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DESIGN GUIDELINES FOR AGRICULTURAL SOIL WARMING SYSTEMS UTILIZING WASTE HEAT

by

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ABSTRACT

This work was performed to provide potential users of soil warming systems with some general guidelines for the design of a soil warming installation. Although a detailed design is not included, the general configuration of such a system is discussed.

A computer program that solves the equations governing heat and water transfer in soils was used to simulate the operation of a soil warming system composed of a series of buried pipes at uniform spacing and depth carrying warm water. The results include temperature and moisture content distributions for various soil warming system pipe spacings and depths and for varying weather conditions. Annual temperature cycles are presented for Portland, Oregon; Athens, Georgia; and St. Paul Minnesota; for soil with no heating; and for soil with a continuously operating soil warming system.

The conclusions include suggested soil warming system pipe spacing, depth and size. Recommendations concerning irrigation methods are also included.

SECTION I

INTRODUCTION

The use of soil warming systems in agriculture appears attractive for several reasons. Plant growth rate is increased appreciably by warming the soil to temperatures in the range of 20 to 32°C (Beall, 1973; Boersma, et al. 1974; Berry and Miller, 1974). Soil warming can extend the growing season, increase the percent of seed germination and provide frost protection. For example, tomatoes and cucumbers exhibit increased growth and earlier ripening when grown in greenhouses maintained in the 25-30°C temperature range. Bush beans cultivated on a plot with a soil warming system have been double-cropped where only one crop was possible without the system (Boersma et al., 1974).

The potential of soil warming systems for frost protection is limited to foliage near the ground and is probably of little value in open fields. Berry and Miller (1974) reported that a greenhouse heated only by a soil warming system maintained a temperature of 2°C (36°F) at 1 foot above ground, while the temperature 5 feet above the ground in the greenhouse was -8°C (17°F) and the outside temperature was -21°C (-5°F).

Soil warming has been accomplished by burying electrical cables in the soil to provide heating. Although this method can provide arbitrary heating rates to the soil, it is expensive to operate and consumes electrical energy. Rykbost (1973) reported energy consumption rates for a demonstration plot of approximately 2000 to 6000 Kilowatt-hours/day for 300 square meters. This power usage is equivalent to 8.0×10^5 - 2.4×10^6 kw/acre/mo. At a cost of 3¢/kw-hr., operating expenses would range from $24,000 to $72,000 per month per acre. The expenses of electrical soil warming in a greenhouse would be somewhat less but still of the same magnitude as for open fields. Use of electric power plant waste heat for soil warming is comparatively inexpensive and uses energy that would otherwise be wasted. Closed-cycle condenser cooling water is particularly attractive because the temperature is usually considerably higher and more constant than open-cycle flow. This allows for better design and greater effectiveness. Use of power plant condenser cooling water for soil warming does have the disadvantage that the need for soil warming is greatest when the condenser cooling water temperature is the lowest, i.e., in winter. However, the condenser cooling water will provide heating throughout the year.

Installation of a soil heating system requires a large capital investment and the economic breakpoint depends on achieving the optimal design, or layout, for the crops to be grown. Some field performance data are available, which when incorporated with a mathematical model of heat and moisture flow (Sepaskhah, 1974) permit examination of the performance of alternative designs. This paper examines some alternatives for several climates in the United States. It is not intended as a detailed design manual for any one field or location.

SECTION II

CONCLUSIONS

Detailed design of a soil warming system would include the stated considerations for a particular soil, climate, and crop. For the soil and climates considered in this paper, the recommended design would include the following suggestions:

1. Use a pipe depth of 30-50 cm (13-19 in.)
2. Provide irrigation at the heating pipe.
3. To avoid corrosion problems, plastic pipe (polyurethane or polyvinylchloride) is recommended.
4. A 1" diameter pipe appears most economical on the basis of the cost analysis presented.
5. A pipe spacing of 140 cm or greater appears adequate for the Portland, Oregon, climate while a 280 cm pipe spacing is adequate for the Athens, Georgia climate. An extremely cold climate similar to the 1970 St. Paul, Minnesota weather would require pipe spacings less than 100 cm even though 140 cm pipe spacing provided significant heating.

SECTION III

THE SOIL WARMING SYSTEM

The soil warming system examined in this research applies to open field operations and is composed of parallel pipes buried in the soil at uniform spacing and depth. Since installation costs are high, it is desirable to be able to predict the effects of the system to ensure that the pipes are laid at appropriate depths and spacing. The mathematical model used employs partial differential equations governing heat and mass transfer in porous media. Axial variations along the pipe are ignored, the soil is assumed to be saturated at a depth of 200 cm, and the soil temperature is considered constant at a depth of 1350 cm. Neglecting axial variations along the pipe introduces little error because the flow rate of the condenser cooling water may be made high enough to produce a small temperature drop along the pipe. The axial temperature gradients would be much smaller than the radial gradients and therefore negligible. The soil surface is treated as a plane with no foliage. Radiant, convective, and evaporative heat transfer at the surface is considered.

At the surface, the heat and mass fluxes are found by using weather data along with empirical convection coefficients. The equations are solved on a digital computer for the desired boundary conditions.

A laboratory experiment (Sepaskhah, 1974) was modeled to verify the results of the computer simulation. The experimental apparatus consisted of an insulated box of soil with a heat source and water source located on one wall at a depth of 32 cm. The box was 48 cm high by 40 cm wide and the particular soil modeled was a loamy sand. The temperatures and moisture contents were measured and are presented in Figures 1 and 2 for comparison with the results of the computer simulation. The experimental and simulated results are in fair agreement and the computer simulation is assumed valid for these conditions.

Irrigation of the soil subjected to soil warming is desirable, if not necessary. Without irrigation, the soil dries and therefore is less suitable for raising crops. The soil warming is also inhibited by low moisture content since the thermal conductivity of soil decreases with decreasing moisture content. Figure 3 presents temperature distributions after 31 days of simulated operation for a loamy sandy soil for 1) soil warming with no irrigation, 2) irrigation at the heating pipe, and 3) surface irrigation. The irrigation rates were 10.8 cm/day (4.25 in/day), while the pipe depth was 50 cm and the spacing was 140 cm. Both the unirrigated and the surface irrigated simulations indicate less warming of the soil than does the soil warming simulation with irrigation at the pipes.

Figure 4 presents the moisture content distributions for the cases presented in Figure 3. The initial moisture content is a function of depth only and is presented as point values versus depth. The moisture content for the surface irrigated simulation and the simulation for no irrigation varied only slightly in the horizontal direction. The moisture contents for these two cases are therefore presented as average values at the various depths. For example, the moisture content at 60 cm depth was 0.263 cm^3/cm^3 initially, and after 31 days of operation was 0.249 cm^3/cm^3 for no irrigation, 0.344 cm^3/cm^3 for surface irrigation and ranged from 0.42 to 0.38 cm^3/cm^3 for subsurface irrigation. It is noted that the unirrigated example is drier than the initial distribution and that the surface irrigated example is drier than the one with

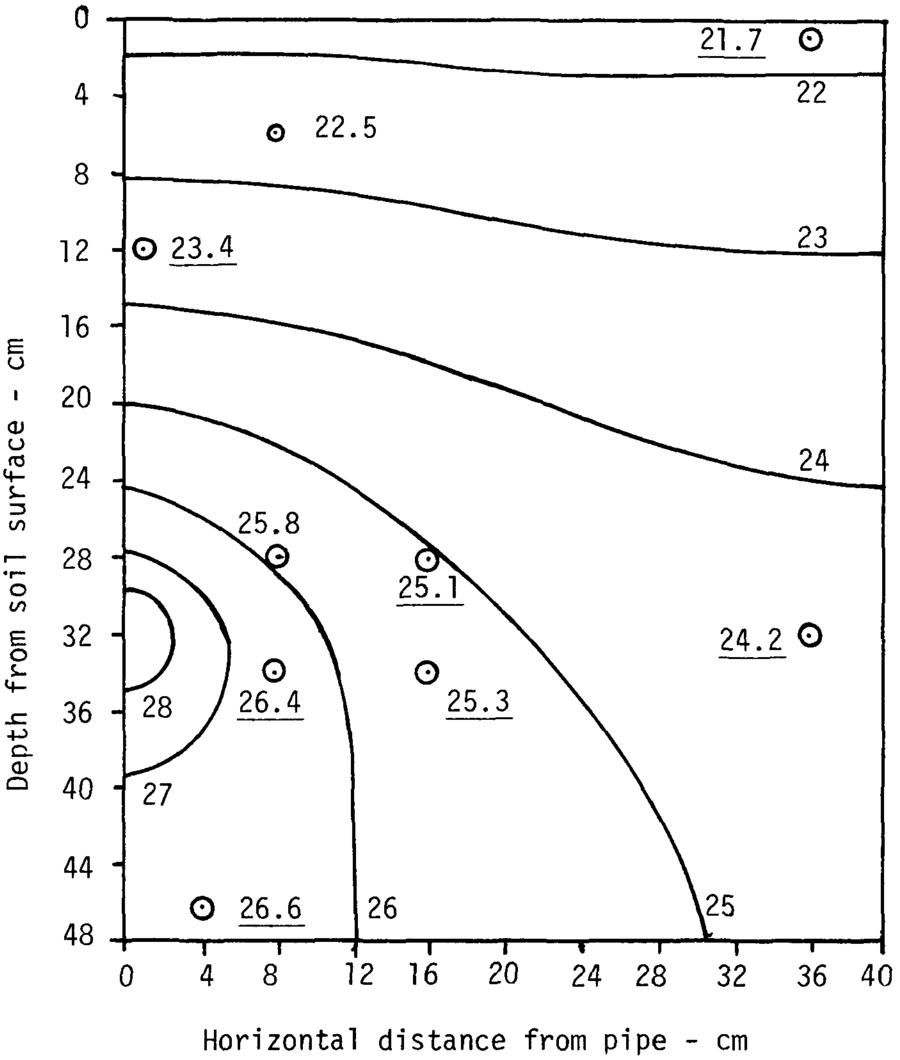

Figure 1. Comparison of calculated temperature (°C) with experimental values from Sepaskhah (1974).

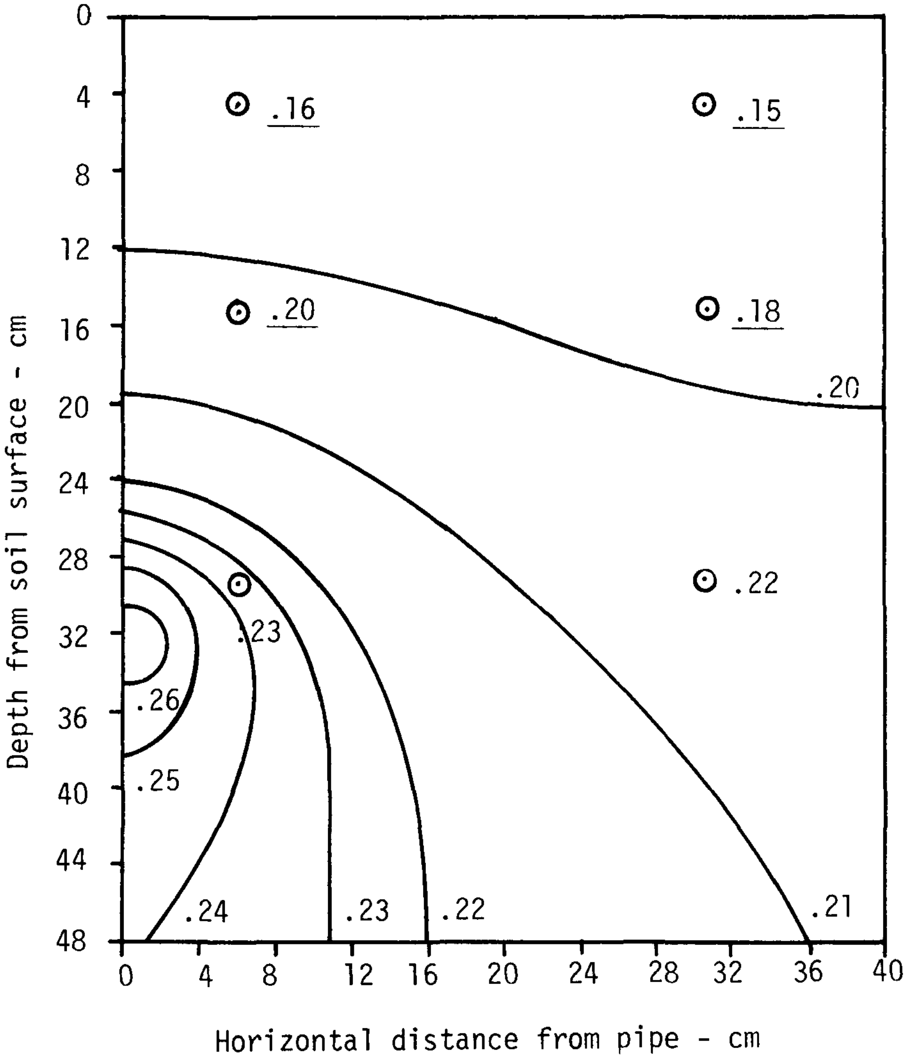

Figure 2. Comparison of calculated moisture content (cm^3/cm^3) with experimental values from Sepaskhah (1974).

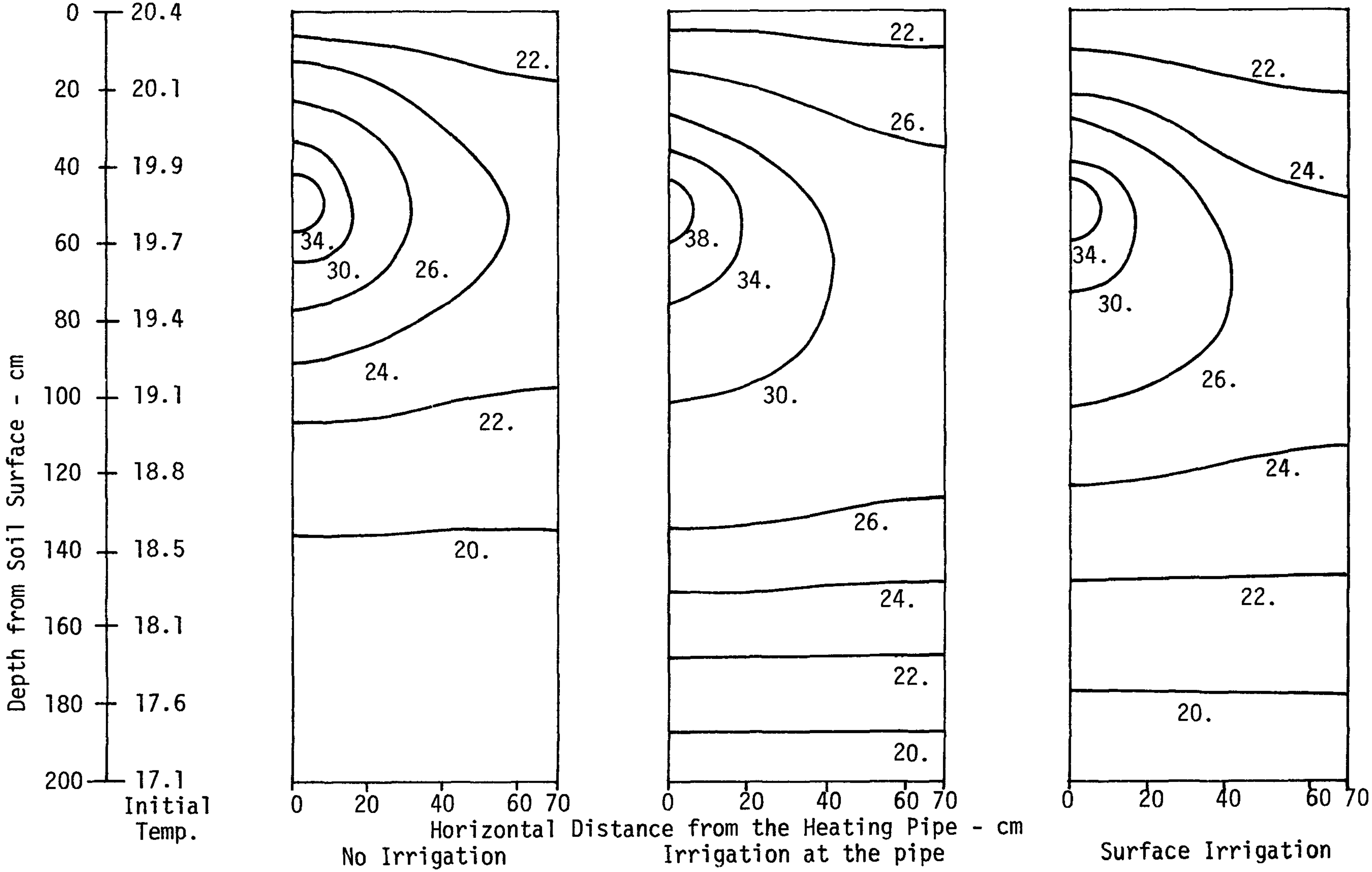

Figure 3. Temperature distributions (°C) for various irrigation methods. The simulations are for average August weather data for Portland, Ore and for a pipe temperature of 41°C.

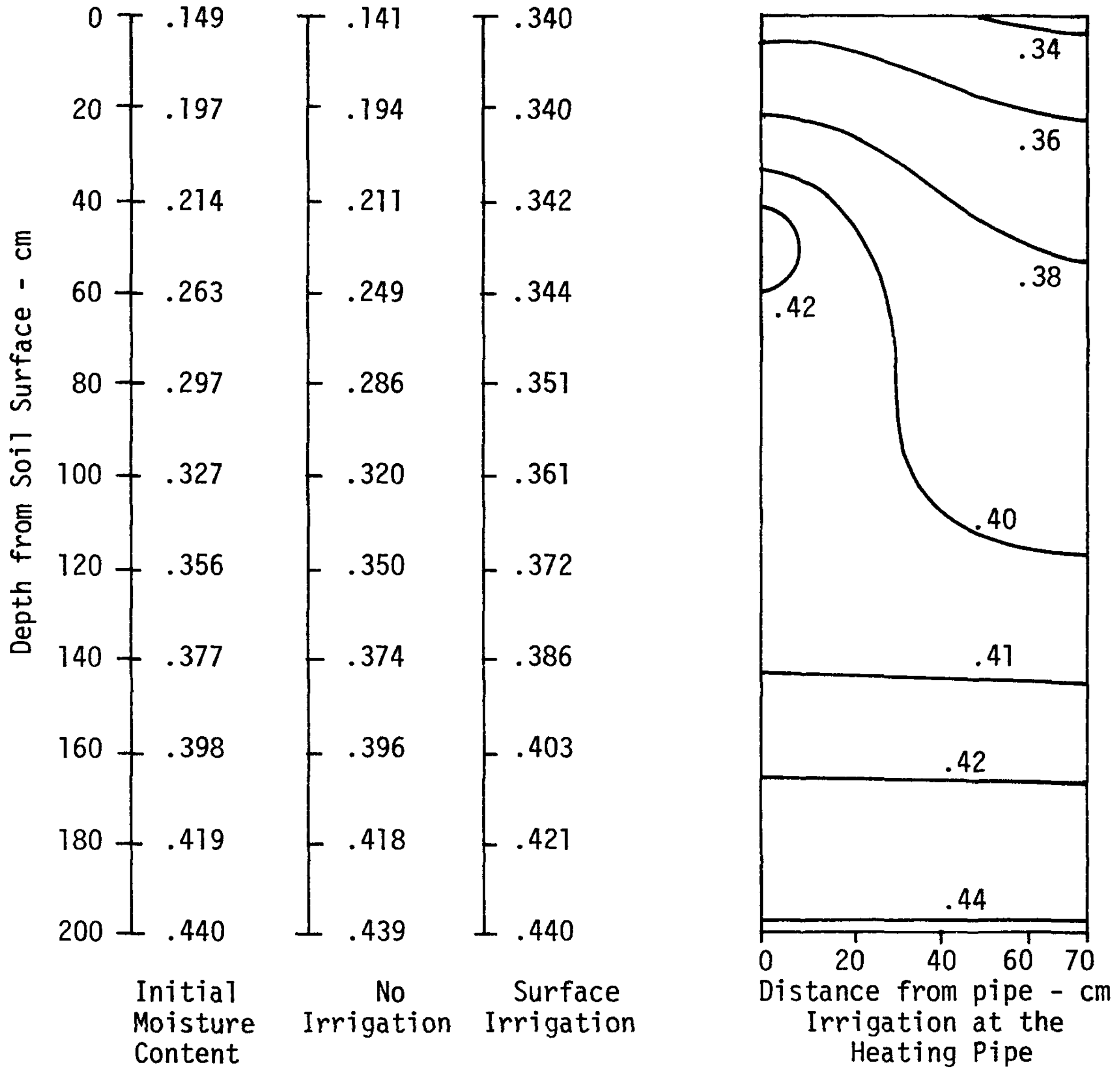

Figure 4. Moisture content distributions (cm^3/cm^3) for various irrigation methods. The simulations are for average August weather data for Portland, Ore. and for a pipe temperature of 41°C.

irrigation at the pipes even though the irrigation rates were the same. Furthermore, it is expected that prolonged operation of a soil warming system with no irrigation at the pipe would result in drying near the pipe. Rykbost (1973) reported a very dry region (Moisture content equal to 0.09 cm^3/cm^3) from 0 to 2 cm from the heating pipe for soil warming in an open field with surface irrigation. The computer program does not predict this because the node size is 10 cm and moisture content is approximated by one mean value over the 10 cm x 10 cm volume. Reduced moisture content at the heating pipe reduces soil warming because thermal conductivity decreases with decreasing moisture content.

Subsurface irrigation offers additional benefits in the form of reduced water consumption. Hanson and Williams (1968) and Hanson, et al (1970) report production of equivalent yields of cotton with 25 percent savings in water consumption using subsurface irrigation instead of furrow irrigation. Zetzsche (1964) and Newman (1965) reported 42 percent water savings in growing cotton with subsurface irrigation.

Incorporation of a subsurface irrigation system with the subsurface soil warming system is recommended since irrigation at the heating pipe increases the warming of the soil and reduces water consumption. A simple method of providing both heating and irrigation would be to locate a small porous pipe for irrigation over a larger heating pipe. The use of two pipes -- one to irrigate and one to heat -- should not be much more expensive than soil warming with surface irrigation since surface irrigation also requires piping. The subsurface irrigation system is a permanent installation, therefore labor costs for operation should be minimal and tend to offset the higher capital outlay. Potential problems, such as root clogging of the irrigation pipe and maintaining the desired irrigation flow rate, are not considered insurmountable obstacles to successful operation.

SECTION IV

RESULTS

The model used in this research simulated irrigation provided at the heating pipe. The soil warming system was simulated for 31 days using January and August weather data and pipe temperatures starting with temperature and moisture contents representative of an unheated soil. The soil warming and irrigation system pipe spacings were 140, 280, and 560 cm while pipe depths of 50 and 100 cm were used. Typical computer simulations are shown on Figures 5 through 7. The average increase of soil temperature and moisture content in the soil profile from the surface to a depth of 100 cm and the percent of this region with a temperature of 24°C or higher were calculated. These quantities are presented in Table 1. Table 2 shows the average increase in soil temperature and the average increase in moisture content in the soil profile to a depth of 200 cm and the percent of the 200 cm region with a temperature of 24°C or higher. Since increased moisture content and temperature represent more favorable conditions for plant growth, these quantities are used to evaluate the relative benefits of the different pipe spacings and depths.

It is observed from these simulations that the increase in water content is greatest for the 50 cm pipe depth, that the 50 cm pipe depth provides better soil warming for the 0 to 100 cm region and that the 100 cm pipe depth provides better soil warming for the 0 to 200 cm region. Based on the increased moisture content and the fact that plants have ultimate root depths considerably less than 200 cm in the early half of the growing season, and that few plants or soils reach to 200 cm depth, the shallower pipe depth is deemed more beneficial.

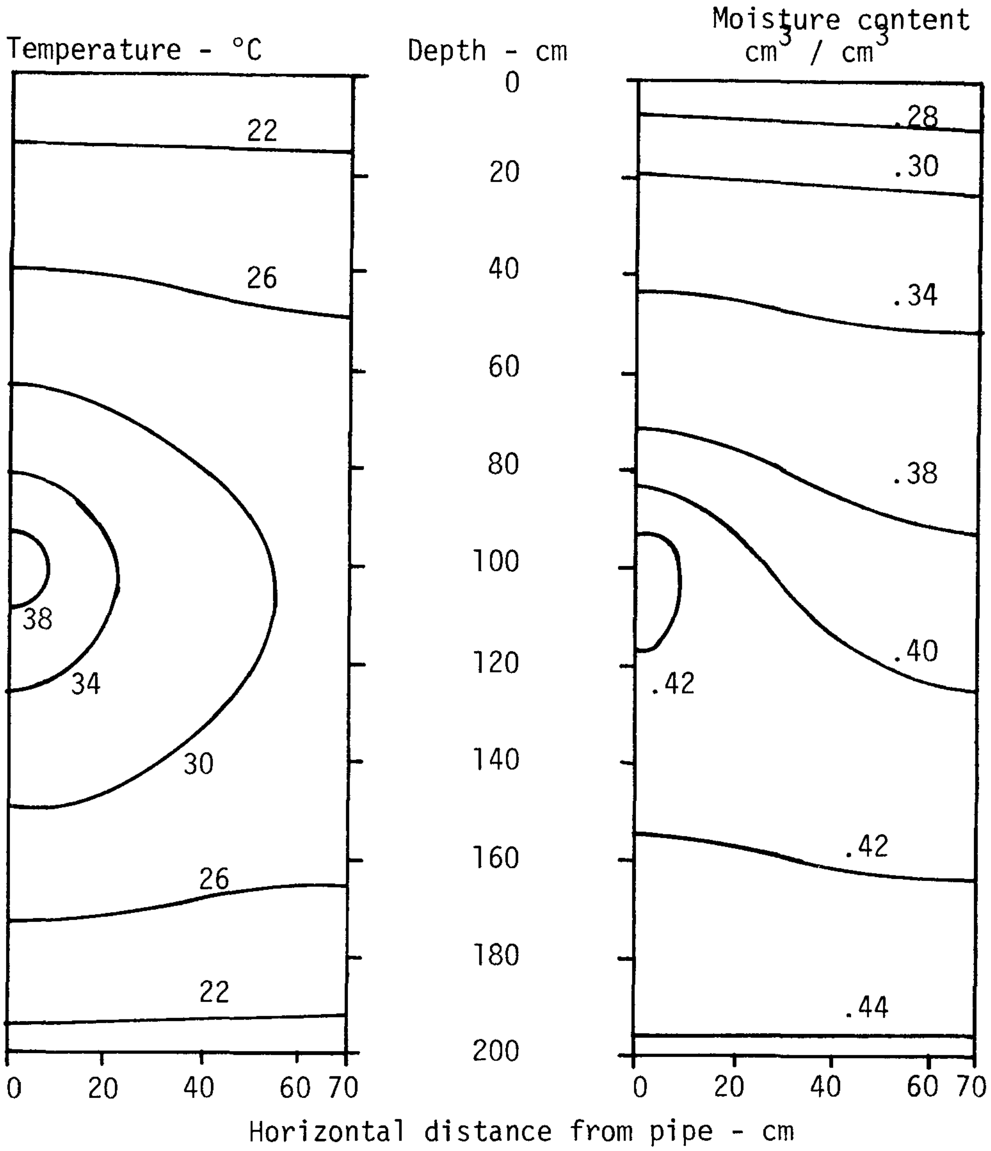

Figure 5. Temperature and moisture content distributions for a pipe spacing of 140 cm and a pipe depth of 100 cm and average monthly weather data and condenser discharge temperature (41C) for Portland, Ore. in August. Simulation is for 31 days of operation.

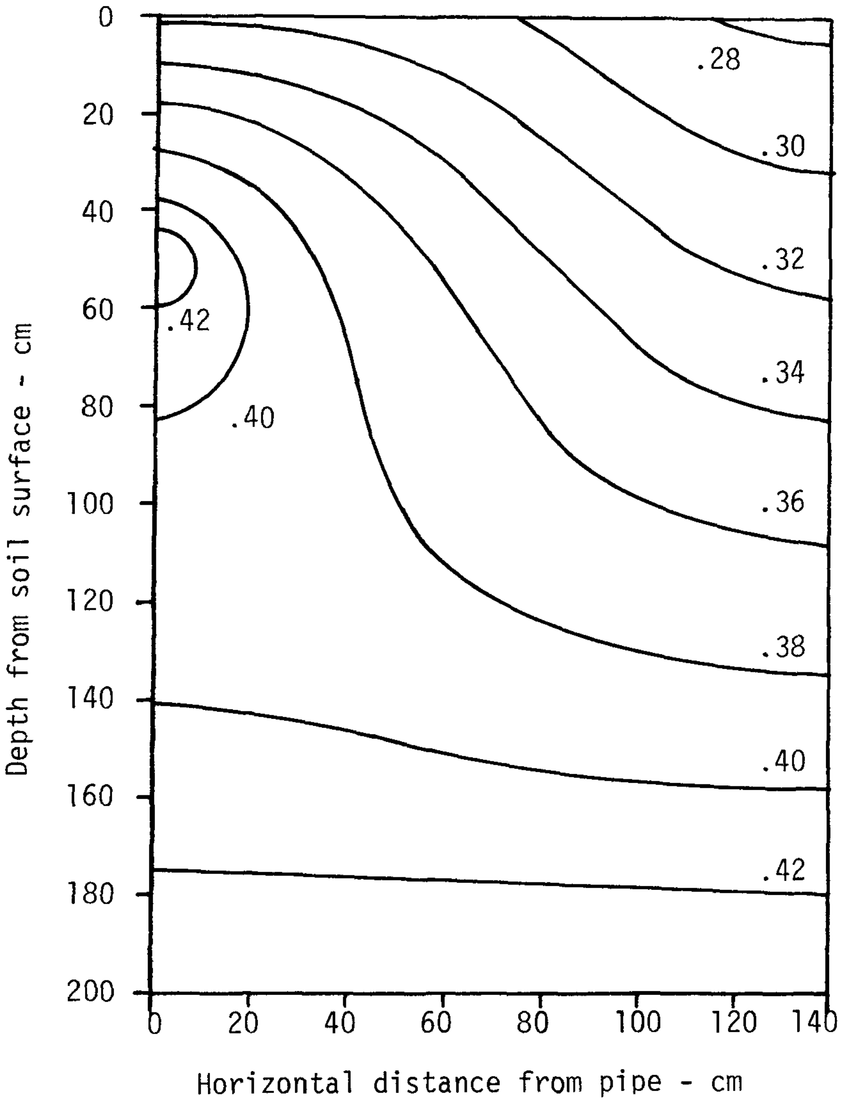

Figure 6. Moisture content distribution for a pipe spacing of 280 cm and a pipe depth of 50 cm for average monthly weather data and condenser discharge temperature for Portland, Ore. in January. The simulation is for 31 days of operation.

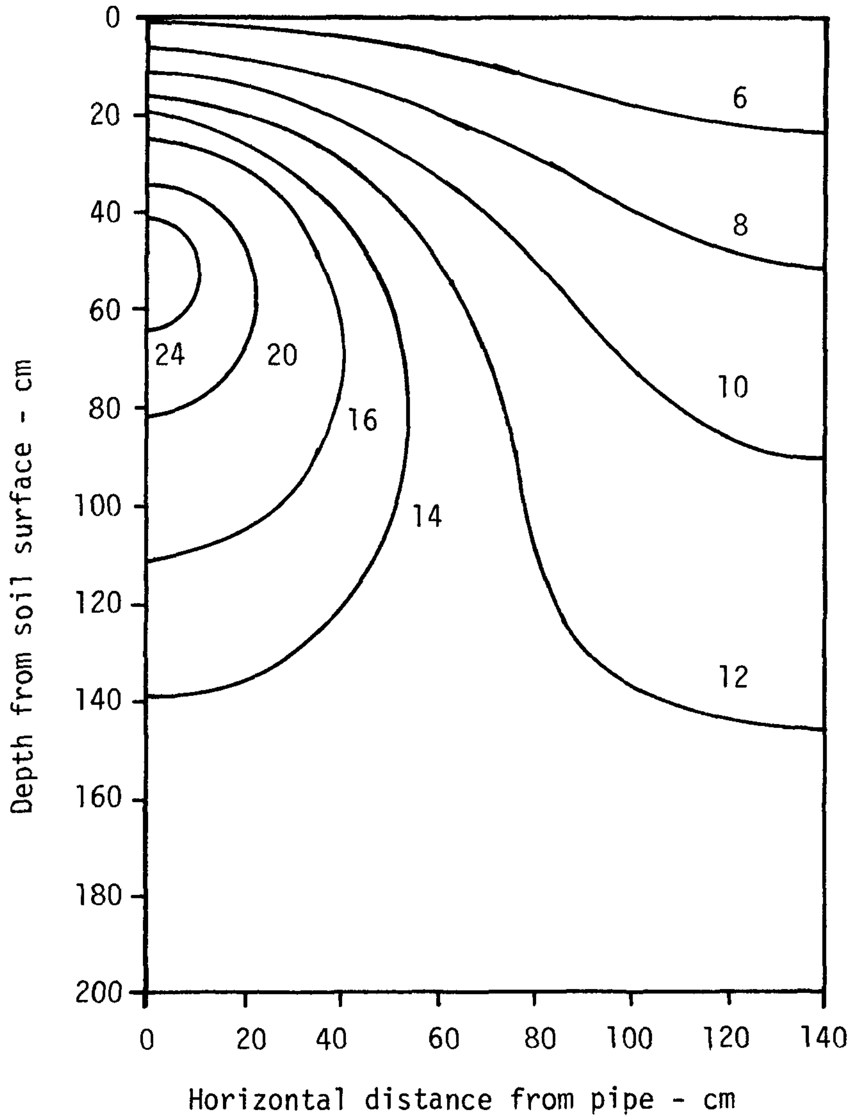

Figure 7. Isotherms (°C) for a pipe spacing of 280 cm and a pipe depth of 50 cm for average monthly weather data and condenser discharge temperature (29°C) for Portland, Ore. in January. The simulation is for 31 days operation.

Table 1. SOIL WARMING AND IRRIGATION SYSTEM EFFECTS FOR A 0 TO 100 CM DEPTH.

	Spacing (cm)	Pipe Depth (cm)		Pipe Depth (cm)		Pipe Depth (cm)	
		50	100	50	100	50	100
		Percent of Soil Above 24°C		Ave. Temp. Increase (°C)		Ave. Moisture Increase (cm^3/cm^3)	
January							
	140	2.16	1.50	7.99	6.16	.104	.0673
	280	1.14	0.58	4.22	3.05	.0654	.0385
	560	0.84	0.46	2.42	1.91	.0423	.0237
August							
	140	83.2	72.2	9.04	7.65	.144	.0997
	280	36.8	28.2	4.15	3.69	.101	.0640
	560	18.0	16.3	2.62	1.60	.0601	.0346

Table 2. SOIL WARMING AND IRRIGATION SYSTEM EFFECTS FOR A 0 TO 200 CM DEPTH.

	Spacing (cm)	Pipe Depth (cm)		Pipe Depth (cm)		Pipe Depth (cm)	
		50	100	50	100	50	100
		Percent of Soil Above 24°C		Ave. Temp. Increase (°C)		Ave. Moisture Increase (cm^3/cm^3)	
January							
	140	1.08	2.19	5.12	6.06	.0634	.0473
	280	0.57	0.86	2.44	2.83	.0386	.0264
	560	0.42	0.77	1.44	1.76	.0254	.0163
August							
	140	65.6	77.0	7.12	8.50	.0846	.0638
	280	20.7	28.2	2.31	3.76	.0569	.0397
	560	14.5	16.4	1.99	1.65	.0337	.0211

Operation of the soil warming system over the entire growing season would also result in higher temperatures than those based on 31 days of operation. Figure 8 presents the results of a simulation for January conditions for 72 days operation with pipe spacing of 280 cm and depth of 50 cm. Comparison with Figure 7 illustrates the effect of prolonged system operation, since the temperatures presented in Figure 8 are appreciably higher than those of Figure 7.

Since installation is a major cost, the soil warming system should be a permanent installation. Provision must, therefore, be made for subsequent cultivation of the soil. Therefore, the soil warming pipes should be buried deeper than the maximum cultivation depth. A pipe depth of 30-50 cm (13-19 in.) is recommended to provide optimum irrigation, allow for cultivation, and provide the maximum amount of soil warming to the roots over the entire growing season.

From the data developed by the computer simulations, pipe spacings of 140 cm appear adequate for open field operation in moderate climates. The data presented in Tables 1 and 2 also indicate that decreasing the pipe spacing increases the soil warming and irrigation effects of the soil warming system.

While there are indications of the effect of the pipe spacing in the results presented in Tables 1 and 2, no optimum pipe spacing can be specified without performing a complex economic study of the benefits derived from decreasing pipe spacing compared to the increased costs caused by decreasing pipe spacing.

To further estimate the effects of the warming system for annual operation, the computer simulation used average monthly weather data for

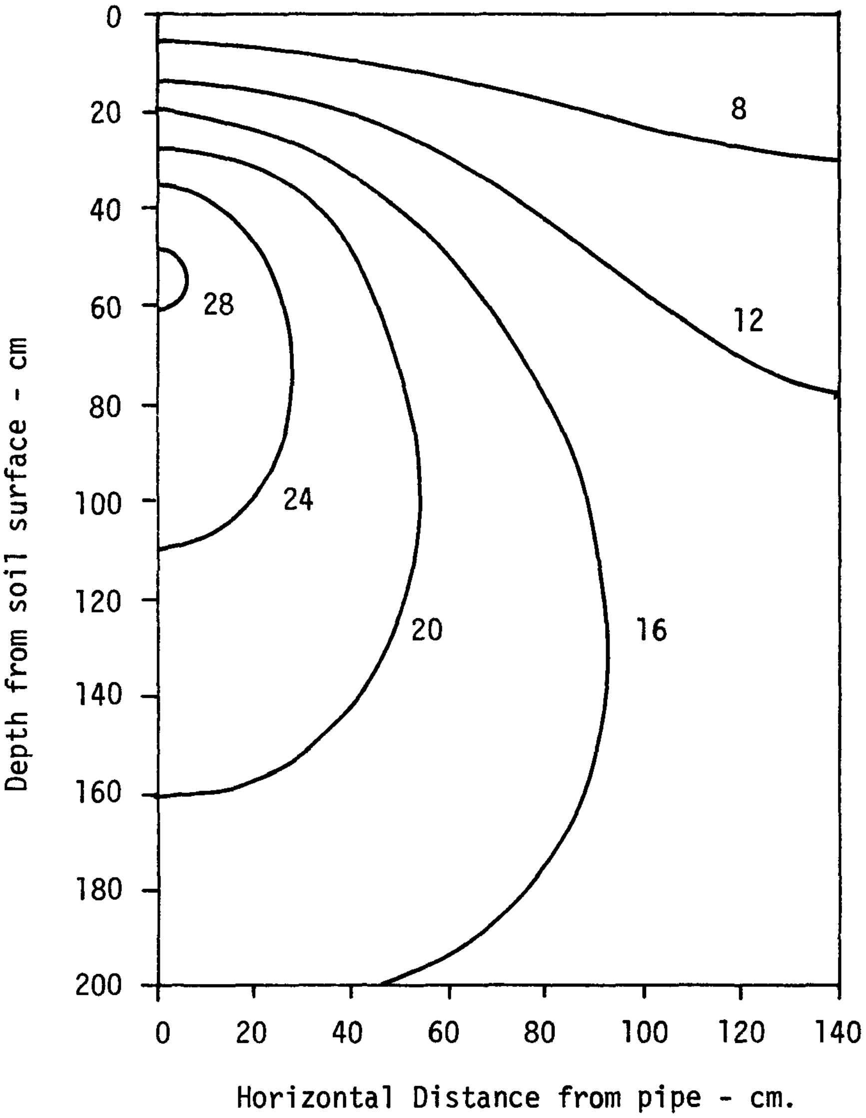

Figure 8. Isotherms (°C) for a pipe spacing of 280 cm and pipe depth of 50 cm for 72 days of operation in Portland, Ore. for January weather data.

1970 together with average monthly condenser discharge temperatures to simulate operation for the entire year of 1970. Average monthly weather data for 1970 were used and the condenser discharge temperature was estimated by adding 22.2°C (40°F) to the calculated wet bulb temperature. Figure 9 presents the average temperature at 10 cm depth for Portland weather data for 1970 and for average predicted condenser discharge temperatures for the Trojan nuclear power plant located near Portland. Figure 10 shows the average temperature at the 20 cm depth for 1970 Portland operation. Pipe depth was 50 cm and the pipe spacing was 140 cm.

Simulations were also made for a warm climate, Athens, Georgia, and for a cold climate, St. Paul, Minnesota. Figures 11 and 12 show the annual temperature variations at the 10 and 20 cm depths for unheated soil and for heated soil with a pipe depth of 50 cm and pipe spacings of 140 and 280 cm for the Athens climate. Figures 13 and 14 show annual temperature variations for St. Paul.

An indication of benefits from operation of the soil warming system can be obtained from Figures 9 through 14. As an example, Figure 9 may be used to estimate the time by which the growing season could be extended by use of soil warming systems. Without soil warming, a crop with a seed germination temperature of 10°C could not be planted until March. With soil warming, however, the required temperature is reached approximately 15 weeks earlier at the 10 cm depth. Similarly, the late growing season temperatures are extended appreciably.

SOIL WARMING PIPE SIZE

A typical heating rate was calculated from the results of the computer simulation for 140 cm pipe spacing, 50 cm pipe depth and January weather conditions. The heating rate, q, was:

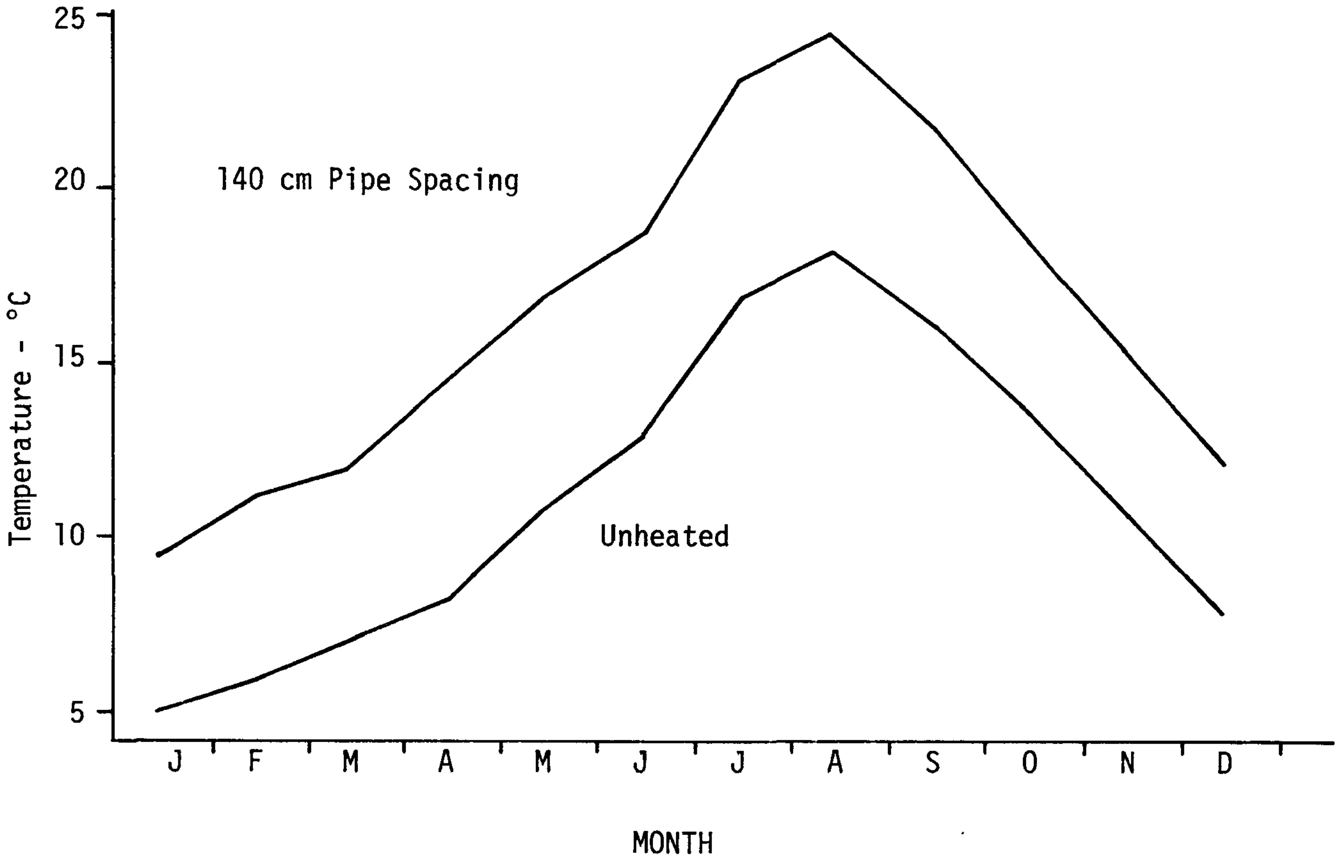

Figure 9. Simulated Annual temperature variation at 10 cm depth in Portland, Ore., 1970. Pipe Depth is 50 cm.

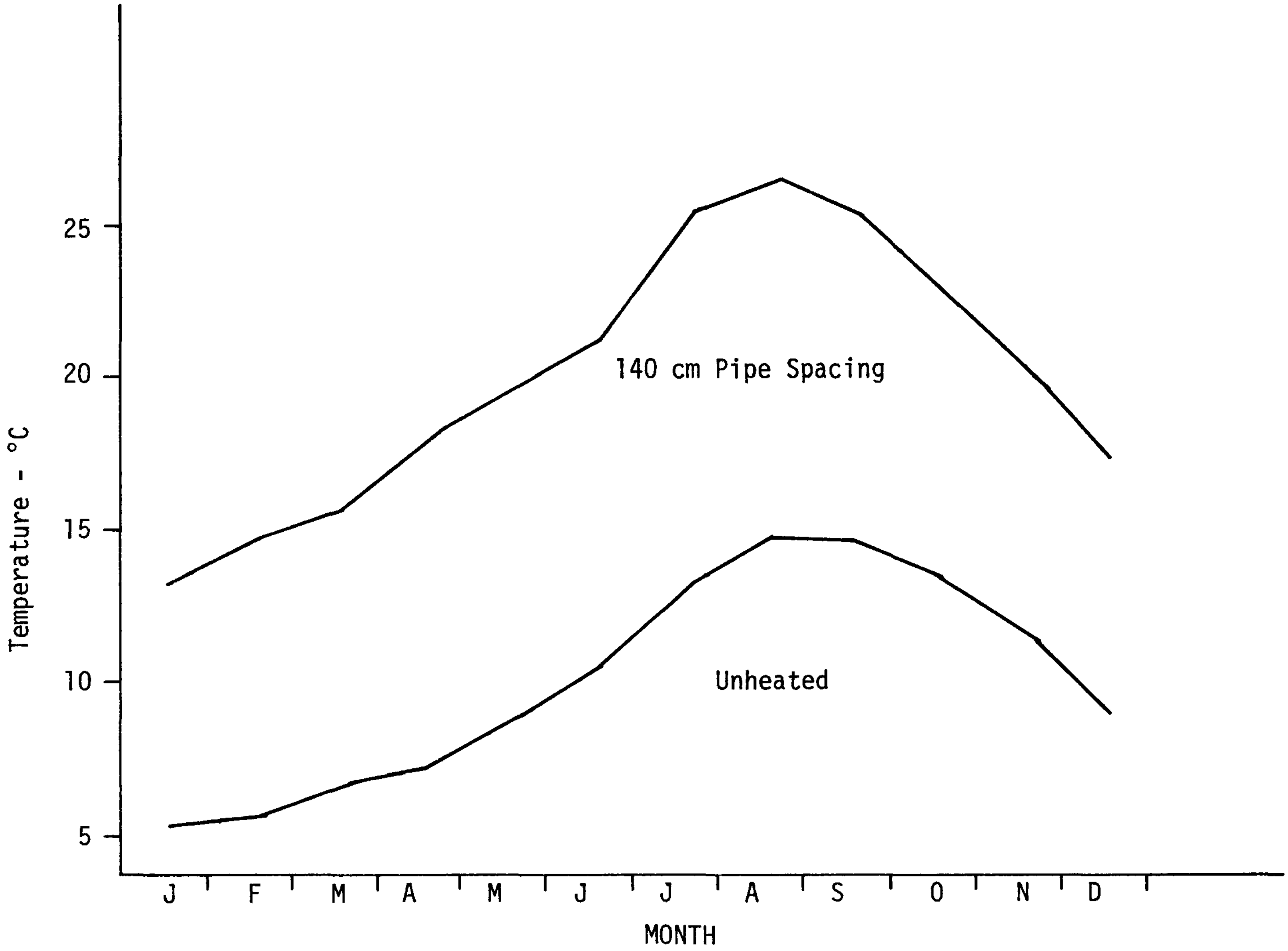

Figure 10. Simulated annual temperature variation at 20 cm depth in Portland, Ore., 1970. Pipe depth is 50 cm.

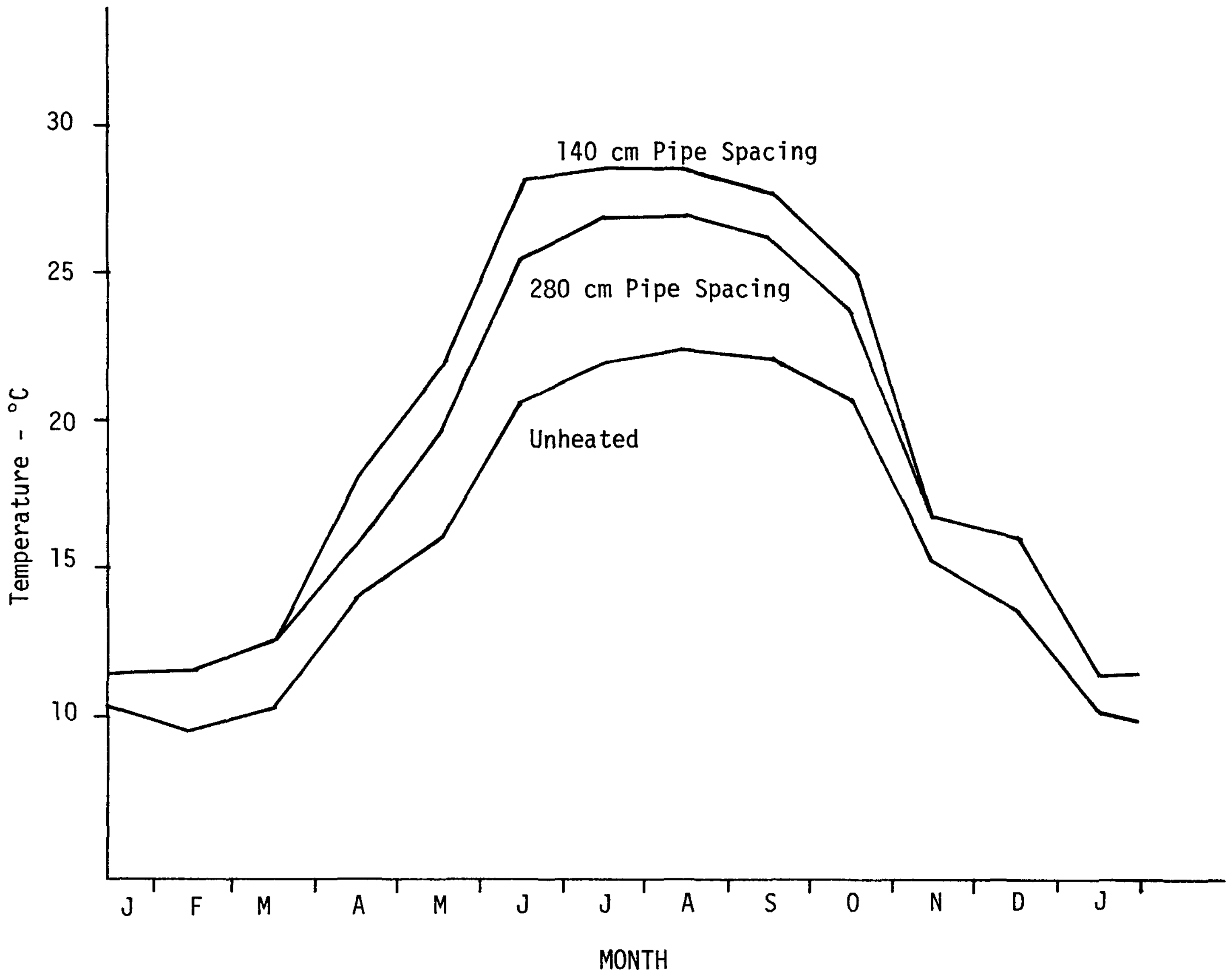

Figure 11. Simulated annual temperature variation at 10 cm depth in Athens, Ga., 1970. Pipe depth is 50 cm.

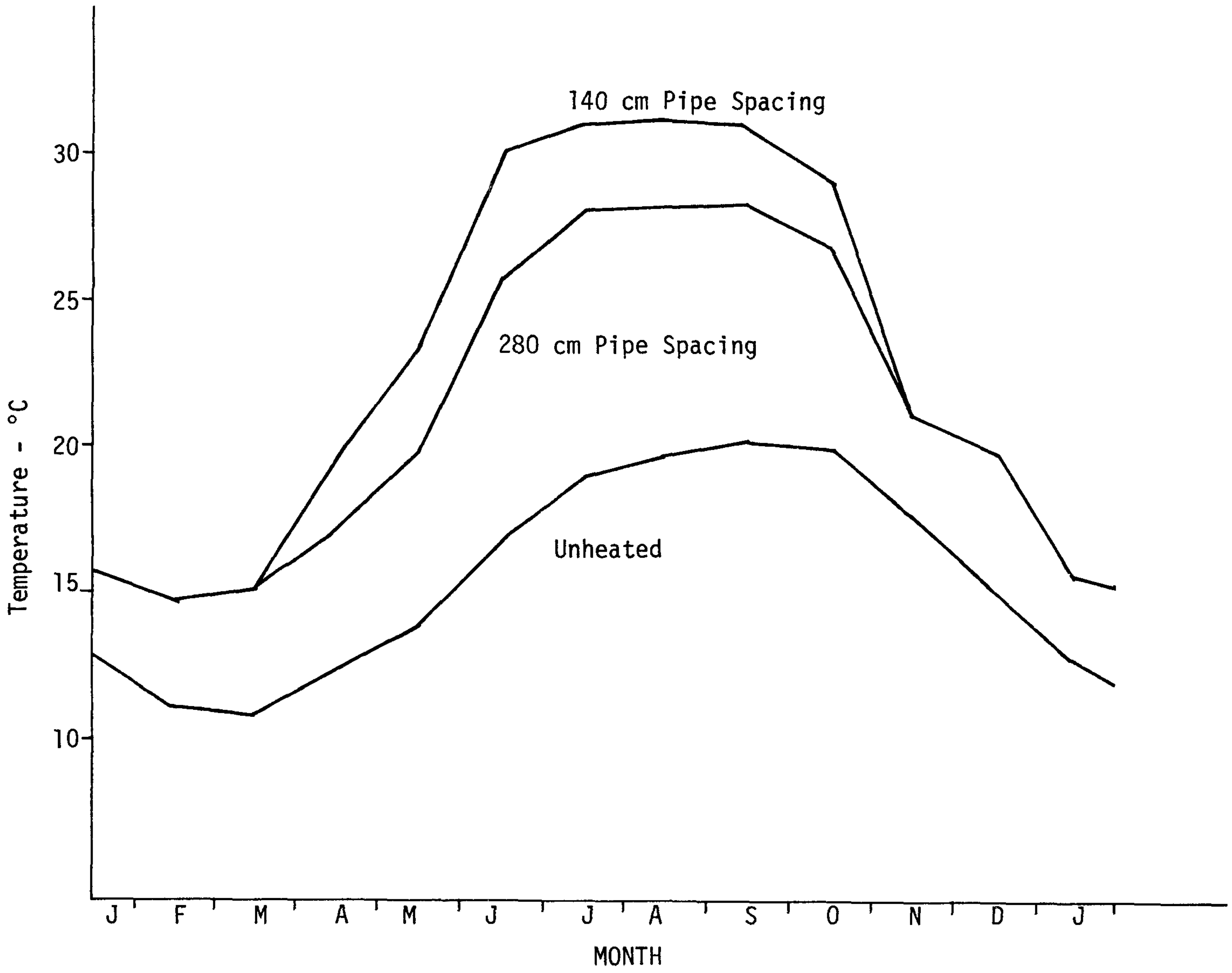

Figure 12. Simulated annual temperature variation at 20 cm depth in Athens, Ga., 1970. Pipe depth is 50 cm.

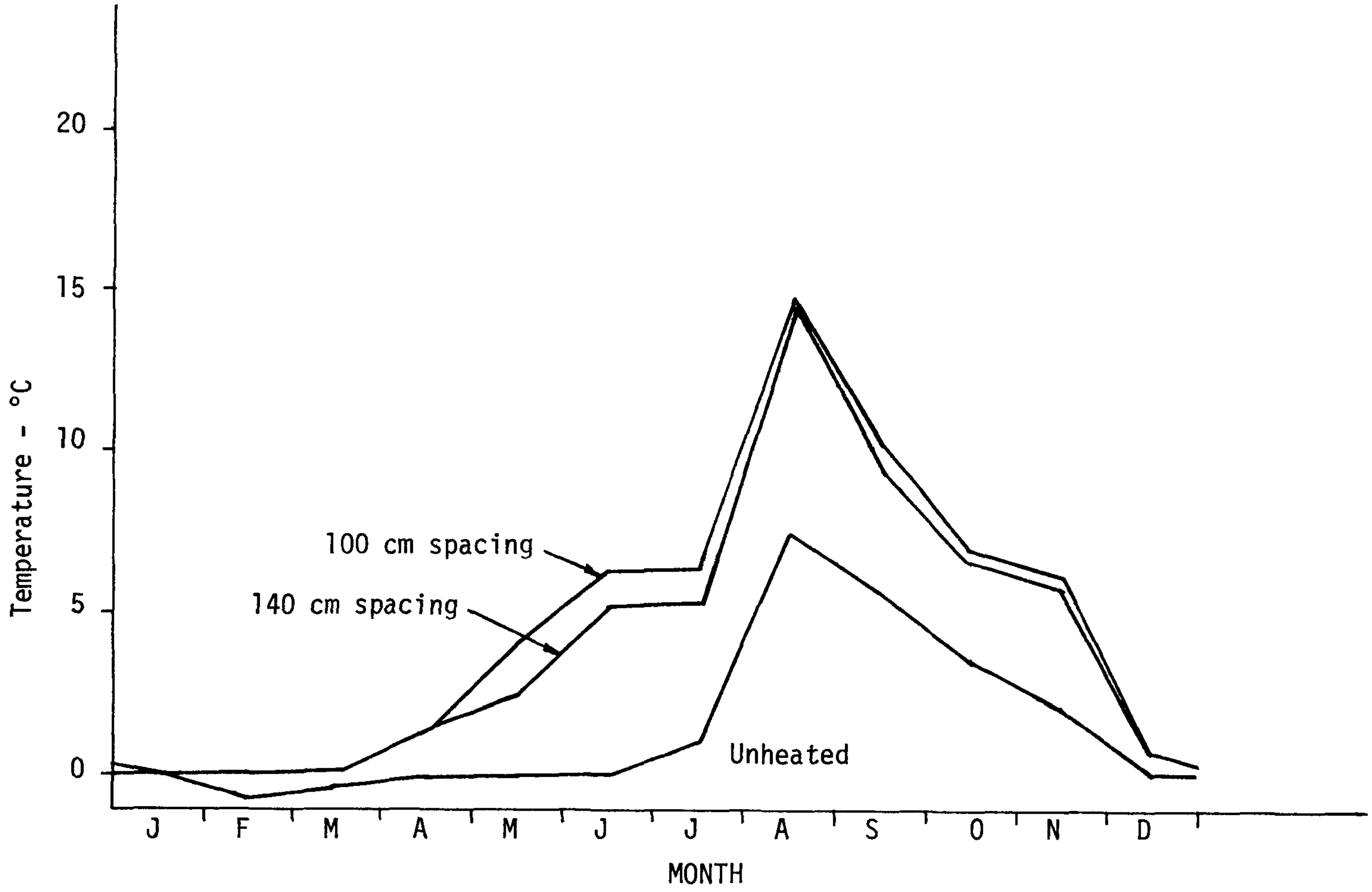

Figure 13. Annual temperature variation at 10 cm depth in St. Paul, Minn., 1970. Pipe depth is 50 cm.

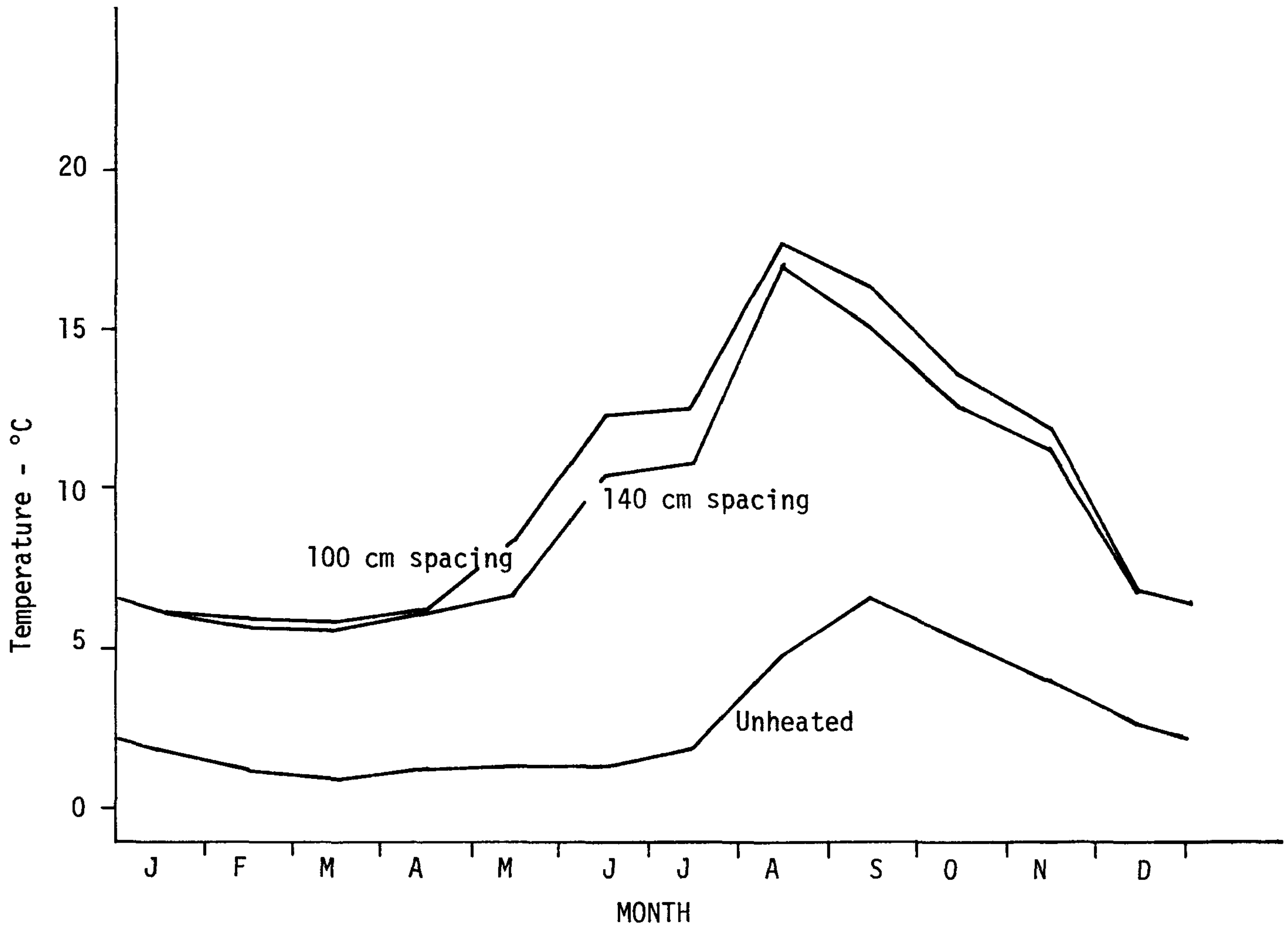

Figure 14. Annual temperature variation at 20 cm depth in St. Paul, Minn., 1970. Pipe depth is 50 cm.

$q = 0.22$ cal/cm-sec

To estimate the pumping requirement the water flow rate was calculated from an energy balance:

$$q = \dot{m}c \frac{dT}{dx}$$

Since it is desirable to minimize axial temperature gradients to provide effective soil warming, the temperature gradient $\frac{dT}{dx}$ is chosen to be small. For this calculation a 1°C temperature drop in 100 meters is chosen. The water flow rate is then:

$$m = q(c\frac{dT}{dx})^{-1}$$

$$m = (.22 \text{ cal/cm-sec}) \ \ [(1 \text{ cal/g-C}) \ \ (1°/10000 \text{ cm})]^{-1}$$
$$m = 2200 \text{ g/sec} \ \ (4.9 \text{ Ft}^3\text{/min})$$

For a 1/2" diameter pipe the average velocity is:

$$v = m/\rho_A = 1740 \text{ cm/sec } (57 \text{ Ft/sec})$$

The viscosity of water at 40C is:

$$\nu = 0.008 \text{ cm}^2\text{/sec}$$

The Reynolds number is:

$$\begin{aligned} Re_D &= VD/\nu = 1740(1.27)/.008 \\ &= 2.7 \times 10^5 \end{aligned}$$

The friction factor for a smooth pipe is:

$$f \sim 0.014$$

The pressure drop is:

$$\Delta P = f \frac{\rho v^2}{2\ g} \ \frac{L}{D}$$

$$\Delta P = .014 \frac{(1)(1740)^2}{(2)(\ 980)} \quad \frac{10000}{1.27}$$

$$\Delta P = 170{,}000 \text{ g/cm}^2 \text{ (58Psi)}$$

The pumping requirement, W, for 100 m of 1/2" diameter piping is:

$$W = m\Delta P/\rho = (2200)\ 0.7 \times 10^5$$
$$= 37.4 \text{ Watts}$$

The pressure drop for a 1" diameter pipe is:

$$\Delta P = .017 \frac{(435)^2}{2(980)} \quad \frac{10000}{2.54}$$

$$= 6461 \text{ g/cm}^2 \text{ (2.2 psi)}$$

The pumping requirement for 1" diameter piping is:

$$W = 1.42 \text{ watts/100 meters}$$

The pumping requirement for a 2" diamter pipe is:

$$W = .05 \text{ Watts/100 meters}$$

Based on a cost of 8.6¢, 12¢, and 35¢ /FT for 1/2", 1", and 2" PVC pipe, respectively, a pumping efficiency of 50%, 5 years of pumping and a cost of 3¢ /kw-hr, the costs of the piping and pumping for 100 meters are:

$$\text{Costs} = \text{Pipe Cost} + (5)\ 365(24)(.\tfrac{1}{5})(\tfrac{W}{10000})(.03)$$

= \$126.50 for 1/2"
= \$ 43.10 for 1"
= \$116.14 for 2"

Based on this simple cost analysis, the 1" diameter PVC pipe would be chosen.

SECTION V

REFERENCES

1. Beall, S. E. 1973. Conceptual design of a food complex using waste warm water for heating. Journal of Environmental Quality. Vol. 2, No. 2.

2. Berry, James W. and Herman H. Miller, Jr. 1974. A Demonstration of Thermal Water Utilization in Agriculture. U.S. Environmental Protection Agency EPA-660/2-74-011. Corvallis, Oregon.

3. Boersma, L., L. R. Davis, G. M. Reistad, J. C. Ringle, and W. E. Schmisseur. 1974. A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations. Oregon State University Engineering Experiment Station Bull. No. 48. Corvallis, Oregon.

4. Hanson, E. G., B. C. Williams, D. D. Fangmeier, and O. C. Wilke. 1970. Influence of Subsurface Irrigation on Crop Yields and Water Use. Proceedings of National Irrigation Symposium. University of Nebraska, Lincoln, Nebraska.

5. Hanson, E. G., and B. C. Williams. 1968. Subsurface Irrigation of Cotton. Proceedings of National Irrigation Drainage Speciality Conference, Phoenix, Arizona, American Society of Civil Engineers. p. 281-292.

6. Newman, J. S. 1965. Evaluation of Subirrigation of Crop Production. Proceedings of West Texas Water Conference, 3:97-103.

7. Rykbost, K. A. 1973. An Evaluation of Soil Warming for Increased Crop Production. PhD thesis. Oregon State University, Corvallis, Oregon.

8. Sepaskhah, A. R. 1974. Experimental Analysis of Subsurface Heating and Irrigation on the Temperature and Water Content of Soils. PhD thesis. Oregon State University, Corvallis, Oregon.

9. Zetzsche, J. B., Jr. 1964. Evaluation of Subirrigation with Plastic Pipe. American Society of Agricultural Engineers. Paper No. 64-731. St. Joseph, Michigan.

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16. ABSTRACT

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A computer program that solves the equations governing heat and water transfer in soils was used to simulate the operation of a soil warming system composed of a series of buried pipes at uniform spacing and depth carrying warm water. The results included temperature and moistrue content distributions for various soil warming system pipe spacings and depths and for varying weather conditions. Annual temperature cycles are presented for Portland, Oregon; Athens, Georgia; and St. Paul, Minnesota; for soil with no heating; and for soil with a continuously operating soil warming system.

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17. KEY WORDS AND DOCUMENT ANALYSIS

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