PB85-121127

Economics of Ground Freezing for Management of Uncontrolled Hazardous Waste Sites

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Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Oct 84

EPA-600/D-84-270
October 1984

THE ECONOMICS OF GROUND FREEZING FOR MANAGEMENT OF UNCONTROLLED HAZARDOUS WASTE SITES

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U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/D-84-270	2.	3. RECIPIENT'S ACCESSION NO. PB8 5 121127
4. TITLE AND SUBTITLE THE ECONOMICS OF GROUND FREEZING FOR MANAGEMENT OF UNCONTROLLED HAZARDOUS WASTE SITES		5. REPORT DATE October 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John M. Sullivan, Jr., Dartmouth College Daniel R. Lynch, Dartmouth College Iskandar K. Iskandar, U.S. Army CRREL		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT NO. TEJY1A
		11. CONTRACT/GRANT NO. IAG No. DW96930180-01
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED Conference Paper
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

16. ABSTRACT

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The economics of the process is discussed based on the Poetsch method for ground freezing. Vertical drill holes with concentric refrigeration lines are spaced along the desired freezing line. Temperature-measuring instrumentation is appropriately placed to monitor the progress of the freeze front.

Plotting costs for equipment rental, drill expenses, fuel costs and time as a function of refrigeration line spacing produces an overall expense estimate that can be used to compare ground freezing with other barrier construction technologies. Preliminary results showed ground freezing to be an economically competitive alternative to slurry wall and grout curtain construction for a wide range of thermal conditions. The system is limited to temporary treatment due to maintenance expenses. Ground freezing has the added features of low noise and minimal environmental disturbance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 38
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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ABSTRACT

Ground freezing for hazardous waste containment is an alternative to the traditional and expensive slurry wall or grout curtain barrier technologies. The parameters quantified in this analysis of it include thermal properties, refrigeration line spacing, equipment mobilization and freezing time constraints.

The economics of the process is discussed based on the Poetsch method for ground freezing. Vertical drill holes with concentric refrigeration lines are spaced along the desired freezing line. A header or manifold system provides coolant to an interior pipe, with the return line being the outer casing. A self-contained refrigeration system pumps coolant around the freezing loop. Temperature-measuring instrumentation is appropriately placed to monitor the progress of the freeze front.

Soil parameters significantly affect the cost analysis. Fine-grained soils with high moisture retention can double the overall barrier expense compared to coarse-grained soils

with low moisture characteristics. The data needed to calculate the required thermal parameters for technical and economic assessment of ground freezing are routinely obtained during the geotechnical and hydrologic site examination. Consequently, there are no additional site examination costs for the ground freezing treatment.

High-moisture-retention soils require long refrigeration times due to their latent heat capacity. They require closer refrigeration line spacing and higher refrigeration power than low moisture soils for the same time period constraint. Plotting costs for equipment rental, drill expenses, fuel costs and time as a function of refrigeration line spacing produces an overall expense estimate that can be used to compare ground freezing with other barrier construction technologies. Preliminary results showed ground freezing to be an economically competitive alternative to slurry wall and grout curtain construction for a wide range of thermal conditions. The system is limited to temporary treatment due to maintenance expenses. Ground freezing has the added features of low noise and minimal environmental disturbance.

Acknowledgments and Disclaimer

This work was supported by the U.S. Environmental Protection Agency (EPA), Disposal Branch, Solid and Hazardous Waste Research Division, and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, N.H., under Interagency Agreement DW 930180-01-0. A portion of the work was conducted at the Thayer School of Engineering at Dartmouth College in Hanover. The authors acknowledge the assistance of Janet Houthoofd, project officer, EPA. Citation of brand names does not constitute an endorsement by either EPA or CRREL. The information contained in this publication represents the authors' opinions and not those of EPA or CRREL.

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INTRODUCTION

Artificial ground freezing is not a new technology. There exists a 100-year tradition of shaft sinking in which ground freezing has been used. The increasing application of ground freezing for civil engineering projects in recent years is mainly due to the following advantages:[1]

1) In principle, ground freezing can be used in all types of soils.

2) Ground freezing is a very flexible construction method which can meet many boundary conditions and requirements.

3) Very little or no environmental concern is associated with the method when dealing with soils for civil engineering purposes.

During ground freezing the temperature of the soil water is lowered below the freezing point. The freezing temperature of soil solutions is not 32°F (0°C) as for pure water, since dissolved ions in the soil lower the freezing point. However, empirical relations exist that quantify the freezing point of soils.[2-5] It might be argued that the freezing point of hazardous waste is much lower than that of soil systems. While this is a valid point, artificial freezing is done in the soil surrounding the hazardous waste and not in the waste itself. Therefore, uncontaminated soil data are usable. When the soil temperature is lowered to the freezing point important changes begin to occur in soil properties. The strength of the soil is substantially increased and the soil permeability decreases. The potential use of ground freezing in hazardous waste remedial action is based on these two important points. The increase in soil strength upon freezing means that a frozen zone of soil can be formed around or underneath a hazardous waste site or between the site and an uncontaminated environment without adding concrete, slurry walls, steel sheet pile walls, or grout for injection. Also, the frozen zone of soil becomes practically impermeable.

The first use of artificial freezing was in 1862 in Swansea, Wales. The purpose was to support a mine shaft project, which was used for mine production, material and personnel access, ventilation, and emergency escape exits. In 1883 Poetsch patented a method of ground freezing with cooling pipes[6] which, with some modification, is still in use. In this method vertical drill holes with standard steel casings are uniformly spaced along the desired freezing line. Bore diameters accommodate 3- to 6-inch pipe. Standard black pipe half the bore diameter is inserted in each casing, forming two concentric cylinders. A header or manifold system provides coolant such as calcium chloride brine at -4°F (-20°C) to the interior pipe, with the return line being the outer casing. The manifold system runs along the freezing line to reduce thermal losses. A self-contained refrigeration system pumps coolant around the freezing loop.

An open loop system which uses an expendable coolant such as liquid nitrogen (LN_2) has the advantage over brine freezing in that it achieves a much lower temperature (-321°F or -196°C) in a very short time. Therefore, LN_2 is useful in emergency cases where time is limited. Also, the fast freezing of contaminated soil by LN_2 will result in immobilization of chemicals, as the soil water (with contaminants) will freeze in situ.[7] Brine freezing, on the other hand, has the advantage of freezing the soil walls in a more regular shape. Temperature measuring instrumentation is appropriately placed for monitoring the progress of the freeze front. Figure 1 shows a schematic representation of the two freezing methods.

According to Braun and Nash[8] the use of ground freezing in the mining industry has advantages over conventional methods (dewatering, grouting, slurry walls, caissons):

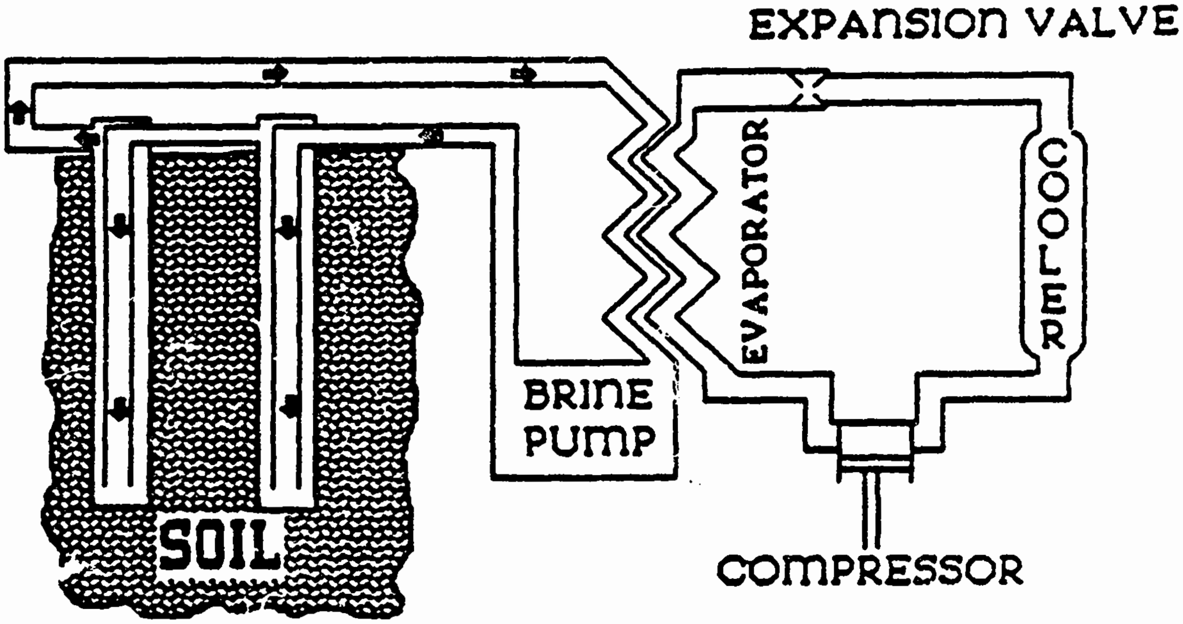
1) It does not require extensive geological data.

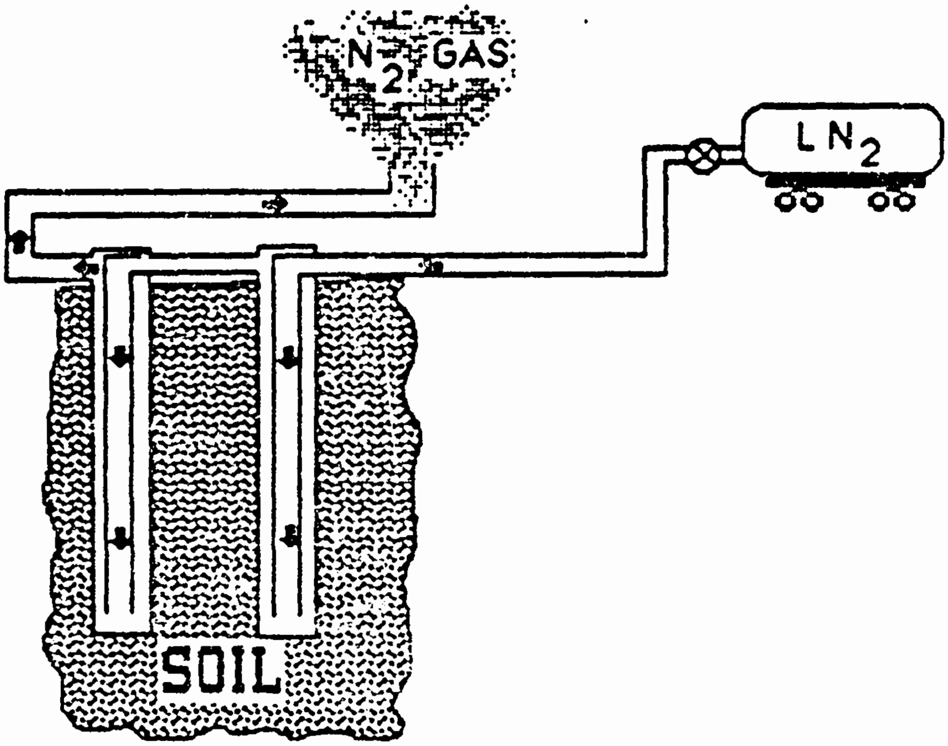
2) It serves several temporary functions, such as support of an excavation, groundwater control and structural underpinning.

3) It is adaptable to practically any size, shape or depth.

4) Excavation can be kept unobstructed as no bracing or sheathing is usually required.

5) It does not disturb the groundwater quantity or quality.


EXPANSION VALVE
EVAPORATOR
COOLER
BRINE PUMP
COMPRESSOR
SOIL


N2 GAS
LN2
SOIL

6) It is environmentally acceptable, as no chemicals will be added, and there is less disturbance to the site.

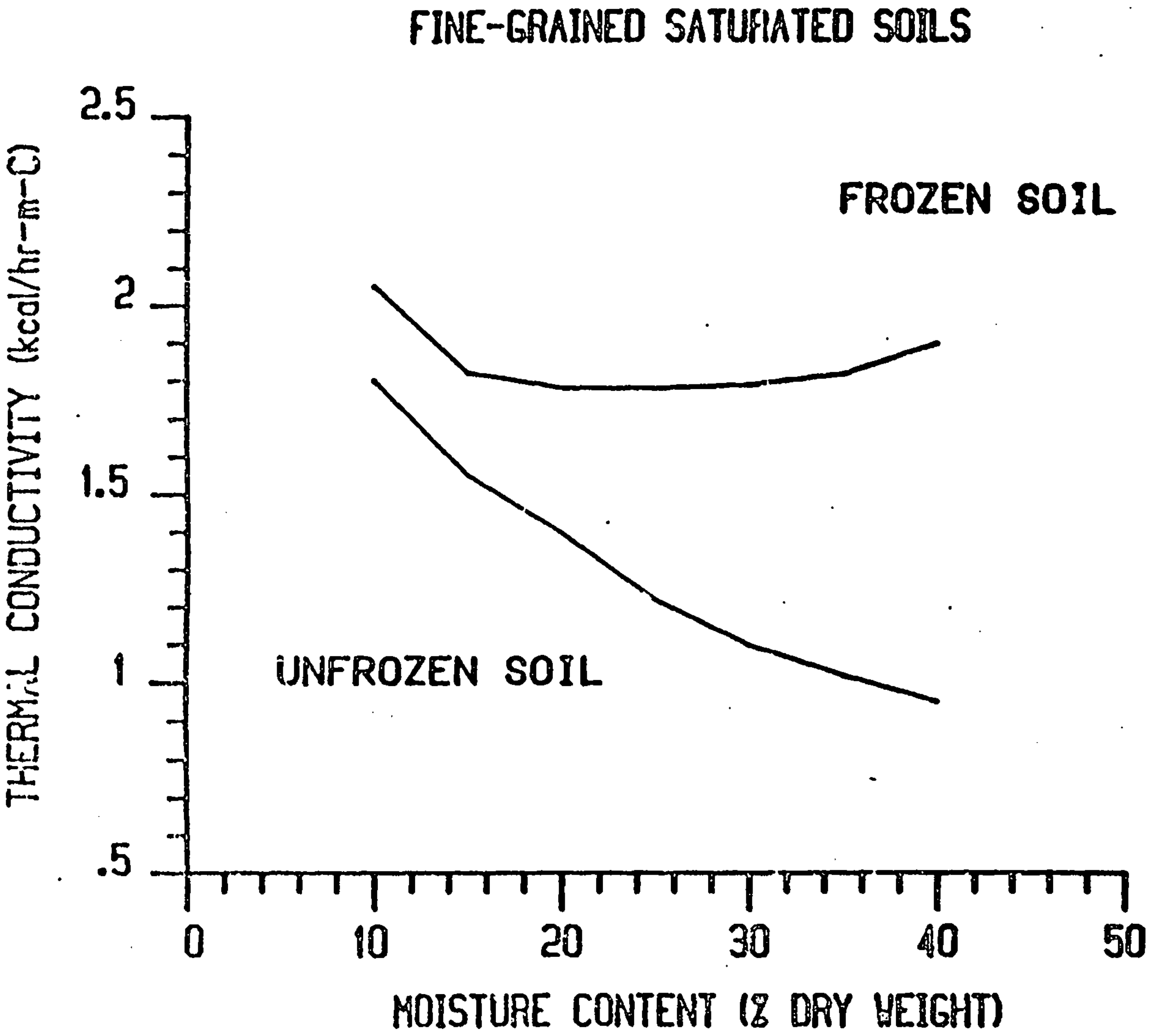
Through 1978, more than 200 deep mine shafts had been driven by artificial soil freezing.[9]

In addition to its use in the mining industry, ground freezing has been used for construction of open excavations and deep unsupported construction trenches. For example, it was used during the construction of subways in Moscow, and in Zurich.[10,11] About 70 inclined tunnels and over 30 excavations were made by soil freezing. The use of ground freezing in the Moscow project saved 700 tons of metals and 500 cubic meters of timber, and the project was completed 11 to 12 months early.[10,11] This project was circular, with a 40-m diameter and 20-m average depth. The frozen wall thickness was 5.6m.

In North America, artificial freezing has been used since 1888.[8] In 1959 it was necessary to enlarge a twin railroad tunnel in Montreal. Construction problems arose because of the presence of a plastic layer of clay in the soil and because the tunnel was located under the city and ran beneath service pipelines and two large buildings. Artificial soil freezing was successfully utilized in this project.[12]

In 1964 liquid nitrogen (LN_2) was used for artificial soil freezing in Argenteuil, France. In this project a collector sewage pipe housed in a tunnel broke. The sewage flooded the tunnel and seeped to a nearby stream. The influx was stopped by circulating LN_2 through 25 freezing probes. Later a concrete wall was constructed between the polluted area and the fresh water stream.[13]

The economics of ground freezing as a means of hazardous waste containment is discussed below. These cost analyses are based on existing construction practices and proven freezing technologies. The data needed to calculate thermal parameters required for technical and economic assessments of ground freezing are routinely obtained during the geotechnical and hydrologic site examinations. This site-specific information is required to evaluate the technical feasibility of the containment alternatives.[14] The thermal data are obtained primarily from soil texture, moisture content and temperature measurements. The specific heat of soils depends primarily on the water content since the volumetric heat-capacity ratio for water to most dry soils is about 5. The thermal conductivity of coarse-grained soils is significantly larger than that of fine-grained soils. Both saturated soil types exhibit a decrease in thermal conductivity with increasing water content. Moisture content measurements determine the latent-heat energy requirements and establish whether or not the soil is saturated. A saturated soil system is desirable for an impermeable frozen barrier, and is assumed throughout this analysis. Lunardini[15] provides extensive data relating these site examination measurements to soil thermal properties. As an example, figure 2 displays thermal


FINE-GRAINED SATURATED SOILS
THERMAL CONDUCTIVITY (kcal/hr-m-C)
2.5
2
1.5
1
.5
FROZEN SOIL
UNFROZEN SOIL
0
10
20
30
40
50
MOISTURE CONTENT (% DRY WEIGHT)

conductivity as a function of moisture content for a fine-grained saturated soil.

ECONOMIC CONSIDERATIONS

There are no additional site examination costs for the ground freezing treatment, as opposed to alternate containment modes. Therefore, the economics of the site-specific investigation (i.e. geotechnical, hydrologic and lab filter-cake permeability testing) are unchanged from the EPA estimate of \$20,000 - \$80,000.[14]

Table I lists unit costs for most of the equipment required for ground freezing. Equipment mobilization involves transport of the boring rig, refrigeration units, piping and site-clearing equipment. The site preparation requirements for ground freezing are relatively low. The barrier must be saturated with water if the soil moisture content is inadequate. Land clearing is necessary for equipment access along the freezing route. Excavation and heavy duty land clearing are not usually required for ground freezing. Capital costs include drilling and pipe system expenses. The drill-hole steel casings are not recovered at the completion of the project. However, the header system and interior cooling lines can be rented on a monthly basis. Energy requirements involve rental of the refrigeration units, electrical consumption and expendable coolants if used.

Table I: Unit Costs for Ground Freezing Equipment and Supplies.*

	Daily Output	Total Costs ($)		
1) Mobilization[17]		100/unit		
Dozer, drill rig, refrigeration unit over 100 miles add		1/mile/unit		
2) Clear wooded lot (trees<10 in. dia.)[17]	0.7 A+	2450/A		
Grub stumps and remove	1.5 A	1100/A		
Dozer medium duty clearing	3,000 Y^2	0.31/Y^2		
3) Header pipe system[17]	Month - rental costs per L.F. of pipe	1	2	3
70 GPM 3 in. dia.		1.40	0.85	0.65
150 GPM 4 in. dia.		1.60	0.90	0.70
400 GPM 6 in. dia.		2.50	1.00	0.75
4) Well hole drilling[18]	100 L.F.			
4 in. ID steel casing		9/L.F.		
5 in. ID steel casing		12/L.F.		
6 in. ID steel casing		15/L.F.		
Drive shoe		75/well		
5) Black steel pipe[18]				
2 in. dia.**		0.22/L.F./M		
3 in. dia.		0.36/L.F./M		
6) Self-contained refrigeration units[16]				
7 ton refrigeration		150/day		
110 ton refrigeration		2000/week		
7) Liquid N_2[19]		1.23/100 ft^3		
8) Electricity		0.10 per kwh		

---

* All prices include parts, labor, operating and profit for subcontractor unless otherwise noted.

** 2 in. pipe ($5.20/L.F.) - Rent at 2 yr. writeoff = 0.22/L.F./M
3 in. pipe ($8.66/L.F.) - Rent at 2 yr. writeoff = 0.36/L.F./M

\+ A = acre, Y^2 = square yard, L.F. = lineal foot, M = month

The time constraint for the frozen wall plays a primary role in the cost estimate. Mechanical refrigeration units rated at 5-110 tons of refrigeration are readily available.[16] These units provide the manifold system with reusable coolant at -4°F (-20°C) when operated within their appropriate capacity range. Expendable LN_2 is available in large quantities when the demand for a rapid freezing front is required. For this system, the expanded N_2 gas is vented directly to the atmosphere. The refrigeration units are replaced with LN_2 tanks and control valves that regulate the LN_2 flow based on the vent temperature.

Sanger and Sayles[20] provide a sound methodology for thermal computations of frozen ground. Their energy requirements and freezing time estimates are somewhat more conservative than those predicted by finite element simulations and actual field measurements.[21,22] However, for this preliminary economic analysis their predictions are appropriate. Sanger and Sayles predict the expenditure of energy based on reasonable assumptions about the heat transfer process in the soil. The energy per unit length, Q, time, t, and power per unit length, P, required to freeze a cylinder of radius R is a function of the soil thermal properties, thermal conductivity, k, thermal capacity, c, latent heat of fusion, L, and the temperature difference between the coolant and soil.[20]

Ignoring second-order effects they derived the energy estimate to be

$$Q = \pi R^2 \left[\frac{\left(a_r^2 - 1\right)}{2\ln(a_r)} c_2 T_2 + L + \frac{c_1 T_0}{2\ln(R/r_0)} \right] \qquad (1)$$

where the first term in brackets accounts for the energy required to reduce the unfrozen soil temperature from T_2 down to freezing. The second term of Eq. (1) is the energy associated with the transformation from unfrozen soil to frozen soil at the freezing temperature, i.e. the latent heat of fusion, L. The last term describes the energy used in reducing the frozen soil temperature from freezing to the refrigeration temperature. The time required to freeze the column to a radius R is

$$t = \frac{R^2 L_I}{2k_1 T_0} \left(2\ln(R/r_0) - 1 + \frac{c_1 T_0}{L_I} \right) \qquad (2)$$

and the power requirement is

$$P = \frac{dQ}{dt} = \frac{2\pi k_1 T_0}{\ln(R/r_0)} \qquad (3)$$

where the symbol definitions and units are as given in Table II. The total power requirement is larger than that expressed in Eq. (3) due to inefficiencies in the refrigeration system. A 15 percent thermal loss along the header system is assumed. The refrigeration system is conservatively rated at 0.21 ton of refrigeration per horsepower.[6] The energy required for brine pumps and

Table II: Symbol Definitions and Units.

a_r	A factor which when multiplied by R defines the radius of temperature influence on the freeze pipe. Dimensionless - usually $3 < a_r < 5$.[20]
c_1, c_2	Volumetric specific heat capacity for frozen and unfrozen soils, respectively. Btu/ft^3/°F (cal/cm^3/°C)
K_1, K_2	Thermal conductivity for frozen and unfrozen soils, respectively. Btu/hr/ft/°F (cal/s/cm/°C)
L	Latent heat of fusion. Btu/ft^3 (cal/cm^3)
L_I	Latent heat effects plus heat requirements of unfrozen soil.[20] $L_I = \frac{(a_r^2 - 1)}{2 \ln(a_r)} c_2 T_2 + L$
P	Power per unit length of pipe. Btu/hr/ft (cal/s/cm)
Q	Freezing energy per unit length of pipe. Btu/ft (cal/cm)
R	Radius of frozen soil column. ft (cm)
r_o	Radius of freeze pipe. ft (cm)
T_2	Absolute value of (unaffected soil temperature - freeze temperature) °F (°C)
T_o	Absolute value of (pipe temperature - freeze temperature). °F (°C)
t	Time to freeze soil to a radius of R. s (s)

cooling fans is estimated at 20 percent of the refrigeration load.

The economics for ground freezing and slurry wall construction are based on a 3-foot wall thickness. Once the soil columns merge according to Eq. (2) Sanger and Sayles approximate the frozen soil thickness at 0.79 times the soil column diameter. If this wall thickness is less than 3 feet, the wall increases in thickness as a planar front according to separate equations in [20]. This design thickness is a limitation of the slurry wall excavation equipment and not a result of structural support or permeability requirements; nevertheless, we have used it for the frozen wall to establish a baseline comparison.

Examining Eqs. (1) and (2) one notes that the energy and time requirements are proportional to the square of the radius of each cylinder. Initially, one might expect an economic advantage for a thin-wall construction via multiple cylinders of small radius. However, the final cost analysis shows intermediate-radius cylinders as the most economical due to the reduced number of drill holes required. In addition to the economic gains, a thicker wall has greater seepage resistance, although this is unquantified in this analysis.

Once the frozen wall is formed, a reduced refrigeration load maintains the wall while the contained hazardous waste is being treated or removed for proper disposal. The maintenance economics are conservative as they are based on a wall that continues to increase in thickness. The maintenance power requirement is half that of Eq. (3) for soil columns having diameters (1/.79) times the design thickness. (The factor 1/2 enters because each soil column has merged with adjacent frozen columns.) This power requirement coupled with equipment rentals and manpower comprise the maintenance expense of the wall. A substantial amount of time exists after the refrigeration unit is removed due to the latent heat stored in the frozen wall. If the wall facial area is large compared to the thickness a one-dimensional melt analysis is applicable. Carslaw and Jaeger[23] provide an analytic solution for a simplified one-dimensional melt problem. The region $x > 0$ is initially solid at the melting temperature. The wall face at $x = 0$ is raised to a constant temperature above the melting temperature. The position of the frozen/unfrozen plane is given by

$$X = 2\lambda(t\,k_2/c_2)^{\frac{1}{2}} \tag{4}$$

where the numeric constant, λ , is a function of the thermal soil properties. For the frozen wall situation melting occurs on both sides. Rearranging Eq. (4) the time required to melt the wall (i.e. $X = 1.5$ feet) is

$$t = \frac{X^2}{4\lambda^2(k_2/c_2)} \tag{5}$$

It should be noted that the specific heat capacity of the frozen wall increases the actual wall energy storage. However, this additional energy storage was not included in the melting analysis.

EXAMPLE CASES

Case (1):

The hypothetical situation is a 10-acre hazardous waste site located 150 miles from the drilling and refrigeration contractors. The EPA Handbook for Remedial Action at Waste Disposal Sites recommends a slurry wall 1000 ft long and 3 ft wide to be placed down to the bedrock on the up-gradient side of the site. The depth to the bedrock averages 40 feet. Table III summarizes EPA slurry wall estimates and our artificial ground freezing estimates for saturated coarse quartz sand initially at 45°F (7.2°C). Figure 3 plots the cost as a function of freezing rod spacing. It can be seen from Table III that artificial ground freezing is an acceptable solution, provided the containment time requirement is short (less than 135 days). Thereafter, the daily maintenance costs make the ground freezing alternative unattractive. Examining fig. 3 one can see that as the drill spacing becomes tighter, the fuel costs, equipment rentals and time for wall completion are reduced. These results agree with Eqs. (1) and (2). A tight drill spacing yields small frozen soil column radii. This reduces the

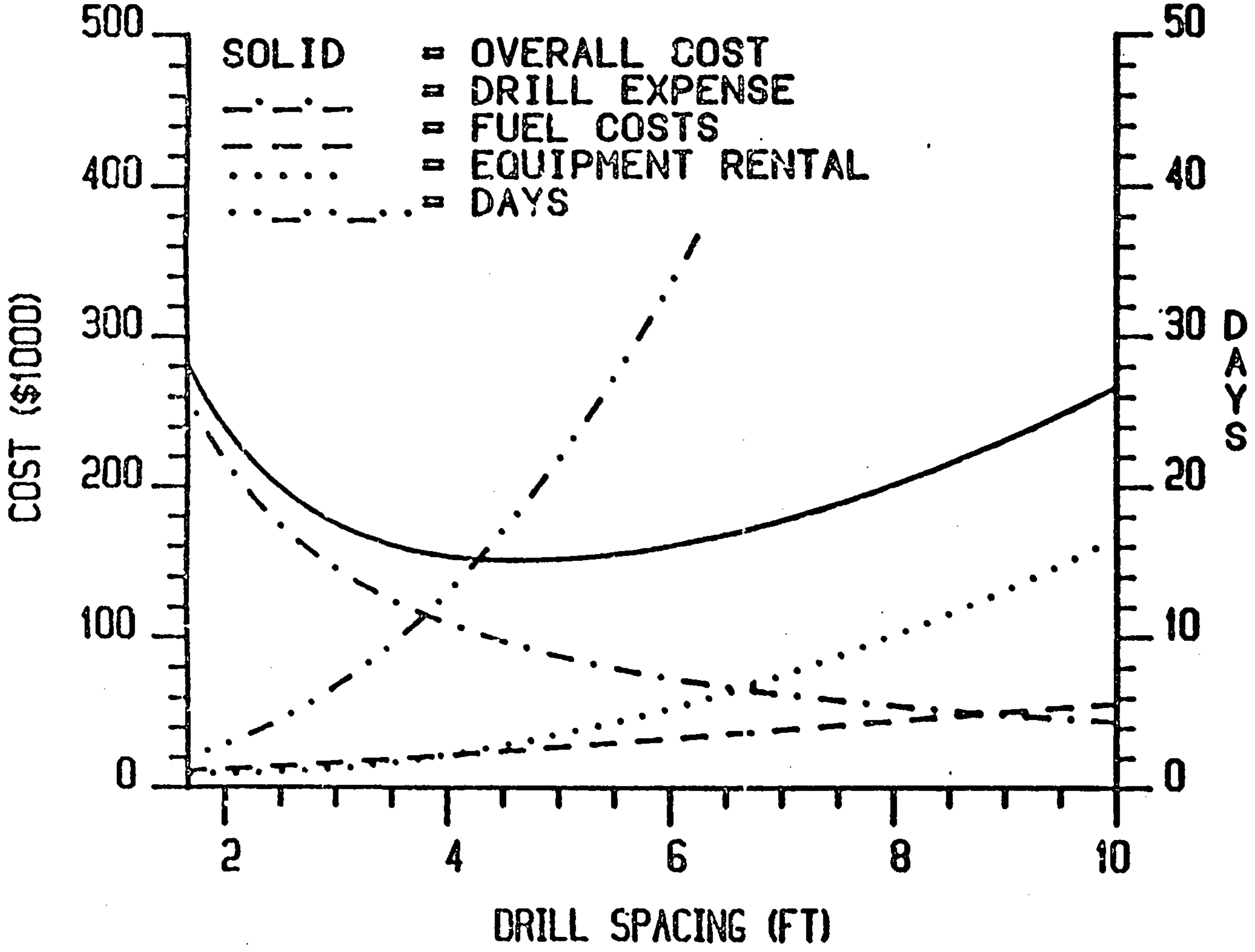
Table III: Slurry Wall and Frozen Ground
Construction Estimates.

Activity	Unit Costs*	Total Costs
A. SLURRY WALL[14]		
Testing - geotechnical, hydrologic and lab filter cake permeability	N.A.	$20,000 - $80,000
Equipment Mobilization - hydraulic backhoe, bulldozer, slurry mixer, etc.	N.A.	$20,000 - $80,000
Slurry trenching, excavation, mixing and backfilling	$\$45-\$70/Y^2$	$200,000 - $310,000
Maintenance	-	-
Overall	N.A.	$240,000 - $470,000
Average	-	$355,000
B. ARTIFICIAL GROUND FREEZING		
Testing - geotechnical, hydrologic and lab filter cake permeability	N.A	$20,000 - $80,000
Equipment Mobilization, clear, 4 inch drill casing	$\$21.4/Y^2$	$95,000
Rent - refrigeration, 4 in. header 2 in. pipes, manpower	$\$6.9/Y^2$	$30,500
Energy consumption	$\$5.7/Y^2$	$25,500
Maintenance	$\$0.31/Y^2$/day	$1400/day
Extra melt time due to latent heat (numeric constant in Eq. (4) = .1614)		25 days
Overall**	Maintenance +	$171,000-$231,000
Average	Maintenance +	$200,000

* See Table I for unit costs. Y^2 is square yards for depth x linear dimension. A 3-foot wall thickness is assumed in all calculations.

** Figure 3 at 18 day freeze time with 214 drill holes.

FROZEN WALL 1000 X 3 X 40 FT

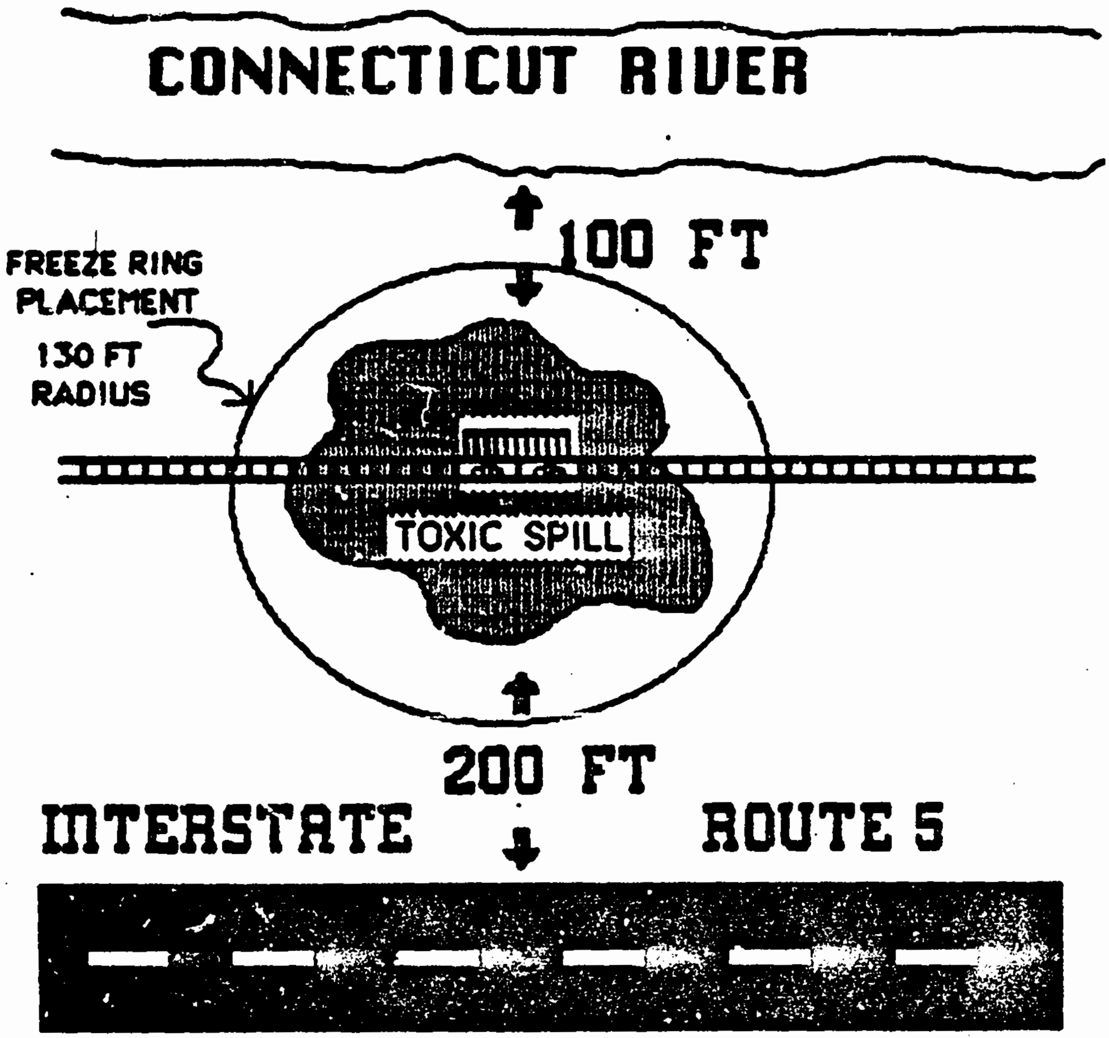


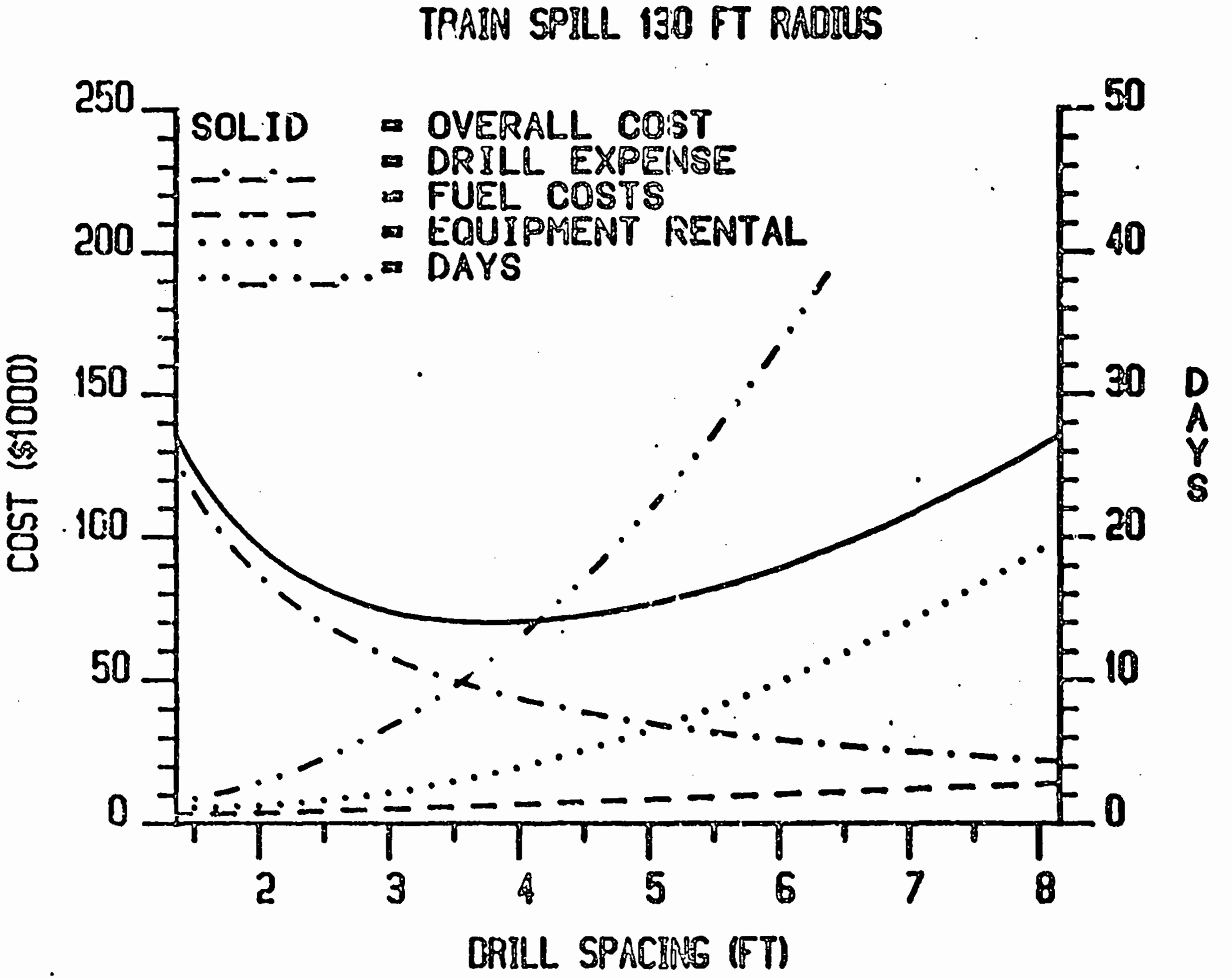
overall energy requirement and permits use of less expensive refrigeration equipment. The drawback of the close drill spacing is the expense associated with the drilling operation. The lineal footage of piping, a drive shoe for each well drilled, and the labor charge per vertical foot drilled overwhelm all other economic parameters.

Case (2):

Consider the situation where a derailed chemical car disperses a toxic substance over an area adjoining a railroad track, fig 4. Surrounding towns impose a time constraint on the chemical and transportation companies for containment of the waste. A preliminary week is required to define the hazardous spill and obtain general site test results. Initial drill samples estimate the barrier depth at 15 feet. Assuming the pollutant diffuses horizontally one foot per day the frozen wall is planned at a radius of 130 feet. This information is used to generate the economic overview presented in figure 5. The optimum cost design calls for a 3.8-foot drill spacing with a 12-day freezing time. If there is insufficient time remaining to freeze the soil before the time constraint is reached the drill spacing is reduced, with an associated increase in overall costs.

The thermal properties used in both of the above examples are those determined by O'Neill[25] for saturated quartz sand. The following cases show the economic and time dependence as a function of thermal parameters based on the


CONNECTICUT RIVER
100 FT
FREEZE RING PLACEMENT
130 FT RADIUS
TOXIC SPILL
200 FT
INTERSTATE
ROUTE 5


TRAIN SPILL 130 FT RADIUS
SOLID = OVERALL COST
_ . _ . _ = DRILL EXPENSE
_ _ _ = FUEL COSTS
. . . . . = EQUIPMENT RENTAL
. . _ . . _ . . = DAYS
COST ($1000)
250
200
150
100
50
0
DAYS
50
40
30
20
10
0
2
3
4
5
6
7
8
DRILL SPACING (FT)

train spill example geometry. Using data from Lunardini[15] for saturated soils the full range of soil texture and moisture content effects is examined. Table IV summarizes the optimum design configuration for the various soils, and figures 6-9 show the economic overview of each soil system. The results show that increasing the soil moisture content increases the time required to establish a frozen wall. For these high-moisture soils, mechanical refrigeration would need a tight drill spacing to satisfy the same time constraint in the train car spill case. However, an expendable LN_2 system with a 2.5-ft drill spacing establishes an impermeable barrier within eight days of pumping. This compares to a 22-day refrigeration time for a mechanical system under the same conditions of saturated fine-grained soil with a 40% moisture content, fig 8. The LN_2 frozen wall assumed a $-75^{\circ}F$ ($-60^{\circ}C$) vent temperature for the freezing pipes. The economics of expendable coolants are variable and generally hard to quantify. Veranneman and Rebhan[26] approximate LN_2 consumption at 800 kg of LN_2 per m^3 of frozen soil. Stoss and Valk[13] approximate the LN_2/brine expense ratio at 2 for large freezing projects (>700m^3) with maintenance periods exceeding 30 days. Consequently, once the LN_2 system establishes the barrier, a mechanical refrigeration unit maintains the system during the waste treatment process.

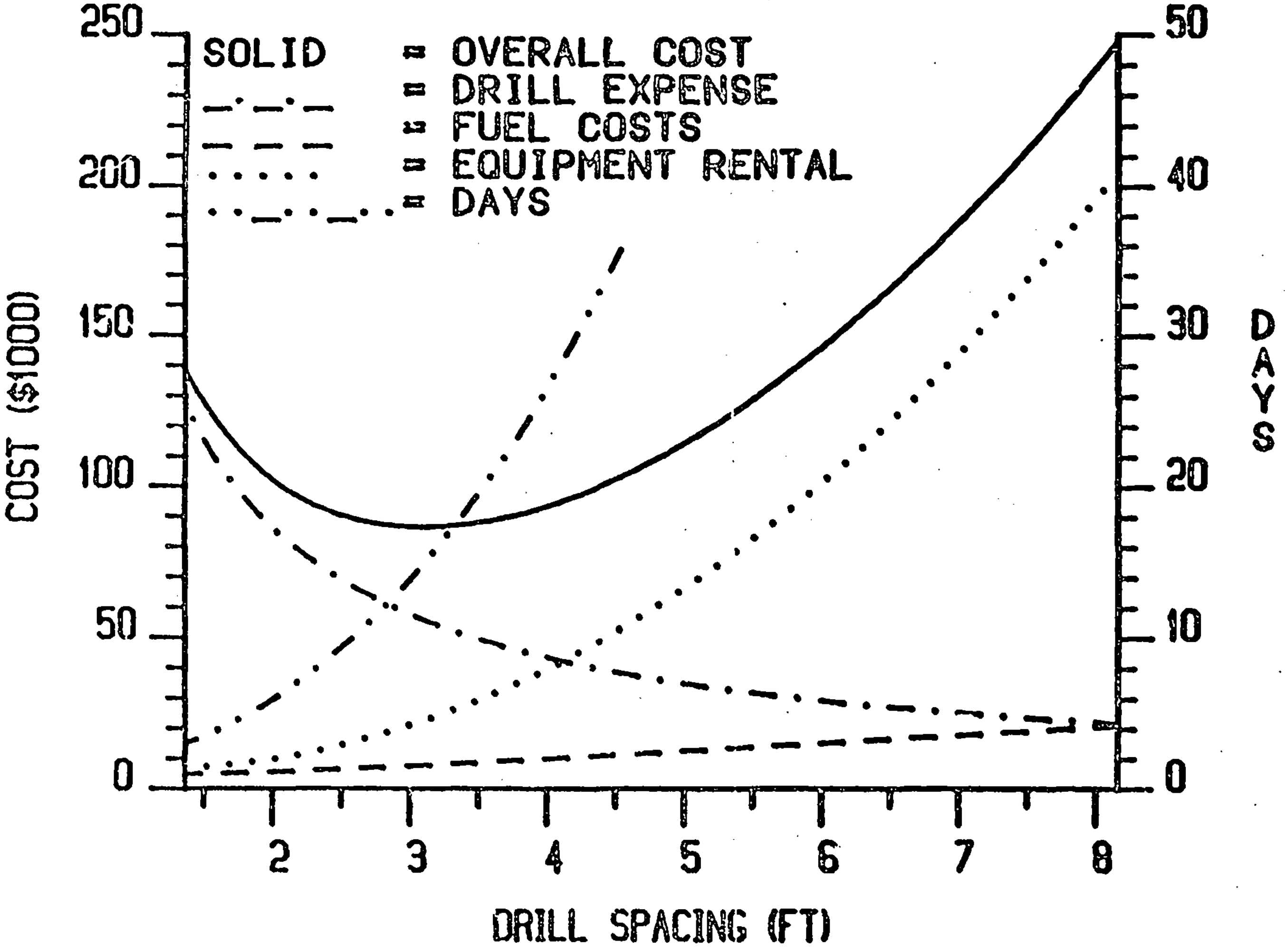
Table IV: Thermal Parameter Effects on Cost and Time Performances for Saturated Soils

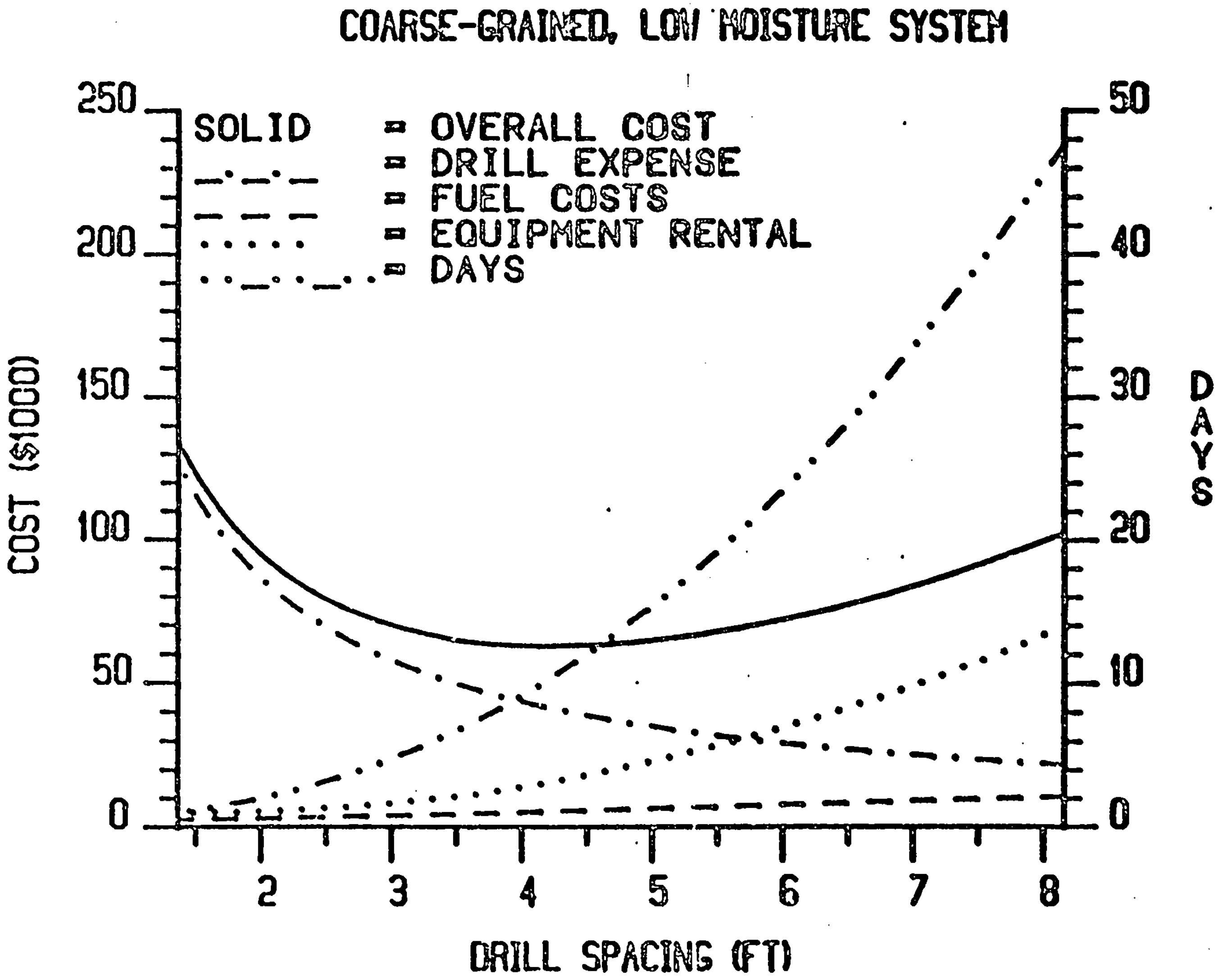
Saturated Soil Texture	k_1 cal/cms°C	c_1 cal/cm^3°C	c_2	L cal/cm^3	Moisture Content % of Dry Weight	Cost \$/yard^2 of Perimeter	Time Days	Figure
Coarse Grain	.00653	.44	.71	40	40	64	15	6
	.00972	.44	.54	15	10	46	10	7
Fine Grain	.00264	.47	.72	40	40	82	22	8
	.00472	.46	.56	15	10	56	14	9
O'Neill[25] Thermal Properties	.009	.398	.589	23.5	-	-	-	3,5

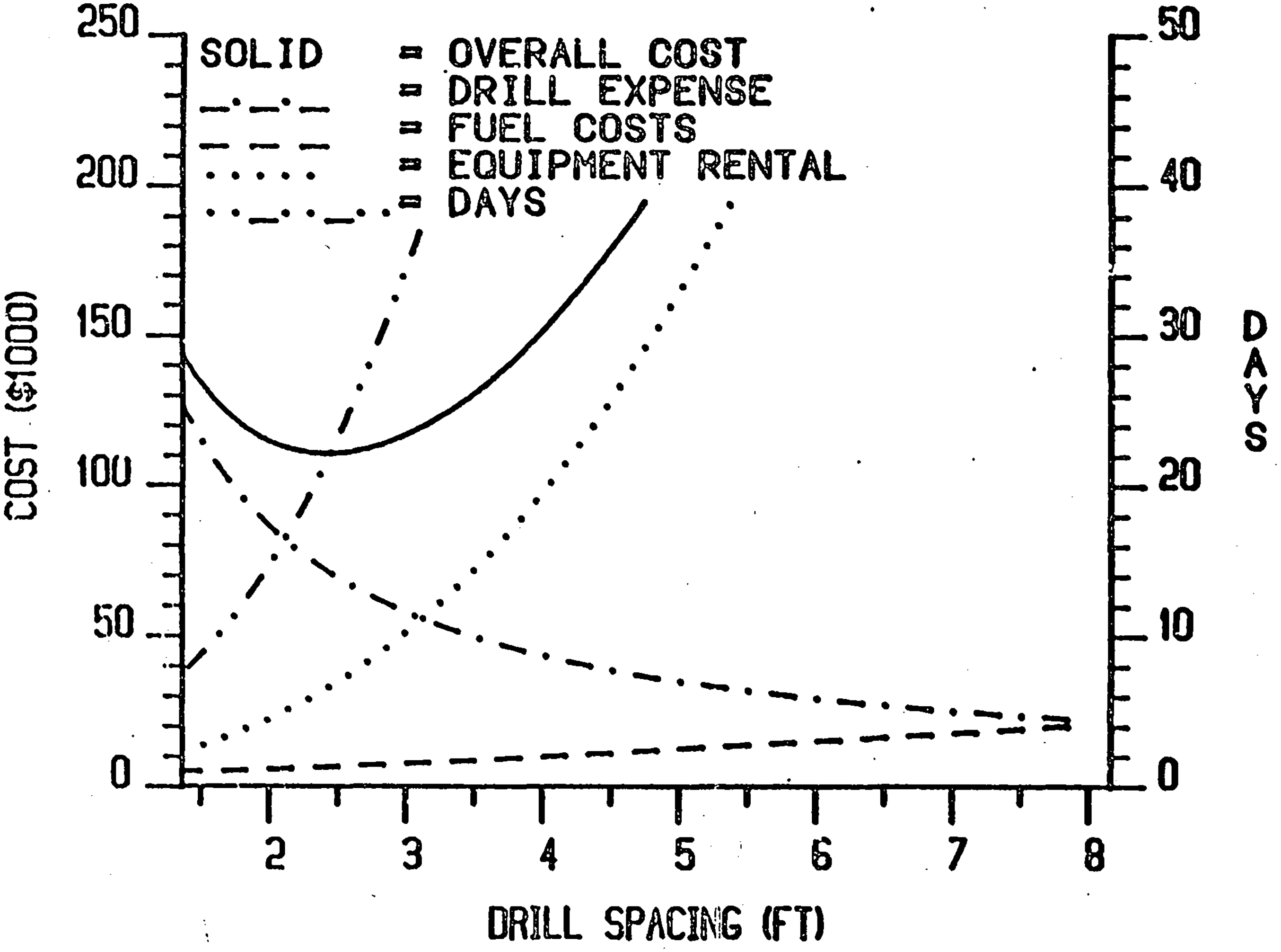
Cost estimate based on a wall 816 ft. round, 15 ft. deep.

For comparison: Slurry wall[24] \$75/y^2 of wall

COARSE-GRAINED, HIGH MOISTURE SYSTEM

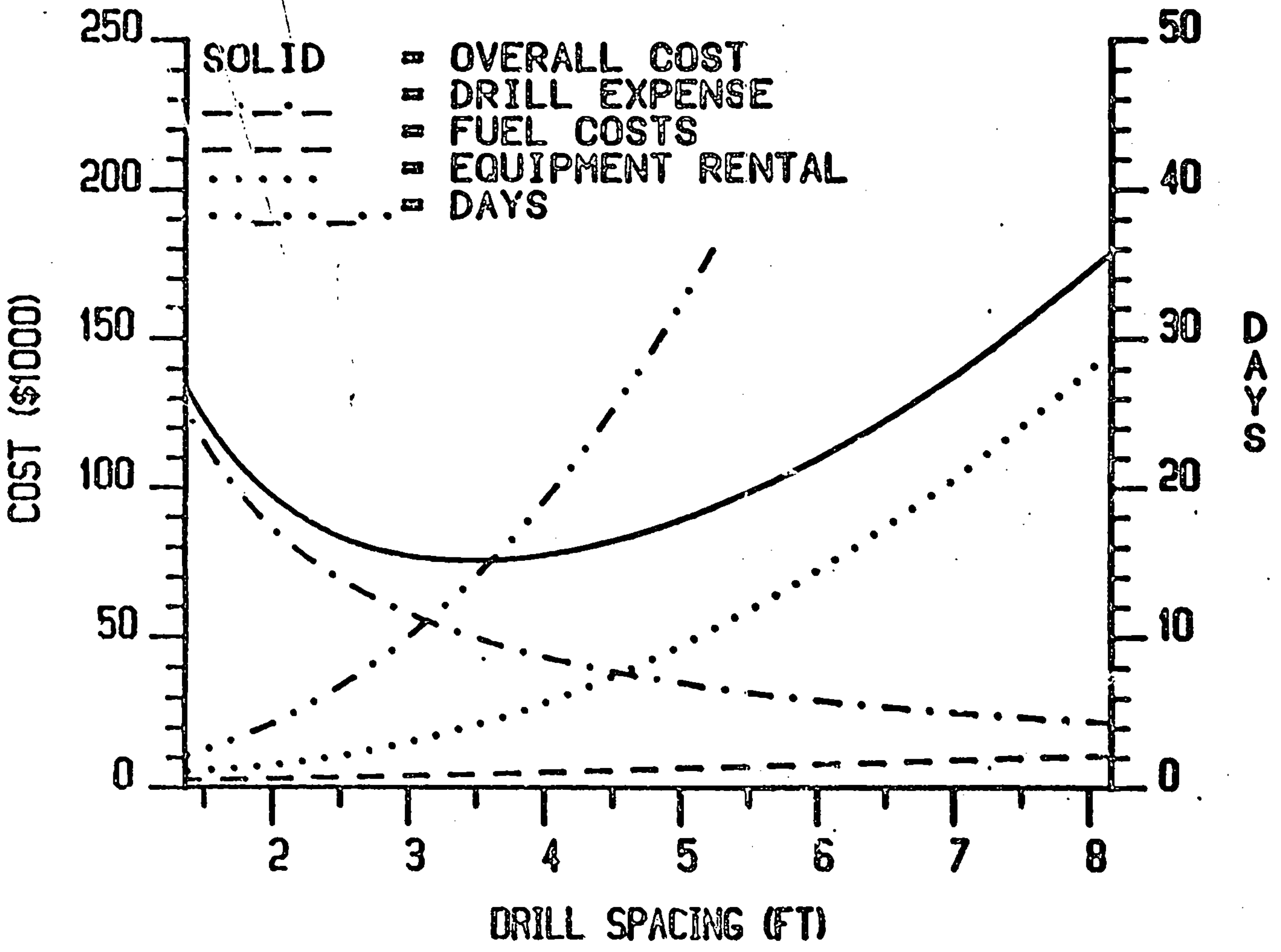



COARSE-GRAINED, LOW MOISTURE SYSTEM
SOLID = OVERALL COST
= DRILL EXPENSE
= FUEL COSTS
= EQUIPMENT RENTAL
= DAYS
COST ($1000)
250
200
150
100
50
0
DAYS
50
40
30
20
10
0
2
3
4
5
6
7
8
DRILL SPACING (FT)



FINE-GRAINED, HIGH MOISTURE SYSTEM

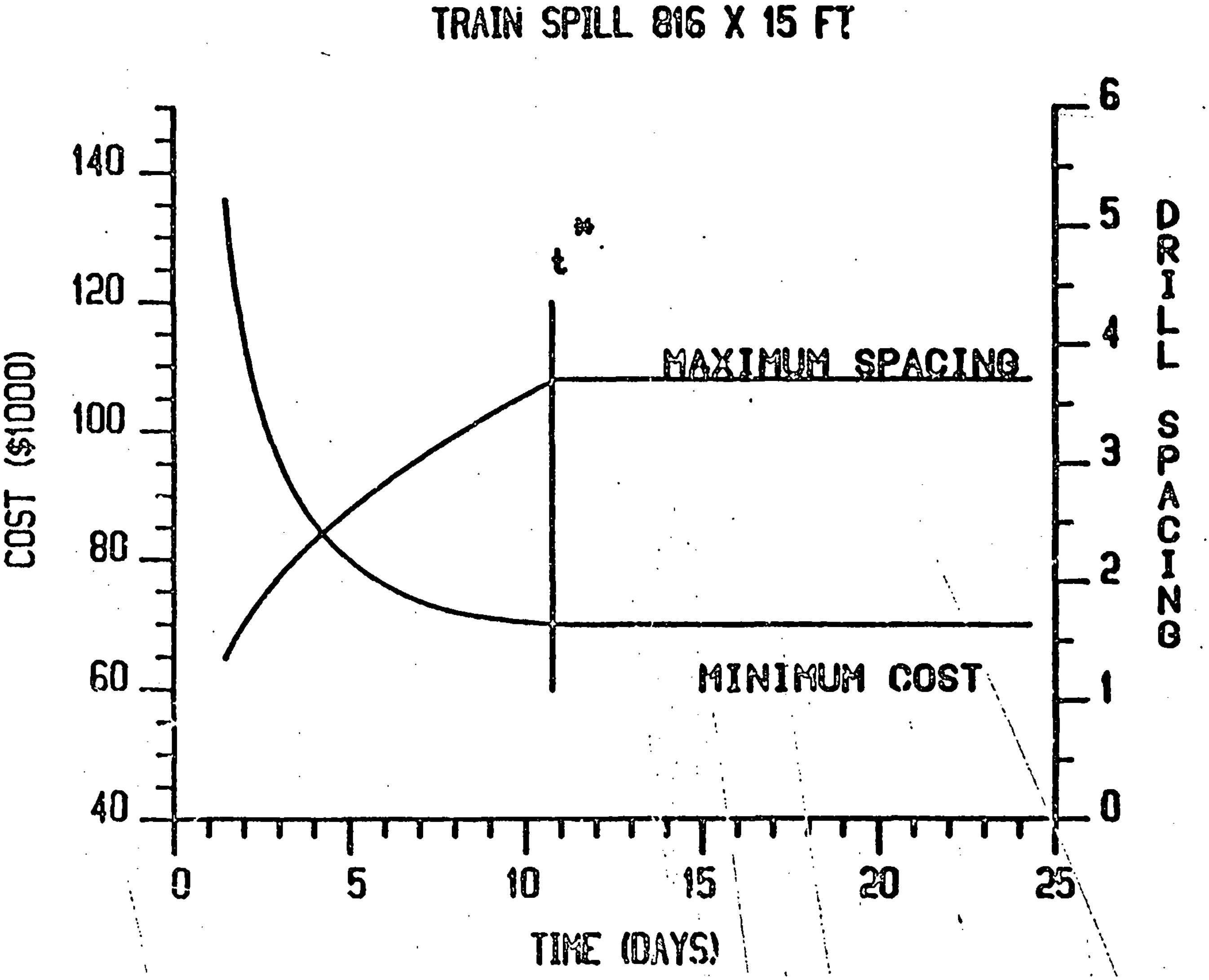
FINE-GRAINED, LOW MOISTURE SYSTEM



An alternate economic overview is presented in figure 10 in which we introduce a constraint on the maximum allowable freezing time. The minimum cost for a given geometry and thermal conditions is plotted as a function of maximum allowable freezing time; t^* is the optimal (least cost) freezing time from the unconstrained figure 5. If the time constraint is greater than t^* then the optimum spacing is selected. For time constraints less than t^* the cost rises following the curves as in fig. 5. Figure 10 was constructed using the train spill data.

CONCLUSIONS

Ground freezing as a means of hazardous waste containment can be a cost effective operation for a large range of thermal conditions. Soil parameters were shown to significantly affect the cost analysis. Fine-grained soils with high moisture retention can double the overall barrier expense compared to that of coarse-grained soils with low moisture characteristics. However, irregardless of the thermal conditions presented herein, the drilling operation was the primary cost factor whenever a time constraint less than or equal to the optimum spacing was imposed. The economic advantage of ground freezing over alternate barrier technologies is limited to temporary treatment sites due to the thermal maintenance expense.


TRAIN SPILL 816 X 15 FT
COST ($1000)
140
120
100
80
60
40
DRILL SPACING
6
5
4
3
2
1
0
t*
MAXIMUM SPACING
MINIMUM COST
0
5
10
15
20
25
TIME (DAYS)

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