at probe IV where the measured temperature is warmer than the isothermal boundary temperature chosen, and at deep locations in probe V where excess thermal perturbation is predicted.

To illustrate the separate perturbations of the relatively warm bottomed lagoon and the cool surface embankment, another run was made with the conditions as shown in Figure 25, but with the lagoon replaced by a vegetated ground surface temperature of -4.1°C.

A simple steady state analysis was carried out to indicate the changes in the annual ground temperatures that may be expected in the future. These are also plotted and indicate that near the surface, which is the area of primary interest, steady state conditions have been reached, but at depth a few more degrees of warming will result. Further thawing, except for random annual variations, is therefore not expected.

7.2 Transient State Analysis

The transient state analysis was carried out utilizing a finite element computer program (Hwang et al, 1972; EBA Engineering, 1975). The geometry of the embankment was simplified to reduce the number of nodal points to 108, while ensuring that the most critical area, at the lagoon-embankment interface, was included. The vertical boundaries were made adiabatic. The element arrangement, soil stratigraphy and properties, and the surface geometry utilized to estimate the field conditions are shown in Figure 30. The temperature-dependent soil properties, including latent heat, are considered the model. The surface temperature is calculated by a heat balance calculated for each surface type from the long term Inuvik airport air temperature, snow depth, wind velocity and solar radiation as shown in Figures 31 to 34. The temperatures measured during 1973-74 are also shown for comparison. The temperatures at the bottom of the lagoon are shown in Figure 35. Intermediate points on the upstream embankment slope were inferred from the prescribed lagoon and the calculated vegetated slope temperatures.

The lagoon embankment was built-up periodically because of settling, however, the final geometry was utilized throughout this model. The initial rate of the thaw is therefore underestimated. By not including the downstream lower embankment surface, the predicted thaw depth at the downstream vertical adiabatic boundary is also underestimated, but this does not appreciably influence the temperatures near the embankment-lagoon interface.

Simple one-dimensional runs were made to check the input data. The results for the vegetated surface at probe V (Figures 36 to 39) agree well with the measured results. The gravel surface results were good in the summer but very much warmer than the measured near-surface temperatures in the winter. However, as indicated earlier, the measured winter temperatures are unreliable. The predicted thaw depth was to the bottom of a 2.4 m gravel pad.

With the input data previously described, the two-dimensional computer model was used to simulate 17 years of operation. The predicted and measured temperatures for year 17 at various depths for probes II and

III locations are shown in Figures 40 to 45. Again, the summer values are close but the winter temperatures, particularly those near the surface, are much lower.

The predicted location of the 0°C and -0.57°C isotherm for the 17 year period at the upstream model boundary, approximately 2.5 m from the toe and at the location of probe II, are shown in Figures 46 and 47. A permanently thawed zone is predicted under the lagoon. After approximately 12 years the bottom boundary of the thawed zone is at the 1.8 m depth, is not influenced by the periodic surface temperature, and is declining slowly. The predictions at probe II location also indicate a high rate of thawing in the first few years, and much slower after that. Periodic steady state conditions are reached in 3 years. The predicted depth of thaw at probe II after 17 years is approximately 3.1 to 3.7 m, while the measured value was approximately 4.2 m. This discrepancy may be due to an overestimate of the silty organic layer thickness and/or moisture content, errors in interpolating the measured thaw depth, or other factors. The location of the -0.57°C isotherm indicates that only a slight increase in ground temperatures would result in considerably deeper thawing than predicted.

Figures 48 to 50 show the predicted location of the 0°C and -0.57°C isotherms for the model cross-section at representative times during the seventeenth year.

8. DISCUSSION

8.1 Field Data

The soil sampling program indicates that the study area is typical of much of the Inuvik and Mackenzie Delta areas. The undisturbed site is overlain by a layer of organic peat approximately 0.3 m thick, and the brown silt subsurface soil has excess ice content of approximately 70% v/v near the surface and decreases with depth.

The measured ground temperatures indicate the effects of the air temperatures as modified by the undisturbed vegetated surface, the gravel embankment and the lagoon. The ground temperatures at probe V show only slight increases due to the influence of the lagoon, while the near-surface temperatures at probe IV are primarily influenced by the gravel surface and embankment itself. Probes III and II show progressively more influence as a result of the lagoon. These thermal influences are indicated in the mean annual ground temperatures as well as the seasonal depth of thaw, which is approximately 4.3 m at probe II nearest the lagoon and 2.4 m at probe IV at the downstream edge, while the undisturbed site indicates no significant influence, thawing only to 0.6 m. The thawed zone under the embankment completely refreezes each winter.

The lagoon bottom temperatures indicate that there has been a permanent thawed zone created under it, although the lagoon contents freeze to the bottom during the winter. The thaw depth was not measured, but it was calculated to be approximately 7 to 8 m deep after nearly two decades of operation at locations removed from the embankment edge effects and the warm outfall. The temperatures indicate that after centuries of continuous operation, the thaw bulb beneath the lagoon would extend completely through the permafrost layer, which is approximately 100 m thick.

However, within the embankment and its immediate foundation soils, particularly within the active layer, the periodic steady state conditions are likely to prevail. This implies that the thermal regime at the edge of the lagoon should now be independent of the initial transient effects, such as the particular time of year of embankment construction. This is indicated by a comparison of the measured temperatures and thaw depth for similar periods in successive years. Other time dependent effects, such as the random fluctuations of periodic annual temperature and seasonal snow conditions, will influence the surface and ground temperatures. At present there are only a few months of overlapping readings to compare, but these indicate that periodic steady state conditions prevail within and under the embankment. This would indicate that there will be only periodic increases in the seasonal thaw depth under the embankment, and therefore there will be negligible future settlement caused by ground thawing. In any case, the near-surface soils which have the highest excess ice contents have already been thawed, and therefore deeper thawing would result in less percentage settlement than already experienced.

Utilizing the information for similar soils presented by Speers et al (1973) and the near-surface soils data, the total thaw settlement would be approximately 40%. The compaction of the organic layer would have to be added to this. This quick estimate agrees very well with the estimated field value of 40 to 50%.

There do not appear to have been stability problems, and the large settlement has primarily been a maintenance problem. The pervious nature of the wide, low embankment and the underlying organic layer would have aided in alleviating any near-surface excess pore pressures. The high latent heat of the original ice-rich organic surface and silt may also have reduced the rate of thaw, particularly in the first few warm seasons.

The thaw-consolidation under the lagoon has created a slight depression, typical of thermokarst lake formation. Further settlement may be expected if the transient thaw front encounters ice-rich soils. The soil samples from depths greater than 7 to 8 m, the calculated thaw depth, indicate that there is little excess ice and therefore only normal consolidation would occur. However, soil condition and, in particular, ice content can vary considerably over short distances and generalization cannot be made safely.

Measurements indicate that the entire pervious gravel embankment and a variable thickness of the underlying silt thaw each year. This design, therefore, does not prevent seepage through the embankment or within the organic layer between it and the relatively impervious silt. At the study site no evidence of seepage was found. However, seepage icing was observed during the early winter months of 1973 at the downstream toe of the embankment, in an area approximately 150 m northwest of the sewer outfall (Photo 3). At this location, the embankment height and the hydrostatic head are greater than at the study site. At the study site, the water level is only slightly above the original ground level and this is probably the major barrier to seepage. There was also no apparent environmental alteration in the area adjacent to the embankment as a result of any seepage through the embankment. Although inconclusive, bacteriological samples obtained from one slough beside the embankment indicated no public health hazard.

8.2 Steady State Analysis

A steady state analysis was carried out and the results compared to the measured mean annual temperatures. Steady state conditions have not been achieved, therefore, a quasi-steady state technique based on the prediction of the mean thaw front under the lagoon after 17 years of operation was utilized.

The measured embankment surface temperatures, which were later found to be unreliable, were utilized as the surface boundary condition and, therefore, the predicted temperatures, as to be expected, were too cold.

When the measured temperatures at ground levels within the embankment were used as the top boundary condition the agreement was improved. Although this indicates the validity of the prediction method, verification with future data is required.

The steady state results ignore the important contributions from the periodic surface temperature and only indicate the "average" thermal conditions. Because of the non-linearity of the latent heat contribution and temperature dependent thermal soil properties, a simple periodic surface attenuation cannot be simply added to steady state solutions. This limits the usefulness of this type of analysis to geotechnical problems below the active layer. However, in many thermal problems the advantages of the useful super-position technique warrant their simplification so that latent heat effects can be indirectly included and simple steady state predictions can be used.

8.3 Transient State Analysis

The simplified embankment geometry and representative soil stratigraphy were subjected to 17 years simulated operation by a finite element computer model. The program incorporated a heat balance at the ground surface to calculate the ground temperatures from the meteorological data.

The measured winter temperatures are unreliable, therefore, at this time it is difficult to compare the measured and predicted temperatures. The summer, or warm period temperatures, however, show good agreement. The predicted thaw depth below the embankment is approximately 3.1 m and this completely refreezes each winter. Periodic steady state conditions under the embankment were essentially reached after 3 years. Beneath the lagoon a permanent thawed zone is predicted. After 17 years the thaw depth is descending very slowly, independently of the transient surface temperatures.

The transient state results validate the geometric simplifications that were made. Future computer runs on similar problems need only be run to simulate approximately 5 to 10 years of operation to achieve results that would be adequate for engineering design purposes. Naturally, an estimate of longer-term thawing and a safety factor would have to be made and incorporated in this design estimate.

The simplified geometry of the embankment used in the model indicates how the problem may be simplified for analytical solutions. This would entail the combination of the thermal influences from the three distinctive surfaces, which are the embankment surface, the lagoon bottom, and the upstream embankment slope.

9. CONCLUSIONS

The field data, collected after 17 years of operation, indicate that the 2.4 m high Inuvik wastewater impoundment embankment, and approximately 1.5 to 2 m of the underlying foundation, thaw each summer and completely freeze back by early January. The thaw depth is deeper at locations closer to the warm lagoon. Beneath the lagoon, a permanent thawed zone has developed.

The use of low moisture content, relatively high thermal conductivity earth and gravel, to construct the embankment, contribute to this deep, active layer. As well, this material is pervious when thawed, and there is a potential for seepage which could result in environmental damage and endanger public health. At the study site no seepage was detected, largely because of the low hydrostatic head.

The thaw-consolidation of the high ice content foundation soils has been approximately 1.5 m, and for practical purposes can be considered to have failed. The construction of a wide, non-cohesive embankment, and retention of the original organic layer, would have aided in the dissipation of excess pore pressures near the foundation surface, and in minimizing thaw-consolidation damage to the embankment. The large settlement has, therefore, resulted in maintenance problems which have amounted to near reconstruction. The thaw-settlement of the lagoon itself has resulted in the initial stage of a typical thermokarst lake.

Theoretical results were hampered by the unreliability of the near-surface temperatures, measured during the cold period by the probes constructed within P.V.C. tubes. These were found to be hollow, instead of filled with packing to prevent air currents.

The quasi-steady state analysis, used to estimate temperatures after 17 years of operation, compared well with the measured mean annual ground temperatures. The best results were obtained when the measured near-surface temperatures were neglected. At locations further from the lagoon the predicted temperatures were warmer, which would be expected. A steady state analysis, which would only occur after a very long time period, was also carried out. This indicated, that near the surface, periodic steady state conditions have essentially been reached, and further thawing under the embankment would only be due to random climatic variations. Beneath the lagoon the permafrost, which is approximately 100 m thick, will eventually be completely thawed, however this will take many centuries.

The predicted transient state results indicate the trends found in the measured data, and present a more complete analysis of the thermal performance of the embankment. Agreement during the warm period after 17 years of simulation was good, but it is difficult to assess the winter temperatures. However, the predicted values appear more reasonable than the unreliable measured near-surface data.

The finite element model under-estimates the depth of thaw. This may be due to over-estimate of the thickness and/or moisture content of the compressed, organic silt layer beneath the embankment, and other factors, including errors in interpolating the measured temperatures from the widely spaced thermistors. The large distance between the 0°C and the -0.57°C isotherm indicates the sensitivity to interpolation errors, in both the measured and predicted data. The predictions are, however, adequate for engineering design purposes. Future computer runs for similar conditions may require only 5 to 10 years' simulation, thereby greatly reducing the computing time.

10. IMPLICATIONS AND RECOMMENDATIONS

From the Inuvik lagoon case history, field study and theoretical results, as well as other related arctic engineering works, a number of general comments can be made with respect to lagoon construction in permafrost regions. The overall types of construction that will be utilized may be classed as passive or active techniques.

10.1 Passive Construction

Designs which are based on the prevention of embankment foundation thawing are grouped under passive construction techniques. In very cold regions, the short summer and shallow, active layer may result in little or no foundation thawing, and the permafrost level may naturally rise into the embankment resulting in an impervious frozen core. In such cases, the freeboard height would be determined by the maximum thaw depth, and the embankment would have to be wide enough to reduce edge effects. In slightly warmer regions, artificial hydrophobic insulation layers may be used to reduce the thermal influence of the periodic surface temperatures. Placing insulation under the embankment will generally raise the steady state temperatures in the foundation, by reducing the ground cooling caused by the embankment and increasing the thermal perturbation created by the warm lagoon. The maximum thaw depth, however, will be reduced, due to the damping of the periodic temperatures within the high thermal resistance insulating layer. If the insulation layer was placed along the upstream slope, only the thermal influence of the lagoon would be reduced. As well, a hydrophobic insulation would act as an impervious layer to reduce possible seepage. Vertical insulation layer placed in a slot cut into the foundation would act as a seepage barrier, as well as a thermal cut-off wall. Again, from simple steady state analysis, it can be seen that where the absolute value of the mean ground surface temperature is greater than the lagoon temperature, roughly corresponding to the continuous permafrost region, the insulation will in fact raise the foundation temperatures and result in greater thawing. Therefore, this design would be more applicable in the discontinuous permafrost region. Drawbacks to the use of artificial insulations are the high capital and installation costs, and possible damage as a result of any settlement, particularly differential settlement. Any resulting breach in the thermal and seepage barrier would have self-propagating results therefore. Generally, the use of insulation layers would be used only as an aid rather than a singular design.

In areas where the embankment and lagoon construction would cause detrimental deep thawing, and perhaps elimination of permafrost under the embankment, natural or artificial refrigeration could be used. These would be similar to techniques used for water storage dam construction, except that, due to the low height, only horizontal conduits would be practical. Where natural air cooling is used to refreeze and super-cool the embankment, foundation, or an impervious frozen cut-off wall, relatively short length conduits must be used. Longer sections and positive control may be achieved by using fans to force winter air through the conduits. Another form of possible natural cooling would be the use of horizontal thermopiles, which have been used for building foundation (e.g., Miller, 1971), and suggested for hot pipeline use (Rice, 1972). Artificial cooling during the summer, by pumping a refrigerant fluid through pipes emplaced in the embankment or seepage cut-off wall, would require much more equipment and have high operation costs. However, barring mechanical failures, this system ensures freezing even in the discontinuous "warm" permafrost zone. Operational cost of this system may be reduced by storing the winter's "cold" in tanks of salt solution (Johnson, 1971). All of the natural and artificial refrigeration methods would be greatly assisted by insulating the embankment surfaces to reduce heat gain by the enclosed frozen section. Revegetating, shading in the summer, and removing snow in winter would also aid in cooling the embankment.

Where passive construction is used to prevent foundation thawing, seepage through the foundation and embankment must be prevented. This may be accomplished by maintaining a frozen core within the embankment by the methods previously outlined, or by constructing an impervious soil core or installing an impervious membrane within the embankment. The foundation-embankment interface would require special attention.

Although passive construction is possible, the high construction, operation and maintenance costs would generally detract from the relatively inexpensive and low maintenance advantages of sewage lagoon treatment. However, in some applications, such as the inflow and outflow sections, and where local massive ice is encountered, these techniques may be useful, or indeed the only solution.

10.2 Active Construction

An active foundation design in permafrost regions is one which allows thawing, but any settlement and instability that may result is considered. Under the lagoon and upstream embankment slope, this is the only practical solution. At these locations, and perhaps under the embankment as well, measures may be required to decrease the total thaw and rate of thaw, in order to minimize settlement and possible instability problems.

The most obvious way to reduce settlement is by avoiding high ice content soils. This may not be feasible in some locations, and if massive ice is encountered it will greatly complicate the design and increase the cost, perhaps to the point where it is uneconomical and other treatment methods must be sought. In many cases, the settlement may be reduced by pre-thawing or removal of the generally high ice content, near-surface organic and soil layers. Excavation is expedient but expensive, and would probably be limited to the embankment foundation area. Natural pre-thawing, by removal of the surface organic layer, will generally only thaw a few feet per year, although many artificial methods may be used to accelerate this. Both of these techniques must be approached with adequate planning, particularly where supersaturated soils may result.

Where differential settlement is expected, non-cohesive embankment soils should be used. This, however, may allow seepage which will increase the thaw depth, or even perpetuate thawing if the foundation soils are pervious when thawed. If local, relatively impervious soils are available, these would be used to construct an impervious section. Lagoon embankments are generally quite small, therefore, rather than installing a core, it will generally be advisable to construct the downstream half of the embankment of non-cohesive soils. Further from the lagoon the thaw depth, and therefore the settlement, is reduced, and the use of generally, higher moisture content and lower thermal conductivity non-cohesive soils will further reduce the thaw depth. Where impervious soils are not available, impervious membranes could be used. These, however, may be damaged by embankment settlement, and therefore it may be prudent to install the vertical membrane after the initial settlement, which can be large.

Stability problems may arise during the thawing of permafrost foundations, particularly fine-grained, high ice content soils. These can be reduced by avoiding construction on slopes, designing low, wide embankments with flat upstream slopes, reducing the total thaw and the rate of thawing, the promotion of excess moisture and pore pressure dissipation, and other measures. In some cases, the embankment may indeed fail as far as stability, theory and settlement are concerned, without major horizontal movement and other functional problems.

Measures which reduce the total thaw depth generally also reduce the rate of thaw, and therefore increase foundation stability. Staged construction may also be used to reduce the rate of thawing under the embankment and the lagoon. This may include pre-thawing of the whole area, selective excavation, or simply the construction of a very low starter embankment to promote thawing of the near-surface, high ice content soils before the construction of the final embankment and filling the lagoon. Where large settlement and instability are predictable or imminent, the lagoon may even be filled with water for the first year or two before sewage input, so that any initial embankment failure would not endanger public health or cause serious environmental damage. Where large embankment settlements are possible, periodic maintenance will be required to retain the desired freeboard. The embankment, particularly the upstream section, could also be constructed with an initial surcharge. In many areas, settlement will be the greatest during the first few years, however, personnel, maintenance equipment and materials must be available to make immediate repair to the damaged embankment.

10.3 Seepage

The reduction or elimination of seepage is an important factor in the thermal-related design, including thaw-settlement and instability, as well as the function design, including public health and environmental protection. In the former case, sensible heat transport by seepage through the embankment or the foundation will promote deep thawing, with its associated problems. In the case of substantial seepage in warm permafrost areas, there may be progressive thawing and the complete thawing of permafrost in the foundation. The seriousness of these will depend on soil conditions. By the outfall end of the lagoon the sewage should be sufficiently stabilized, and any seepage would receive additional filtration and soil treatment and therefore would be less objectionable than the actual effluent. Even there, however, during the ice-covered period, this will not be true and seepage should be controlled and collected to prevent infiltration or discharge to the surrounding area. Where this cannot be done in compliance with public health and environmental guidelines, then seepage must be prevented. Methods to achieve this, including physical methods such as reduced hydrostatic head, impervious soil embankment or core construction, the use of impervious membranes, and thermal methods such as designs which maintain a frozen core and/or cut-off wall, have been previously outlined.

10.4 Siting

It is obvious that the three main areas of concern with respect to lagoon and embankment construction, settlement, stability and seepage, require trade-offs in the design.

Many adverse situations can be avoided by field surveys and soils investigation, particularly where there is some flexibility in the location criteria. Flat, low-lying areas or natural depressions will improve stability

11. NEEDS FOR FURTHER STUDY

With respect to this study, the immediate need is to repair the thermistor tubes and arrangements have been made to do this. It would be desirable to determine the thaw depth under the lagoon near the embankment. This could probably be done with a steel rod hammered through the thawed soil in the early winter, when there is sufficient ice thickness to support movement. An augered hole through the embankment at that time would indicate approximately the maximum thaw depth, and would provide a check on the thermistor data interpolation.

Weekly temperature recordings should continue. This will provide additional maximum thaw depth data which can be compared to those already recorded, and also more reliable winter embankment surface temperatures. When obtained, these should be compared to the predicted values and the steady state predictions can be re-run with the new mean annual surface temperatures.

The steady state and transient state techniques used in this study have proven to be useful in determining ground temperature changes, resulting from water impoundment in a permafrost region. A further engineering tool would be an analytical solution to this problem. Although many assumptions would have to be made, the usefulness of such an approximate solution warrants some additional theoretical work.

The emphasis of this report has been the thermal regime of the lagoon after it has operated for 17 years. Further field study is required during the first few years of operation of an impoundment embankment in the permafrost region. During this time the settlement and pore pressures will be the largest and both of these, as well as temperatures, should be measured. The new lagoon system proposed for Inuvik, N.W.T., or another study site, may be selected.

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APPENDIX 1 STEADY-STATE MODELS

Simple steady-state models can often be used to approximate much more complicated boundary and internal conditions, and aid in understanding and deriving their solution. Two simple problems related to the temperature regime, as a result of two isothermal surface regions, are presented in this Appendix.

The difference in thermal conductivity between the thawed and frozen soil can be incorporated; however, the geothermal gradient must be added to the calculated temperatures.

Two Isothermal Regions

Figure 27 presents a cross-section which is perpendicular to the line separating two semi-infinite isothermal surfaces at temperatures T_1 and T_2, imposed on the planar boundary of a semi-infinite solid of uniform conductivity. The boundary is denoted by the continuation of the line OX, with the point O representing the separation point of the two isothermal regions, and which is taken as the origin of a set of cartesian co-ordinates as shown.

The set of steady-state isotherms on this diagram are represented by straight lines passing through the point O. The equation defining the temperature distribution is given by Carslaw & Jaeger (1959).

$$T\ (X,Y,) = T_2 + (T_1 - T_2)\ \frac{\arctan}{\pi}\ (Y/X) \qquad \text{(A1.1)}$$

$$= T_2 + (T_1 - T_2)\ (\theta/\pi\ ), \qquad \text{(A1.2)}$$

(Angles in radians)

where θ is the angle between the line OX and the isotherm of temperature T.

If the region with which $T<T_f$ $(T<T_f<T_2)$ has conductivity K_F and the remaining region where $T>T_f$ has conductivity K_T, then in the solution (A1.1) or (A1.2) replace T and T_2 by T' and T_2, respectively here:

$$T' = \begin{cases} (K_T\ /\ K_F)\quad (T - T_f) + T_f & \text{for } T>T_f \\ T & \text{for } T<T_f \end{cases} \qquad \text{(A1.3)}$$

and

$$T_2 = (K_T\ /\ K_F)\quad (T_2 - T_f) + T_f \qquad \text{(A1.4)}$$

The verification of this transformation is included in Appendix 2.

An Isothermal Strip

Figure 28 presents a similar cross-section as described previously in Section A1.1, however, one isothermal surface, or strip, is bordered by similar isothermal regions. The origin is taken at one of the surface temperature interfaces. The temperature distribution can be easily calculated using the equations in Sections A1.1 to A1.4 and the superposition principal for steady state problems, which allows the simple addition of thermal influences.

$$T(X,Y) = T_2 + (T_1 - T_2) \left[\frac{\arctan Y/X}{\pi} + \frac{\arctan Y/W-X}{\pi} \right] \quad \text{(A1.5)}$$

The difference in thermal conductivity of the frozen and thawed soil may be considered by utilizing the transformations in Equations (A1.3) and (A1.4).

Often it is desirable to locate a particular isotherm. This is easily facilitated, since the temperature isotherms are a family of coaxial circles passing through the ends of the isothermal boundary strip, whose centres lie along the perpendicular to the centre line of that strip.

With the conditions shown in Figure 29, the isothermal circles can be located from:

$$r = c/\sin \beta \quad \text{(A1.6)}$$
$$H = c/\tan \beta \quad \text{(A1.7)}$$

where $\beta = \pi T$
and T = Temperature Ratio

$$= (T_f - T_1) / (T_2 - T_1) \quad \text{(A1.9)}$$

The thermal conductivity transformation as given in Equations (A1.3) and (A1.4) can also be applied to this solution.

APPENDIX 2 STEADY-STATE WITH VARIABLE CONDUCTIVITY

This Appendix presents the solution to the steady-state heat flow between two isotherms in a medium when the conductivity is purely a function of the temperature.

The diffusion equation which describes heat-conduction, in a three-dimensional medium of varying conductivity with no heat sources, may be written in cartesian co-ordinates (Carslaw and Jaeger, 1959).

$$\frac{\partial}{\partial x}\left(K\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial Y}\left(K\,\frac{\partial T}{\partial Y}\right)+\frac{\partial}{\partial Z}\left(K\,\frac{\partial T}{\partial Z}\right)=\gamma_c\,\frac{\partial T}{\partial t} \qquad \text{(A2.1)}$$

Here, γ and c, respectively, represent the density and specific heat of the medium K denotes thermal conductivity, and the partial derivative on the right-hand-side gives the variation of temperature with time. Specializing to the steady flow of heat in a region with time-independent boundary conditions, the partial derivative with respect to time makes no contribution and the equation becomes in more compact notation,

$$\text{div } K \text{ grad } T = 0 \qquad \text{(A2.2)}$$

Here, div and grad denote, respectively, the divergence and gradient operations of vector analysis.

When the thermal conductivity is purely a function of temperature (A2.2) may be rewritten as:

$$\text{div grad } T' = \nabla^2 T' = 0 \qquad \text{(A2.3)}$$

which is of the form for describing time-independent, steady-state heat flow in a medium of constant conductivity (Laplace's equation). In (A2.3), we have

$$T' = T_1 + \frac{1}{K_1}\int_{T_1}^{T} K\,dT \qquad \text{(A2.4)}$$

where K_1 is the conductivity when $T - T_1$, the lowest boundary temperature. In Appendix 1, the temperature variation assumed for K is:

$$K = K_F + (K_T - K_F) \times H(T - T_f) \qquad \text{(A2.5)}$$

where, in this case, K_T and K_F represent the thermal conductivities of thawed and frozen soil, respectively, and T_f denotes the freezing temperature. In (A2.5), $H(T-T_f)$ is the Heaviside step-function, given by:

$$H\,(T - T_f) = \begin{cases} 0 & T<T_f \\ 1 & T>T_f \end{cases} \qquad \text{(A2.6)}$$

Solving (A2.3) with the boundary conditions prescribed in Appendix 1 recovers (A2.1) or (A2.2) and substituting (A2.5) into (A2.4) generates the transformation given by (A1.3) and (A1.4).

APPENDIX 3

Photo 1 The Nodwell mounted Mayhew rig drilling through the Inuvik embankment. Probe I was lowered through the cut in the ice in the foreground.

Photo 2 The Inuvik lagoon embankment, looking N.W., showing the completed termination boxes on both sides of the embankment.

Photo 3 An extensive seepage icing at the end of October, 1973, near the downstream toe of the Inuvik lagoon embankment in an area about 150 m N.W. of the sewer outfall.

Table 1: PHYSICAL AND THERMAL SOIL PARAMETERS

Test Hole Probe No.	Hole Depth (m)	Effective Depth (m)	γw (g/cm^3)	γd (g/cm^3)	w (%)	V_I/V (%)	K_T (mcal/s cm °C)	C_F (cal/cm^3 °C)	C_T (cal/cm^3 °C)	L (cal/cm^3)
IV	1.5	0.3	1.39	0.64	115.5	75.9	0.15	0.50	0.87	53.6
III	2.7	0.6	1.68	1.16	44.5	56.8	0.25	0.49	0.75	37.2
III	3.0	0.9	1.94	0.76	153.5	71.4	0.15	0.74	1.33	84.4
V	1.2	1.2	1.36	0.57	139.4	78.6	0.15	0.51	0.91	57.2
IV	3.6	2.4	1.76	1.20	47.2	55.1	0.25	0.52	0.81	40.8
II	5.2	2.7	1.76	1.27	38.3	52.4	0.29	0.50	0.74	35.1
V	2.7	2.7	1.82	1.28	43.1	52.2	0.27	0.53	0.80	39.6
V	4.9	4.9	1.79	1.22	45.9	54.1	0.25	0.53	0.81	40.4
II	7.9	5.5	2.00	1.49	34.3	44.3	0.31	0.55	0.81	36.8
IV	9.1	7.9	1.97	1.53	28.5	42.6	0.34	0.52	0.74	31.4
IV	10.7	9.4	1.98	1.56	26.6	42.0	0.36	0.52	0.73	29.9

LEGEND FOR TABLE 1

The effective depth shown in Column 3 represents the depth below the top of the foundation soil.

γw = Wet density

γd = Dry density

w = Water content as a percent of dry unit weight

V_I/V = Volumetric excess ice content as a percent of total volume assuming saturated samples

K_F = Conductivity of frozen soil

K_T = Conductivity of thawed soil

C_F = Volumetric heat capacity of frozen soil

C_T = Volumetric heat capacity of thawed soil

L = Volumetric latent heat of soil

The conductivities given in Table 1 are evaluated using the data of Kersten (1949). The frozen soil conductivity for all the samples collected is 0.52 mcal/s cm^{o}C (Nixon and McRoberts, 1973).

The volumetric heat capacities and latent heats were evaluated using the relations given by Nixon and McRoberts (1973) and, for the latter parameters, assuming that 10% by mass of the total water content was unfrozen.

TABLE 2 INUVIK CLIMATIC DATA*

MONTH	Air Temperature (°C) 10 Year** Mean	1973	1974	Precipitation (cm) 10 Year** Mean	1973	1974
January	-31.1		-25.8	2.0		3.6
February	-29.8		-33.7	1.2		0.7
March	-24.7		-26.8	1.5		0.1
April	-14.5		-18.2	1.6		0.3
May	- 0.8		- 0.6	1.7		0.3
June	10.2		7.1	1.9		1.8
July	13.4		12.5	3.7		5.7
August	10.4		9.4	4.6		4.2
September	2.8	(5.8)	2.0	2.1	0.6	1.5
October	- 8.0	(- 7.4)	-13.9	3.7	2.0	3.0
November	-21.6	-21.1	(-22.3)	1.7	1.4	3.6
December	-26.9	24.0	(-31.9)	1.8	0.6	2.2
Year	-10.1	-11.1		27.5		

* Obtained at the Inuvik airport; elevation 60m.

**1957 to 1971.

TABLE 3 NEAR SURFACE TEMPERATURE FACTORS (n)

Description	Mean Temperature	Freezing Index	Thawing Index	Surface Factor (n) Freezing Period (Winter)	Surface Factor (n) Thawing Period (Summer)
Air	-11.08(1)	5078	1087	--	--
Natural Vegetation Cover	- 4.18(2)	2746	1225	0.54	1.13
Embankment Surface	- 7.57(3,5)	4231(5)	1476	0.83(5)	1.36
	- 7.08(4,5)	4212(5)	1635	0.83(5)	1.50

(1)Measured daily at Inuvik airport.

(2)Measured weekly at Station 34.

(3)Measured weekly at Station 8.

(4)Measured weekly at Station 25.

(5)UNRELIABLE

TABLE 4

EMBANKMENT TEMPERATURE DATA AND ANALYSIS
November 5, 1973 to October 29, 1974

PROBE	STATION	DEPTH (m)	MINIMUM (°C)	MAXIMUM (°C)	RANGE (°C)	MEAN (°C)	AMP[1] (°C)	LAG[2] (Days)	FI[3] (°C-Days)	TI[4] (°C-Days)
	AIR(5)		-46.7	28.9	75.6	-11.08	23.80	-	5078	1087
	1	-	-18.6	26.1	44.7	- 3.40	17.63	42	2800	1561
	2	-	- 9.2	20.6	29.7	1.06	10.89	49	1025	1410
	3	-	- 4.2	17.8	22.0	2.59	8.73	42	438	1379
I	4	-	- 3.3	16.7	20.0	3.13	7.72	42	255	1392
	5	-	- 8.9	16.7	25.6	1.47	0.90	42	869	1406
	6	-	-11.4	16.7	28.1	0.58	11.02	42	1171	1381
	7	-	- 5.0	15.8	20.8	2.71	7.75	42	397	1384
	8(5)	0.0	-35.0	23.3	58.3	- 7.57	23.94	14	4231	1476
	9(5)	0.61	-24.7	18.9	43.6	- 7.14	18.08	28	3665	1068
	10	2.13	-12.2	4.4	16.7	- 3.55	7.14	49	1441	243
	11	3.66	- 6.9	0.0	6.9	- 2.43	3.18	70	885	0
II	12	5.18	- 4.4	-0.6	3.9	- 2.15	1.65	98	784	0
	13	6.71	- 3.3	-1.1	2.2	- 2.03	1.03	98	737	0
	14	8.23	- 2.8	-1.4	1.4	- 1.97	0.73	140	718	0
	15	9.75	- 2.8	-1.7	1.1	- 2.05	0.52	175	745	0
	16	11.28	- 2.8	-1.9	0.8	- 2.19	0.32	196	795	0
	17	0.61	-21.9	14.7	36.7	- 5.32	16.02	42	3007	1069
	18	2.13	-12.2	1.1	13.3	- 3.77	6.72	49	1423	53
	19	3.66	- 7.8	-0.3	7.5	- 3.06	3.46	77	1112	0
III	20	5.18	- 5.0	-0.8	4.2	- 2.60	1.83	91	947	0
	21	6.71	- 3.9	-1.4	2.5	- 2.56	1.15	112	931	0
	22	8.23	- 3.3	-1.7	1.6	- 2.46	0.79	147	896	0
	23	9.75	- 3.1	-1.9	1.2	- 2.39	0.55	175	871	0
	24	11.28	- 2.8	-1.9	0.9	- 2.40	0.33	175	873	0
	25(5)	0.0	-35.8	26.9	62.7	- 7.08	24.27	0	4212	1635
	26(5)	0.61	-20.6	25.8	46.4	- 4.71	18.17	-	3154	1439
	27	2.13	- 9.7	0.6	10.3	- 3.03	5.19	77	1128	25
	28	3.66	- 6.9	-0.6	6.4	- 2.94	2.85	84	1069	0
IV	29	5.18	- 5.0	-1.1	3.9	- 2.82	1.74	98	1027	0
	30	6.71	- 3.9	-1.7	2.2	- 2.81	1.17	112	1023	0
	31	8.23	- 3.6	-1.9	1.7	- 2.69	0.82	175	978	0
	32	9.75	- 3.3	-2.2	1.1	- 2.67	0.59	175	972	0
	33	11.28	- 3.1	-2.2	0.8	- 2.63	0.38	175	957	0
	34	0.0	-16.9	26.4	43.3	- 4.18	15.64	0	2746	1225
	35	0.61	-10.3	1.1	11.4	- 3.89	6.26	49	1458	43
	36	3.66	- 6.1	-1.4	4.7	- 3.56	1.86	98	1297	0
	37	6.71	- 4.2	-2.2	1.9	- 3.26	0.94	189	1188	0
V	38	14.33	- 3.3	-2.8	0.6	- 3.01	0.30	427	1097	0
	39	21.95	- 3.3	-2.8	0.6	- 3.08	0.17	-	1120	0
	40	29.57	- 3.1	-2.5	0.6	- 2.82	0.19	-	1027	0
	41	37.19	- 3.1	-2.5	0.6	- 2.67	0.26	-	968	0
	42	44.81	- 2.5	-1.9	0.6	- 2.25	0.19	-	821	0
	43	52.43	- 2.2	-1.7	0.5	- 1.80	0.28	-	655	0
	44	60.05	- 1.4	-1.1	0.3	- 1.23	0.23	-	451	0

FOOTNOTES:

(1)Amplitude is calculated from the Mean Deviation

(2)Lag Time is the phase displacement (in days) of the coldest temperature relative to the air temperature.

(3)FI and TI refer to Freezing and Thawing Indices at each station.

(4)Air temperature is measured at the Inuvik airport. Ten year mean is - 10.1°C.

(5)UNRELIABLE

FIGURE 1 AIRPHOTO OF INUVIK LAGOON AREA

FIGURE 2 PLAN OF INUVIK LAGOON

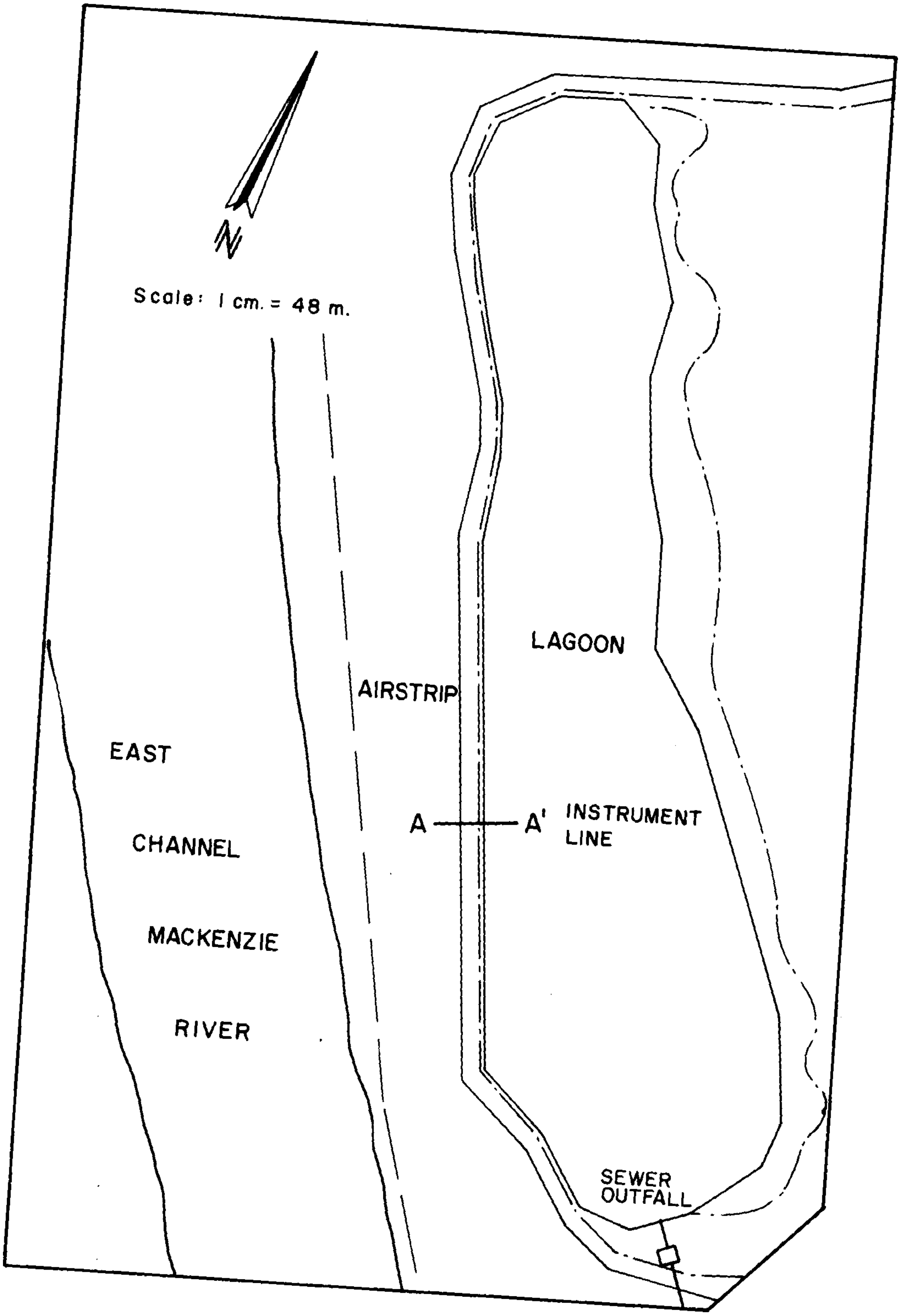


FIGURE 3 PLAN OF STUDY SITE

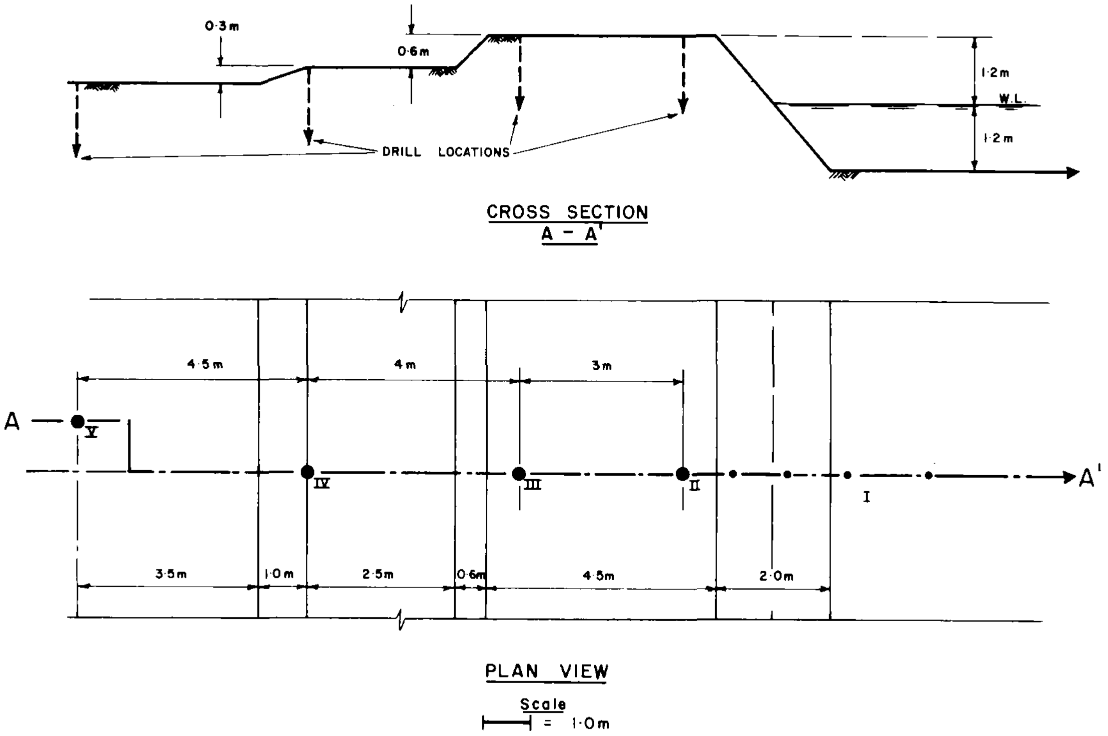


FIGURE 4 LOCATIONS OF THE TEMPERATURE STATIONS

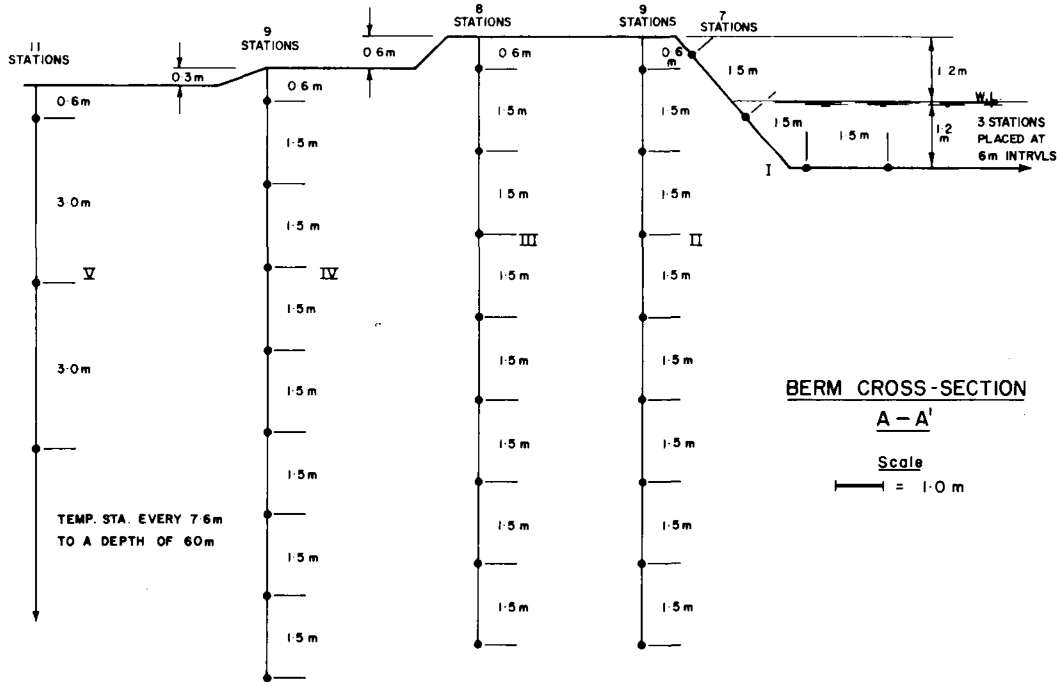
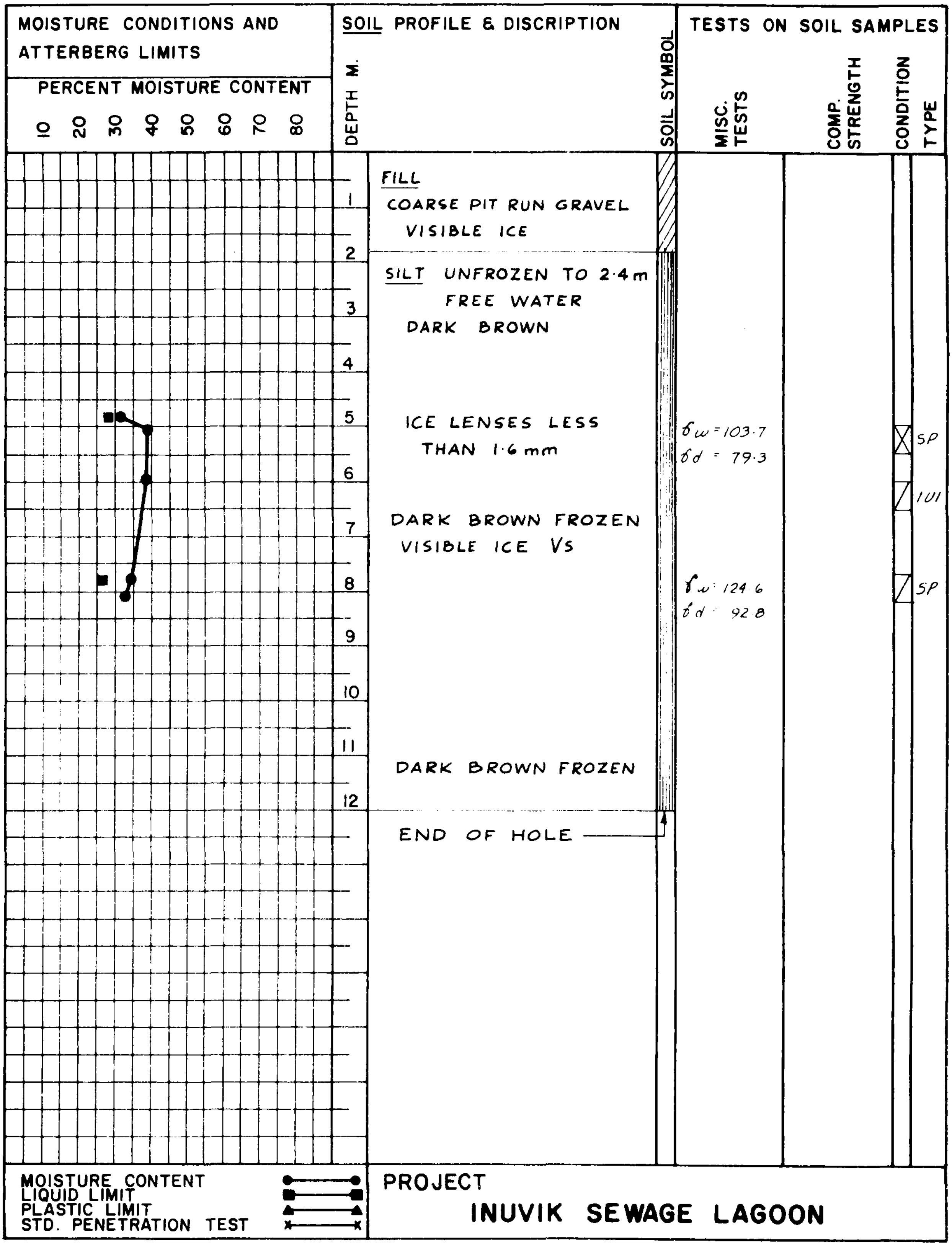


FIGURE 5 TEST HOLE AT PROBE II 23 OCT 1973

TESTS HOLE LOG & SUMMARY OF LABORATORY TESTS – INUVIK NWT.



FILL
COARSE PIT RUN GRAVEL
VISIBLE ICE

SILT UNFROZEN TO 2·4m
FREE WATER
DARK BROWN

ICE LENSES LESS
THAN 1·6 mm

DARK BROWN FROZEN
VISIBLE ICE Vs

DARK BROWN FROZEN

END OF HOLE

$\gamma_w = 103{\cdot}7$
$\gamma_d = 79{\cdot}3$

$\gamma_w : 124{\cdot}6$
$\gamma_d : 92{\cdot}8$

PROJECT
INUVIK SEWAGE LAGOON

FIGURE 6 TEST HOLE AT PROBE III 23 OCT 1973

TESTS HOLE LOG & SUMMARY OF LABORATORY TESTS – INUVIK NWT.

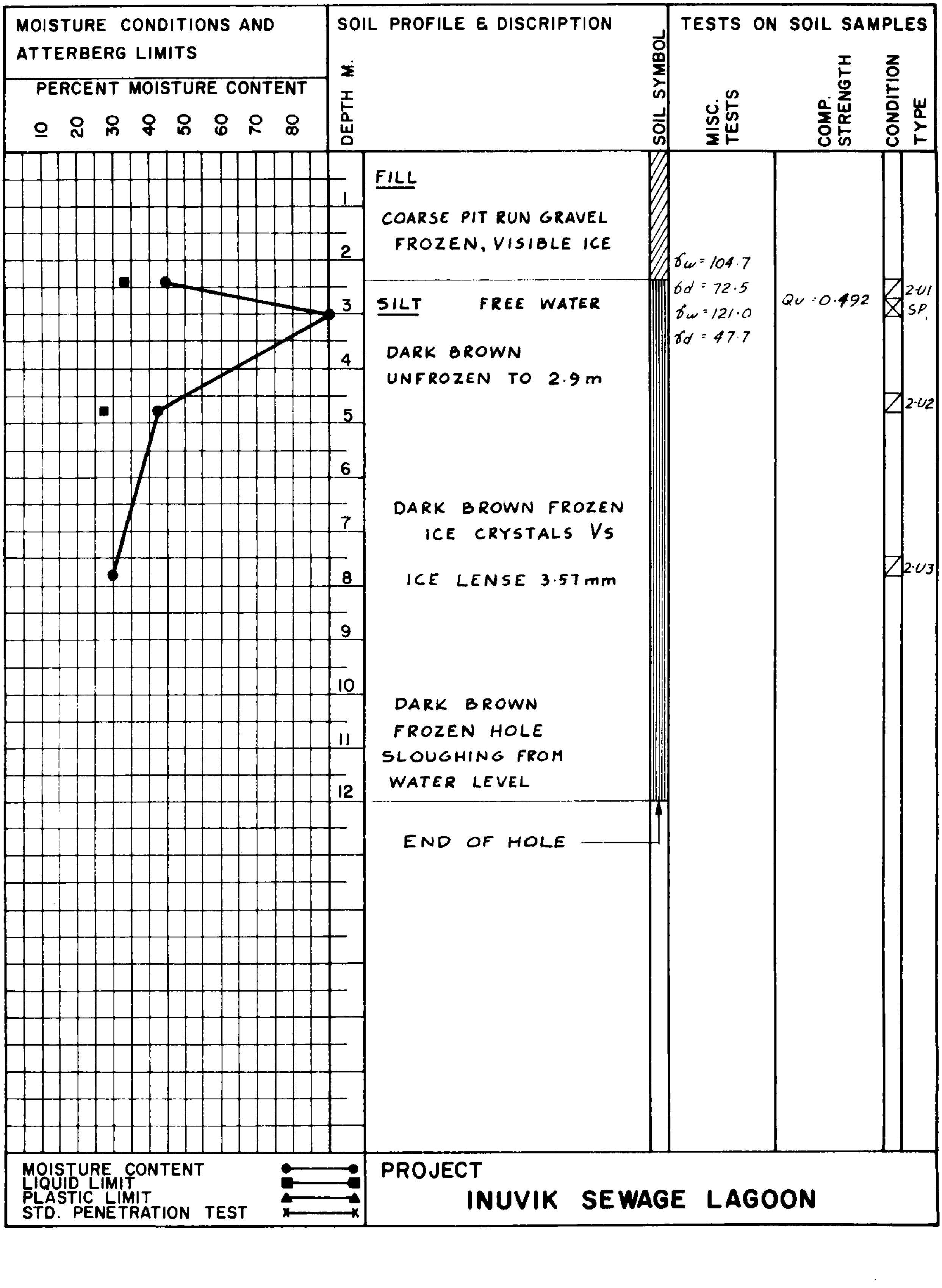
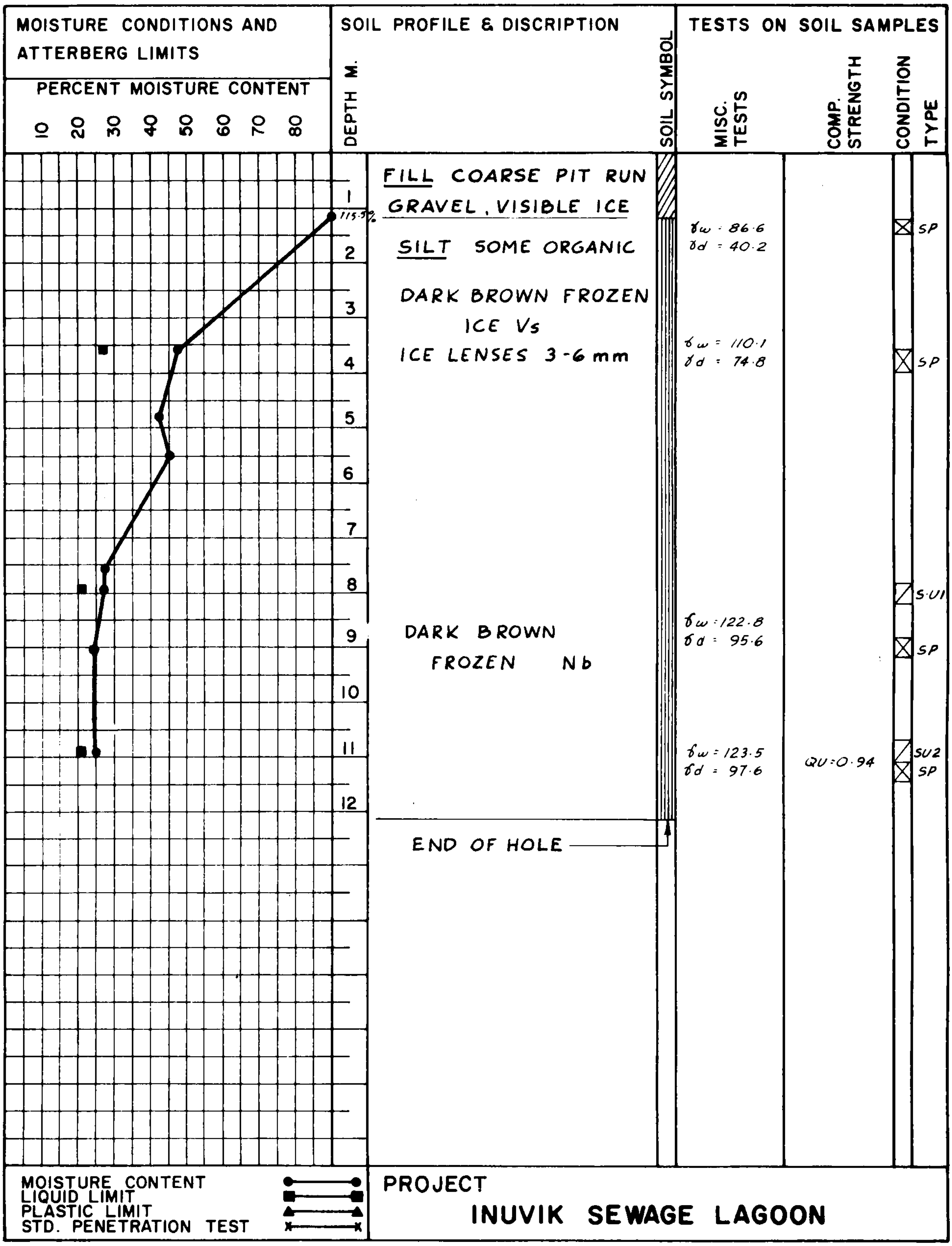


FIGURE 7 TEST HOLE AT PROBE IV 23 OCT 1973

TESTS HOLE LOG & SUMMARY OF LABORATORY TESTS – INUVIK NWT.



FILL COARSE PIT RUN GRAVEL, VISIBLE ICE

SILT SOME ORGANIC

DARK BROWN FROZEN
ICE Vs
ICE LENSES 3-6 mm

DARK BROWN
FROZEN Nb

END OF HOLE

MISC. TESTS	COMP. STRENGTH	CONDITION	TYPE
γ_w = 86.6 γ_d = 40.2		☒	SP
γ_w = 110.1 γ_d = 74.8		☒	SP
		◩	S·U1
γ_w = 122.8 γ_d = 95.6		☒	SP
γ_w = 123.5 γ_d = 97.6	QU = 0.94	◩ ☒	SU2 SP

PROJECT
INUVIK SEWAGE LAGOON

FIGURE 8 TEST HOLE AT PROBE V 23 OCT 1973

TESTS HOLE LOG & SUMMARY OF LABORATORY TESTS – INUVIK NWT.

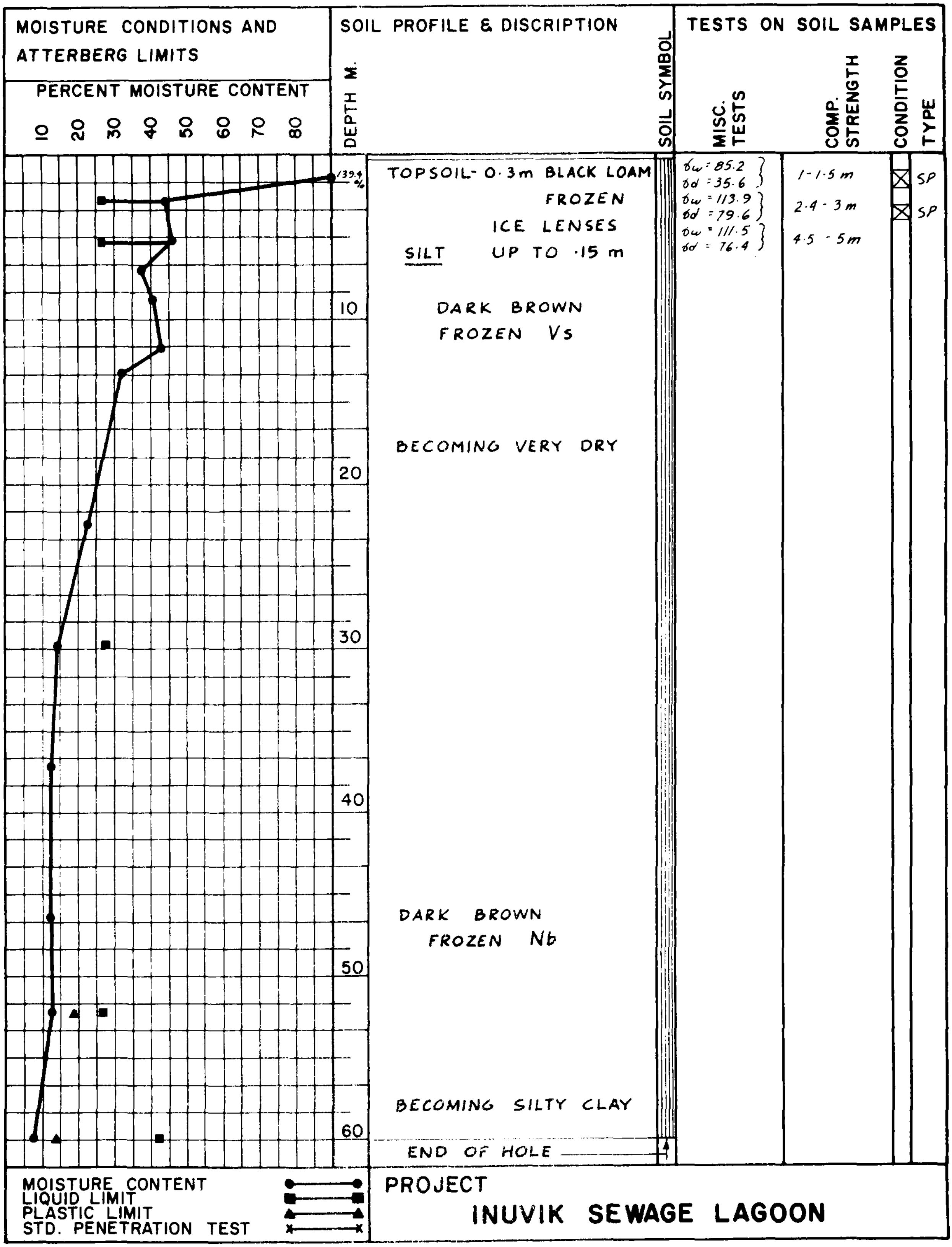


FIGURE 9 GRADATION CURVES

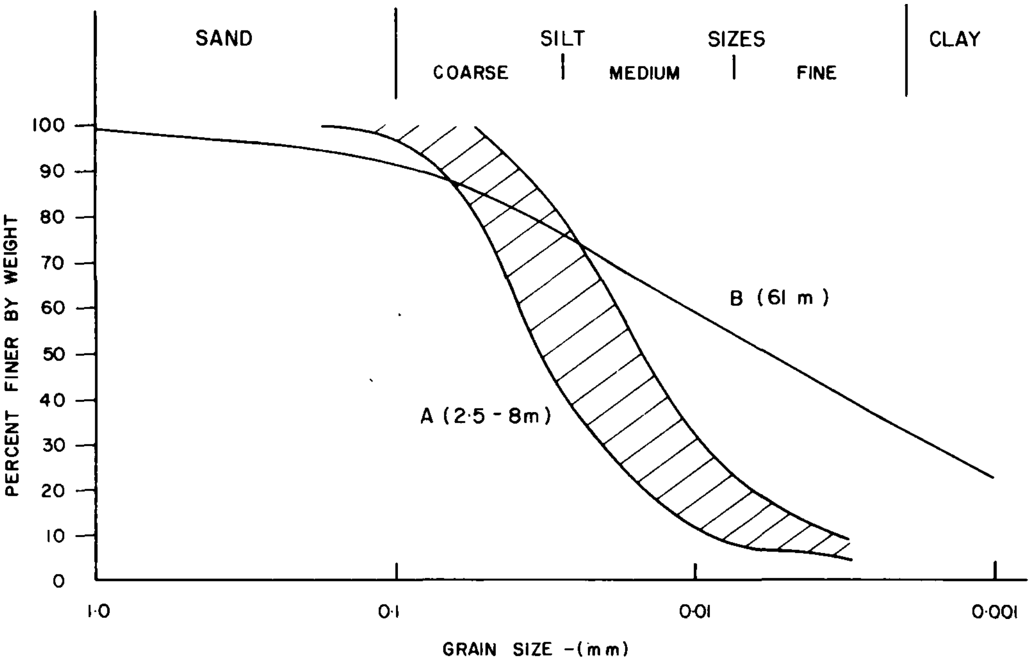


FIGURE 10 - MINIMUM, MAXIMUM AND MEAN WEEKLY AIR TEMPERATURES AT INUVIK AIRPORT AND SINE CURVE APPROXIMATION

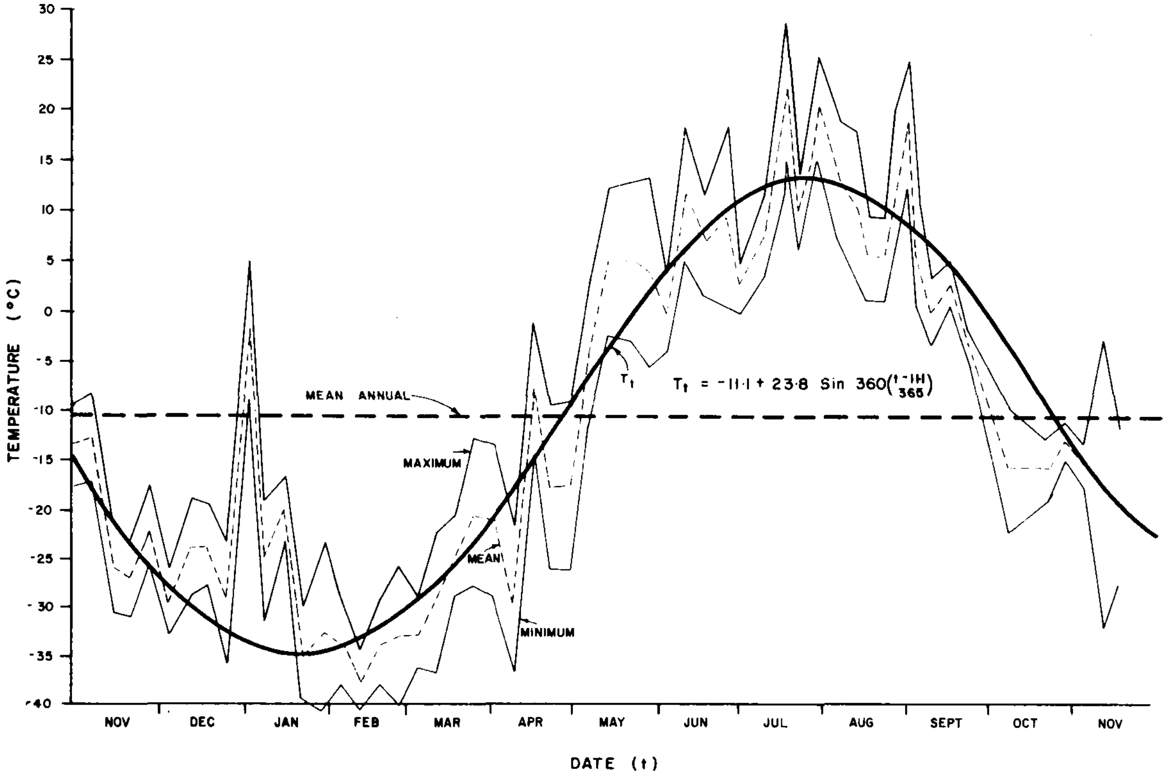


FIGURE 11 MEASURED GROUND TEMPERATURES AT PROBE II

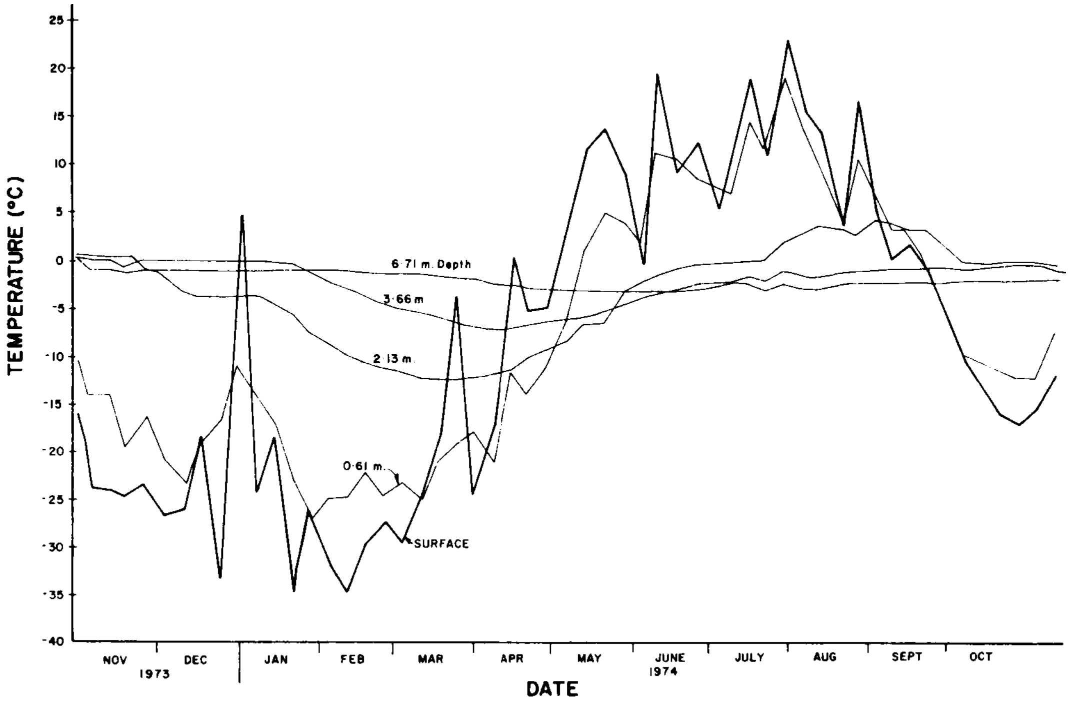


FIGURE 12 MEASURED GROUND TEMPERATURES AT PROBE III

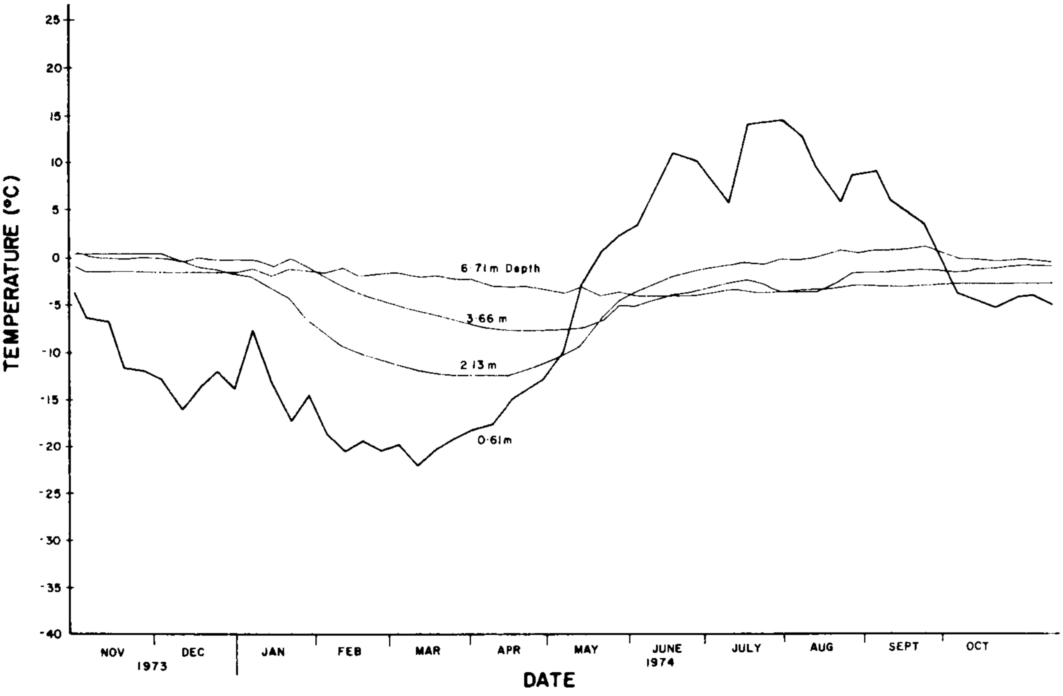


FIGURE 13 MEASURED GROUND TEMPERATURES AT PROBE IV

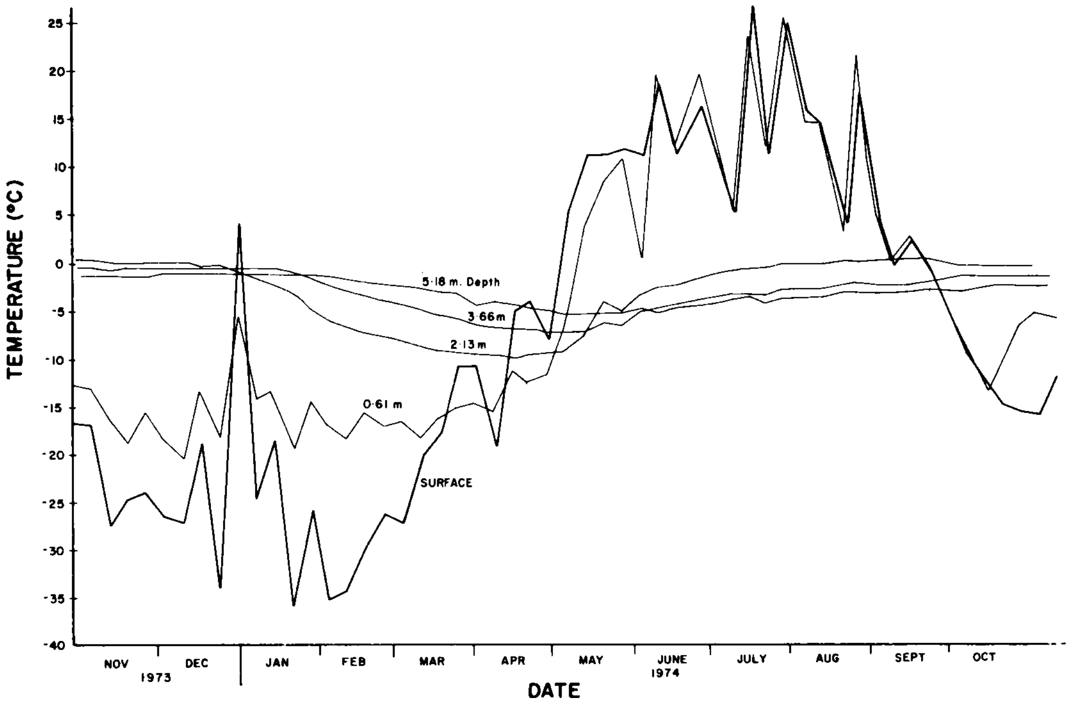
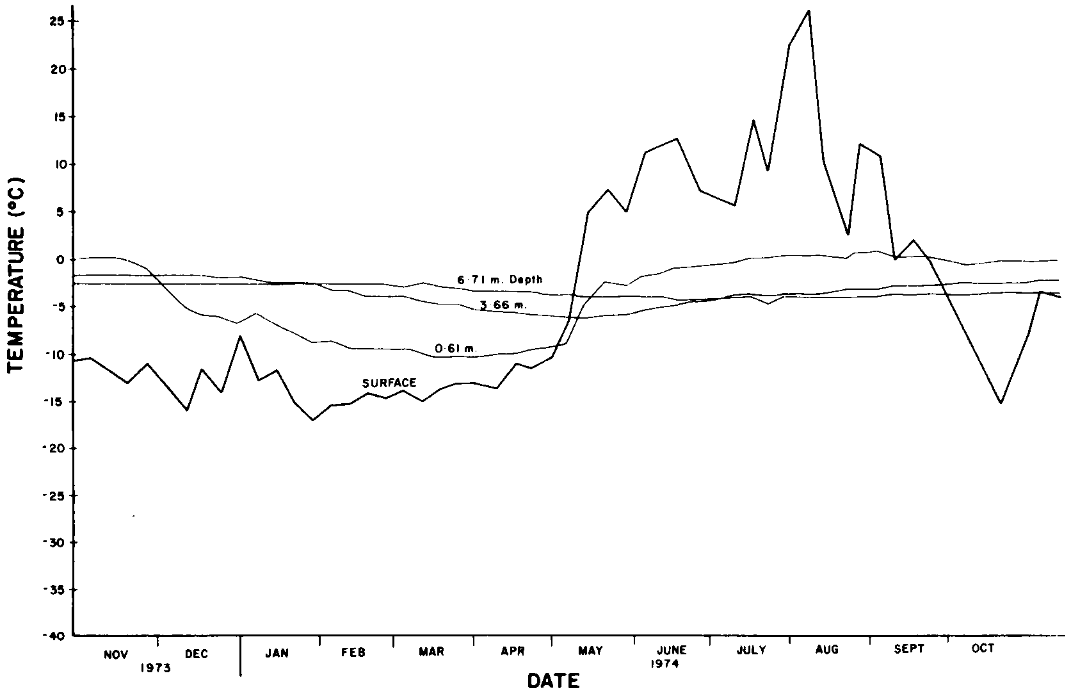


FIGURE 14 MEASURED GROUND TEMPERATURES AT PROBE V



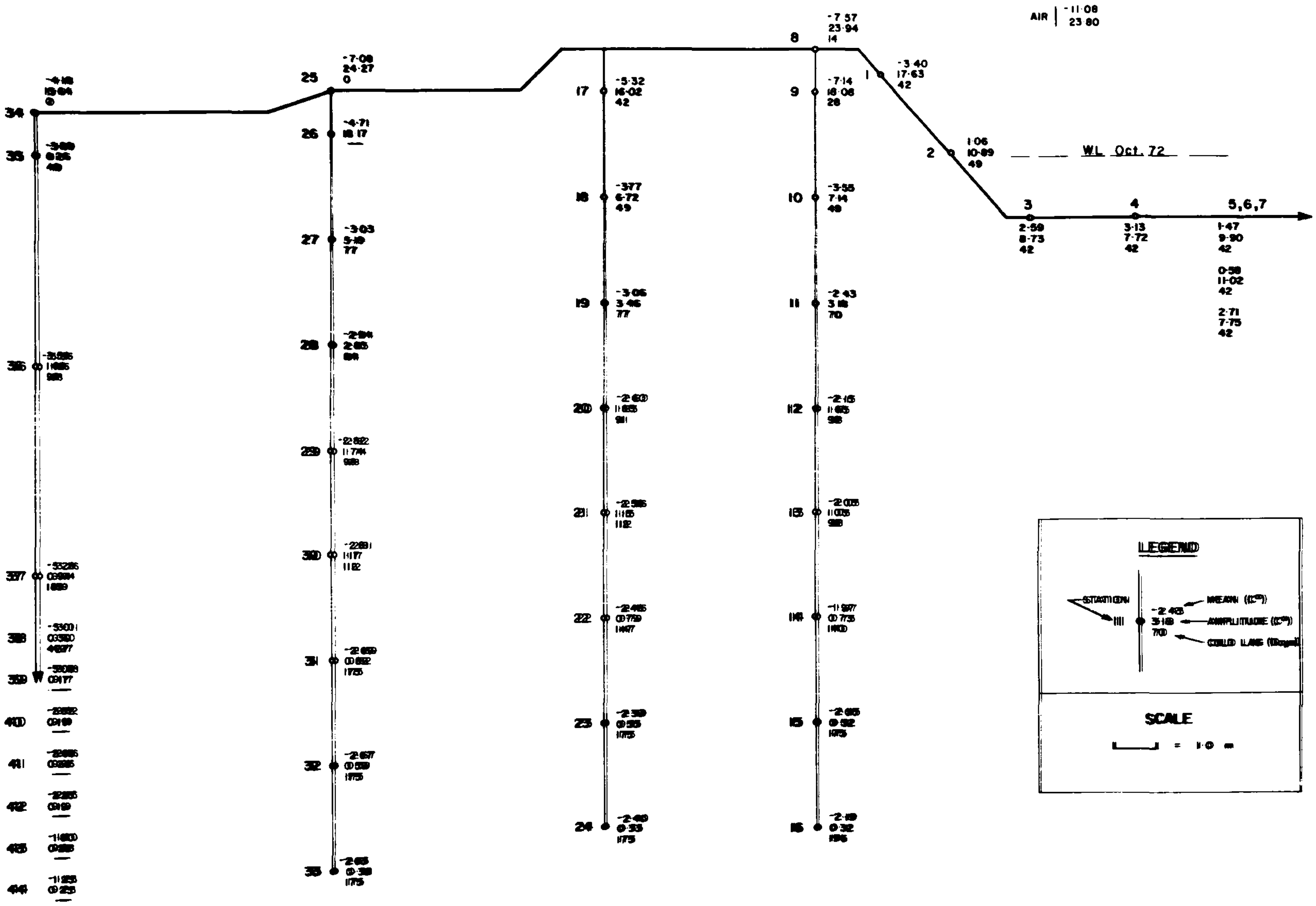


FIGURE 15. EMBANKMENT TEMPERATURE DATA

FIGURES 16,17&18 LOCATION OF FREEZING ISOTHERMS AS INTERPRETED FROM GROUND TEMPERATURE DATA

LEGEND

FIGURE 16			FIGURE 17			FIGURE 18		
CODE	DATE	COMMENTS	CODE	DATE	COMMENTS	CODE	DATE	COMMENTS
1	05/11/73	-Start of data collection	27	06/05/74	- Start of ground thawing period.	45	09/09/74	- Start of freeze back period.
3	19/11/73		28	13/05/74		47	23/09/74	
5	03/12/73		29	21/05/74		49	07/10/74	
7	17/12/73	Freeze back period approximately 110 days	31	03/06/74		51	21/10/74	
9	31/12/73		33	17/06/74	Thawing Period Approximately 130 days	53	04/11/74	
11	14/01/74		35	03/07/74		55	19/11/74	
12	21/01/74	- End of freeze back period.	37	16/07/74		57	02/12/74	
			39	29/07/74				
			41	12/08/74				
			43	26/08/74				
			45	09/09/74	- Start of ground freezing period.			

NOTE* CODE refers to designation in Figures to identify isotherms at the date indicated and is also the number of weeks since the start of temperature data collection.

FIGURE 16

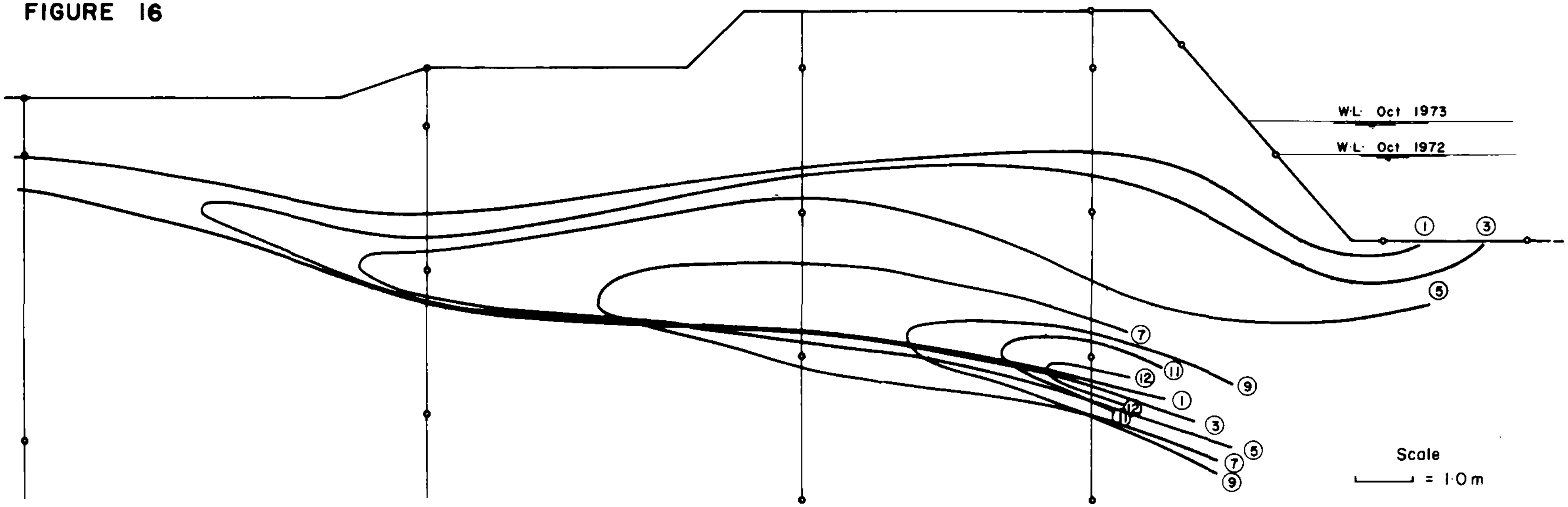


FIGURE 17

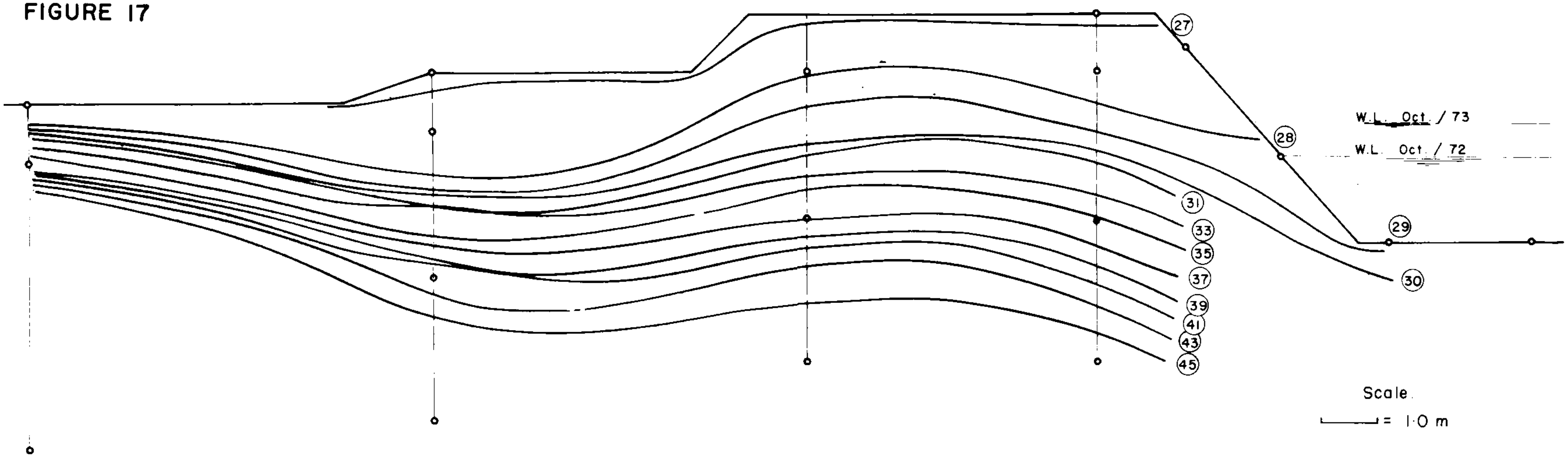


FIGURE 18

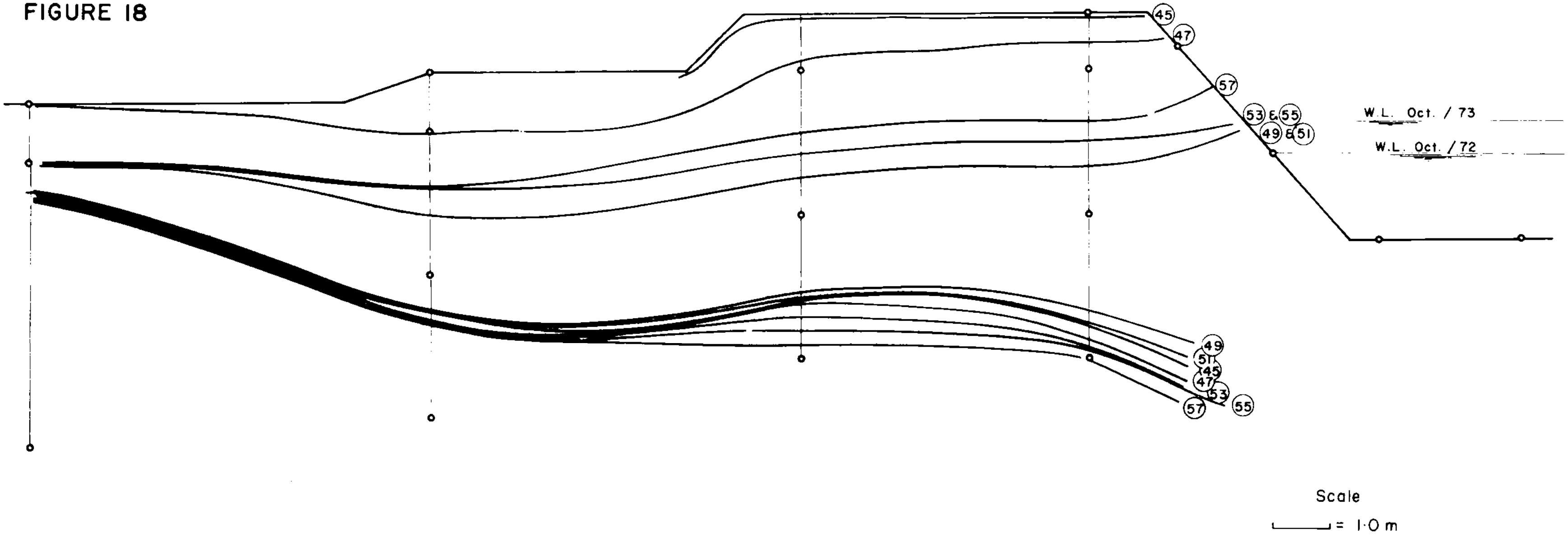


FIGURE 19 GROUND TEMPERATURE INFORMATION FOR PROBE V

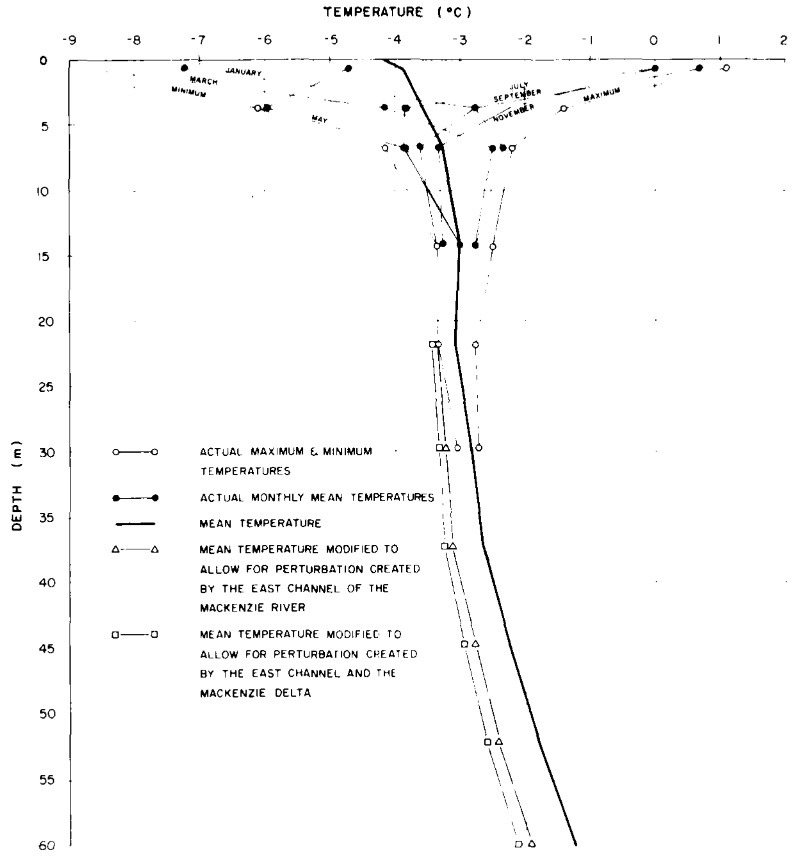


FIGURE 20 STEADY STATE APPROXIMATIONS

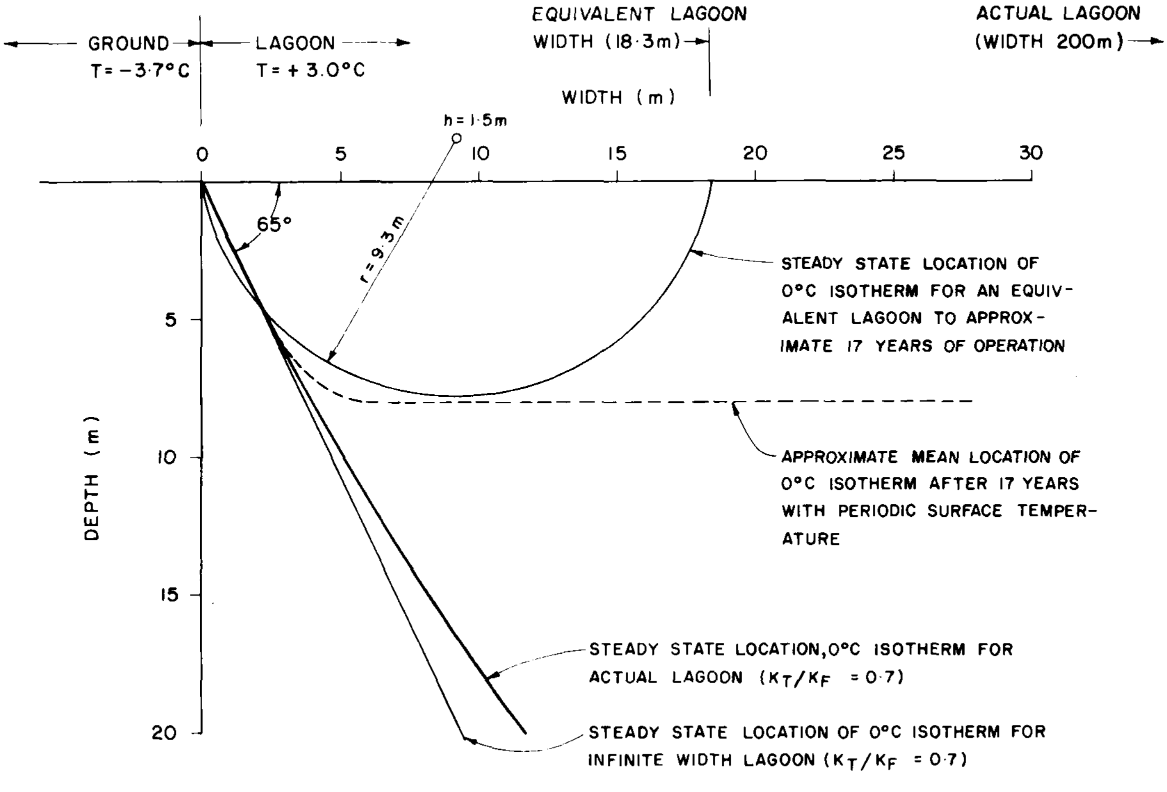


FIGURE 22 PROBE III

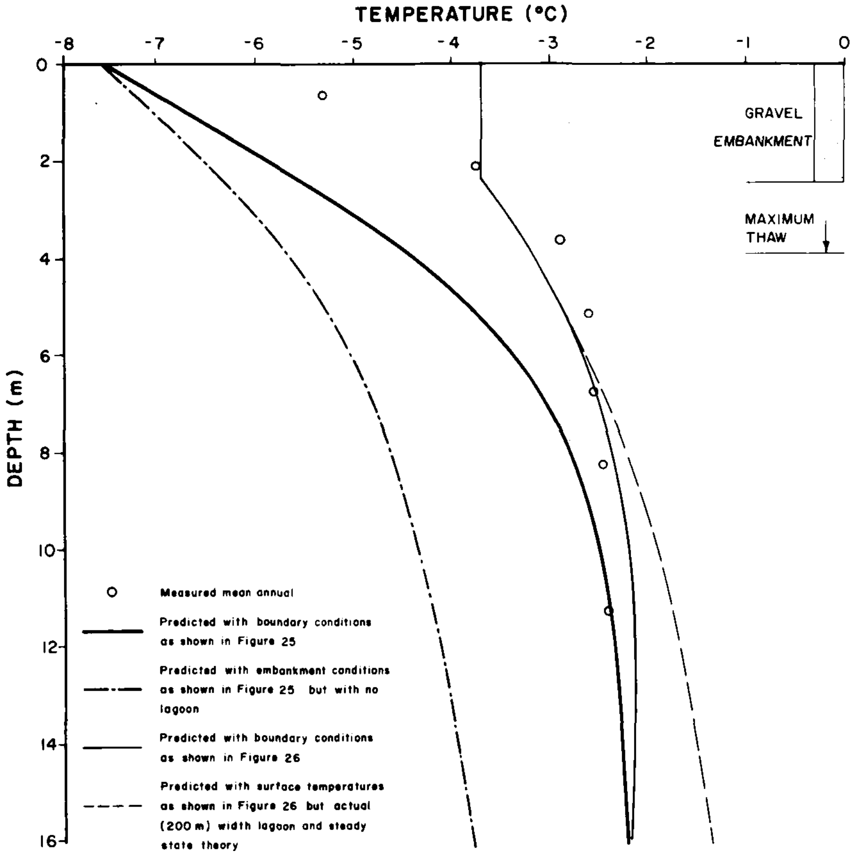
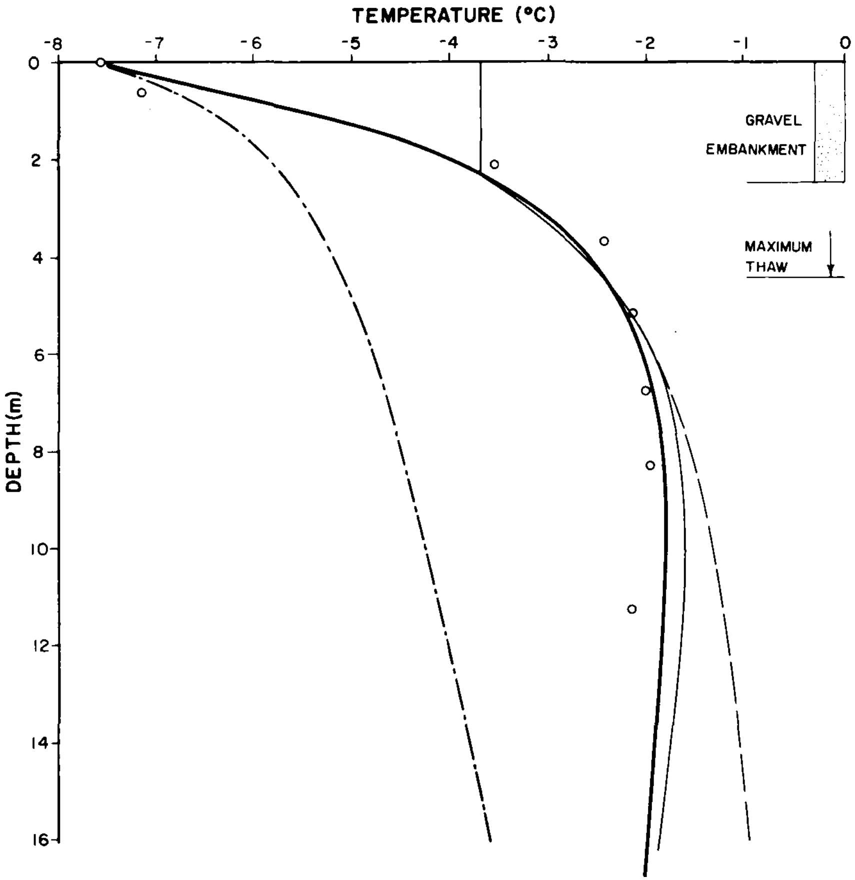


FIGURE 21 PROBE II



MEASURED MEAN AND PREDICTED QUASI-STEADY STATE GROUND TEMPERATURE

FIGURE 24

PROBE V

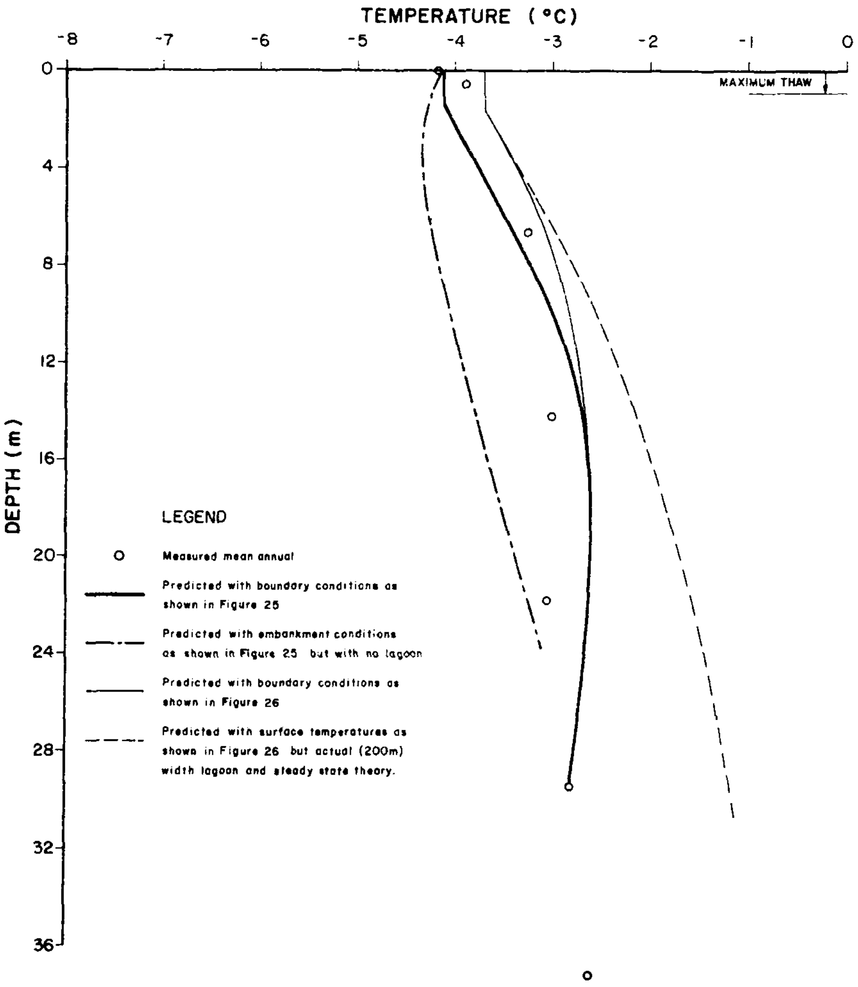
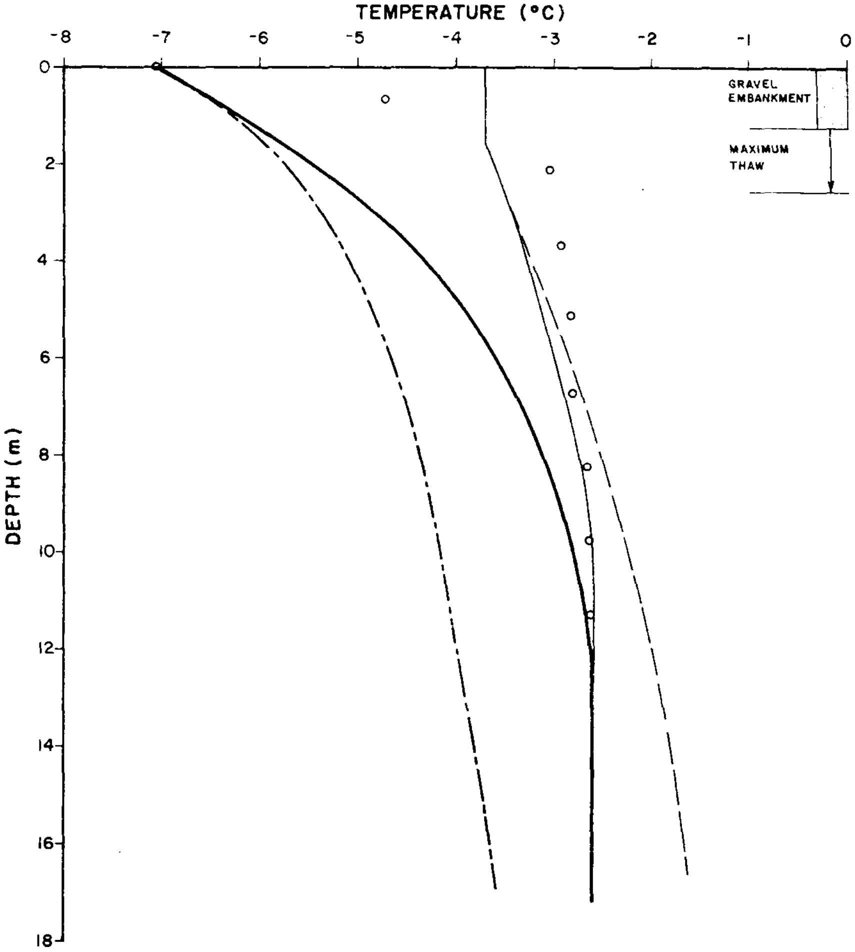


FIGURE 23

PROBE IV



MEASURED MEAN AND PREDICTED QUASI-STEADY STATE GROUND TEMPERATURES

FIGURES 25, 26 BOUNDARY CONDITIONS FOR QUASI-STEADY STATE PREDICTION USING FINITE DIFFERENCE NUMERICAL SOLUTION

FIGURE 25 MEASURED SURFACE TEMPERATURES

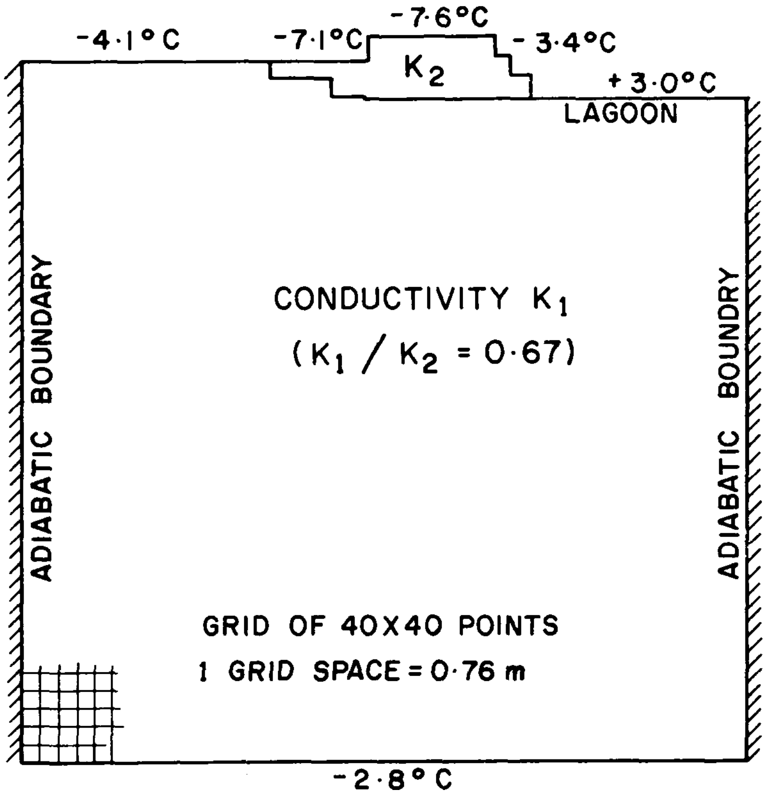


FIGURE 26 APPROXIMATE TEMPERATURE AT BOTTOM OF EMBANKMENT

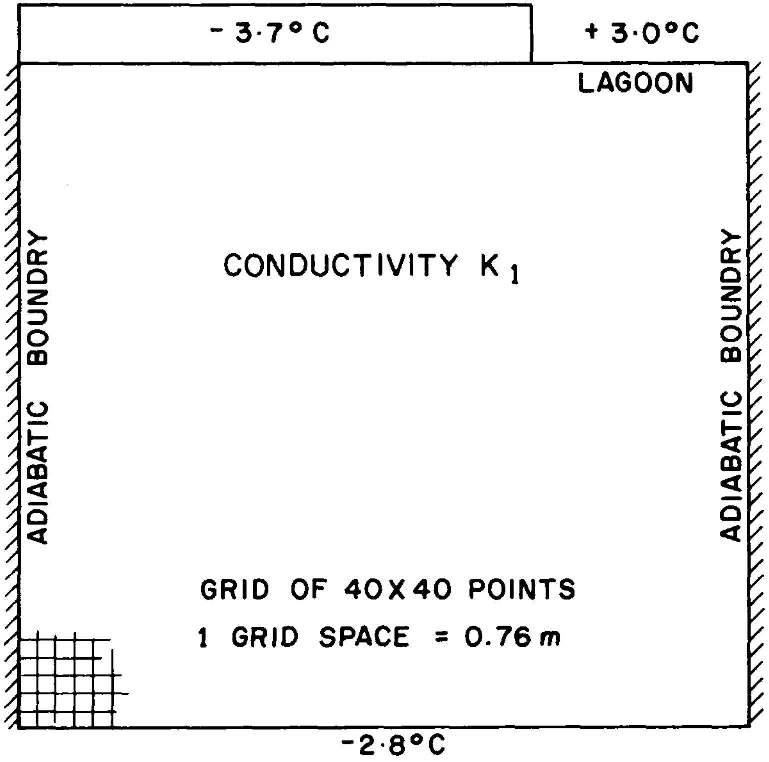


FIGURE 27 COORDINATE REPRESENTATION FOR TWO ISOTHERMAL REGIONS

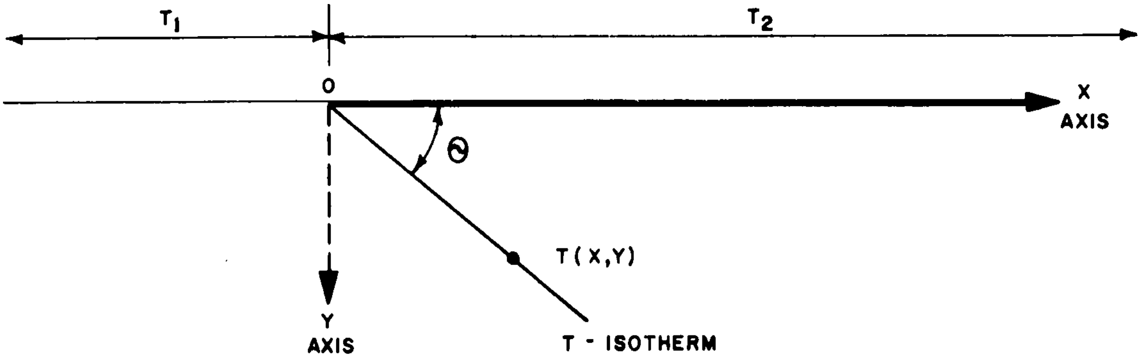


FIGURE 28 COORDINATE REPRESENTATION FOR AN ISOTHERMAL STRIP

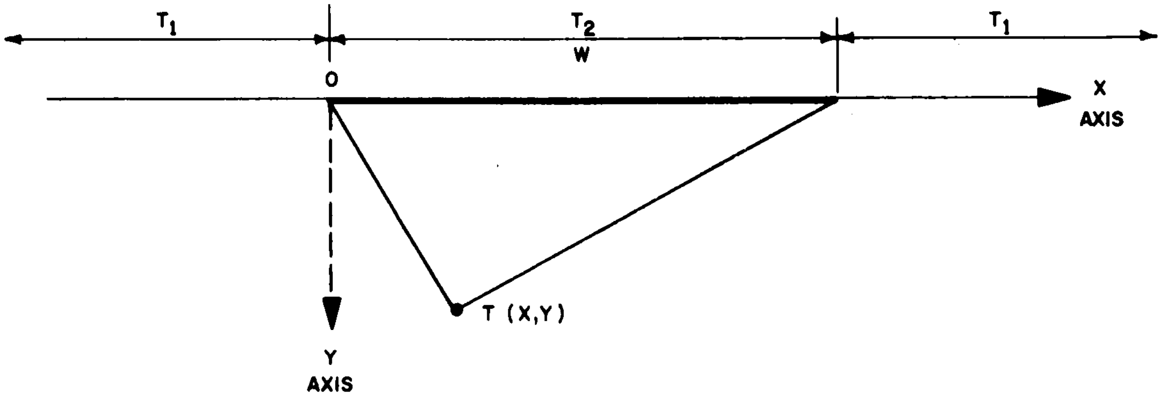
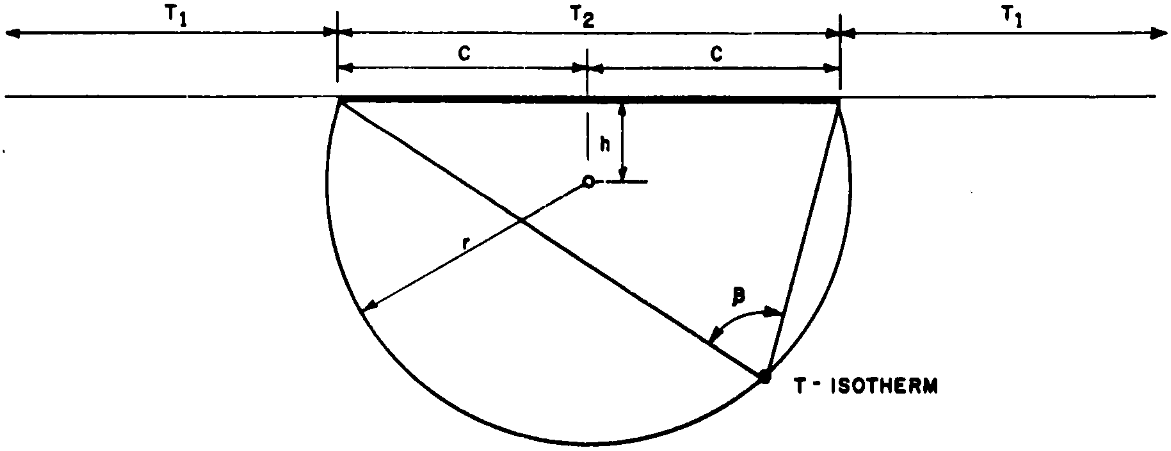
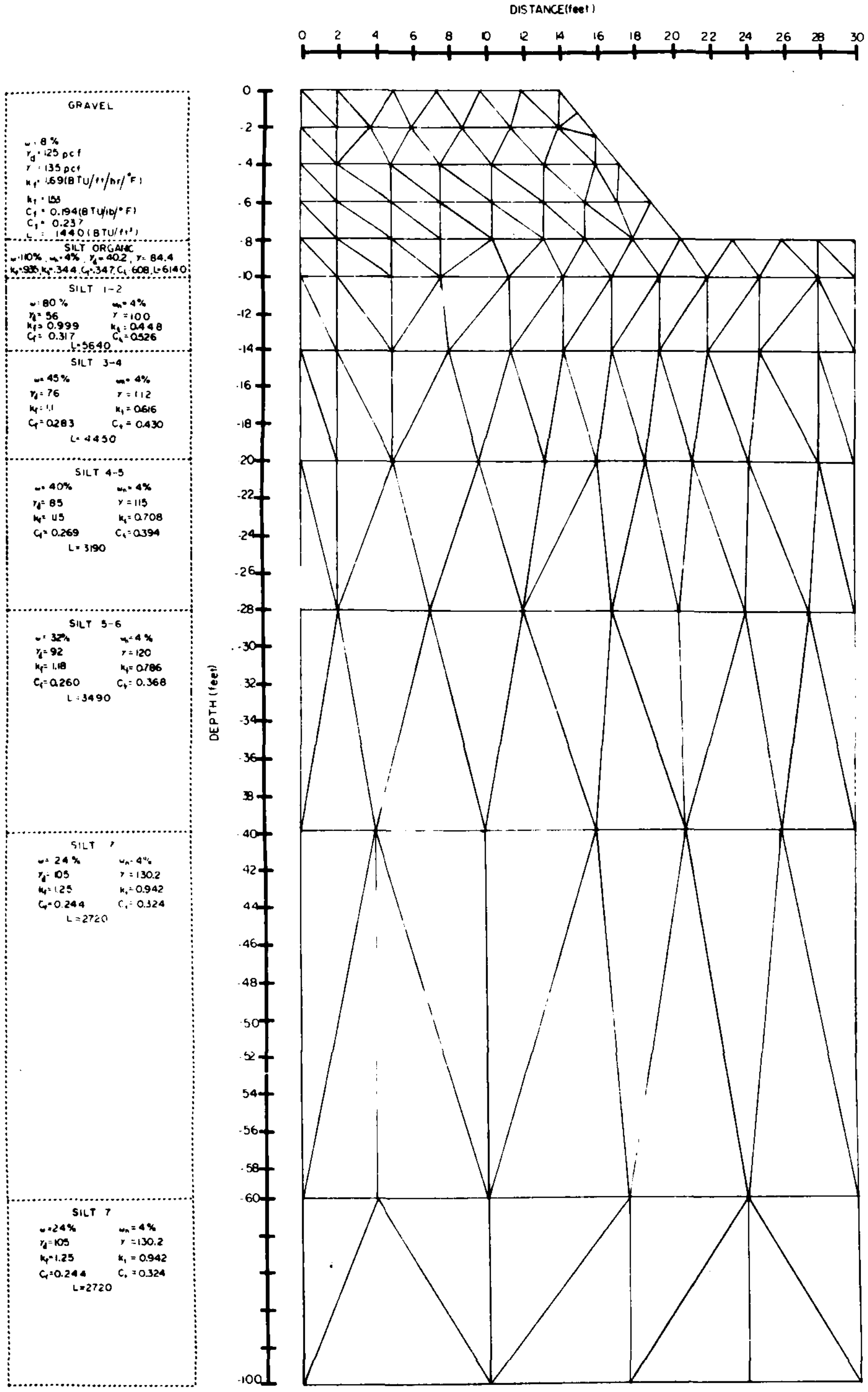
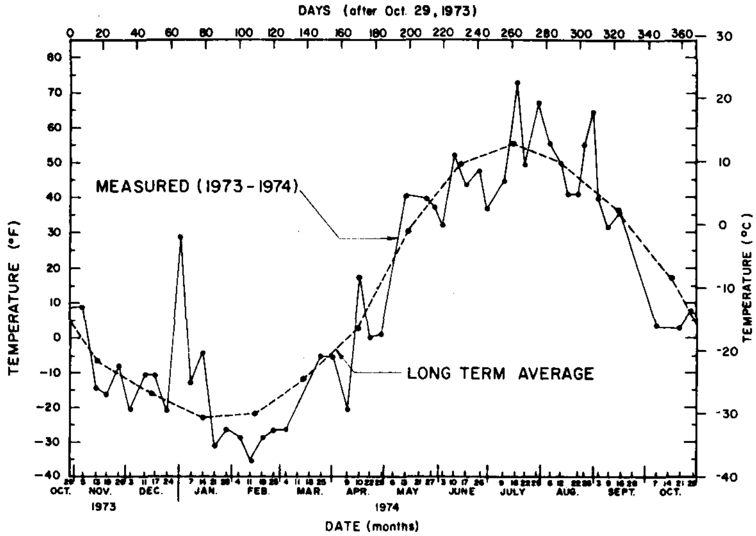


FIGURE 29 ISOTHERM REPRESENTATION FOR AN ISOTHERMAL STRIP





DWN. BY	EBA Engineering Consultants Ltd.	**Embankment and Soils Representation for Finite Element Grid**	DWG 30
DATE DWN.			
SCALE			
JOB No.			SHT. No.



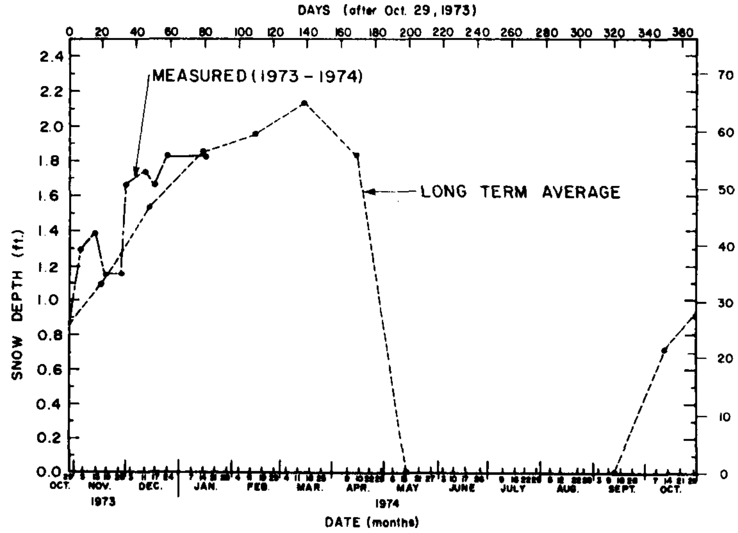
DWN BY: R G L
DATE DWN MAY 26, 1975
SCALE AS SHOWN
JOB No E - 749

Engineering Consultants Ltd.

AIR TEMPERATURE AT INUVIK

DWG. 31

SHT No



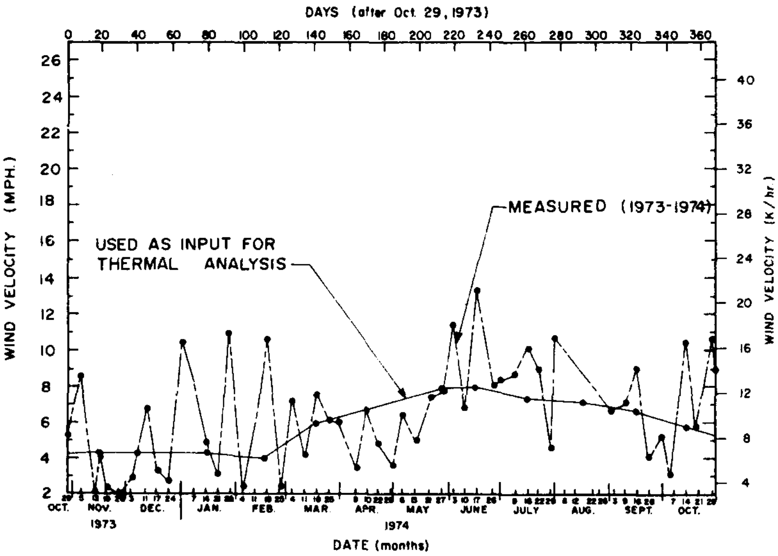
DWN BY: R G L
DATE DWN MAY 26, 1975
SCALE AS SHOWN
JOB No E - 749

Engineering Consultants Ltd.

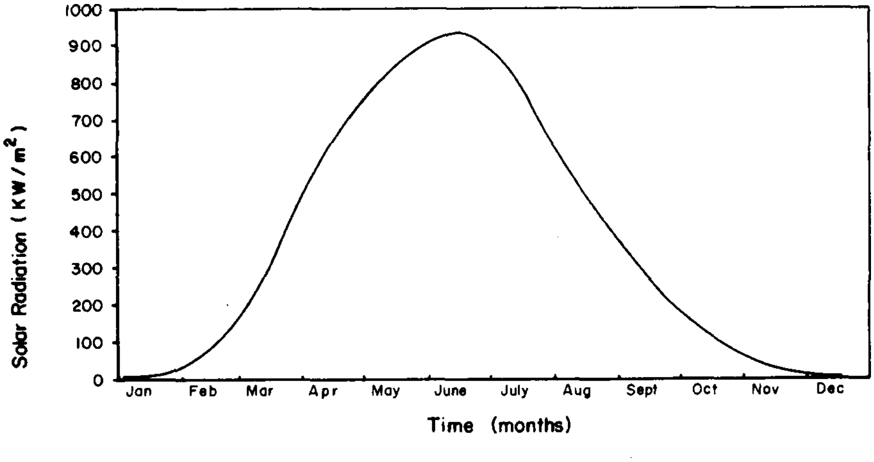
SNOW DEPTH

DWG. 32

SHT No

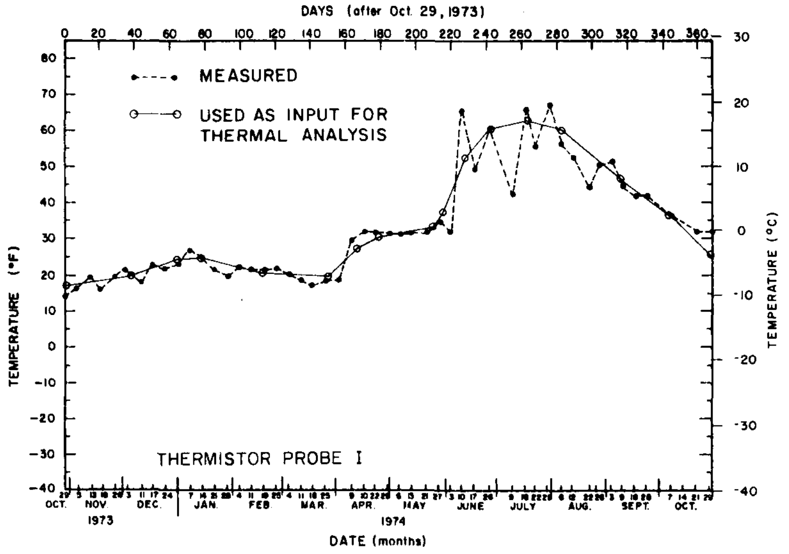


DWN BY R.G.L	Engineering Consultants Ltd.	WIND VELOCITY	DWG 33
DATE DWN MAY 26,1975			
SCALE AS SHOWN			
JOB No. E - 749			SHT No

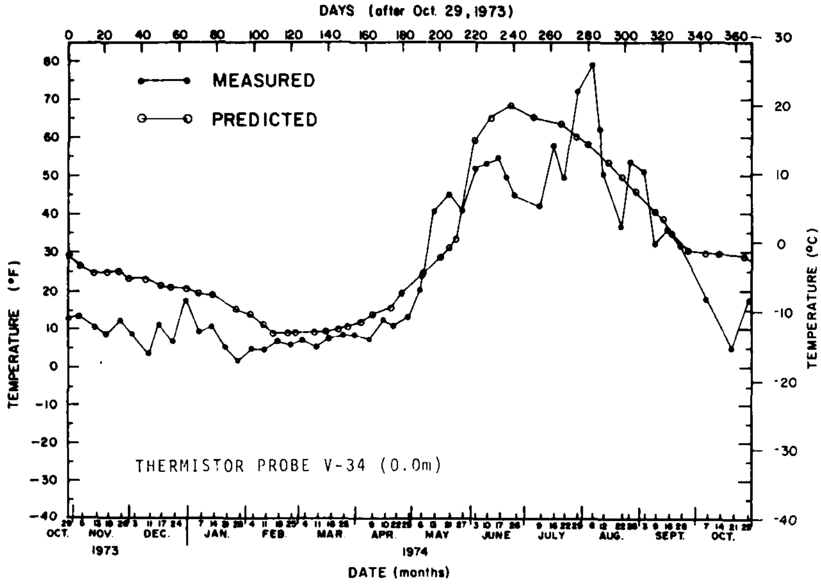


YEARLY VARIATION OF SOLAR RADIATION AT INUVIK

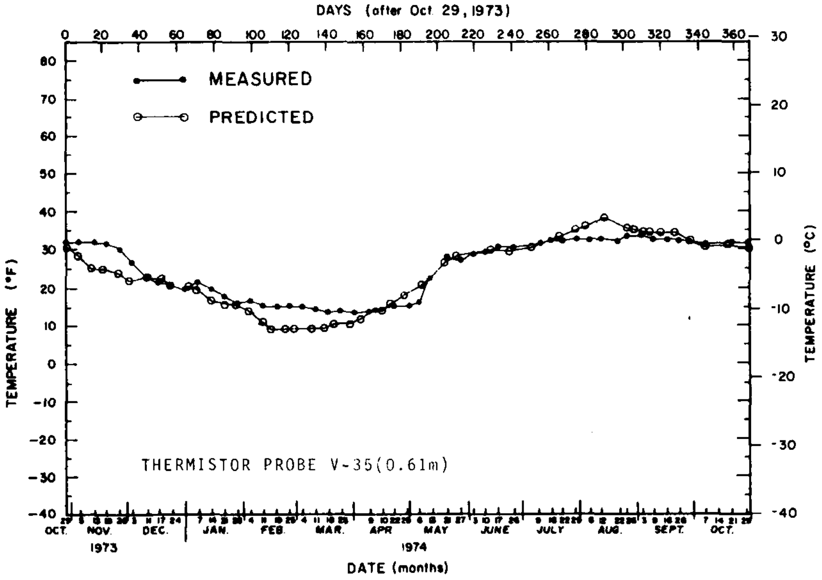
	DWG 34
EBA Engineering Consultants Ltd.	



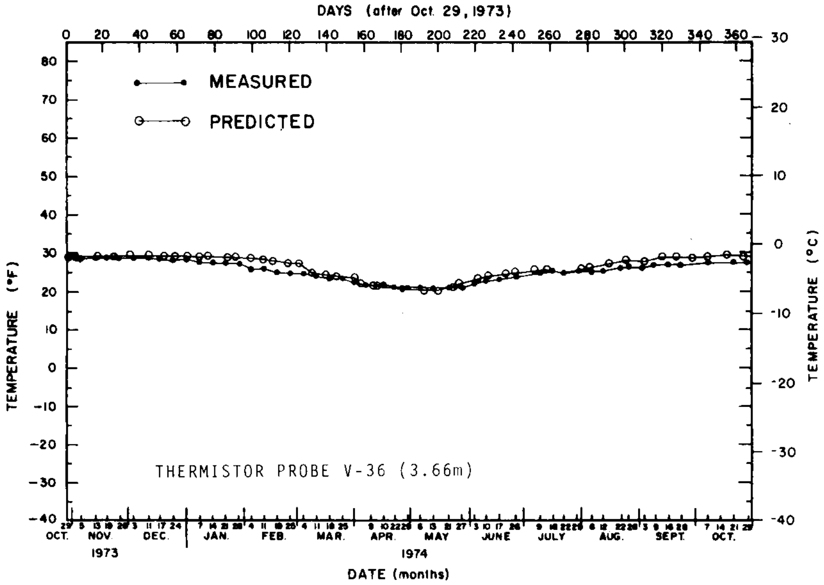
DWN BY R G L DATE DWN MAY 26,1975 SCALE AS SHOWN JOB No E - 749	Engineering Consultants Ltd.	TEMPERATURE VARIATION AT THE BOTTOM OF THE LAGOON	DWG 35 SHT No



DWN BY R.G.L. DATE DWN MAY 26,1975 SCALE AS SHOWN JOB No E - 749	eba Engineering Consultants Ltd.	COMPARISON OF MEASURED & PREDICTED TEMPERATURE	DWG 36 SHT No.



DWN BY R.G.L. DATE DWN MAY 26,1975 SCALE AS SHOWN JOB No E - 749	eba Engineering Consultants Ltd.	COMPARISON OF MEASURED & PREDICTED TEMPERATURE	DWG 37 SHT No.

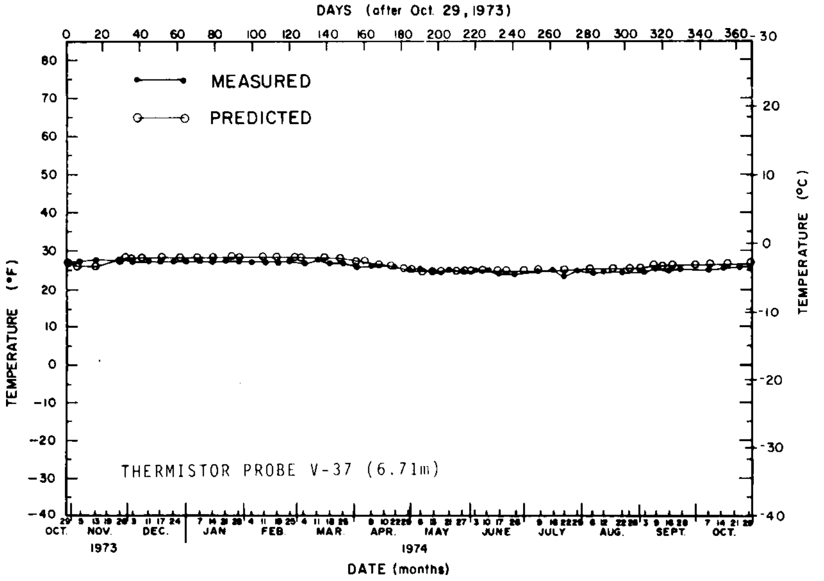


DWN BY R G L
DATE DWN MAY 26,1975
SCALE AS SHOWN
JOB No E - 749

Engineering Consultants Ltd.

COMPARISON OF MEASURED & PREDICTED TEMPERATURE

DWG 38
SHT No

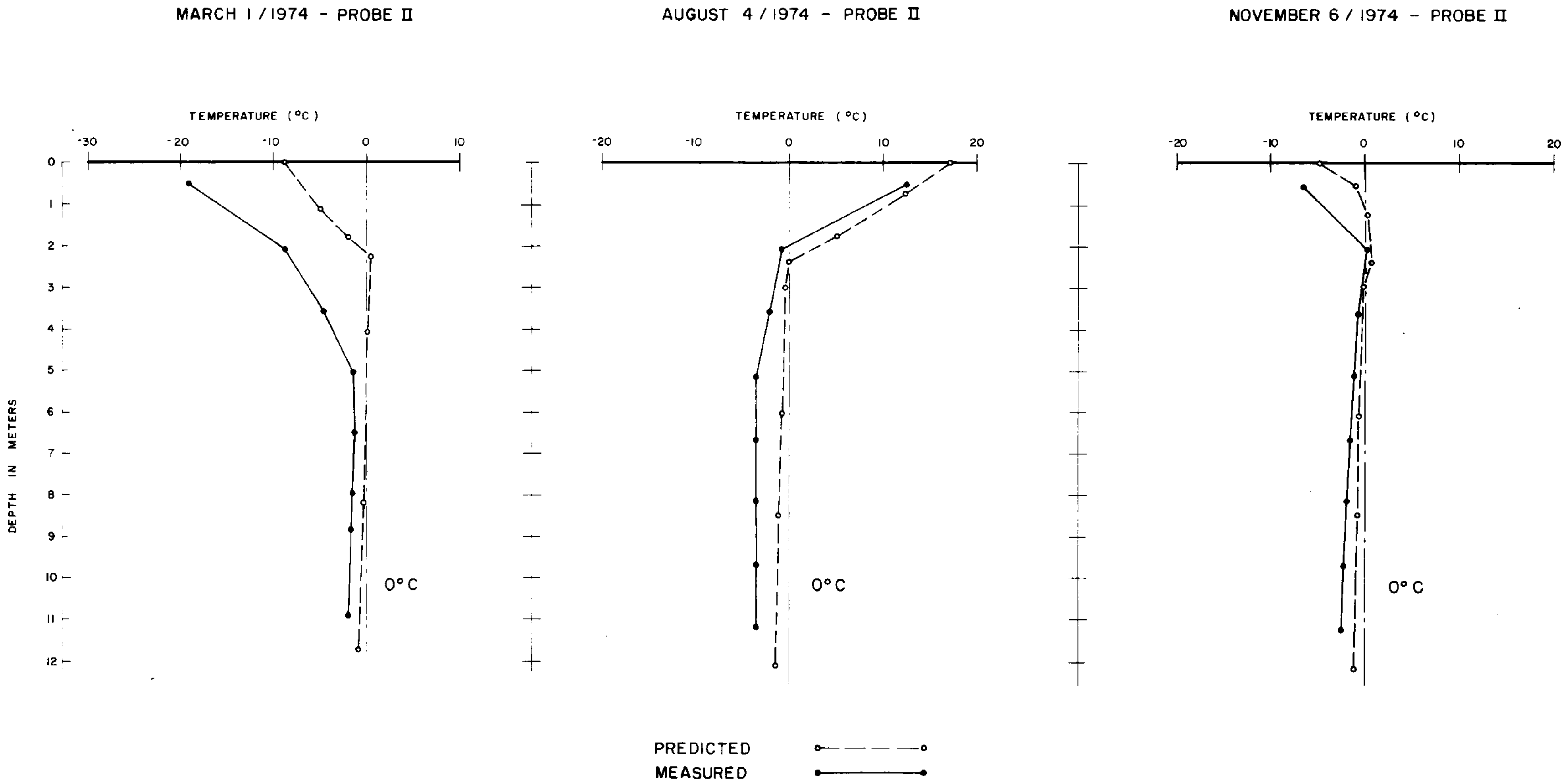


DWN BY R G L
DATE DWN MAY 26,1975
SCALE AS SHOWN
JOB No E - 749

Engineering Consultants Ltd.

COMPARISON OF MEASURED & PREDICTED TEMPERATURE

DWG 39
SHT No


MARCH 1 / 1974 - PROBE II

AUGUST 4 / 1974 - PROBE II

NOVEMBER 6 / 1974 - PROBE II

FIGURE 40,41,42 COMPARISON OF MEASURED AND PREDICTED TEMPERATURES FOR TWO DIMENSIONAL MODEL

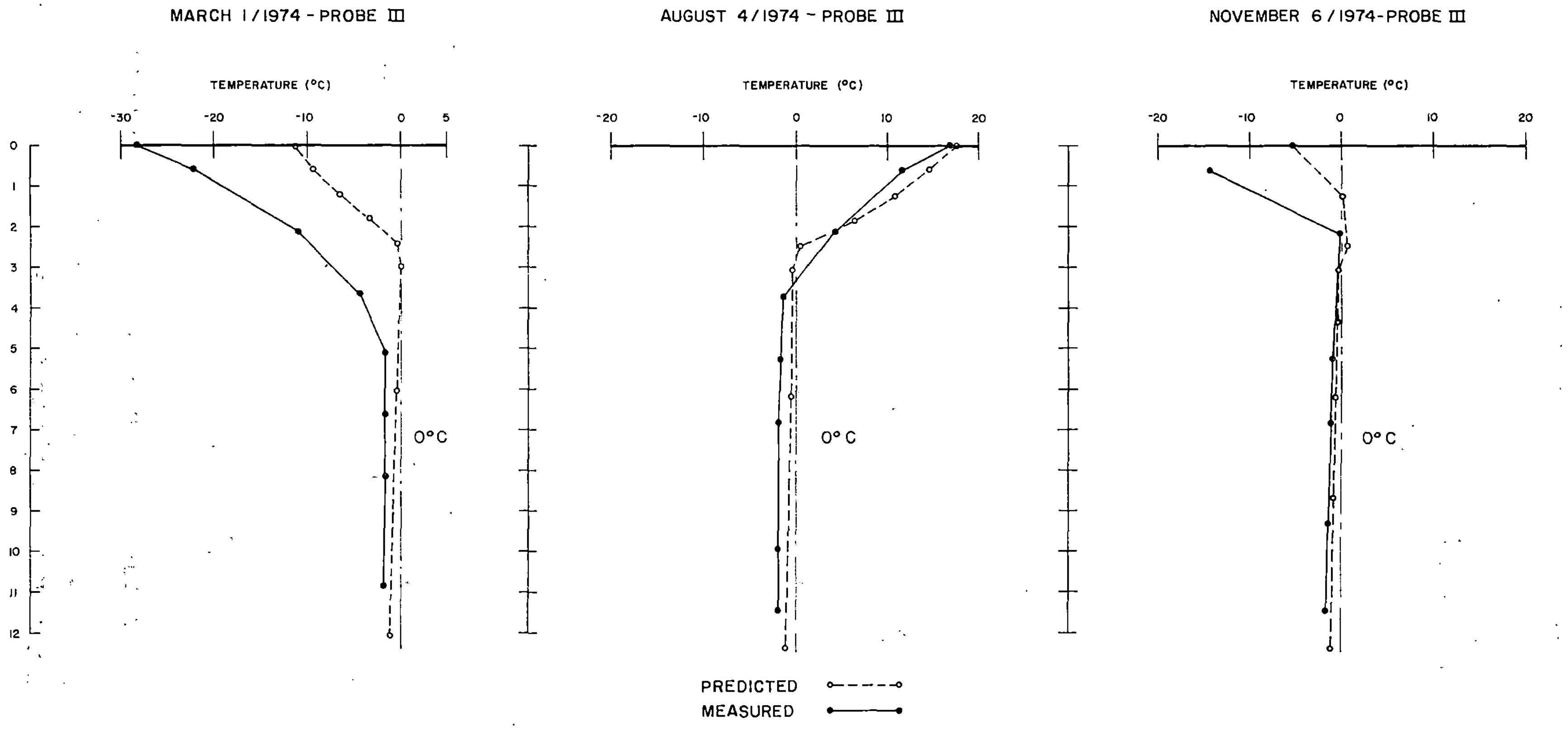
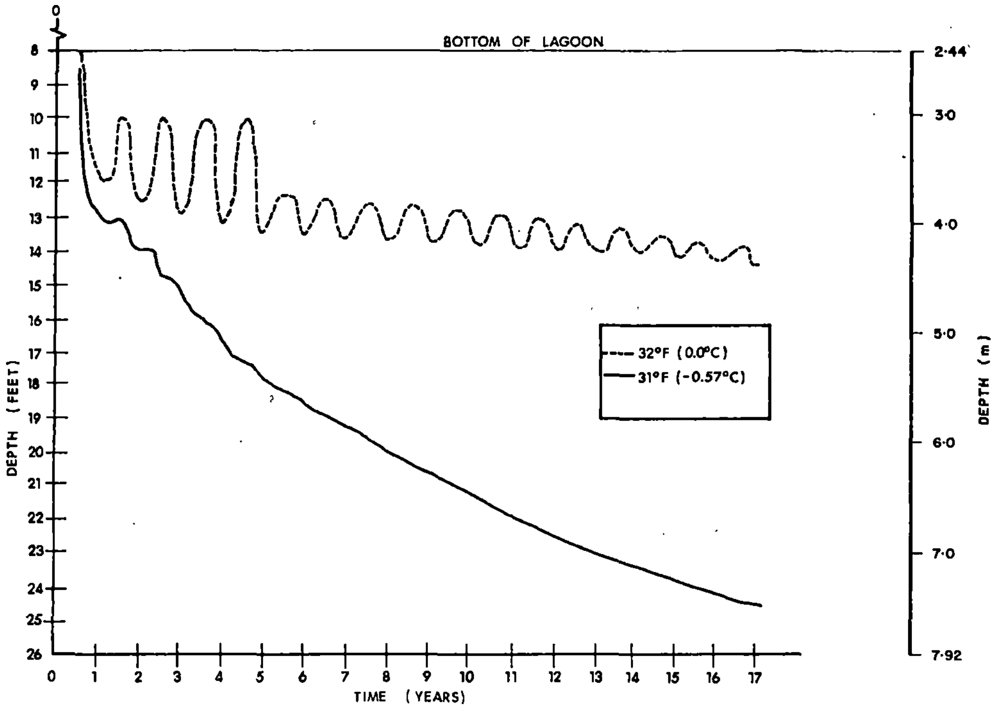
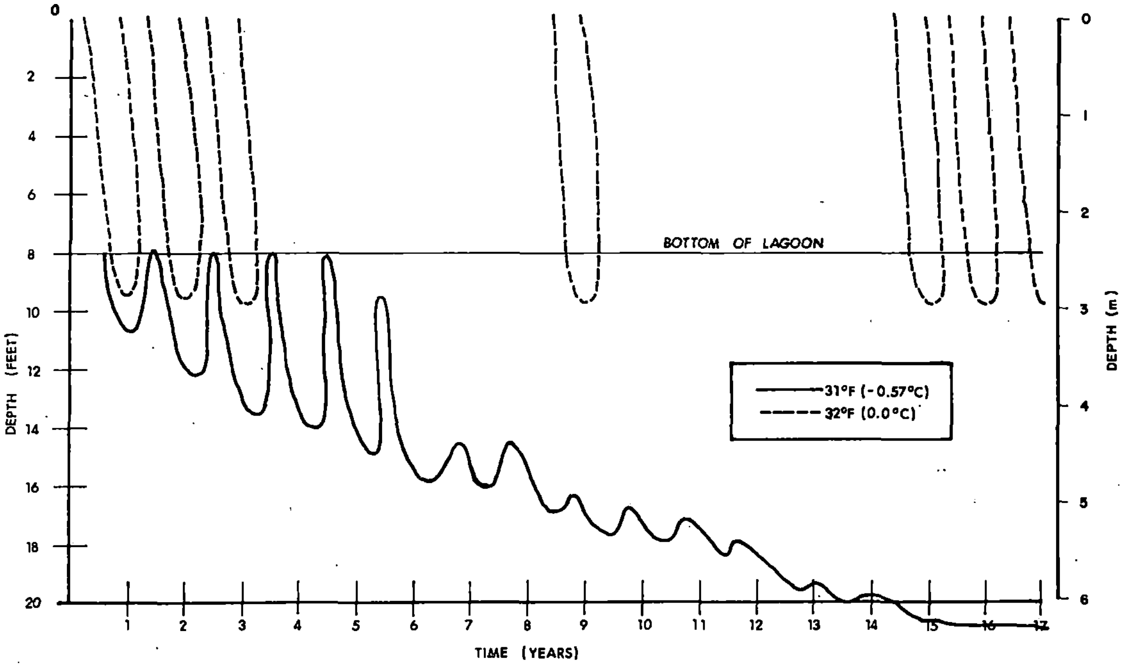


FIGURE 43,44,45 COMPARISON OF MEASURED AND PREDICTED TEMPERATURES FOR TWO DIMENSIONAL MODEL



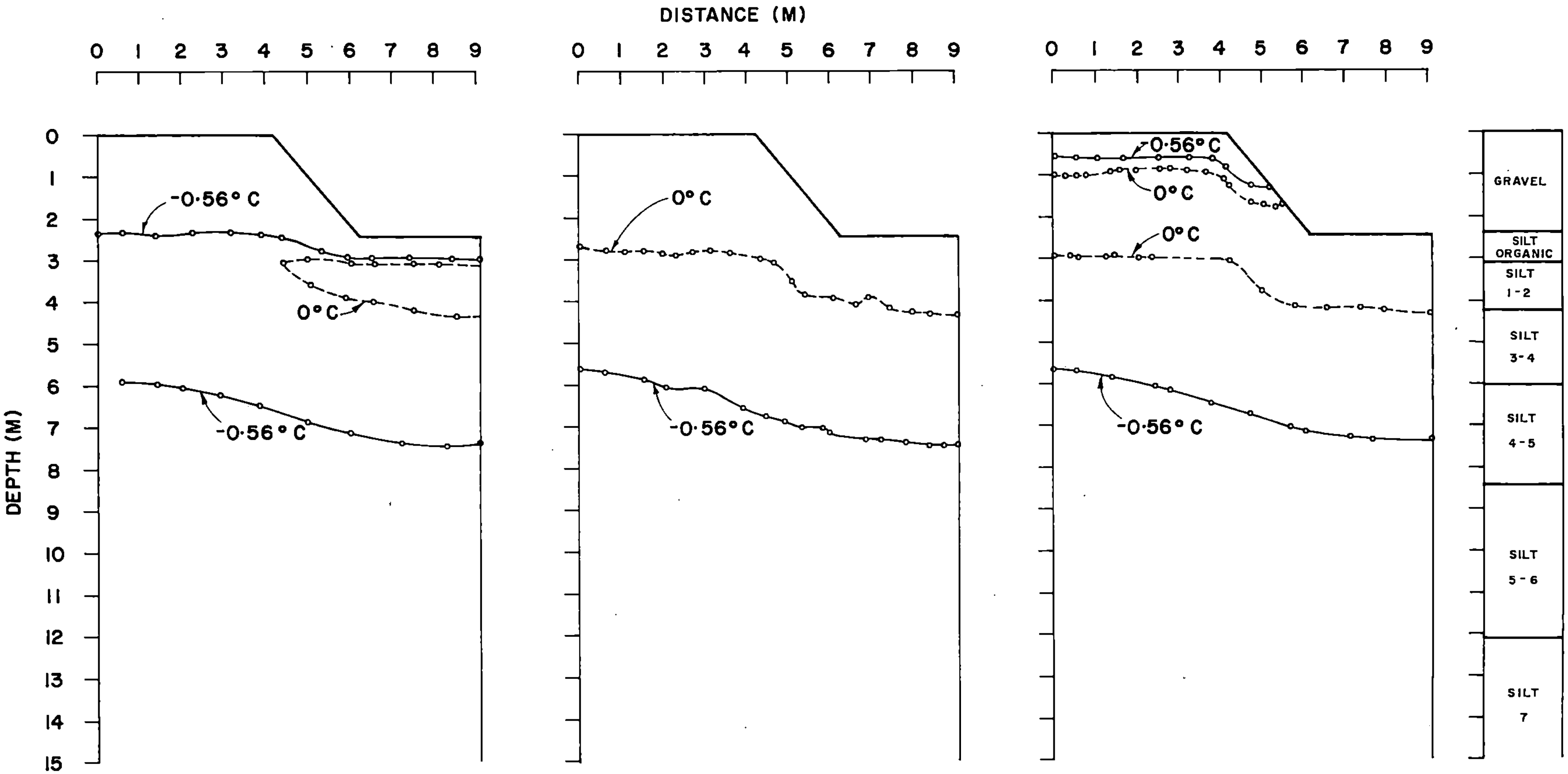
PREDICTED LOWER 0°C & -0·57°C ISOTHERMS UNDER LAGOON

EBA Engineering Consultants Ltd.	DATE OCT.20/75	SCALE SHOWN	JOB No. E-749	DWG No. 46



PREDICTED 0°C & -0·57°C ISOTHERMS AT PROBE II

EBA Engineering Consultants Ltd.	DATE OCT.20/75	SCALE SHOWN	JOB No. E - 749	DWG No. 47



MARCH 1, 1974 AUGUST 4, 1974 OCTOBER 26, 1974

FIGURE 48, 49, 50 -0·56° C & 0° C ISOTHERMS